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The role of neurosonography in the prenatal diagnosis of fetal central nervous system anomalies: A narrative review[1]

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Abstract: *Introduction:* Fetal neurosonography is an advanced ultrasound technique for prenatal assessment of the central nervous system (CNS), enabling detailed analysis of brain anatomy and detection of both subtle developmental disturbances and complex congenital malformations. With technological progress and standardization of examination techniques, it has evolved from a method used mainly to detect structural defects into a tool for assessing fetal brain maturation and development, becoming the primary imaging method for the CNS in prenatal diagnostics. *Aim:* This paper presents the contemporary role of neurosonography in the prenatal diagnosis of the fetal central nervous system, with particular emphasis on its clinical applications, diagnostic capabilities, limitations, and prospects for further development. *Method:* It is an analysis of current literature on fetal neurosonography and a narrative review, including the guidelines of the International Society of Ultrasound in Obstetrics and Gynecology (ISUOG) and publications concerning examination technique, clinical indications, applications of neurosonography, and new directions in its development. *Results:* Contemporary prenatal CNS diagnostics is based on a two-tier model comprising screening examination and detailed neurosonography performed in cases of suspected abnormalities or the presence of risk factors. Neurosonography is used for the diagnosis of brain developmental malformations, the assessment of cortical maturation, the evaluation of neuronal migration disorders, and the detection of changes associated with intrauterine growth restriction, congenital heart defects, intrauterine infections, and genetic diseases. The method enables detection of subtle neurodevelopmental disturbances even before unequivocal morphological changes appear. Its effectiveness, however, depends on gestational age, imaging quality, and the examiner's experience. In selected cases, diagnostics are supplemented by fetal magnetic resonance imaging. Artificial intelligence, radiomics, and quantitative neurosonography are also gaining increasing importance, as they may enhance the precision and objectivity of prenatal assessment. *Conclusions:* Neurosonography constitutes the primary method for the prenatal assessment of the central nervous system. Its role systematically extends beyond the diagnosis of structural defects, encompassing assessment of brain maturation, qualification for genetic diagnostics, and support in evaluating neurological prognosis. The integration of modern imaging techniques with artificial intelligence tools and molecular diagnostics creates prospects for earlier detection of neurodevelopmental disorders and further development of personalized prenatal diagnostics.
Keywords: prenatal diagnosis; neurosonography; fetal central nervous system; neurodevelopment; fetal magnetic resonance imaging (MRI).

Introduction

Fetal neurosonography is a specialized ultrasound method for evaluating the central nervous system (CNS), enabling detailed analysis of brain anatomy and detection of both subtle developmental deviations and complex congenital anomalies. Although it originated from routine ultrasonographic assessment of fetal anatomy, technological advances have made it a distinct field of prenatal diagnosis. The first reports of transvaginal imaging of the fetal CNS were published in the early 1990s (Monteagudo et al., 1991). Major advances followed improvements in ultrasound systems and transducers and the

1 Article in Polish language: https://stowarzyszeniefidesetratio.pl/fer/67p_Pawl.pdf

development of digital image-processing methods, which enabled increasingly high-quality, detailed imaging. At the same time, standardization of examination techniques consolidated neurosonography as the principal method of prenatal CNS assessment and the first-line modality for diagnosing many CNS abnormalities. In selected cases, ultrasound assessment is complemented by magnetic resonance imaging (MRI) (Paladini et al., 2021). Evaluation of the fetal brain remains one of the greatest challenges in prenatal diagnosis because of the dynamic development and structural complexity of the CNS during fetal life. Some abnormalities become apparent only later in pregnancy or after birth. Accurate interpretation therefore requires high-quality equipment, appropriate examination techniques, and substantial examiner expertise (Eixarch et al., 2023; Paladini et al., 2021). In recent years, neurosonography has evolved from a method focused primarily on detecting structural CNS anomalies into an advanced tool for assessing fetal brain development and maturation. Increasing imaging resolution and improved knowledge of normal prenatal development now permit identification of subtle disturbances in brain architecture and markers of atypical neurodevelopment before unequivocal morphologic changes appear.

Contemporary applications of neurosonography therefore extend beyond diagnosing congenital anomalies.

The method is increasingly used to assess cortical maturation, diagnose acquired CNS injury, and identify fetuses at increased risk of neurodevelopmental impairment, including those affected by fetal growth restriction (FGR), congenital heart disease, and intrauterine infection. This broader scope makes neurosonography not only a diagnostic tool but also a source of information on prenatal brain development and the potential neurologic prognosis of the fetus and child (Eixarch et al., 2023; Malinger et al., 2020).

These findings have important clinical implications: they allow clinicians to individualize diagnostic and therapeutic management and coordinate multidisciplinary prenatal and postnatal care, while providing parents with reliable information about prognosis, the child's possible developmental course, and available treatment and support. Care for a fetus with disease, particularly CNS abnormalities, requires a multidisciplinary team that may include maternal-fetal medicine specialists, neonatologists, pediatric neurologists and neurosurgeons, clinical geneticists, infectious disease specialists, and, in many cases, palliative care specialists.

This narrative review presents the contemporary role of neurosonography in prenatal diagnosis of the fetal central nervous system, with particular emphasis on current indications, diagnostic capabilities, limitations, and future directions. The authors also emphasize the complexity of this field and the need to individualize management in each case.

1. Neurosonography in contemporary prenatal diagnosis

Assessment of the fetal CNS is an integral component of ultrasonography at every stage of pregnancy. As fetal development progresses, CNS anatomy becomes increasingly differentiated, and successive structures and morphologic features emerge that cannot be evaluated earlier in gestation. Consequently, the information obtained during ultrasonography changes with gestational age and CNS maturity. Contemporary prenatal CNS diagnosis therefore follows a two-tier approach, progressing from screening assessment of fetal anatomy during routine ultrasonography to detailed neurosonography when an abnormality is detected, or risk factors are present (Eixarch et al., 2023; Malinger et al., 2020).

It identifies abnormalities that require further evaluation, while targeted neurosonography provides detailed characterization. his two-tier approach preserves screening effectiveness while ensuring comprehensive evaluation of brain structures in fetuses at increased risk of disease (Eixarch et al., 2023; Malinger et al., 2020).

This model is founded on screening examinations performed in accordance with current recommendations, the findings of which determine whether detailed neurosonography is required (Paladini et al., 2021).

1.1. Screening examinations

Screening examinations, routinely performed in pregnant populations, constitute the first stage of prenatal assessment of the fetal CNS. Teir purpose is to confirm normal development of cerebral structures or identify abnormalities that require specialist evaluation. The scope of CNS assessment changes with gestational age, reflecting dynamic brain development and the sequential appearance of anatomic structures (Malinger et al., 2020).

