

## Normal Maturation of the Neonatal and Infant Brain: MR Imaging at 1.5 T<sup>1</sup>

The pattern of normal white-matter maturation as demonstrated with high-field-strength magnetic resonance (MR) imaging was investigated. Eighty-two neurologically normal infants were examined with a 1.5-T unit with use of spin-echo T1-weighted and T2-weighted pulse sequences. The infants ranged in age from 4 days to 2 years. The images were assessed for qualitative changes of white matter relative to gray matter in 14 anatomic areas of the brain and correlated with the patient's age. The MR images showed that changes of brain maturation occur in an orderly manner, commencing in the brain stem and progressing to the cerebellum and the cerebrum. Changes caused by brain myelination were seen earlier on T1-weighted images than on T2-weighted images, possibly because of T1 shortening by the components of the developing myelin sheaths. The later changes on the T2-weighted images correlated best with the development of myelination as demonstrated with histochemical methods. T1-weighted images were most useful in the monitoring of normal brain development in the first 6–8 months of life; T2-weighted images were more useful after 6 months. The milestones in the MR appearance of normal maturation of the brain are presented. Persistent areas of long T2 relaxation times are seen superior and dorsal to the ventricular trigone in all infants examined and should not be mistaken for ischemic change.

**Index terms:** Brain, growth and development, 10.92 • Brain, MR studies, 10.1214 • Infants, newborn, central nervous system • Infants, newborn, MR studies • Magnetic resonance (MR), in infants and children

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**T**HE brain matures in an organized, predetermined pattern, correlating with the functions the newborn or infant performs at various stages of development (1). The myelination of white matter is an important component of brain maturation because it facilitates the transmission of neural impulses through the nervous system (2). Magnetic resonance (MR) imaging is well suited to the task of assessing myelination of the brain because it surpasses both computed tomography (CT) and ultrasound (US) in contrast sensitivity (3).

White-matter maturation has been investigated with intermediate-field-strength MR (0.35–0.5 T) (4–6). In the time since these reports, 1.5-T MR units have become more widely employed in clinical settings. These units currently produce images with improved signal-to-noise ratio and, in general, improved spatial detail in comparison with intermediate-field-strength units. In addition, the T1 relaxation times are prolonged at higher field strengths. It is therefore important to establish standards for the appearance of normal white-matter maturation at 1.5 T.

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### PATIENTS AND METHODS

MR images of 82 infants were retrospectively evaluated by the authors. The patients ranged in age from 4 days to 2 years, and the age distribution is shown in Figures 1 and 2. The infants were referred for evaluation of a nonneurologic problem or a nonspecific neurologic complaint such as macrocephaly or a suspicion of child abuse. Infants with a history of prematurity, birth asphyxia, low Apgar score, neonatal seizures, sepsis, neoplasm, chemotherapy, developmental delay, or any congenital anomaly were not included in this study. Images were obtained with a superconducting magnet operating at 1.5 T (Signa; General Electric Medical, Milwaukee) with a resonant frequency of 63.8 MHz. The images were acquired with use of a 128 × 256 or 256 × 256 matrix, at 12–20-cm fields of view, and with two excitations. In the later part of the study, an extremity coil was used in the imaging of most patients under 4 months of age. A standard 24-cm head coil was employed in studying the remaining patients. Section thickness was 5 mm, with an intersection gap varying from 1 to 2.5 mm. Spin-echo (SE) sequences were obtained with a repetition time (TR) of 600 msec and an echo time (TE) of 20–25 msec in 66 patients and a TR of 2,500 msec and TE of 70 msec in 82 patients. Only the second echo of the T2-weighted sequence was evaluated, since first-echo signal sampling often occurred near the crossover point of the intensities arising from gray and white matter and resulted in diminished contrast between the two tissues in many patients.

Relative intensity and structure of the gray and white matter tracts were examined and recorded in the following 14 anatomic areas: the middle cerebellar peduncle, deep and superficial occipital white matter, deep and superficial frontal white matter, centrum semiovale, genu and splenium of the corpus callosum, anterior limb of the internal capsule, anterior and posterior portions of the posterior limb of the internal capsule, thalamus, lentiform nucleus, and pons. The relative gray- to white-matter intensity was graded subjectively by a consensus of three of the authors (A.J.B., B.O.K., D.E.J.) on a scale from +2 to –2. The normal gray- to white-matter intensity pattern of an adult

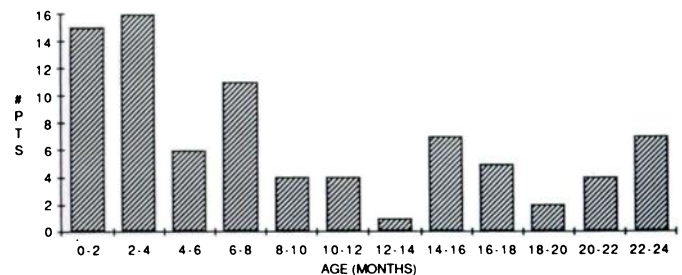
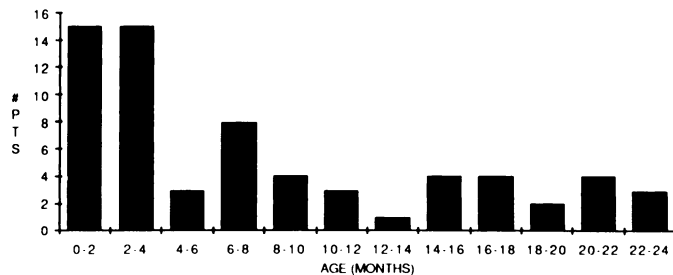
(gray matter clearly less intense than white matter on T1-weighted images, obviously more intense on T2-weighted images) was assigned a grade of +2. The reverse intensity pattern was assigned a grade of -2. Diminished or questionable contrast was given a value of +1 or -1. Areas of no contrast between white matter and adjacent gray matter were assigned a value of 0. In each region studied, the relative intensity was plotted graphically by age in order to demonstrate trends in white-matter maturation.

