How to obtain diagnostic planes of the fetal central nervous system using three-dimensional ultrasound and a context-preserving rendering technology

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The antenatal evaluation of the fetal central nervous system (CNS) is among the most difficult tasks of prenatal ultrasound (US), requiring technical skills in relation to ultrasound and image acquisition as well as knowledge of CNS anatomy and how this changes with gestation. According to the International Guidelines for fetal neurosonology, the basic assessment of fetal CNS is most frequently performed on the axial planes, whereas the coronal and sagittal planes are required for the multiplanar evaluation of the CNS within the context of fetal neurosonology. It can be even more technically challenging to obtain "nonaxial" views with 2-dimensional (2D) US. The modality of 3-dimensional (3D) US has been suggested as a panacea to overcome the technical difficulties of achieving nonaxial views. The lack of familiarity of most sonologists with the use of 3D US and its related processing techniques may preclude its use even where it could play an important role in complementing antenatal 2D US assessment. Furthermore, once a 3D volume has been acquired, proprietary software allows it to be processed in different ways, leading to multiple ways of displaying and analyzing the same anatomical imaging or plane. These are difficult to learn and time consuming in the absence of specific training. In this article, we describe the key steps for volume acquisition of a 3D US volume, manipulation, and processing with reference to images of the fetal CNS, using a newly developed context-preserving rendering technique.

Key words: Crystal Vue, magnetic resonance imaging, multiplanar imaging, neurosonology, postprocessing

Three-dimensional (3D) ultrasound (US) has the potential to improve the confidence of an anatomic diagnosis suspected on 2-dimensional (2D) imaging. Enhanced resolution of newly developed US probes has dramatically improved the diagnostic potential of 2D US; however, it ultimately consists in a tomographic technique of a 3D object. On the other hand, the offline multiplanar navigation of 3D volumes can provide better visualization and recognition of normal fetal anatomy and more accurate definition of fetal abnormalities compared to 2D US.[1–6] For these reasons, this technology has been shown to be helpful for the evaluation of the fetal central nervous system (CNS)[7–9] and particularly of the posterior fossa,[10–13] the cortical layer,[14–17] midline structures,[18–20] and the optic chiasm.[21,22] In addition, 3D US may provide advantages for the assessment of the face.[23,24] Several authors have focused on 3D US as a complementary tool in the evaluation of the secondary palate[25–32] or the fetal mandible,[24,33] and recent reports have suggested that the subjective[34–40] or semi-automated[41] detection of facial dysmorphisms using 3D US can contribute to the identification of highly suggestive features of genetic syndromes. Also skeletal,[42–44] cardiac,[45–53] and thoraco-abdominal[54,55] imaging may benefit from 3D US assessment, whereas more recent advances in 3D imaging have focused on the implementation of intelligent software for the automated data extraction from 3D volume datasets for clinical purposes. Within this scenario, fetal intelligent navigation[56–59] and the 5D CNS+[60] software have been designed with the aim to provide the clinicians valuable and reliable tools capable of simplifying the ultrasound assessment of the fetal heart and brain, respectively.

Although the role of 3D US as a potential complementary tool in the advanced assessment of the fetal CNS has been demonstrated[2–4,6–8] and is acknowledged in the International

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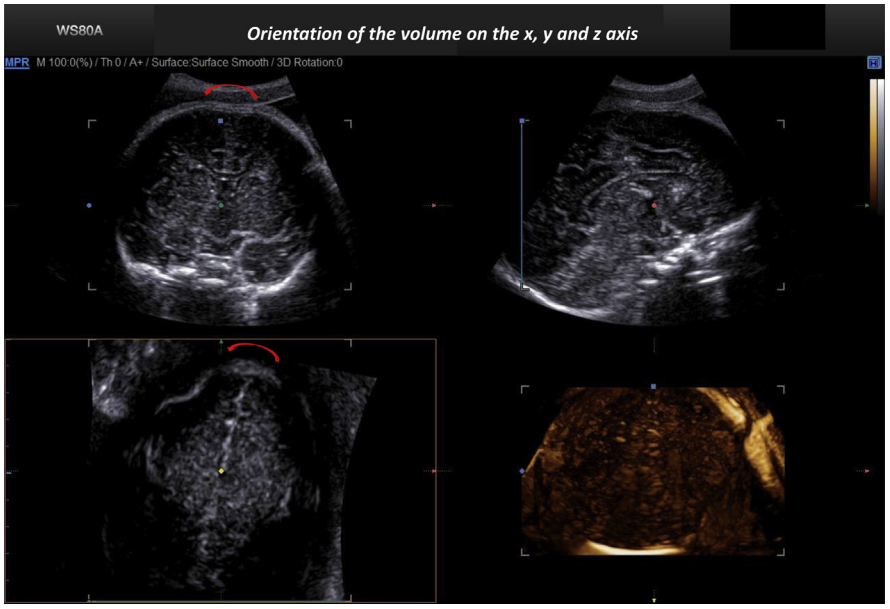
FIGURE 1
Brain volume acquired on the coronal plane through the anterior fontanelle