Current recommendations recommend performing the first CNS ultrasound between 11 and 14 weeks of gestation to allow an initial assessment of the developing nervous system. Although many cerebral structures have not yet reached maturity, the most severe developmental anomalies, including anencephaly, holoprosencephaly, encephalocele, and major spinal dysraphism, can be detected (Karim et al., 2024; Minister Zdrowia, 2025).

First-trimester CNS assessment includes evaluation of the calvarium, cerebral falx, cerebral hemispheres, and lateral ventricles containing the choroid plexuses, which form the characteristic 'butterfly' appearance confirming normal division of the forebrain into two symmetric hemispheres. More posteriorly, the thalamus and posterior fossa structures are visualized, including the brainstem (BS), the fourth ventricle represented by the intracranial translucency (IT), and the cisterna magna. The examination should be completed by assessing the shape and continuity of the spine (Borowski, et al. 2020).

Assessment of the hindbrain in the sagittal plane is particularly important. Measuring the brainstem (BS) and the distance between the brainstem and occipital bone (brainstem-to-occipital bone, BSOB), then evaluating their ratio, may increase early detection or suspicion of open spina bifida and selected posterior fossa anomalies. The normal BS/BSOB ratio is <1. An increased ratio results from displacement of posterior fossa structures and is among the earliest sonographic markers of open spina bifida (Lachmann et al., 2011; Volpe et al., 2016). Despite the increasing diagnostic value of first-trimester ultrasonography, assessment of posterior fossa structures and the BS and BSOB parameters is still not routinely performed at all centers, potentially limiting early diagnosis of selected CNS anomalies.

The scope of first-trimester assessment nevertheless remains limited because many cerebral structures have not yet reached a sufficiently advanced stage of development. Consequently, a normal examination does not exclude abnormalities that become apparent later in pregnancy (Karim et al., 2024).

Second-trimester ultrasonography plays a key role in the prenatal diagnosis of CNS anomalies. Most developmental brain abnormalities are detected during this examination, and their identification indicates the need for detailed neurosonography (Malinger et al., 2020). At this stage, current screening standards allow comprehensive evaluation of major intracranial structures, including the lateral ventricles, cavum septi pellucidi, thalami, cerebellum, cisterna magna, and spine (Borowski et al., 2020; Malinger et al., 2020). Detection or suspicion of an abnormality during screening warrants detailed neurosonography, which permits multiplanar evaluation of the brain and more precise characterization of the findings (Paladini et al., 2021).

The diagnostic capabilities of ultrasonography also change during the third trimester. Imaging conditions remain favorable early in the trimester; however, progressive calvarial mineralization gradually reduces ultrasound penetration and hampers detailed assessment of cerebral structures. Conversely, later examinations can detect abnormalities that emerge only near the end of the second trimester or during the third trimester, including disorders of cortical maturation and some acquired CNS injuries, and can monitor previously diagnosed abnormalities (Eixarch et al., 2023; Malinger et al., 2020).

1.2. Screening neurosonography and detailed neurosonography

Contemporary prenatal CNS diagnosis is based on a two-tier ultrasound model comprising screening and detailed neurosonography. These examinations serve distinct but complementary functions and are integral components of the diagnostic process (Malinger et al., 2020).

Screening neurosonography is performed as part of routine ultrasonography in the first, second, and third trimesters (Minister Zdrowia,

2025). Its purpose is to confirm normal CNS development and identify findings suggestive of a developmental anomaly or brain injury. It includes assessment of the basic intracranial structures in accordance with current recommendations and serves as the principal means of identifying patients who require further diagnostic evaluation (Borowski et al., 2020).

Screening is performed with a transabdominal transducer in three standard axial planes: transventricular, transthalamic, and transcerebellar. These planes assess the shape and dimensions of the skull, lateral ventricles, choroid plexuses, interhemispheric fissure, cavum septi pellucidi, basal ganglia, cerebellum, and cisterna magna. The spine is also assessed in the axial, coronal, and sagittal planes (Malinger et al., 2020).

Detailed neurosonography is an advanced ultrasound examination performed when screening identifies an abnormality or when risk factors for CNS disease are present. Its purpose is to characterize detected findings precisely and evaluate brain structures that are not visible or are difficult to assess during screening. Unlike screening, detailed neurosonography includes additional coronal and sagittal planes, most commonly obtained through the fontanelles or cranial sutures, thereby enabling more detailed analysis of CNS anatomy (Malinger et al., 2020). Neurosonography experts most often perform detailed assessment with a transvaginal transducer, whose higher frequency provides substantially greater image resolution. Obtaining optimal imaging planes often requires gentle manipulation of the fetal head through the maternal abdomen (Eixarch et al., 2023).

Table 1. Principal indications for detailed neurosonography and examination objectives

Indication	Objective of detailed neurosonography	Clinical relevance
Abnormality detected during screening	Confirm the diagnosis, determine the extent of the abnormality, and identify associated anomalies	Plan further prenatal evaluation and perinatal management
Ventriculomegaly	Assess brain anatomy and determine the cause of ventricular dilation	Establish prognosis and select further testing (MRI, genetic testing, TORCH)
Posterior fossa abnormalities	Differentiate developmental anomalies and evaluate hindbrain structures in detail	Establish the diagnosis and prognosis
Abnormal development of the corpus callosum or midline structures	Evaluation of associated anomalies and brain maturation	Risk assessment of neurodevelopmental impairment
Abnormal head circumference (microcephaly or macrocephaly)	Identify the cause of abnormal brain growth	Differentiate malformations, infections, and genetic disorders
Suspected intrauterine infection	Detect inflammatory markers and CNS damages	Assessment of brain injury and prognosis
Fetal growth restriction (FGR)	Assess brain maturation and look for changes associated with chronic hypoxia	Identify fetuses at risk of neurodevelopmental impairment
Twin pregnancies complicated by TTTS or sFGR	Detect CNS injury due to hemodynamic disturbances at an early stage	Monitor neurologic sequelae
Complex congenital heart disease	Assess associated CNS abnormalities and brain maturation	Improve counselling and the postnatal care plan.
Suspected genetic disorder or multiple-anomaly syndrome	Identify characteristic CNS abnormalities	Guide genetic testing
Suspected hypoxia or CNS injury	Assess acquired lesions and their evolution	Monitor disease progression and plan further management
Relevant obstetric or family history	Exclude recurrent CNS anomalies or detect early pathology	Individualize prenatal surveillance

TTTS, twin-to-twin transfusion syndrome; sFGR, selective fetal growth restriction; MRI, magnetic resonance imaging; TORCH, acronym for a group of congenital infections (Toxoplasma gondii, Others [including syphilis, varicella-zoster virus, parvovirus B19, Zika virus, and HIV], Rubella virus, Cytomegalovirus, and Herpes simplex virus).

This approach maintains screening effectiveness while providing in-depth evaluation in pregnancies requiring specialist assessment of the fetal brain. In clinical practice, detailed neurosonography is now the standard for advanced ultrasonographic evaluation of the fetal central nervous system (Malinger et al., 2020).