We performed calculations using the equations for signal intensity  $I$  in spin-echo imaging sequences. For single echoes the equation was  $I = N(H) f(v) (1 - 2e^{-(TR-T1)/T1} + e^{-TR/T1}) e^{-TE/T2}$ , where  $N(H)$  refers to the number of mobile hydrogen protons,  $f(v)$  is a term that relates to the effect of flow and was not a factor

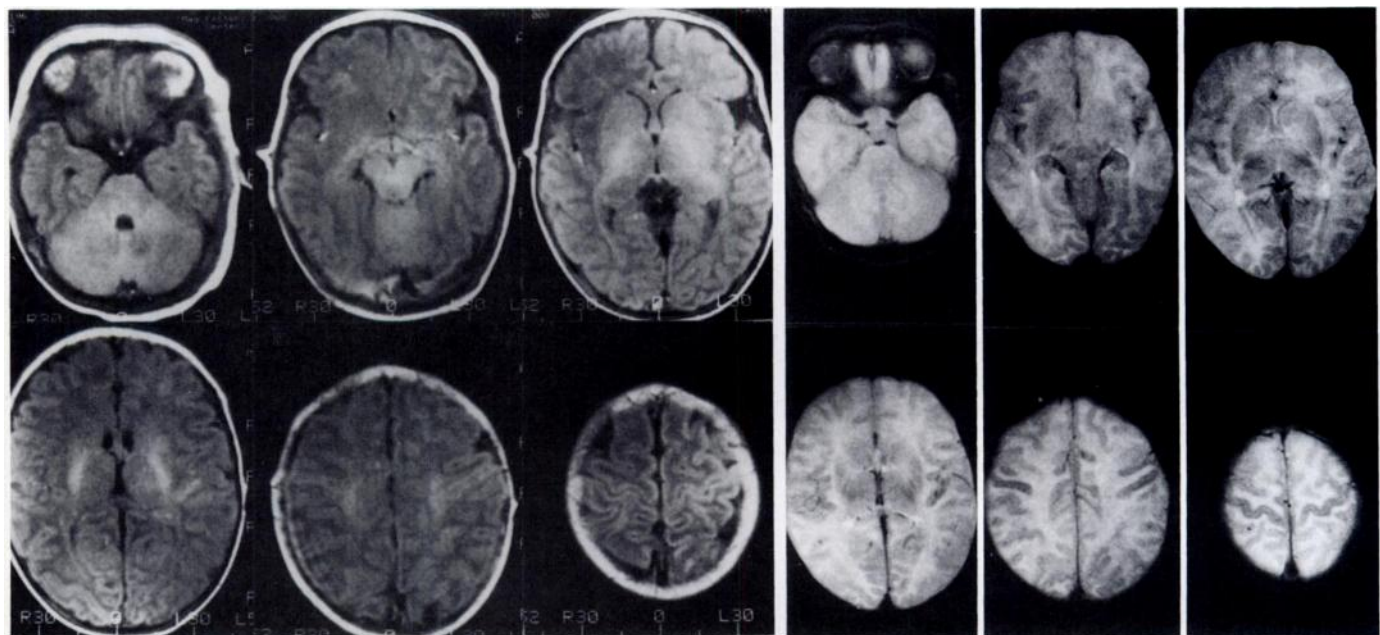
**Table 1**  
Ages when Changes of Myelination Appeared

Anatomic Region	Age when Changes of Myelination Appeared	
	T1-weighted Images	T2-weighted Images
Middle cerebellar peduncle	Birth	Birth to 2 mo
Cerebellar white matter	Birth to 4 mo	3-5 mo
Posterior limb internal capsule		
Anterior portion	Birth	4-7 mo
Posterior portion	Birth	Birth to 2 mo
Anterior limb internal capsule	2-3 mo	7-11 mo
Genu corpus callosum	4-6 mo	5-8 mo
Splenium corpus callosum	3-4 mo	4-6 mo
Occipital white matter		
Central	3-5 mo	9-14 mo
Peripheral	4-7 mo	11-15 mo
Frontal white matter		
Central	3-6 mo	11-16 mo
Peripheral	7-11 mo	14-18 mo
Centrum semiovale	2-4 mo	7-11 mo

Note.—T1-weighted sequence was SE 600/20 (TR msec/TE msec). T2-weighted sequence was 2,500/70.



**Figures 1, 2.** Histograms show the age distribution of patients whose (1) T1-weighted images and (2) T2-weighted images were used in the study.



**Figure 3.** MR images in the brain of a healthy 1-month-old infant. (a) T1-weighted images show high signal intensity in the dorsal brain stem, the decussation of the superior cerebellar peduncles, the optic tracts, the posterior limbs of the internal capsules, the optic radiations, and the central corona radiata. Also noted is increased signal intensity in the paracentral gyri. This corresponds to known myelination of the white matter within the gyri shortly after birth. (b) On T2-weighted images, the maturation of the white matter is manifested as a decrease in signal intensity. On these images, the low signal intensity is seen in the dorsal brain stem, the posterior aspect of the posterior limb of the internal capsule, the ventrolateral thalamus, and the paracentral gyri of the cortex. The T2-weighted images correspond more closely to the temporal sequence of brain myelination, as demonstrated with histochemical staining techniques.

in the areas of brain that were studied, and  $T_I$  is the inversion time. For double echoes the following equation was used:  $I = N(H) f(v) (1 - 2e^{-(TR-3T_I)/T_I} + 2e^{-(TR-T_I)/T_I} - e^{-TR/T_I})e^{-TE/T_2}$ .

Known values for the  $T_1$  and  $T_2$  relaxation times of immature brain (4) were substituted into the equation, along with the  $TR$  and  $TE$  values for our  $T_1$ -weighted and  $T_2$ -weighted spin-echo imaging sequences. A series of calculations was then performed, while varying the values of  $T_1$  and  $T_2$  by 1%, to determine the relative sensitivity of the  $T_1$ - and  $T_2$ -weighted sequences to these values.

## RESULTS

In general, the changes in white-matter maturation were seen best on  $T_1$ -weighted images during the first 6 months of life and on the second echo of the  $T_2$ -weighted images between the ages of 6 and 18 months. Maturation generally proceeded from central to peripheral (centrifugal), from inferior to superior, and from posterior to anterior. The results are summarized in Table 1.