After acquisition, the volume is orientated along the x, y and z axis. In this case, the goal is to obtain an optimal midsagittal (top right) and transthalamic coronal plane (top left).

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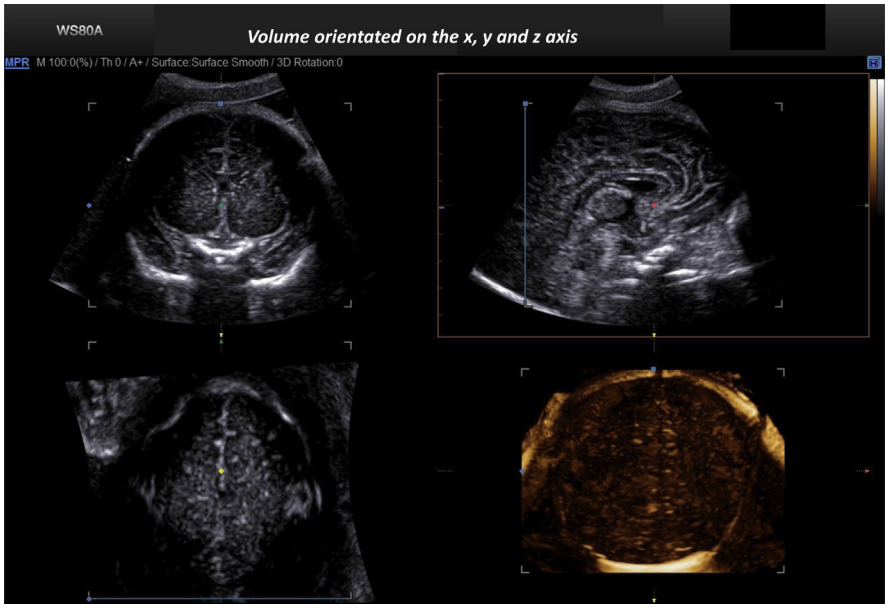
Guidelines for fetal neurosonology,[61] 3D US has not found yet a niche in fetal or general obstetric imaging and is not considered to be a necessary investigation. This is partially because of the multiplicity of different technologies, all of which have an impact on the cost of an ultrasound machine, and the time needed to process the 3D volume. Also, there is little consensus as to the ideal method of volume acquisition, settings, and analysis of the volume, which may explain why 3D ultrasound has arguably not had the impact in imaging in prenatal diagnosis that might have been expected. Furthermore, although the performance and interpretation of anatomic structures with 2D ultrasound is the subject of increasingly rigorous training requirements[62–64] this has currently not been established for 3D US. Finally, after the 3D volume has been acquired, commercial systems will allow it to be processed in different ways,[31,32,42,43,65–68] leading to many ways of displaying and analyzing the same anatomical imaging or plane, and the lack of familiarity with postprocessing of most practitioners may preclude the extraction of information from the volume dataset even in those cases in which 3D US can complement the antenatal US assessment.

FIGURE 2
Correct orientation of the brain volume along the x, y, and z axis



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There remains little consensus among experts as to the value of different postprocessing settings. Crystal Vue is a context-preserving postprocessing technique for 3D volumes manufactured by Samsung Medison Co. Ltd (Seoul, Republic of Korea) that is not dissimilar to HDlive Silhouette (GE Healthcare, Chicago, IL)[68–71] and allows easier differentiation between tissues with different echogenicity by enhancing contrast. In this Expert Review, we detail how 3D volumes are optimally obtained, which settings are used to optimize the anatomical sections, and how postprocessing techniques, in this case, Crystal Vue,[32,36] are used.