Acquiring the appropriate imaging planes requires not only high-quality equipment but also examiner expertise. Therefore, detailed neurosonography should be performed at centers with appropriate technical resources and personnel experienced in prenatal CNS diagnosis (Malinger et al., 2020).

1.3. Indications for detailed neurosonography

Detailed neurosonography is indicated when screening reveals a fetal CNS abnormality or when factors associated with an increased risk of CNS anomalies are present. Its purpose is not only to confirm the abnormality but also to characterize it precisely, assess associated anomalies, establish prognosis, and guide further diagnostic management (Malinger et al., 2020).

Table 1 presents principal indications for detailed neurosonography based on ISUOG recommendations (Eixarch et al., 2023; Malinger et al., 2020).

The indications for detailed neurosonography continue to expand. The examination is now used not only to diagnose structural anomalies but also to assess fetal brain maturation, monitor changes arising during fetal disease, and identify markers with potential prognostic relevance to subsequent neurologic development. The following sections discuss these contemporary applications.

2. Detailed neurosonography: examination technique

Detailed neurosonography is an advanced ultrasound examination that permits multiplanar assessment of the fetal central nervous system. Unlike screening, it is not limited to basic cerebral structures but enables detailed analysis of brain anatomy, detection of subtle developmental abnormalities, and assessment of CNS maturation. A central component is the acquisition of axial, coronal, and sagittal planes, which provide complementary information and enable comprehensive evaluation of intracranial structures (Malinger et al., 2020; Paladini et al., 2021).

Transvaginal ultrasonography is the preferred approach to detailed neurosonography. The fontanelles and cranial sutures serve as natural acoustic windows, providing higher-resolution images than the transabdominal approach. Image quality is comparable to that obtained during transfontanellar ultrasonography in neonates and permits detailed evaluation of fetal brain structures (Eixarch et al., 2023; Paladini et al., 2021). The transvaginal approach is preferred for fetuses in cephalic presentation; when it cannot be performed, such as in breech presentation, neurosonography may be conducted transabdominally (Paladini et al., 2021).

The examination begins with assessment of the brain in the standard axial planes used for screening. The evaluation is then extended to the coronal and sagittal planes, which are fundamental to detailed neurosonography. In clinical practice, obtaining images that allow optimal evaluation of individual anatomic structures and reliable characterization of abnormalities matters more than acquiring every recommended plane (Paladini et al., 2021).

Coronal planes primarily permit evaluation of midline structures and hemispheric symmetry. Standard assessment includes four planes: transfrontal, transcaudate, transthalamic, and transcerebellar. These demonstrate the frontal horns of the lateral ventricles, cavum septi pellucidi, corpus callosum, thalami, third ventricle, choroid plexuses, circle of Willis, and posterior fossa structures, including the cerebellar hemispheres and vermis. Multiplanar analysis increases diagnostic sensitivity for developmental anomalies that routine screening may miss (Paladini et al., 2021).

Sagittal assessment includes the midsagittal plane and two parasagittal planes. The midsagittal plane is particularly important because it simultaneously demonstrates the entire corpus callosum, cavum septi pellucidi, cavum Vergae, brainstem, fourth ventricle, cerebellar vermis, and cisterna magna. The parasagittal planes allow detailed assessment of lateral

ventricular morphology, the choroid plexuses, and cerebral parenchyma, complementing evaluation in the axial and coronal planes (Eixarch et al., 2023).

Detailed neurosonography also includes assessment of the spine and spinal cord in the sagittal, axial, and coronal planes, including continuity of the vertebral structures, the spinal canal, and the course of the spinal cord. Particular attention should be paid to the conus medullaris, whose position changes with gestational age. Also assess its morphology, as abnormalities may indicate neural tube defects or other developmental disorders of the fetal spinal cord (Eixarch et al., 2023; Paladini et al., 2021).

2.1. Assessment of fetal brain maturation

One of the most important developments in contemporary prenatal neurosonography is the shift from assessing brain anatomy alone to evaluating development and maturation. Until recently, ultrasonography was used primarily to detect structural CNS anomalies. High-resolution imaging and a better understanding of normal prenatal development now allow assessment of cortical maturation and neuronal migration. In many cases, subtle disturbances in brain development can be identified before unequivocal morphologic or clinical changes appear (Eixarch et al., 2023; Pooh et al., 2019).

Cortical development is dynamic and closely related to gestational age. As pregnancy progresses, cerebral sulci and gyri appear sequentially; their presence, morphology, and degree of development reflect normal neuronal migration and organization. Assessment requires detailed knowledge of normal prenatal development according to gestational age. Cortical maturation analysis should be an integral part of every neurosonographic examination and should be performed in all appropriate imaging planes (Eixarch et al., 2023).

The Sylvian fissure is one of the best-characterized markers of brain maturation and becomes visible at approximately 18 weeks of gestation. Its shape and degree of opercularization change predictably over subsequent weeks; deviations from the expected appearance may indicate abnormal fetal cortical development. Assessment of the Sylvian fissure angle has been shown to detect cortical developmental abnormalities before other sonographic findings appear. This parameter is therefore considered one of the most promising markers for prenatal assessment of brain maturation (Pooh et al., 2019).

Other cerebral sulci can be assessed later in pregnancy. The parieto-occipital sulcus is generally visible from approximately 19 weeks of gestation, whereas the cingulate sulcus becomes visible at approximately 24 weeks. The olfactory sulci cannot be assessed in the coronal plane until approximately 28 weeks. Analyzing the sequence in which individual sulci appear and their degree of development allows comparison of brain maturation with gestational age and complements conventional anatomic assessment (Eixarch et al., 2023).

The cat-ear lines (CEL) sign has also received increasing attention. Visible from approximately 19 weeks of gestation in anterior coronal planes, it consists of symmetric hyperechoic lines extending from the lateral ventricles toward the surface of the cerebral hemispheres. This finding can be evaluated only by ultrasonography and reflects normal neuronal migration. Delayed appearance or abnormal CEL morphology may be an early marker of neuronal migration disorders and malformations of cortical development, including lissencephaly, polymicrogyria, schizencephaly, and subependymal heterotopia (Matsuzawa et al., 2023). Importantly, the CEL sign has no equivalent on MRI, underscoring the unique role of neurosonography in assessing early cortical development.

Assessment of brain maturation does not replace conventional anatomic evaluation but substantially complements it. It may reveal developmental abnormalities when structural changes are still subtle or absent. This is one of the most rapidly evolving areas of prenatal neurosonography and is increasingly applied not only to developmental anomalies but also to fetuses at increased risk of neurodevelopmental impairment, including those with fetal growth restriction, congenital heart disease, or intrauterine infection. Neurosonography can thus identify both structural anomalies and fetuses at risk of neurodevelopmental impairment before fixed morphologic changes occur (Paladini et al., 2021).