### $T_1$ -weighted Images

The overall appearance of  $T_1$ -weighted images in neonates was similar to that of  $T_2$ -weighted images in adults: White matter was of lower

signal intensity than was gray matter. The intensity of white matter relative to gray matter increased with maturation.

Neonatal posterior fossa structures including the medulla, the dorsal midbrain (Fig. 3), and the inferior and superior cerebellar peduncles exhibited high signal intensity at birth. An increase in signal intensity of deep cerebellar white matter appeared near the end of the 1st month and steadily increased, with arborization into the folia appearing in the 3d month. By 3 months of age, the cerebellum had an appearance like that seen in the adult (Fig. 4). Signal intensity in the basis pontis increased less rapidly, occurring during the 3d-6th months.

Neonatal supratentorial structures including the decussation of the superior cerebellar peduncles, the ventral lateral region of the thalamus, and the posterior limb of the internal capsule exhibited high signal intensity (Fig. 3) at birth. This high signal intensity proceeded rostrally from the pons along the corticospinal tracts into the cerebral peduncles, posterior limb of the internal capsule, and central portion of the centrum semiovale. The pre- and post-central gyri were of high signal intensity by about 1 month of age

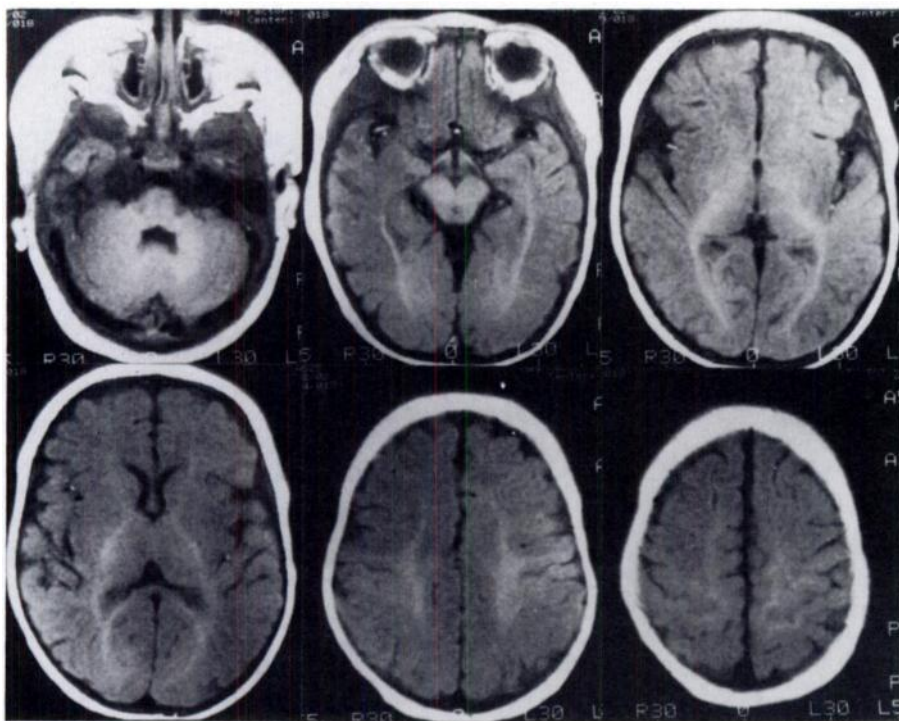
(Fig. 3). The change to high signal intensity in the motor tracts was essentially complete by 3 months. In infants younger than 1 month of age, high signal intensity was present in the optic nerve, optic tracts, and optic radiations; extension into the occipital white matter surrounding the calcarine fissure was present by 3 months of age (Fig. 4). While the posterior limb of the internal capsule was of high signal intensity at birth, high signal intensity did not develop in the anterior limb until subjects reached 2-3 months of age. The splenium of the corpus callosum showed an increase in signal intensity in all infants by 4 months (Fig. 5). The increase in signal intensity proceeded rostrally; the genu was of high signal intensity in all cases by 6 months (Fig. 6). Typically, at 3-4 months the splenium was high in signal intensity, while the genu was low in signal intensity. Maturation of the subcortical white matter other than the visual and motor cortices was seen beginning at 3 months. The deep white matter matured in a dorsal to rostral direction, with the deep occipital white matter maturing first and the frontal white matter last. Peripheral extension and increasing complexity of arborization of the subcortical white matter continued until approximately 7 months in the occipital white matter and 8-11 months in the frontal white matter. Minimal changes were seen on the  $T_1$ -weighted images after 8 months.

### $T_2$ -weighted Images

The overall appearance of the newborn brain on  $T_2$ -weighted images was similar to that of the adult  $T_1$ -weighted image in that the white matter was more intense than the gray matter. Maturation in these sequences was seen as the reduction in intensity of white relative to gray matter.

In the posterior fossa at birth, the inferior and superior cerebellar peduncles and the dorsal pons were of low signal intensity (Fig. 3). The middle cerebellar peduncles began to decrease in signal intensity in the 2d-3d months. Arborization began to develop at approximately the 8th month and reached an adult appearance at approximately 18 months.

In the neonate, the decussation of the superior cerebellar peduncles, the ventral lateral region of the thalamus, and faint patches of the posterior portion of the posterior limb of the internal capsule were of