Technique of Crystal Vue imaging: from volume acquisition to postprocessing

Volume acquisition

Three-dimensional US volumes consist of a high number of 2D frames (or slices), which are acquired with volumetric transducers. Any scanning plane—axial, coronal, or sagittal—is potentially suitable for the volume acquisition, depending upon the fetal lie and position

and the features of the structure that is being evaluated. For example, volumes for the evaluation of the posterior fossa are usually acquired transabdominally on an axial plane through the lamboid suture but also may be obtained transvaginally on a coronal plane through the anterior or the posterior fontanelle or on a midsagittal plane through the sagittal suture, depending upon the fetal head position.[10,11] The fundamental basis underlying 3D US is that whatever the plane of acquisition, the image can be oriented to show the fetal structures in a standardized way.

Postprocessing: multiplanar mode

After acquisition, 3D volumes are usually displayed in 3 windows in the 3 orthogonal planes x, y, and z. Using the cursors, the examiner is able to move back and forth on 1 plane and evaluate the corresponding changes on the other 2 planes. Furthermore, the examiner can move the fetal volume into a position that is often not achievable with live scanning using conventional US.

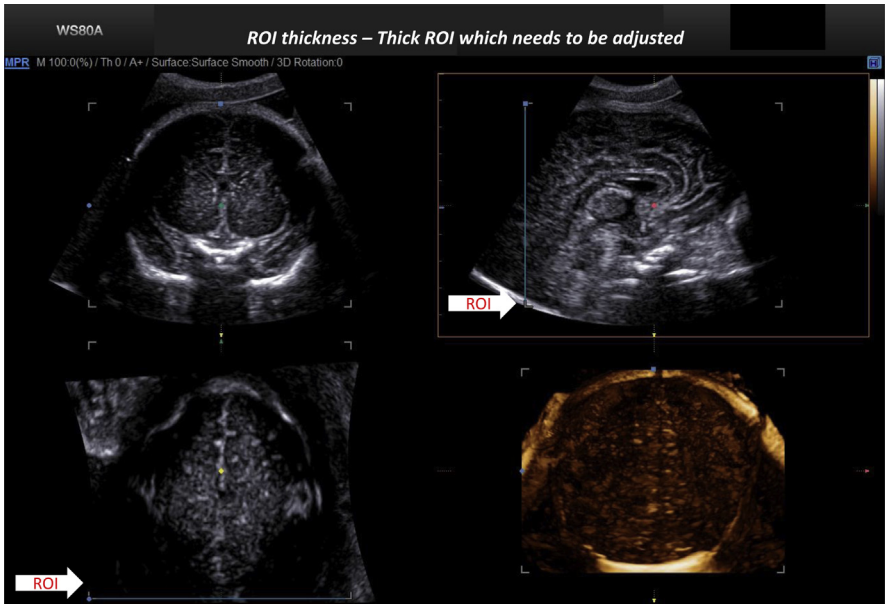
Postprocessing: rendering

Rendering refers to the use of dedicated software that is applied to the stored 3D volumes to obtain the desired mixture of contrast, light, and transparency and that retrieves additional information. This may include data on the surface or the skeleton of the index volume, allowing principally for the translucency and smoothing of the image to be modified.

Factors affecting the quality of the acquired volume

The quality of the volume acquired depends on the limitations inherent to the physics of ultrasound, for example, maternal obesity, fetal lie, and depth of imaging, which apply to both 2D and 3D imaging; furthermore, the presence of fetal movements or movements of the transducer will affect the integrity of the volume acquired. The volume resolution also depends upon the number of slices that constitute the index volume. Their overall number varies depending upon the "scan angle." For a

FIGURE 3
Adjustment of the thickness of the region of interest (ROI)



In this case, a thick region of interest does not allow the visualization of the rendered view of the transthalamic coronal plane, which is displayed in the bottom right quadrant (region of interest pointed by the arrows).

