The Grand Unifying Theory of Bright Echoes in the Fetal and Neonatal Brain

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The purpose of this presentation is to illustrate that the high-amplitude reflecting structures in the fetal and neonatal brain can be explained by the echogenicity of their leptomeningeal coverings or leptomeningeal origins. The leptomeninges, especially the pia mater, constitute the “grand unifying theory of bright reflectors” in the fetal and neonatal brain. Images from fetal and neonatal sonograms were selected to illustrate the objectives above.

Key Words—brain anatomy; fetus; neonate; pia mater; sonography

Sonography of the fetal and neonatal brain has advanced dramatically over the past several decades. Investigational interest in the fetal brain has been driven primarily by the desire to diagnose fetal anomalies because central nervous system anomalies are among the most common and devastating of birth defects. Initially, only marked abnormalities such as anencephaly and advanced hydrocephalus were discovered in utero. Today, advancements in instrumentation allow for the accurate diagnosis of many malformations of the brain, even before 20 weeks of development.

Additionally, correlation of sonography of the premature neonatal brain with known developmental neuroanatomy has resulted in a much improved understanding of the appearance of the fetal brain because examination of “newborn children” now begins commonly at 25 to 26 weeks of development (essentially a late-second-trimester fetus).

A clear understanding of normal developmental anatomy is the foundation from which to diagnose anomalous development. Many errors of interpretation were made during the initial period of sonographic evaluation of normal fetal intracranial anatomy. These errors occurred because “fluid” and “solid” areas of the brain did not appear as anticipated: it was initially expected that the lateral ventricles would appear anechoic, being dominated by cerebrospinal fluid (CSF). Instead, their appearance was dominated by a highly echogenic choroid plexus. Conversely, the bulk of neural tissue (the telencephalon, diencephalon, and mesencephalon) is relatively hypoechoic compared with other solid tissues in the human body.

Intracranial structures that generate high-amplitude echoes are typically easy to observe and least likely to be obscured by technical problems. Two types of tissue are brightly echogenic and, therefore, most easily seen during the examination of the fetal and neonatal brain. These tissues are the choroid plexus and the brain coverings: the dura (pachymeninx) and pia-arachnoid (leptomeninx), both...
formed by mesenchymal cells that migrate to the developing head from the neural crest and prechordal mesenchyme. Interestingly, and importantly from the perspective of this analysis, the stroma of the choroid (the part of the choroid plexus within its thin walls made of tela choroidia) is formed by those same mesenchymal cells within the developing leptomeninx, which migrate into the invaginating tela choroidia (the precursor of the definitive choroid plexus) during the seventh embryonic week. Therefore, it seems that all intracranial structures that generate high-amplitude ultrasonic reflections are pia. This idea is the basis of the grand unifying theory of bright echoes in the brain.

What is the source of these echoes? An understanding of this question requires some knowledge of the structure of the leptomeninges and the subarachnoid space. The arachnoid layer is composed of large cells with numerous cell junctions, no extracellular space, and no extracellular collagen. The many tight junctions in this layer serve as a barrier to the movement of fluids and ions. The layer also contains fibroblasts that attach to the inner surface of the arachnoid layer and form specialized arachnoid trabeculae that bridge the subarachnoid space and surround the vessels contained within it as well as attach to pia on the surface of the brain (Figure 1). We propose that the combination of the large cells of the arachnoid layer, the arachnoid trabeculae, and the vessels within the subarachnoid space are the source of the characteristic echoes that characterize the surface of the developing brain and allow one to explain the variations in echogenicity seen in the cisterns surrounding the fetal and neonatal brain. The following pictorial essay explores specific central nervous system structures in the fetus and neonate, with an emphasis on the echogenicity attributable to the relative amount of leptomeningeal/choroid tissue.

The Brightest Echogenic Structures

The most strikingly echogenic structures in the fetal and neonatal brain are the choroid plexus, the brain surface, certain cisterns surrounding portions of the brain, and the deep medullary veins. Their strikingly bright echogenicity compared to surrounding structures can be explained by the their leptomeningeal coverings or leptomeningeal origins. As mentioned above, the brightly echogenic choroid plexus develops by an invagination of vascular pia and dominates the sonographic appearance of the lateral ventricles by the end of the first and beginning of the second trimesters (Figure 2, A and B). By contrast, the mantle of the developing cerebral cortex surrounding the lateral ventricle is hypoechoic. Specular reflections arising from the walls of the lateral ventricle where they are intersected perpendicularly delimit the ventricle from the cortex (Figure 2C). The choroid plexus of the neonatal brain has an identical appearance to that of the fetus and is imaged with great clarity via the anterior, lateral, and posterior fontanelles (Figure 2D).