2.2. Neurosonography in the diagnosis of ventriculomegaly

Ventriculomegaly is among the most frequently diagnosed CNS abnormalities in prenatal practice and one of the most common indications for detailed neurosonography. Although diagnosis is based on a simple measurement of lateral ventricular width, subsequent evaluation requires comprehensive assessment of the entire brain because ventricular dilation is often secondary to other developmental anomalies or CNS damages (Alluhaybi et al., 2022; Eixarch et al., 2023).

Ventriculomegaly is defined as unilateral or bilateral dilation of the lateral ventricle up to 10 mm or greater. Measurement should be performed in the transventricular plane at the level of the parieto-occipital sulcus. In the normally developing fetal brain, lateral ventricular width remains relatively constant, generally measuring 6-8 mm throughout the second and third trimesters (Eixarch et al., 2023). Under current standards, assessing the lateral ventricles is an integral part of second-trimester screening. Most cases of ventriculomegaly are detected during this screening (Alluhaybi et al., 2022; Borowski et al., 2020). Ventriculomegaly detected at screening should always prompt detailed neurosonography. The purpose is not merely to confirm ventricular dilation but, more importantly, to determine its cause and identify associated brain abnormalities that may substantially alter prenatal and postnatal prognosis. Detailed assessment includes the corpus callosum, midline structures, posterior fossa, cerebral cortex, choroid plexuses, and cerebral white matter. Evaluation of cortical maturation and markers of neuronal migration disorders that may not be visible during routine screening is also important (Eixarch et al., 2023; Malinger et al., 2020).

Ventriculomegaly is a sonographic finding rather than a distinct disease entity. It may accompany CNS malformations, genetic disorders, intrauterine infections, intraventricular hemorrhage, brain tumors, neuronal migration disorders, and changes caused by fetal ischemia or hypoxia. In many cases, only comprehensive assessment of the entire brain can establish the underlying etiology and allow accurate prognostication (Pooh, 2021).

Further management depends on the severity of ventriculomegaly and the presence of associated anomalies. Ventriculomegaly is classified as mild (10-12 mm), moderate (13-15 mm), or severe (> 15 mm) (Pooh, 2021). Isolated mild ventriculomegaly is generally associated with a favorable prognosis, and lateral ventricular width normalizes on follow-up in some fetuses (Pisapia et al., 2017; Tank et al., 2022). Severe ventriculomegaly, by contrast, is associated with a high risk of coexisting CNS anomalies, chromosomal abnormalities, and neurodevelopmental impairment (Litwinska et al., 2019). Severe ventriculomegaly is not synonymous with hydrocephalus. Hydrocephalus is a distinct clinical entity resulting from impaired cerebrospinal fluid circulation and increased intracranial pressure, most commonly due to aqueductal stenosis (Pisapia et al., 2017; Pooh, 2021). Distinguishing these conditions is essential for subsequent diagnosis and treatment.

Comprehensive neurosonographic assessment guides selection for further evaluation, including genetic testing and magnetic resonance imaging, which may provide additional information about brain anatomy in selected cases. Neurosonography, genetic testing, and MRI are complementary methods in the differential diagnosis of ventriculomegaly. Nevertheless, detailed neurosonography remains the first-line examination for precise assessment of fetal brain anatomy, monitoring the evolution of findings, and establishing prenatal and postnatal prognosis (Alluhaybi et al., 2022; Pisapia et al., 2017).

2.3. Neurosonography in fetuses with fetal growth restriction (FGR)

Fetal growth restriction (FGR) is among the most common complications of pregnancy and remains an important risk factor for neurodevelopmental impairment. Unlike fetuses with conventional CNS anomalies, most fetuses with FGR have no overt structural brain abnormalities. Growing evidence, however, indicates that chronic placental insufficiency and associated hypoxia produce subtle alterations in brain maturation and organization that can be detected prenatally (Eixarch et al., 2023).

Fetuses with FGR exhibit circulatory redistribution known as the brain-sparing effect. In response to chronic placental insufficiency and progressive hypoxia, adaptive mechanisms redistribute blood flow toward organs essential for survival, particularly the brain and heart. Consequently, cerebral perfusion increases at the expense of peripheral-organ perfusion. On Doppler examination, this redistribution is reflected by decreased vascular resistance in the middle cerebral artery (MCA), expressed as a reduced pulsatility index (PI), together with increased resistance in the umbilical artery (UA). Although brain sparing is initially compensatory and helps maintain oxygen delivery to the developing brain, its persistence indicates advanced adaptation to hypoxia and does not provide complete neuroprotection. Increased cerebral perfusion raises blood volume within the cerebral vasculature; concurrent disruption of flow autoregulation and increased blood-brain barrier permeability may promote fluid extravasation into neural tissue, edema, and microcirculatory dysfunction (Misan et al., 2022; Misan et al., 2023).

These processes alter cortical maturation, drive white matter remodelling, and disrupt the organisation of neuronal networks, which are considered major mechanisms underlying the increased risk of subsequent neurodevelopmental impairment among children affected by FGR (Husen et al., 2019; Sahebdel et al., 2025).

The long-term adverse effects of growth restriction on neurodevelopment are well documented (Shah et al., 2025; Sun et al., 2025). For many years, evaluation of fetuses with FGR was limited to monitoring biometric and Doppler parameters. Attention is now shifting toward CNS development because neurodevelopmental impairment is among the most important long-term consequences of FGR. Contemporary neurosonography can identify subtle alterations in brain architecture that are not visible during routine ultrasonography (Mappa et al., 2024; Sun et al., 2025).

Assessment of cortical maturation is particularly important. Delayed cerebral sulcation, abnormal opercularization of the Sylvian fissure, and delayed maturation of other cortical sulci have been reported in fetuses with FGR and may indicate abnormal neuronal migration and organization (Eixarch et al., 2023; Pooh et al., 2019). These changes are often subtle and require detailed neurosonography performed by an experienced clinician.

Neurosonography also permits assessment of the volume and morphology of selected brain structures, including the corpus callosum, cerebellum, and white matter. An increasing number of studies indicate that severe FGR is associated with adaptive changes involving the developing brain that may correlate with later cognitive function and behavioral disorders. In this context, neurosonography is no longer used merely to exclude structural anomalies; it becomes a tool for assessing the quality of brain development (Mappa et al., 2024).