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FIGURE 4
Adjustment of the thickness of the region of interest (ROI)

The slimmest region of interest is used in order to optimize the rendered view of the transthalamic plane in the bottom right quadrant (region of interest pointed by the arrows).

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FIGURE 5
Control touch screen of the Samsung WS-80 as displayed after volume acquisition

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fixed scan angle of 65°, the number of slices ranges between 70 and 150 for "scan quality low" and "extreme," respectively. The "scan quality" is related to the acquisition speed. Slow speeds result in more scanned "slices" and higher resolution volumes (up to 150 frames for a scan angle of 65°) usually used for nonmoving organs, higher speeds result in fewer "slices."

FIGURE 6
Selection of the icons "Crystal Vue" and "Realistic Vue" from the control touch screen

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Finally, the width of the scan angle is another parameter that needs to be adjusted before the volume acquisition. This will affect the length of the volume acquisition but has no impact on the quality of the acquired volume.

3D ultrasound and Crystal Vue rendering technology: step-by-step guide

This article is intended to describe a step-by-step approach for Crystal Vue imaging, providing examples from unpublished images from normal and abnormal US brain volumes. These were collected during scans performed routinely and were based on clinical indication; all were acquired transabdominally on the axial, coronal, and/or sagittal plane using a 4- to 8-MHz probe—equipped Samsung WS-80 ultrasound machine (Samsung Medison Co Ltd). The quality of the volume acquisition was set to "extreme," and the angle of the volume sweep was adjusted to encompass the index structure.

Once the US volumes were acquired (Figure 1), they underwent offline postprocessing on the ultrasound system. This can also be performed using dedicated "5D viewer software" by Samsung Medison. (Similar software has been developed also by other companies and is available also for other ultrasound systems, for example "4D view" by GE.) Postprocessing with the multiplanar mode is then applied to orient the volume along the X, Y and Z axes (Figure 2). This enables the sonographer to be aware, at any time, of the position of the views within the volume. The region of interest (ROI) is then adjusted to obtain the thinnest slice (Figures 3 and 4). The "Crystal Vue," together with the "Realistic Vue," icon is selected from the control touch screen (Figures 5 and 6). "Realistic Vue" is an additional rendering software available on the Samsung WS-80 ultrasound machine. The combination of Crystal Vue and Realistic Vue is possible, but not always needed.

Volumes are navigated by means of the scrolling function in each plane of the space. The icon "Render setup" (Figure 7) is on the second page of the

control panel of the Samsung WS-80 and allows the rendering plane to changed (Figure 8). As an alternative, the rendering plane can be adjusted by manual rotation in the x, y, and z planes.

Optimization of the rendered views

The rendered views can then be optimized by means of further options available for Crystal Vue software. HD Volume Imaging (HDVI) delivers clearer contrast by enhancing tissue differentiation and edge depiction; the different presets available, which include "brain", "early obstetrics (OB)" and "heart", allow a straightforward selection of the most appropriate HDVI setting for the structure that is being examined (Figures 9–11). By selecting "Crystal Vue Setup" or "Realistic Vue Setup" (Figure 12), the control panel allows the direction of the light source to be changed, either automatically or manually (Figure 13), ultimately obtaining different views of the same diagnostic plane (Figures 14 and 15). In addition, on the same panel, the inversion mode, which demonstrates hypoechoic structures such as ventricles and cystic lesions, may be selected through the icon "Invert" (Figures 16 and 17). To adjust the HDVI transparency, which is labeled "HDVI index" (Figure 18), the optimal compromise between transparency and contrast enhancement is achieved, in our experience, using the setting "3." In Table 1, in Figures 1–18 in the PowerPoint slides, and in the embedded videos, we summarize the recommended steps for the 3D volume postprocessing using Crystal Vue, which usually can be completed in a few minutes for those familiar with 3D volume analysis.

Qualitative Evaluation of Crystal Vue Imaging of the Normal and Abnormal Fetal Brain

For the qualitative evaluation of the Crystal Vue rendering technology and the comparison with magnetic resonance imaging (MRI), normal brain images and 4 abnormal cases were submitted for offline postprocessing and qualitative evaluation by 3 fetal medicine experts (C.L., G.P., A.D.) and a pediatric neurologist (N.S.B.). As per the decision of the consultant responsible for the antenatal care, the abnormal cases were submitted to antenatal MRI. The images were reviewed by the clinician and expert opinion was then obtained from a radiologist specializing in fetal imaging (E.W.) and a pediatric neurosurgeon (Z.T.).