The Brain Surface and Cisterns

The progressively changing surface of the fetal cerebral cortex can be followed throughout development because of the brightly visible margin due to the pial covering of the brain surface. The echogenic leptomeningeal rim highlights the margins of the cortex, showing a smooth cortical rim early in development (Figure 3A) and later outlining the major fissures and sulci of normal cerebral development (Figure 3B). The bright margination provided by the leptomeninges enables one to visualize many relevant brain surfaces, providing the anatomic detail necessary to recognize specific brain anatomy.

Peripheral to the brightly echogenic meningeal surface of the cortex lies the subarachnoid space. The inexperienced sonologist is often initially confused by the appearance of the subarachnoid space, anticipating that it will be dominated by CSF contained within the space (much as early sonol-
Figure 2. A. Axial sonogram of the fetal brain at approximately 13 weeks. The lateral ventricles can be clearly seen, appear ovoid, and are largely filled with choroid plexus (asterisks). The choroid is the easiest structure to recognize because of its size and high-amplitude echogenicity. B. Parasagittal sonogram of the fetal brain at approximately 12 weeks. The choroidal tissue (asterisk) is again the brightest reflector visible. C. The hypoechoic cortical mantle can be distinguished from the echogenic choroid (asterisk) via a thin linear specular reflection (arrow) off the ependymal lining. D. Parasagittal view of the neonatal brain showing an appearance of the intraventricular choroid (asterisk) identical to that seen in utero. Also well seen is the choroidal fissure through which the tela choroidea invaginates to form the definitive choroid plexus. The fissure is virtually “filled” with leptomeninges and, thus, remarkably bright (arrow). Arrowhead indicates specular reflection at the junction of brain tissue and the ventricle.
ogists anticipated that the lateral ventricles would look like fluid-filled cavities. Although it is reasonable to anticipate that the subarachnoid space will be anechoic and the brain parenchyma relatively echogenic, this assumption is untrue in many instances. In fact, the CSF spaces may be more echogenic in various locations than the cortex.

The variability in the echogenicity of cisterns is dependent on the amount of CSF contained within the cistern versus the amount of leptomeninges contained therein. As noted above, the bright margination provided by the leptomeninges within cisterns enables one to recognize specific brain anatomy. The perimesencephalic cisterns are striking examples. The amount of leptomeninges dominates. The ambient cisterns are filled with nerves, veins, and arteries, each of which has a leptomeningeal covering. Thus these, are almost universally observed as brightly echogenic from fetus to fetus or neonate to neonate (Figure 4A). Conversely, the cisterna magna is almost completely filled with CSF (very few structures pass through it) and thus is consistently seen as anechoic (the walls of the Blake pouch are seen passing through the cistern as bright reflectors; Figure 4B). The convexity cisterns are more variable due to greater or lesser numbers of visible bridging vessels and arachnoid trabeculae. Bridging veins, again, are brightly echogenic due to their leptomeningeal coverings. Recall that the subarachnoid space contains both CSF and pia-arachnoid tissue, including the arachnoid tissue. The brightly echogenic leptomeninges in convexity cisterns are largely trabeculae enveloping the bridging veins as they pass from the brain surface to the dura and dural sinuses. It is the relative amount of the two components, leptomeningeal tissue versus CSF, within a given cistern that determines the sonographic appearance. If there are many bridging veins relative to CSF, the cistern appears echogenic (ie, more leptomeninges than CSF; Figure 4C). If the reverse is true, than it appears anechoic (Figure 4D) and many variations in between.

The cerebral midline appears brightly echogenic in fetuses and neonates because the falx cerebri, a pachymeningeal structure, and the bridging veins covered by leptomeninges coursing in the interhemispheric cistern are all brightly echogenic structures (Figures 4C and 5). The bright cerebral midline is usually ascribed to the falx. Interestingly, it is the leptomeningeal tissues more so than

Figure 3. A, The echogenic pial rim (arrows) highlights the surface of the cortex. This “first” bright line inside the calvarial margin always delimits the brain surface. At this stage of brain development, a smooth cortical surface is normal. The falx cerebri is also seen at this stage (arrowhead). B, Later, the brain surface shows increased folding. Major fissures and sulci of the normal cerebral surface are easily seen due to the bright meningeal coverings delimiting the brain surface (arrowheads).
Figure 4. A, Axial view of the midbrain. The midbrain is sharply outlined. In the perimesencephalic cisterns, there is very little cerebrospinal fluid and abundant structures with leptomeningeal coverings. The appearance of the perimesencephalic cisterns enables the examiner to define specific anatomic details. Asterisk indicates interpeduncular cistern; black arrowhead, quadrigeminal plate cistern; white arrowheads, ambient cisterns; and white arrows, crural cisterns. These enable one to easily define the cerebral peduncles (CP). Immediately deep to the quadrigeminal plate cisterns, of course, one finds the quadrigeminal bodies. B, Larger subarachnoid spaces, such as the cisterna magna, have an appearance dominated by cerebrospinal fluid (asterisks). Within the cisterna magna, one often sees the echogenic margins of the Blake pouch (arrowheads) stretching across the cisterna magna and/or the falx cerebelli. C and D. The subarachnoid spaces of the convexities can appear more echogenic (C, asterisks) or anechoic (D, asterisks), depending on the relative contribution of cerebrospinal fluid and specular reflections from the walls of vessels, nerves, and the arachnoid trabeculations.
The cerebellar vermis and the surface tissues of the cerebellar hemispheres often appear as though the neural tissue is bright. However, neural tissue does not create this appearance. The appearance can again be explained by the relative amount of leptomeninges associated with these structures. The cerebellar fissures, covered by leptomeninges, extend below the “surface” of the hemisphere at the apexes of the folia (Figure 6A). The cerebellar vermis has the greatest number of folia and fissures and, thus, intertwined meninges. Therefore, the overall appearance is dominated by the more brightly echogenic leptomeninges (Figure 6, B and C). The relative bright echogenicity of the vermis is maintained in neonatal sonography (Figure 6C).