The relevance of neurosonography in FGR therefore extends beyond prenatal diagnosis. Findings may support neurologic prognostication, identify fetuses requiring particularly intensive surveillance, and guide neonatal and neurologic care after birth. Although most available neurodevelopmental markers remain investigational, their growing number suggests that assessing brain maturation may be-

Table 2. Neurosonographic markers in fetal growth restriction (FGR)

Neurosonographic marker	Change in FGR	Interpretation
Sylvian fissure	Shallow; delayed opercularization	Impaired cortical maturation
Corpus callosum	Reduced length; thinning	White matter remodeling
Cingulate sulcus	Delayed maturation	Delayed cortical development
Parieto-occipital sulcus	Delayed development	Delayed cortical development
Cerebellar vermis	Reduced dimensions	Abnormal posterior fossa development
Fastigium-corpus callosum distance	Reduced	Potential marker of brain remodeling

come an integral component of FGR evaluation (Eixarch et al., 2023). Table 2 presents a detailed list of neurosonographic markers in FGR.

In clinical practice, evaluation of a fetus with FGR should not be limited to excluding structural brain anomalies. Detailed neurosonography permits analysis of markers of brain maturation, including opercularization of the Sylvian fissure, development of other cortical sulci, corpus callosum morphology, white matter appearance, and development of posterior fossa structures. Growing evidence indicates that severe FGR is associated with delayed cortical sulcation and altered development of the corpus callosum and cerebellum, which may reflect impaired CNS maturation before permanent morphologic or clinical changes occur. Although most of these markers require further validation, their assessment may provide valuable prognostic information and complement conventional ultrasound and Doppler parameters (Eixarch et al., 2023; Pooh et al., 2019).

These pathophysiologic processes are reflected neurosonographically by delayed cortical maturation, abnormal sulcation, and altered morphology of midline and posterior fossa structures (Mappa et al., 2024).

3. Neurosonography in the diagnosis of intrauterine infections

Intrauterine infections are among the most important acquired causes of fetal CNS injury. Neurotropic pathogens may disrupt neural cell proliferation, migration, and maturation, resulting in both complex developmental anomalies and injury to the developing brain. Neurosonographic findings depend on the pathogen, timing of infection, and severity of the lesions. Unlike most developmental anomalies, infection-related changes are dynamic and may emerge gradually; therefore, a single normal ultrasound examination does not exclude evolving CNS injury. Serial neurosonography therefore plays a key role in diagnosing and monitoring fetuses with suspected or confirmed intrauterine infection (Malinger et al., 2020).

3.1. Cytomegalovirus (CMV)

Congenital cytomegalovirus (CMV) infection is the most common prenatal viral infection and a leading cause of hearing loss and neurologic disability in children (Leruez-Ville et al., 2024). Neurosonography is the primary modality for CNS imaging in fetuses with suspected CMV infection.

The most frequently reported findings include mild or moderate ventriculomegaly, white matter hyperechogenicity, periventricular cysts, intracranial calcifications, choroid plexus abnormalities, and microcephaly. More advanced cases may demonstrate abnormal cortical development (delayed sulcation and abnormal opercularization of the Sylvian fissure), polymicrogyria, pachygyria, and cerebellar hypoplasia (Benoist et al., 2008; Leruez-Ville et al., 2024).

3.2. Congenital Toxoplasmosis

Congenital toxoplasmosis remains one of the most common parasitic causes of fetal brain injury. Neurosonography most frequently demonstrates ventriculomegaly or hydrocephalus, diffuse intracranial calcifications, particularly in the basal ganglia and cerebral cortex, and cerebral parenchymal atrophy. Severe cases may include microcephaly and abnormal cortical development. Compared with CMV infection, calcifications are generally more diffuse and are more often located outside the periventricular region (Robert-Gangneux & Dardé, 2012).

3.3. Congenital Rubella Syndrome

CNS abnormalities associated with congenital rubella occur much less frequently than those associated with CMV infection or toxoplasmosis. The most common findings are microcephaly, delayed brain maturation, and nonspecific abnormalities of cortical development. In clinical practice, diagnosis relies primarily on the coexistence of CNS and cardiac abnormalities, cataracts, and serologic findings, while neurosonography plays a complementary role (Patel, 2021).

Table 3. Characteristic neurosonographic features of the most common intrauterine infections

Pathogen	Most common neurosonographic findings
CMV	Ventriculomegaly, hyperechoic white matter, periventricular cysts, calcifications, abnormal cortical maturation, polymicrogyria, cerebellar hypoplasia
Toxoplasma gondii	Hydrocephalus, diffuse intracranial calcifications, cerebral atrophy, microcephaly
Zika virus	Severe microcephaly, calvarial collapse, pachygyria/lissencephaly, cortical-subcortical calcifications, cerebellar hypoplasia
HSV	Cerebral necrosis, ventriculomegaly, calcifications
VZV	Microcephaly, cerebral atrophy, nonspecific CNS injury

3.4. Zika Virus Infection

Zika virus infection produces one of the most characteristic neurosonographic patterns among prenatal infections. The typical finding is severe microcephaly with partial collapse of the calvarium. Additional findings include ventriculomegaly, cortical-subcortical calcifications, severe neuronal migration abnormalities, pachygyria, lissencephaly, cerebellar hypoplasia, and cerebral parenchymal atrophy (Brasil et al., 2016; Moore et al., 2017).

3.5. Other Neurotropic Infections

Herpes simplex virus (HSV), varicella-zoster virus (VZV), and other less common pathogens may also injure the developing fetal brain, although these infections are considerably less frequent. Neurosonographic findings are less specific and may include ventriculomegaly, areas of necrosis, calcifications, microcephaly, and secondary cerebral atrophy (Khalil et al., 2016).

Regardless of etiology, neurosonography remains the principal modality for prenatal CNS assessment. It enables detection of structural abnormalities, evaluation of cortical maturation, and monitoring of lesion progression on follow-up. When intrauterine infection is suspected, perform serial examinations because some lesions develop gradually and may not be present at the initial ultrasound assessment (Leruez-Ville et al., 2024; Malinger et al., 2020).

Table 3 presents the principal neurosonographic features of individual intrauterine infections.

4. Neurosonography in fetuses with congenital heart disease

Congenital heart defects (CHD) are among the most common congenital anomalies and occur in approximately 1% of live-born infants.

Growing evidence indicates that abnormal brain development in fetuses with congenital heart disease can be detected prenatally by neurosonography. A systematic review published in 2025 found that fetuses with severe heart defects most commonly demonstrate delayed cortical maturation, manifested by abnormal development of the Sylvian fissure and delayed appearance and maturation of other cortical sulci. Some studies also reported smaller dimensions of the corpus callosum, cerebellar vermis, and other midline structures, suggesting a global delay in brain maturation. The authors emphasized that neurosonography may identify these changes before they are visible with other imaging modalities, making it a promising tool for assessing prenatal neurodevelopment in fetuses with CHD. They also highlighted the need to standardize examination techniques and conduct further prospective studies to determine the prognostic value of individual neurosonographic markers (Monteiro et al., 2025), as well as to evaluate brain maturation and identify subtle changes that may affect subsequent neurologic development (Donofrio et al., 2014; Eixarch et al., 2023).