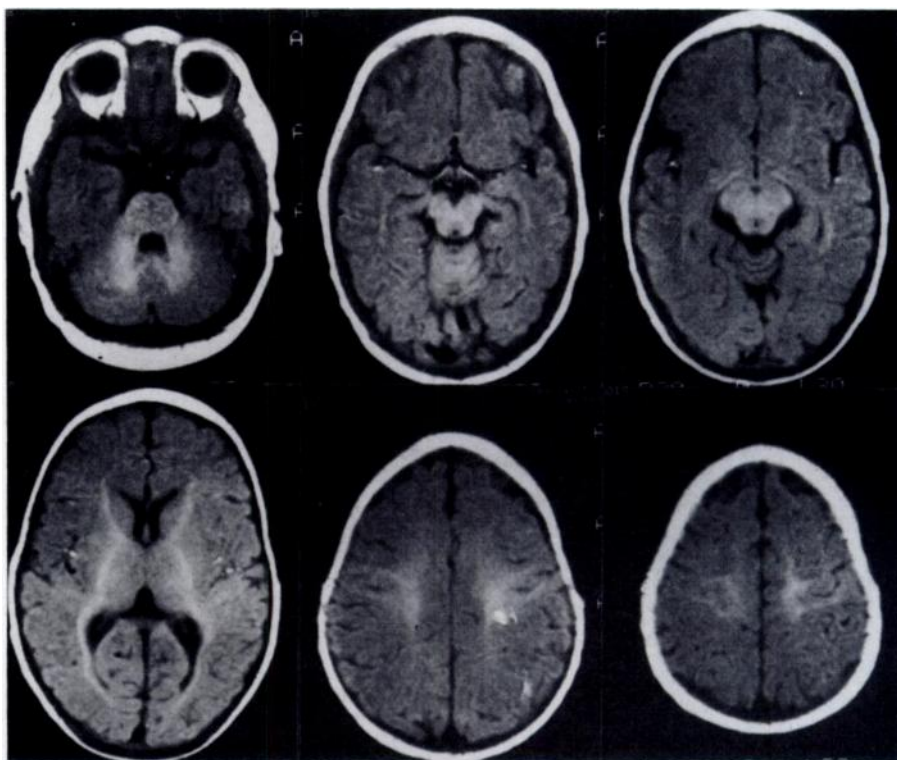
**Figure 4.** MR images in the brain of a healthy 3-month-old infant.  $T_1$ -weighted images show high signal intensity, indicating maturation of the middle cerebellar peduncles and the ventral aspect of the brain stem. Moreover, white-matter maturation is now seen in the anterior limbs of the internal capsule, and there is more extensive maturation of the optic radiations. In the centrum semiovale there is crude arborization of the high signal intensity into the subcortical white matter of the paracentral gyri. The relative high signal intensity of the paracentral gyri themselves has receded by this age.

low signal intensity (Fig. 3). By less than 1 month, the cortex of the pre- and post-central gyri appeared to have lower intensity than the surrounding cortex. At 2 months, patches of low intensity were seen in the central centrum semiovale (Fig. 4), but the paracentral gyri were harder to distinguish from surrounding gyri because the adjacent gyri and subjacent white matter were diminished in intensity. This trend continued, and by 4 months the intensity of paracentral gyri was indistinguishable from that of adjacent gyri. Myelination of the optic tracts began at 1 month; the decrease in signal intensity extended posteriorly along the optic radiations. At 4 months, the calcarine fissure showed evidence of myelination (Fig. 5).

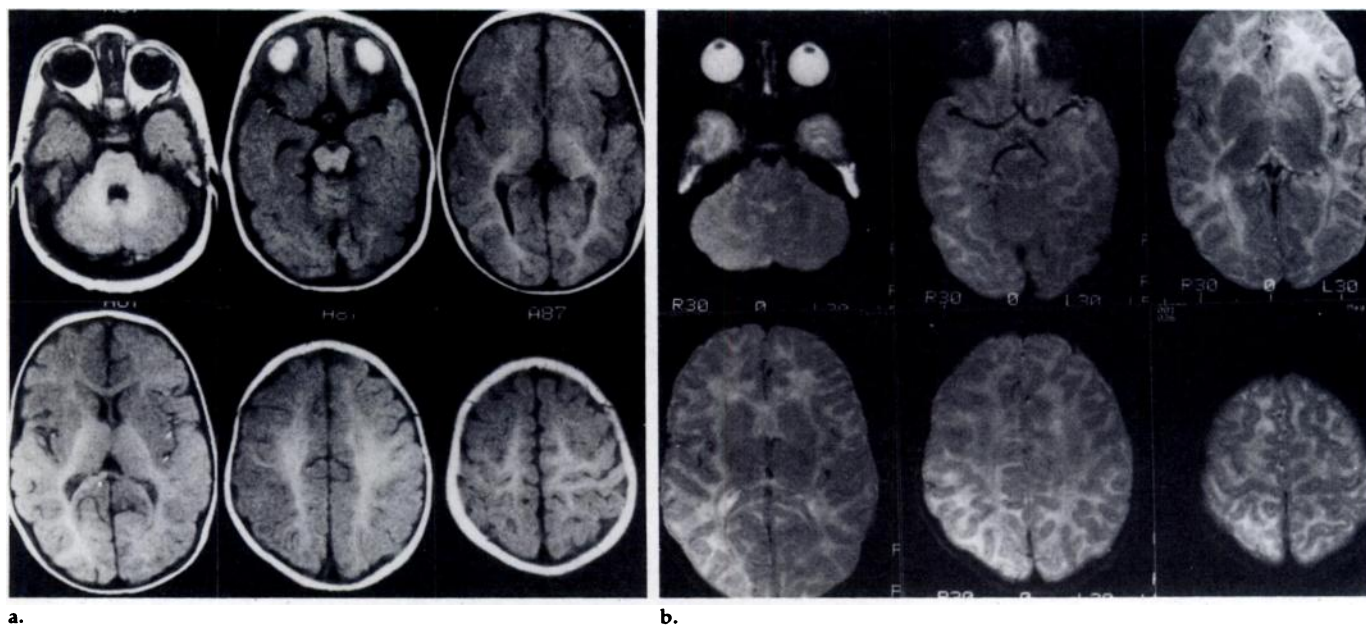
Most deep white-matter tracts myelinated between 6 and 12 months. The internal capsule appears to acquire myelin in a posterior to anterior fashion. The more anterior portion of the posterior limb was visible but thin by approximately 7 months, with progressive thickening up to 10 months. The anterior limb of the internal capsule appears completely myelinated by 11 months in all patients and was detected as early as 7 months in some patients. The corpus callosum matured first in the splenium at 6 months (Fig. 6b) and then in the genu at 8 months (Fig. 7b). The basal ganglia began to diminish in signal intensity relative to the sub-

cortical white matter at 7 months (Fig. 7). This appearance gradually faded, as the surrounding brain lost signal intensity, and was no longer apparent by approximately 10 months (Fig. 8).