Figure 5. The echogenicity of the falx cerebri (arrows) is due to its pachymeningeal origins, but it is the combined echoes from the falx cerebri and the leptomeninges in the interhemispheric cistern that determines the sonographic appearance of the interhemispheric cistern.

Figure 6. A. Axial view of the cerebellum showing the alternating pattern of hypoechoic neural tissue (the folia) and highly echogenic linear fissures (arrows) that are dominated by leptomeninges. B and C (opposite page), Midsagittal view of the echogenic fetal cerebellar vermis (asterisk) in a fetus (B) and a similar view in a 28-week neonate (C). The echogenicity of the cerebellar vermis can be explained by the high number of fissures, all of which are “filled” with leptomeninges.
Other Brightly Echogenic Vascular Structures

The bridging veins, invested with leptomeninges, and arachnoid trabeculae cross the convexity cisterns as described above. Additionally, innumerable blood vessels that course through the white matter are seen as linear bright reflections. These vessels are the deep medullary veins that drain blood away from the deep white matter. Importantly, pia and the subarachnoid space accompany these vessels as they travel through the brain parenchyma. Therefore, again it is pia and arachnoid trabeculae that explain why such tiny vessels generate such high-amplitude echoes. These vessels are commonly seen in fetuses (Figure 7) and have been the source of early errors in estimating the position of the lateral ventricular walls. Initially, the reflections given off by deep cortical draining veins were mistaken for the adjacent lateral ventricular walls.13,15,18,19

However, these vessels are far more important diagnostically in the neonatal brain, where they commonly cause confusion regarding white matter injury in premature neonates. This problem originates from the necessity to view the neonatal brain via fontanelles. This requirement essentially fixes the viewing angle of the deep white matter. Because the deep medullary veins are arranged in a radial orientation, the fixed viewing angle from the anterior fontanelles causes an anisotropic effect, resulting in much greater visibility of the deep veins where they are intersected perpendicularly (Figure 8, A and B). This “blush” is frequently mistaken for white matter injury (often called periventricular leukomalacia). Understanding the origin of these reflectors and the presence of an anisotropic effect caused by the fixed viewing angle can greatly reduce false-positive diagnoses of periventricular leukomalacia. These blushes need to be assessed as to whether one is seeing regular echoes (“lines and dots,” the normal appearance generated by deep medullary veins) versus “patches” or “blotches” of increased periventricular echogenicity (the classic appearance of periventricular leukomalacia; Figure 8, C and D).

Figure 7. Pia invests the deep medullary veins draining the periventricular white matter. These vessels (arrow) are quite bright due to this investiture with pia as they travel through the brain parenchyma. They are seen best where the beam intersects them speculally.
Figure 8. A, Near-axial view of the neonatal brain showing the architecture of the subarachnoid spaces quite elegantly (asterisks). The admixture of meningeal-covered structures and cerebrospinal fluid is clearly seen. One can appreciate that the relative proportions of these components will define the overall echogenicity of the cistern. In addition, the deep medullary veins intersected perpendicularly are seen as "lines" (arrowheads), whereas those intersected in the short axis are seen as "dots" (circles). B, Sagittal view obtained with the transducer in the anterior fontanelle. Because the transducer must stay within the fontanelle, only one projection of the deep medullary veins is seen. These are radially arranged about the ventricle. The veins that are intersected specularly are easily seen (circle), whereas those that are intersected parallel to the beam are not (ie, produced by the anisotropic effect). Therefore, this appearance creates the "blush" commonly described in neonatal head sonograms. Unfortunately, this blush is commonly mistaken for periventricular leukomalacia. C and D, Axial (C) and parasagittal (D) neonatal head sonograms showing the difference between periventricular leukomalacia (asterisks) and the blush created by normal deep medullary veins (arrowheads and circle). The examiner should determine whether they are viewing lines and dots (normal deep medullary veins) versus blotchy areas of increased echogenicity (suspicious for periventricular leukomalacia).
References