The pathophysiologic basis of these changes is chronic hemodynamic disturbance that reduces oxygen and nutrient delivery to the developing brain. Depending on the type of cardiac defect, blood entering the cerebral circulation may be inadequately

Table 4. Neurosonographic markers of impaired brain maturation in fetuses with congenital heart disease

Marker	Change observed in CHD	Interpretation
Sylvian fissure	Delayed opercularization	Delayed cortical maturation
Other cortical sulci	Delayed sulcation	Abnormal neurodevelopment
Corpus callosum	Reduced length	Delayed white matter development
Cerebellar vermis	Reduced dimensions	Delayed posterior fossa maturation
Fastigium-corpus callosum distance	Abnormal values	Marker of global brain maturation

CHD, congenital heart disease.

oxygenated or cerebral blood flow may be reduced, resulting in chronic hypoxia and delayed fetal CNS maturation. Magnetic resonance imaging (MRI) studies have shown that the brains of fetuses with severe cardiac defects develop more slowly than those of healthy fetuses and often correspond in maturity to brains that are 2-4 weeks younger (Clouchoux et al., 2013; Limperopoulos et al., 2010).

Detailed neurosonography can detect many of these changes prenatally. Assessment of cortical maturation, particularly the degree of Sylvian fissure opercularization and the development of other cortical sulci, is especially important. Fetuses with severe heart defects have demonstrated abnormal sulcation and delayed cortical maturation compared with healthy fetuses. Reduced dimensions of the corpus callosum, cerebellar vermis, and other midline structures have also been observed and may indicate globally delayed brain development (Monteiro et al., 2025; Pooh et al., 2019).

Quantitative assessment of neurosonographic markers is also receiving increasing attention. Analysis of corpus callosum length, the fastigium-corpus callosum distance, degree of Sylvian fissure opercularization, and development of other cortical sulci may identify impaired brain maturation before abnormalities become apparent during routine ultrasonography. Although most of these parameters remain investigational, available findings suggest that they may be valuable prognostic markers (Eixarch et al., 2023).

The significance of neurosonography in fetuses with CHD extends beyond prenatal diagnosis. Detecting impaired brain maturation may affect counselling by offering additional evaluation, including fetal MRI, choice of delivery in a tertiary center, or organization of postnatal neurologic care.

Contemporary neurosonography is therefore becoming an important component of comprehensive evaluation in fetuses with severe heart defects, providing information not only about anatomy but also about functional maturation of the developing brain (Monteiro et al., 2025).

The most frequently reported neurosonographic markers in fetuses with congenital heart disease are presented in Table 4.

5. Neurosonography and genetic diagnosis

Advances in genetic testing, particularly the increasing availability of modern molecular diagnostic techniques, have substantially changed the management of fetal CNS abnormalities. The introduction of chromosomal microarray analysis (CMA; SNP-CGH) and next-generation sequencing (NGS), including whole-exome sequencing (WES), into clinical practice has significantly increased detection of genetic causes of developmental brain anomalies. However, the diagnostic yield of these methods depends largely on accurate prenatal phenotype characterisation. Detailed neurosonography therefore plays a key role in selecting patients for further genetic testing and interpreting the results (Lord et al., 2019; Petrovski et al., 2019).

Anatomic abnormalities of the fetal CNS are associated with an increased risk of genetic disorders. In these cases, consider invasive testing with an appropriately selected genetic assay. DNA is most commonly isolated from amniotic fluid obtained by amniocentesis and subsequently evaluated for

Table 5. Indications for genetic testing based on fetal neurosonographic findings

Neurosonographic finding	Most common genetic etiology	Recommended testing
Agenesis/dysgenesis of the corpus callosum	Chromosomal abnormalities, copy number variants (CNVs), and monogenic disorders (including Smith-Lemli-Opitz, Aicardi, and Mowat-Wilson syndromes)	CMA -> WES
Holoprosencephaly	Chromosomal abnormalities (approximately 60% of cases), variants in SHH, ZIC2, SIX3, PTCH1, FGFR1, and CDON, and Smith-Lemli-Opitz syndrome	CMA + WES
Posterior fossa malformations	Chromosomal abnormalities (approximately 16% in Dandy-Walker malformation), CNVs, ciliopathies, and monogenic disorders (including Joubert syndrome)	CMA +/- WES
Lissencephaly/pachygyria/polymicrogyria	Neuronal migration disorders associated with variants in PAFAH1B1 (LIS1), DCX, TUBA1A, CHD7, PAX8, and other genes	WES
Gray matter heterotopia	Sequence variants in FLNA, ARFGEF2, and other neuronal migration genes, and FMR1 repeat expansion	WES, MS-MLPA/PCR
Severe or complex ventriculomegaly	Chromosomal abnormalities, CNVs, and monogenic disorders (after exclusion of intrauterine infection)	CMA -> WES
Multiple CNS anomalies or CNS plus extracranial anomalies	Genetic syndromes of diverse etiology (chromosomal abnormalities, CNVs, and monogenic disorders)	CMA + WES (preferably trio-WES)

CMA, chromosomal microarray analysis; WES, whole-exome sequencing; trio-WES, whole-exome sequencing of the fetus/child and parents; MS-MLPA, methylation-specific multiplex ligation-dependent probe amplification; PCR, polymerase chain reaction.

chromosomal abnormalities and submicroscopic imbalances, including by CMA. Depending on the source, copy number variants (CNVs) are identified in approximately 8-11% of isolated fetal CNS anomalies. If CMA of the extracted DNA yields a normal result, NGS for monogenic disorders may be considered. The scope of NGS depends on the methods available at the diagnostic center. It may include a gene panel, WES, or trio-WES, in which the fetal and parental exomes are sequenced concurrently. This approach permits more accurate interpretation and classification of detected variants with respect to pathogenicity and clinical significance.

Many abnormalities detected by neurosonography are associated with an increased risk of chromosomal abnormalities or monogenic disorders. These include agenesis or dysgenesis of the corpus callosum, posterior fossa malformations, holoprosencephaly, neuronal migration disorders, malformations of cortical development, severe ventriculomegaly, and coexisting developmental anomalies. In these cases, a normal karyotype does not exclude a genetic etiology; therefore, additional CMA or WES is increasingly recommended, particularly when neurosonographic findings suggest a specific disease phenotype (International Society of Ultrasound in Obstetrics and Gynecology et al., 2023; Monaghan et al., 2020). The role of neurosonography extends beyond detecting the anomaly itself. Detailed analysis of brain morphology permits precise phenotyping, which is fundamental to selecting an appropriate molecular diagnostic strategy. Evaluating the location and nature of cortical developmental abnormalities, the degree of Sylvian fissure opercularization, the presence of heterotopia, corpus callosum abnormalities, and posterior fossa anomalies may direct testing toward specific gene groups involved in neuronal migration disorders. Examples include periventricular and subcortical heterotopia occurring in genetic conditions such as ciliopathies, tubulinopathies, inborn errors of metabolism, other monogenic disorders, and chromosomal microaberrations such as 5p or 1p36 deletions (Śmigiel & Szczałuba, 2021). Precise prenatal phenotyping has been shown to increase the diagnostic yield of WES and facilitate clinical interpretation of detected genetic variants (Lord et al., 2019; Petrovski et al., 2019).