The subcortical white matter (other than the calcarine and rolandic areas) matures last, proceeding from the occipital region anteriorly to the frontal lobes, beginning at 9-12 months in the occipital lobe and 11-14



**Figure 5.** MR images in the brain of a healthy 4-month-old infant. T1-weighted images show rostral progression in maturation of the internal capsule, with the anterior limbs now well myelinated. The splenium of the corpus callosum is always myelinated by this age (although not well shown on this image). There is increasing arborization of the white matter in the paracentral regions.



**Figure 6.** MR images in the brain of a healthy 6-month-old infant. (a) T1-weighted images show further progression of brain maturation. Both the splenium and the genu of the corpus callosum are of high signal intensity at this stage. There has been marked progression of the maturation of the centrum semiovale with increased arborization, most notably in the occipital and paracentral regions. (b) On T2-weighted images there is a diminution in signal intensity deep within the centrum semiovale. There is also a relative decrease in the signal intensity of the basal ganglia with respect to the surrounding brain. The splenium of the corpus callosum is of low signal intensity, and there are patches of low signal intensity within the callosal genu.

months frontally (Fig. 9). Peripheral extension of the fine-arborization pattern began at about 1 year and was essentially complete by 18 months (Figs. 10, 11). During the progress of the peripheral extension of the white matter, the mantle of gray matter gave the appearance of pro-

gressive thinning, and the subcortical white matter often had an inhomogeneous appearance.

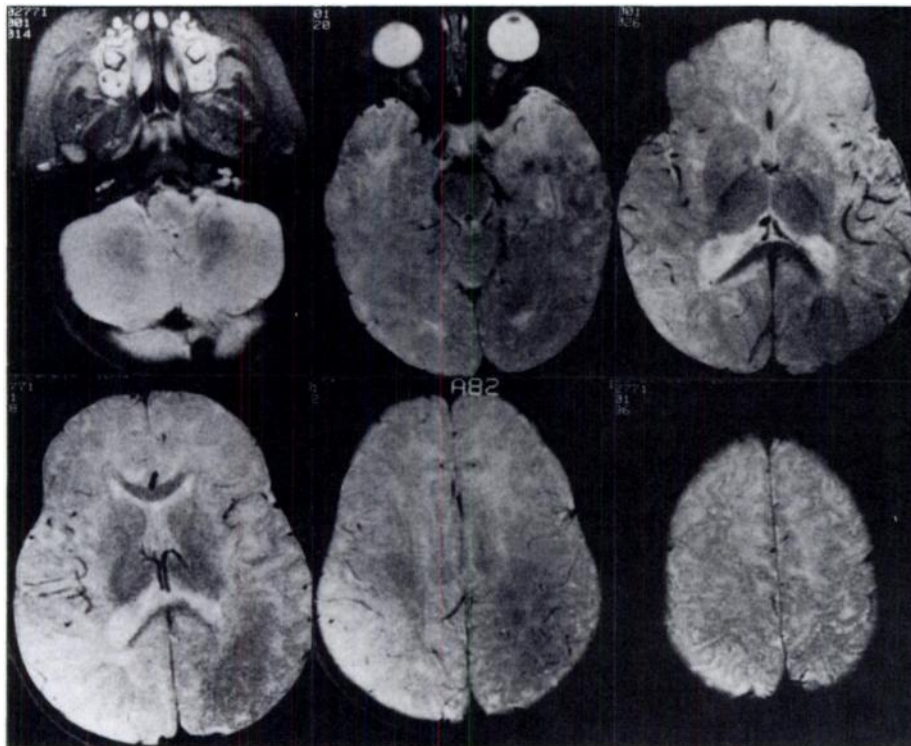
As maturation in the centrum semi-ovale progressed, all subjects examined had a persistent area of high signal intensity in the white matter dorsal and superior to the ventricular

trigones (Fig. 12). This area was most often homogeneous, while in some it was patchy. In all instances the margins of the area were indistinct. It was never associated with any other high-intensity areas in the surrounding white matter.

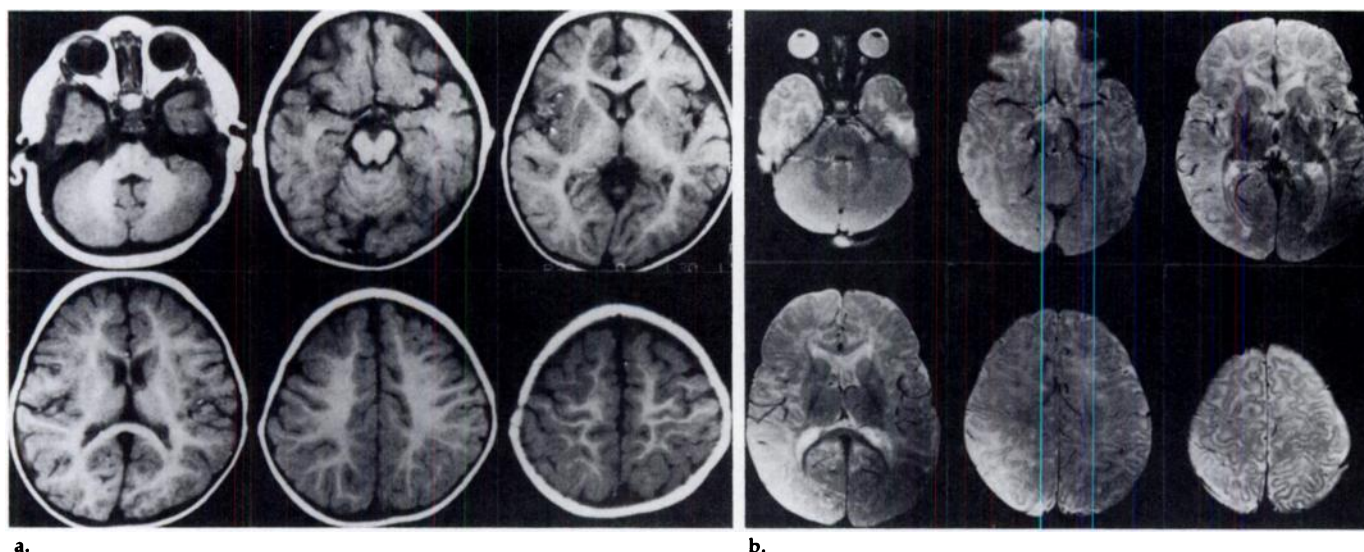
## DISCUSSION

Myelination of the brain begins during the 5th fetal month with the myelination of the cranial nerves and continues throughout life (1). Although normal patterns and chronology of myelination have been established through pathologic studies, their significance and relationship to normal and delayed development have remained unknown. In this communication, we attempt to establish detailed patterns of normal brain development using high-field-strength (1.5-T) MR imaging and to relate the observed changes on the MR images to the biochemical changes of the developing brain and the functional progress of the developing infant.