Independent fetal medicine experts (see Collaborating Authors in Acknowledgments) were e-mailed the same pictures and asked to comment on the quality of imaging of anatomical

FIGURE 7
Selection of the icon "Render Setup" on the second page of the control panel, which can be selected through the arrow at the top left of the screen

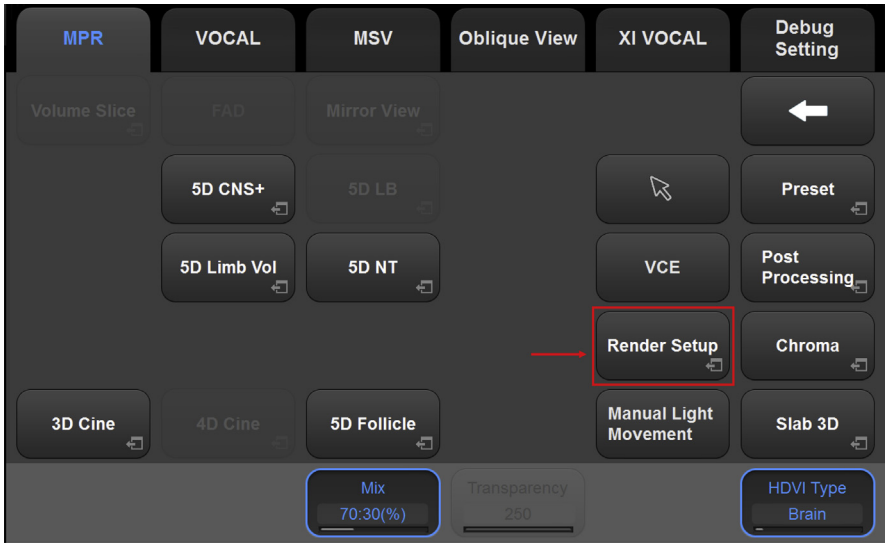

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FIGURE 8
Automated selection of the rendering plane using the highlighted icons