Attention is also increasing for cases without classic structural anomalies in which neurosonography reveals subtle abnormalities of brain maturation, such as delayed sulcation, abnormal opercularization of the Sylvian fissure, or abnormal development of

midline structures. Although the diagnostic value of these markers remains under investigation, their presence may warrant extended genetic testing, particularly when other developmental abnormalities or a positive family history coexist (Eixarch et al., 2023; Monteiro et al., 2025).

Contemporary neurosonography is therefore not only a method of CNS imaging but also a tool for precisely defining the prenatal phenotype. Information obtained during the examination directly influences selection of appropriate genetic tests, interpretation of their results, and prenatal counselling.

Close collaboration among fetal medicine specialists, clinical geneticists, pediatricians, pediatric neurologists, radiologists, neonatologists, and perinatal hospice professionals is becoming the foundation of modern prenatal diagnosis of CNS anomalies. At many tertiary centers, multidisciplinary teams and case conferences provide comprehensive evaluation and reliable information for parents regarding fetal and childhood prognosis, further medical management, treatment options, rehabilitation, and postnatal care (Van den Veyver, 2019). Table 5 presents the genetic tests offered according to the identified phenotypic abnormalities.

6. Limitations of neurosonography

Despite rapid advances in ultrasound technology, neurosonography, like every imaging modality, has inherent limitations. Recognizing these limitations is essential for appropriate interpretation and decisions about further prenatal evaluation. Contemporary neurosonography remains the first-line method for assessing the fetal CNS, but findings should always be interpreted in the context of gestational age, image quality, and the clinical setting (Malinger et al., 2020; Paladini et al., 2021).

One of the principal limitations is the dynamic development of the fetal brain. Numerous CNS structures emerge gradually as pregnancy progresses; consequently, some abnormalities cannot be visualized at earlier developmental stages. This particularly applies to neuronal migration disorders, malformations of cortical development, and certain acquired injuries that may become apparent only in the third trimester or even after birth. A normal result on a single neurosonographic examination therefore does not completely exclude disease that develops later in fetal life (Eixarch et al., 2023; Pooh et al., 2019).

Technical factors also substantially influence examination quality, particularly the quality and resolution of the ultrasound equipment. Examinations performed on systems with limited imaging capabilities carry a high risk of diagnostic error. Detailed brain assessment may also be hindered by an unfavorable fetal head position, advanced gestational age and progressive calvarial mineralization, oligohydramnios, maternal obesity, abdominal surgical scars, or multiple gestation. In these circumstances, it may be impossible to obtain all standard neurosonographic planes, reducing examination sensitivity. In selected cases, image quality may be improved by using the transvaginal approach or repeating the examination after fetal position changes (Paladini et al., 2021).

Another limitation is that neurosonography primarily evaluates the morphology of the developing brain. Despite increasing capabilities for analyzing cortical maturation, many neurodevelopmental disorders are functional or molecular and do not produce detectable prenatal anatomic changes. These include some autism spectrum disorders, intellectual disabilities, and genetic diseases such as inborn errors of metabolism and adrenoleukodystrophies, in which prenatal ultrasonography may appear normal despite subsequent clinical manifestations (Eixarch et al., 2023).

Examiner experience is an important determinant of diagnostic value. Detailed neurosonography is among the most demanding ultrasound examinations in obstetrics and requires not only technical proficiency but also extensive knowledge of embryology and normal fetal brain maturation. Detection of subtle abnormalities improves with examiner experience and adherence to standardized protocols developed by international scientific societies (Malinger et al., 2020; Paladini et al., 2021).

When ultrasound findings remain equivocal, or a disorder that cannot be visualized neurosonographically is suspected, fetal MRI is indicated. The two modalities are complementary rather than competing.

Neurosonography remains the principal diagnostic and longitudinal monitoring tool, whereas MRI provides additional information about structures that are difficult to evaluate sonographically and about selected disorders of brain development (Malinger et al., 2020; Paladini et al., 2021).

7. Neurosonography and fetal magnetic resonance imaging

Rapid advances in prenatal imaging have established fetal magnetic resonance imaging (MRI) as an important complement in diagnosing CNS anomalies. This has not altered the role of neurosonography as the primary modality for fetal brain imaging. Under current International Society of Ultrasound in Obstetrics and Gynecology (ISUOG) recommendations, detailed neurosonography remains the first-line examination for prenatal CNS diagnosis, whereas MRI should be performed only for specific indications as a complementary examination (Malinger et al., 2020; Paladini et al., 2021). It's important to note that both neurosonography and MRI are safe for the pregnant woman and fetus, and do not expose them to the ionizing radiation used in other imaging methods, such as computed tomography.

The primary advantage of neurosonography is the ability to obtain images in real time and to repeat the examination multiple times without exposing the pregnant woman and fetus to a lengthy examination in a noisy environment and without the possibility of movement. It is widely available, relatively brief, and permits simultaneous evaluation of fetal anatomy and vascular flow by Doppler, as well as longitudinal monitoring of abnormalities. With transvaginal and multiplanar imaging, image quality is now comparable to MRI for assessment of many midline and posterior fossa structures (Eixarch et al., 2023; Paladini et al., 2021).

MRI provides superior evaluation of structures that are difficult to assess sonographically, particularly in late pregnancy, when mineralization of the calvarium limits ultrasound penetration. It permits more precise assessment of white matter, the cerebral cortex, posterior fossa, and ischemic or hemorrhagic

Table 6. Most common indications for fetal MRI

Most common indications for fetal MRI
Severe or progressive ventriculomegaly
Suspected malformation of cortical development (including lissencephaly, polymicrogyria, or gray matter heterotopia)
Microcephaly or macrocephaly
Intracranial hemorrhage or suspected hypoxic-ischemic brain injury
Posterior fossa abnormalities
Suspected or confirmed intrauterine infection (particularly CMV or Zika virus infection)
Suspected CNS vascular malformation
Suspected intracranial tumor
Suspected genetic syndrome associated with CNS abnormalities (e.g., tuberous sclerosis)
Equivocal detailed neurosonography or inadequate ultrasound image quality

(Eixarch et al., 2023; Malinger et al., 2020; Paladini et al., 2021).