Our results substantiate previous reports in terms of the chronology of the myelination as manifested by decreased intensity on T2-weighted images (4). Use of a higher field strength with a larger matrix has allowed us to obtain better signal-to-noise ratio and increased spatial resolution, permitting greater confidence levels in determining patterns of myelination. This is exceedingly important in the correlation of specific clinical pictures with the MR find-



**Figure 8.** MR images in the brain of a healthy 10-month-old infant. T2-weighted images demonstrate decreasing signal intensity of the white matter diffusely throughout the brain. This causes a recession of the appearance of hypointensity of the basal ganglia noted in the 6- and 8-month-old patients. The cortex and underlying white matter are essentially isointense throughout most of the brain at this stage. The anterior limbs of the internal capsule were hypointense in nearly all patients at this age.



**Figure 7.** MR images in the brain of a healthy 8-month-old infant. (a) T1-weighted images at this stage show essentially an adult appearance. Fine arborization of the white-matter tracts is seen in the paracentral and occipital regions. Fine arborization is not yet present in the frontal regions. (b) On T2-weighted images, the anterior limbs of the internal capsule are starting to show diminished signal intensity. Both the splenium and the genu of the corpus callosum are of low signal intensity at this age. In the occipital region, the white matter has diminished in signal intensity to the point of isointensity with the calcarine cortex. This same isointensity is present in the paracentral regions.

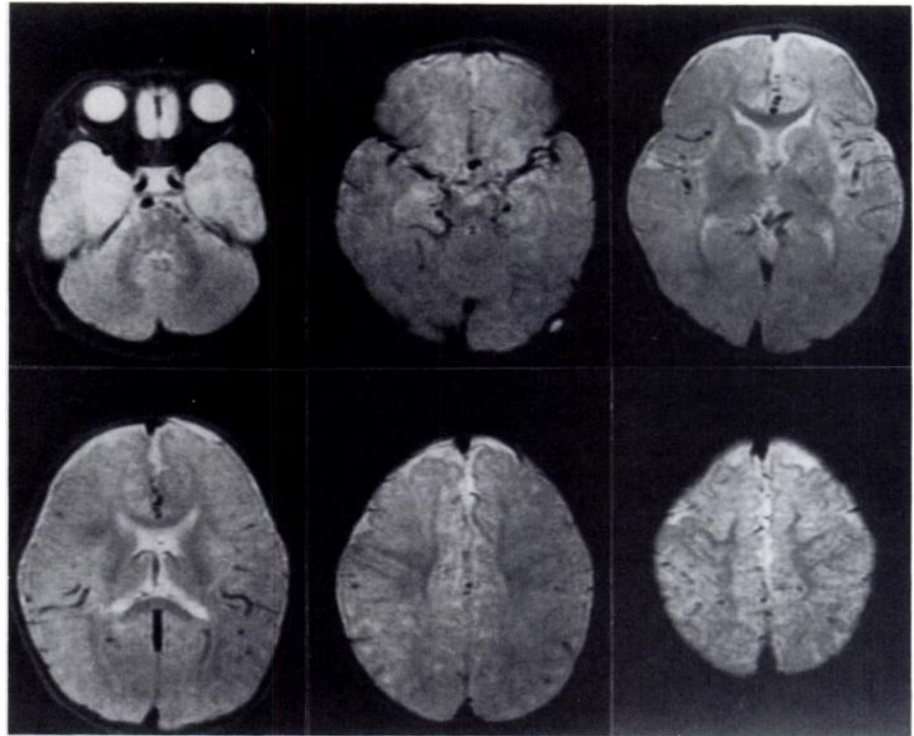
ings. The changes in signal intensity seen on T2-weighted images closely parallel the known pattern of myelination as determined by histochemical studies (1). In the central nervous system, myelination of fiber systems mediating sensory input to the thalamus and cerebral cortex precedes myelination of those that correlate the sensory data into movement.

Therefore, in the brain stem the median longitudinal fasciculus, lateral and medial lemnisci, and inferior and superior cerebellar peduncles, which transmit vestibular, acoustic, tactile, and proprioceptive sense, are myelinated at birth, whereas the middle cerebellar peduncles, which integrate cerebral activities into the cerebellum, acquire myelin later and more slowly. Similarly, in the cerebrum, the geniculate and calcarine (optic), postcentral (somesthetic), and precentral (proprioceptive) regions acquire myelin early, whereas the posterior parietal and frontal areas, which integrate the sensory experience, acquire myelin later.