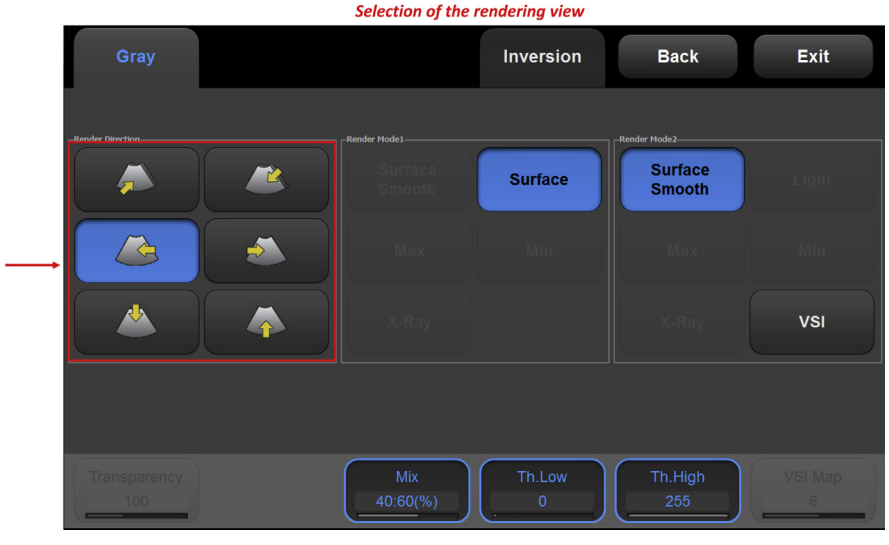

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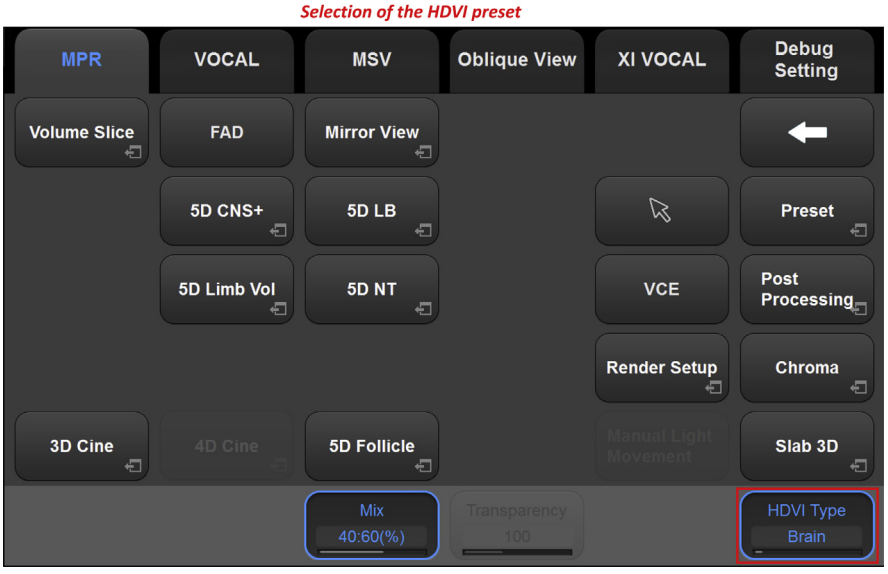
FIGURE 9
Optimization of the rendered view through the selection of the HD Volume Imaging (*HDVI*) setting



Among the available HDVI presents, "Brain" is the one dedicated for the assessment of the fetal central nervous system.

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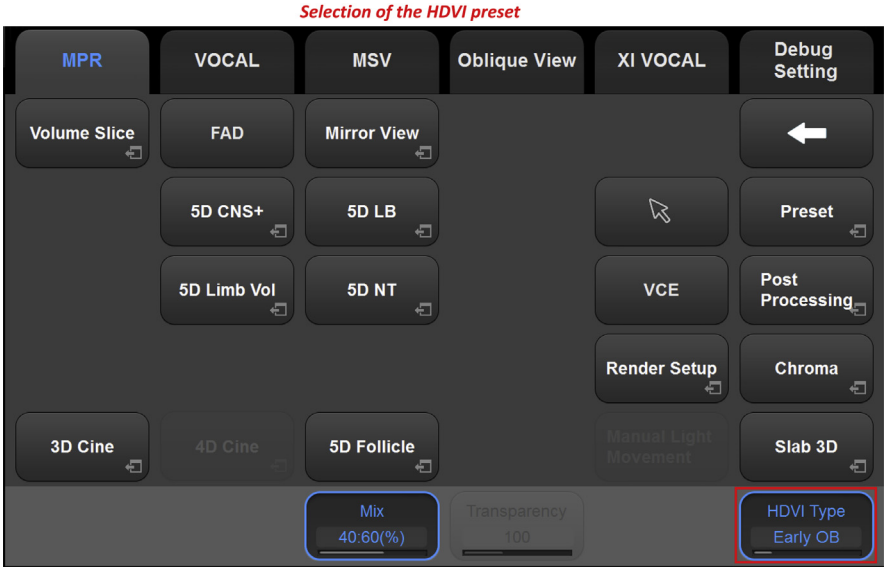
landmarks for the same sections of the fetal brain using multiplanar imaging, Crystal Vue, and MRI.

Axial, coronal, and sagittal views from index volumes are shown in Cases 1–5.

Comparative description of CNS images from ultrasound and MRI

Normal brain images are shown in Case 1. The multiplanar and Crystal Vue transventricular axial views were taken on an axial plane through the lamboid suture from a 28-week fetus. On this view, we labeled the cavum septum pellucidum (CSP) and the ventricular wall (arrows) and observed a better resolution using multiplanar view (Case 1, image 1a). Normal

FIGURE 10
Optimization of the rendered view through the selection of the HD Volume Imaging (*HDVI*) setting



Among the available HDVI presets, "Early OB" performs better in the first trimester and up to 16 weeks of gestation.