Table 7. Comparison of neurosonography and fetal magnetic resonance imaging in prenatal CNS diagnosis

Feature	Neurosonography	MRI
First-line examination	Yes	No
Dynamic assessment	Yes	No
Assessment of vascular flow	Noninvasive Doppler examination	Possible with gadolinium-based contrast; gadolinium is not recommended for fetal imaging
Assessment of cortical maturation	Yes	Yes
White matter assessment	Good	Very good
Neuronal migration disorders	Good	Very good
Serial examinations	Feasible	Limited
Availability	High	Limited
Cost	Low	High
Examination time	Short	Longer

lesions. MRI is particularly useful for diagnosing neuronal migration disorders, selected malformations of cortical development, intracranial tumors, and brain demage related to intrauterine infection or hypoxia (Griffiths et al., 2017; Malinger et al., 2020).

MRI should not, however, replace properly performed neurosonography. In most cases, it is a second-line examination performed after detailed ultrasound assessment. Findings from the MERIDIAN study demonstrated that MRI may provide additional diagnostic information in some fetuses with suspected CNS anomalies, but its greatest value is achieved when it follows high-quality neurosonography (Griffiths et al., 2017). The most common indications for fetal CNS MRI are presented in Table 6.

The complementary nature of these modalities is increasingly emphasized. Neurosonography is the best tool for evaluating dynamic processes during brain development, monitoring changes over time, and analyzing vascular flow. MRI provides additional information about brain microstructure and lesions not visible sonographically. Combining the modalities improves prenatal diagnostic accuracy and permits more precise neurologic prognostication (Griffiths et al., 2017; Paladini et al., 2021).

Technological advances are gradually narrowing the differences between neurosonography and MRI. High-resolution ultrasonography, three-dimensional imaging, and new quantitative methods for assessing brain maturation now allow neurosonography to evaluate many structures that were accessible only by MRI a decade or two ago. Contemporary prenatal diagnosis therefore does not depend on choosing one modality over the other, but on their informed and complementary use according to the clinical findings and gestational age. Table 7 compares the two modalities.

8. Future directions in neurosonography: artificial intelligence, radiomics, and quantitative neurosonography

Fetal neurosonography is among the most rapidly developing fields of prenatal diagnosis. Technological advances over recent decades have enabled a transition from basic assessment of CNS anatomy to detailed analysis of its development and maturation. The next stage in this evolution involves artificial intelligence (AI), radiomics, and quantitative ultrasound image analysis. These technologies are intended to increase diagnostic accuracy, improve reproducibility, and identify subtle changes that remain invisible during conventional visual assessment (Ramirez Zegarra & Ghi, 2023).

The most rapidly developing area is the application of AI and deep-learning algorithms to ultrasound image analysis. Current systems can automatically recognize standard imaging planes, identify fetal brain structures, and perform basic biometric measurements. Experimental studies have demonstrated high accuracy of AI algorithms in identifying appropriate ultrasound planes and supporting detection of selected CNS anomalies. In the future, these solutions may shorten examination time, reduce interobserver variability, and expand access to highly specialized prenatal diagnosis, particularly at centers with less experience (Ramirez Zegarra & Ghi, 2023).

Quantitative neurosonography is developing in parallel and seeks to assess fetal brain development objectively using measurable parameters. Increasing attention is directed toward the degree of Sylvian fissure opercularization, development of other cortical sulci, corpus callosum length, cerebellar vermis dimensions, and other midline structures. Unlike conventional qualitative assessment, quantitative parameters enable longitudinal monitoring of brain maturation and comparison with gestational age-specific reference values. Studies involving fetuses with growth restriction, congenital heart disease, and intrauterine infection suggest that quantitative assessment may detect neurodevelopmental abnormalities before unequivocal morphologic changes emerge (Mappa et al., 2024; Monteiro et al., 2025; Pooh et al., 2019).

Radiomics, which uses advanced computational image analysis, is another promising field. It extracts numerous features describing tissue texture, echogenicity, and spatial organization that are imperceptible during routine ultrasound assessment. Artificial intelligence algorithms can then analyze these data to identify patterns characteristic of specific disorders. Although radiomics in prenatal neurosonography remains investigational, it may facilitate early detection of changes associated with chronic hypoxia, neuronal migration disorders, intrauterine infection, and genetic disease (Gillies et al., 2016; Lambin et al., 2017).

The future of neurosonography also involves integrating data from multiple sources. Models that combine ultrasound imaging, Doppler indices, genetic test results, and clinical data are receiving increasing attention. AI analysis of such complex data sets may ultimately permit more precise prediction of neurodevelopmental impairment and individualization of prenatal care (Ramirez Zegarra & Ghi, 2023).

Despite the considerable potential of emerging technologies, their role is to support rather than replace the examining clinician. Final interpretation of ultrasound images requires consideration of the clinical context, gestational age, and examiner expertise. The future of neurosonography will likely be based on synergy among high-quality ultrasound imaging, quantitative assessment of brain development, molecular diagnostics, and artificial intelligence. Such an integrated approach may enable earlier diagnosis of neurodevelopmental disorders, more accurate counselling, and more personalized maternal and fetal care.

Conclusion

Over recent decades, fetal neurosonography has evolved rapidly from an examination focused primarily on detecting structural CNS anomalies into an advanced tool for comprehensive assessment of fetal brain anatomy, maturation, and development. Technological advances, standardization of examination techniques, and improved understanding of normal prenatal neurodevelopment now permit detection of subtle disturbances in brain architecture that until recently were beyond the capabilities of ultrasonography.

Contemporary neurosonography plays a key role not only in diagnosing developmental CNS anomalies but also in evaluating fetuses at increased risk of neurodevelopmental impairment, including those affected by fetal growth restriction, congenital heart disease, and intrauterine infection. Its role in selecting patients for genetic testing and planning further prenatal and perinatal management is also increasingly important. When additional evaluation is required, neurosonography remains the first-line modality, whereas MRI is a valuable complement that provides additional information in selected clinical situations.

Despite its high diagnostic value, neurosonography remains dependent on operator expertise, image quality, and gestational age. Not all neurodevelopmental disorders manifest as morphologic changes detectable prenatally; interpretation should therefore always integrate the clinical findings and results of other imaging and genetic studies.

Neurosonography provides clinically important information that allows clinicians to individualize diagnostic and therapeutic management and organize multidisciplinary prenatal and postnatal care. It also provides parents with reliable information about prognosis, the child's possible developmental course, and available treatment and support. This information forms the basis of specialist counselling and supports parents in making informed decisions concerning future reproductive plans.

The future of neurosonography lies in further development of quantitative methods for assessing brain maturation, the use of artificial intelligence, and integration of ultrasound data with molecular diagnostics and advanced image-analysis techniques. These innovations may permit even earlier detection of neurodevelopmental disorders, more precise prognostication, and individualized prenatal care. Neurosonography remains the principal tool for prenatal CNS diagnosis. Its role continues to expand beyond anatomic assessment to encompass analysis of brain development and maturation, support for genetic diagnosis, and prognostication. In the coming years, integration with modern imaging technologies and artificial intelligence may establish neurosonography as a cornerstone of precision, personalized prenatal medicine.

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