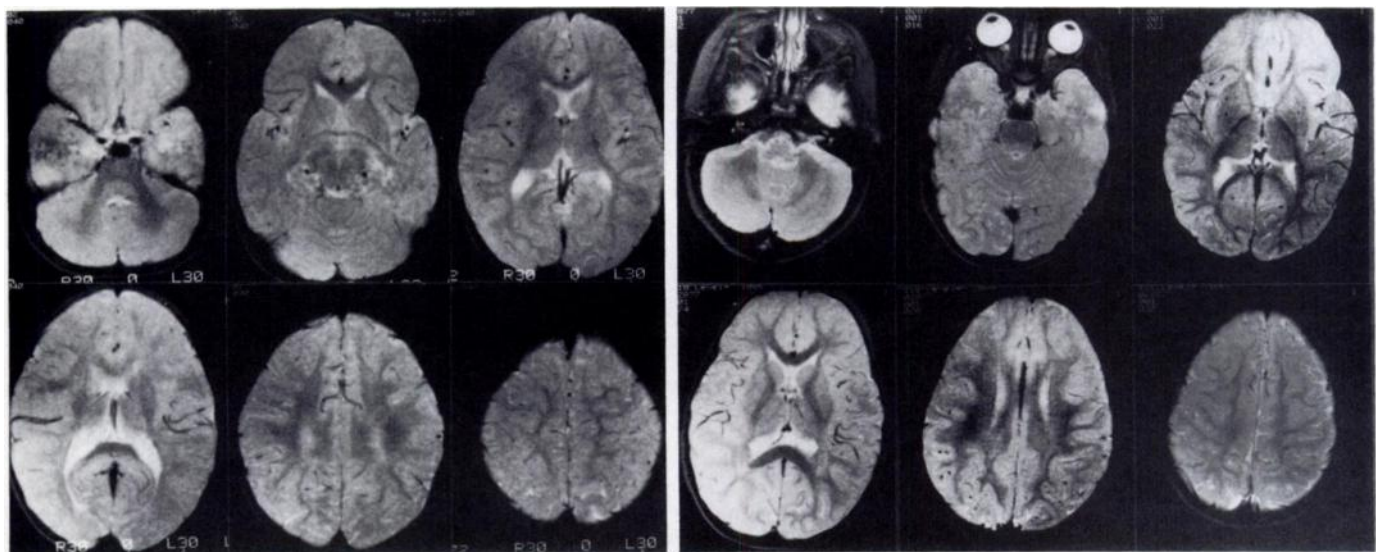
At birth, the dorsal pons, portions of the superior and inferior cerebellar peduncles, the decussation of the superior cerebellar peduncles, the retrolenticular internal capsule, and the lateral thalamus are partially myelinated. These are seen as areas of decreased intensity on the T2-weighted MR images of newborns. Changes occur rather slowly on these images in the first 6 months of life. Some decreased intensity in the optic

tracts and radiations is seen by approximately 2 months, with extension into the calcarine cortex by approximately 4 months. Some decreased intensity is seen in the white matter of the precentral gyrus at approximately 1-2 months, corresponding to the known myelination within this gyrus of specific thalamic

fibers (1). Myelination progresses anteriorly in the internal capsule as first sensory, then motor, and finally association tracts acquire myelin. The anterior limb of the internal capsule is always myelinated by the end of the 11th month. The corpus callosum also acquires myelin from posterior to anterior, with decreased intensity



**Figure 9.** MR images in the brain of a healthy 12-month-old infant. Deep white matter is for the first time hypointense with respect to gray matter at this stage. Some arborization of this low intensity is seen in the paracentral regions.



10.

11.

**Figures 10, 11.** (10) MR images in the brain of a healthy 15-month-old infant. The maturation of the deep white matter has progressed significantly since the 12-month-old stage. Although still somewhat patchy, the supratentorial white matter now shows a great deal of arborization throughout the hemispheres. Note that the arborization and maturation of the white matter is delayed most in the frontal regions. (11) MR images in the brain of a healthy 18-month-old infant. At this age, except for a few patchy areas, the maturation of the white matter is complete on T2-weighted images. A small amount of fine arborization will continue to occur, particularly in the frontal and parietal regions.

seen in the splenium by 6 months and the genu by 8 months, and with uniform decreased intensity in the corpus callosum by approximately 10 months. Myelination of the basal ganglia anticipates that of the centrum semiovale, becoming decreased in intensity by approximately 6 months. This relative appearance recedes as the centrum semiovale acquires myelin.

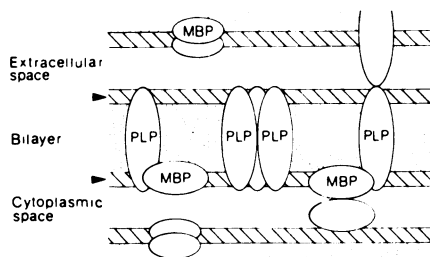
It was puzzling that the increase in signal intensity on T1-weighted images preceded the decrease in intensity on the T2-weighted images, if both changes of intensity were secondary to myelination. Moreover, the discrepancy is mild in certain areas (2 months in the corpus callosum) but marked in others (a 6–10-month delay in the maturation of the centrum semiovale on the T2-weighted images as compared with the T1-weighted images). We performed calculations to determine whether the



**Figure 12.** Axial SE 2,500/70 image of a 15-month-old infant. Persistent areas of high signal intensity occur superior and posterior to the ventricular trigones (arrowheads). These areas are believed to represent the known areas of delayed myelination within the brain ("terminal zones") and should not be mistaken for areas of ischemia or brain damage.

changes we see on the T1- and T2-weighted sequences actually reflect a greater change in T1 contrast than in T2 contrast or whether the T1-weighted sequence is significantly more sensitive to changes in T1 than the T2-weighted sequence is to changes in T2. We found that for T1 and T2 values in the range of immature brain (4), T1- and T2-weighted sequences had similar sensitivity to proportional changes in T1 and T2, respectively. Therefore, the earlier changes on T1-weighted images probably reflect actual T1 contrast preceding T2 contrast in the developing brain. To understand why this increased T1 contrast occurs, it is necessary to examine more closely the structure and maturation of myelin.

Although the precise chemical structure has not been elucidated, myelin (like other membranes) is composed of a bilayer of lipids with several large proteins, most of which



**Figure 13.** Schematic drawing illustrates the probable structure of myelin. Myelin is composed of a bilayer of lipids with several large proteins, most of which span the bilayer (including myelin basic protein [MBP] and proteolipid protein [PLP]). The outer lipid layers (arrowheads) are composed mainly of cholesterol and glycolipids, while the inner portion of the lipid bilayer is composed mainly of phospholipids. It is thought that the high signal intensity seen on T1-weighted images with the maturation of white matter results from T1 shortening caused by the cholesterol, glycolipids, and possibly the proteins in the outer lipid layers of the membrane, whereas it is thought that the diminishing signal intensity seen on the T2-weighted images with maturation results from a decreased number of water molecules caused by the development of the hydrophobic phospholipid inner layer. (Drawing adapted from reference 7.)

span the bilayer (7) (Fig. 13). It has been shown that the composition of the outer layer of the membrane (that communicating with the extracellular space) is close to 50% cholesterol, the remainder being largely glycolipid (7). Svennerholm and Vanier (8) have studied the changing chemical makeup of myelin during brain development. They demonstrated that the proportions of both cholesterol and glycolipid increase in myelin for the first 6–8 months, and that at 6 months the adult ratio is reached and the proportion of these substances remains constant. Since the appearance of T1 shortening occurs in the same topographical sequence as myelination and temporally parallels the rise of cholesterol and glycolipid concentration in myelin, a relationship between these events can be postulated. Moreover, it is known that cholesterol causes shortening of the T1 relaxation time of water (9); glycolipids could presumably do the same if the lipid chains were of the correct length to tumble at or near the Larmor frequency. Proteins can also cause shortening of the T1 of water, and it is known that the protein components of the developing myelin bilayer are accessible to water molecules at the cytoplasmic and extracellular surfaces (7). It seems reasonable to postulate that the likely cause of the early increase in intensity corresponding to the maturation of cerebral white matter is shortening of the T1 relaxation time of the water in the white matter by the protein, cholesterol, or glycolipids in the developing myelin sheaths.

This decreasing signal intensity on T2-weighted images correlates with myelination not only topographically but also temporally. As suggested by Holland et al. (4), these findings are best explained by the decrease in water content of the brain over the first 2 years of life. The loss of water is at least in part secondary to the development of the hydrophobic interior of the lipid bilayer. Svennerholm and Vanier (8) have demonstrated a decrease in the number of saturated long-chain fatty acids in the cerebral white matter over the first 2 years of life with a corresponding increase in monoenes (fatty acids with one double bond). Braun (7) has postulated that the increased rigidity of these monoenes, which are mostly phospholipids, plays an important role in creating and maintaining the hydrophobic fluid structure of the inner lipid layer. Moreover, the Weigert stain, used by Yakovlev and Lecours

**Table 2**  
**MR Imaging (1.5 T) Milestones for Normal Myelination of Brain**

Area of Brain	Maturation Detected (mo)	
	First 6 Months T1-weighted Images	After 6 Months T2-weighted Images, 2d Echo
Cerebellar white matter	3	...
Splenium	4	6
Genu	6	8
Anterior limb of internal capsule	...	11
Frontal white matter	...	14
Adult pattern	...	18

(1) to detect histochemically the process of myelination in cadaver brains, is fairly specific for phospholipids (10). It follows that as myelin matures, it becomes increasingly hydrophobic because of the development of the inner layer of phospholipids. This hydrophobic layer results in the presence of fewer aqueous protons and a diminution in signal intensity on the long TR/long TE spin-echo image secondary to both shortened T2 relaxation time and decrease in spin density. The decrease in water content will be less apparent on T1-weighted images because the increased signal caused by decreased T1-relaxation time is offset by the decrease in spin density.

To summarize the preceding part of the discussion, it seems that heavily T1-weighted images are a better way of detecting the primary process of myelination, whereas T2-weighted images seem better in the evaluation of the associated changes of water loss. Even more heavily T1-weighted imaging sequences, such as inversion-recovery sequences or spin-echo sequences with even shorter repetition and echo times, may prove to be even more sensitive in the detection of developing myelination.

The finding of high signal intensity in the peritrigonal white matter on T2-weighted images is significant because this is a region and an appearance typical of periventricular leukomalacia (10-12). In our limited experience, the lesions of periventricular leukomalacia are more sharply defined and situated more anteriorly and inferiorly near the optic radiations. Moreover, they tend to be more circular in shape, as opposed to the triangular configuration of the regions lying posterior and superior to the trigones in our patients (Fig. 12). The cause of the high intensity signal in these areas may be the known delayed myelination of the fiber tracts involving the association areas of the convexities of the posterior and inferior parietal and posterolateral temporal cortex, which Yakovlev and Lecours called "terminal areas" (1). Some of these regions rarely stain for myelin until the 4th decade (1). We have noticed variable high signal intensity in these areas in pediatric patients throughout the 1st decade and into the 2d decade.

We have identified what we believe are significant milestones in

brain maturation (Table 2). These should be helpful in the identification of those brains in which maturation is delayed. In the first 6 months, the T1-weighted images are the most useful. Extension of high signal intensity distally into the interspaces between the cerebellar folia should be seen by 3 months. The splenium of the corpus callosum should be of moderately high signal intensity by the 4th month, and the callosal genu should be of high signal intensity by 6 months. A pattern essentially identical to that seen in the adult is seen by approximately 8 months. After the subject is 6 months of age, the T2-weighted images become more useful. On these images, the splenium of the corpus callosum should be of low signal intensity by 6 months of age, the genu by 8 months of age, and the anterior limb of the internal capsule by 11 months of age. The deep frontal white matter should be of low signal intensity by 14 months, and the entire brain should have an adult appearance (except for some fine peripheral arborization) by 18 months. The slight disparity of our results compared with those of Holland et al. (4) is most likely a result of the somewhat limited sample size in their study and the ability of our imager to depict finer subtleties in the white-matter changes.

Nowell et al. (13) recently advocated the imaging of newborns and infants with TRs in the range of 3,500 msec in order to overcome the high water content in the infant brain. We found adequate contrast resolution between gray and white matter with a TR of 2,500 msec, even in the youngest patients. Moreover, adequate contrast between gray and white matter was obtained on our T1-weighted sequences with a TR of 600 msec and a TE of 20 msec. Good sedation and the increase in signal-to-noise ratio obtained by the use of an extremity coil in small infants were the most important factors in image quality.

In summary, brain maturation occurs in an orderly manner, commencing in the brain stem and progressing to the cerebellum and cerebrum. The changes appear at different times with T1- and T2-weighted MR images, possibly because of T1 shortening by the components of the developing myelin sheaths. The difference in the maturation rate makes the T1-weighted images more useful in the first 6-8 months of life and the T2-

weighted images more useful thereafter. The maturation of certain key regions of the brain can be used to establish milestones for normal development. A triangular region posterior and superior to the trigones of the lateral ventricles matures quite slowly and should not be mistaken for infarcted or injured tissue. ■

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