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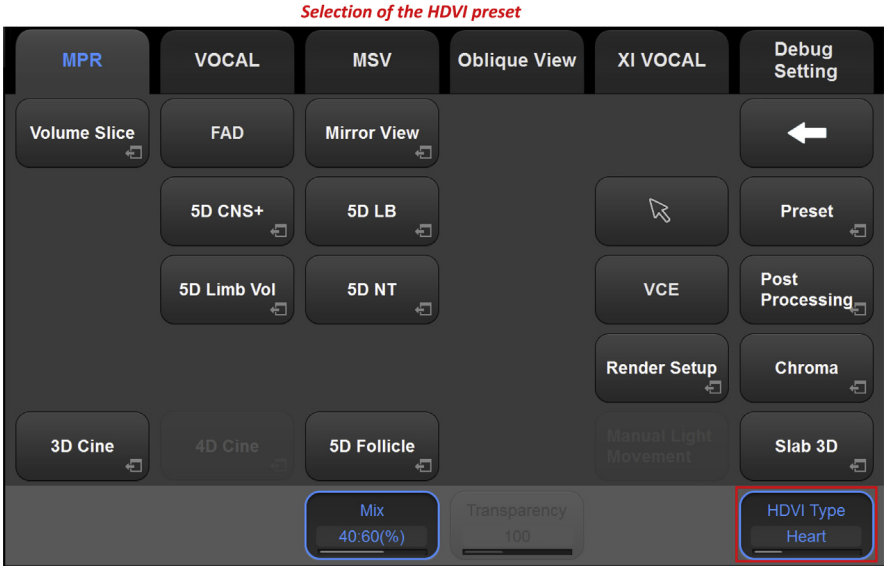
FIGURE 11
Optimization of the rendered view through the selection of the HD Volume Imaging (*HDVI*) setting



"Heart" is the preset developed for the 3D evaluation of the fetal heart.

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coronal and midsagittal US views were obtained from a 33-week pregnant patient who underwent a follow-up scan in uncomplicated monochorionic diamniotic twins. This volume was obtained on the coronal plane through the anterior fontanelle in a breech fetus. Crystal Vue showed high definition of the corpus callosum, the hippocampal fissure, the cingulate sulcus, and the sulcal and gyral pattern (Case 1, images 1e, 1f, 1h, and 1i). In Case 1, images 1j and 1k, a detailed midsagittal view of the normal posterior fossa including the cerebellar vermis with the primary

FIGURE 12
Icons "Crystal Vue Setup" or "Realistic Vue Setup" on the first page of the control panel

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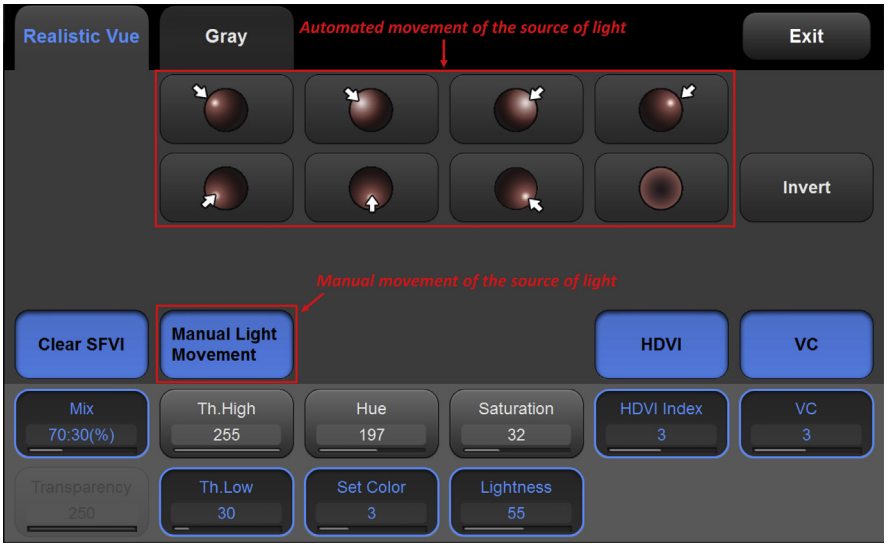
FIGURE 13
Control panel displaying the option for the automated and manual adjustment of the light source



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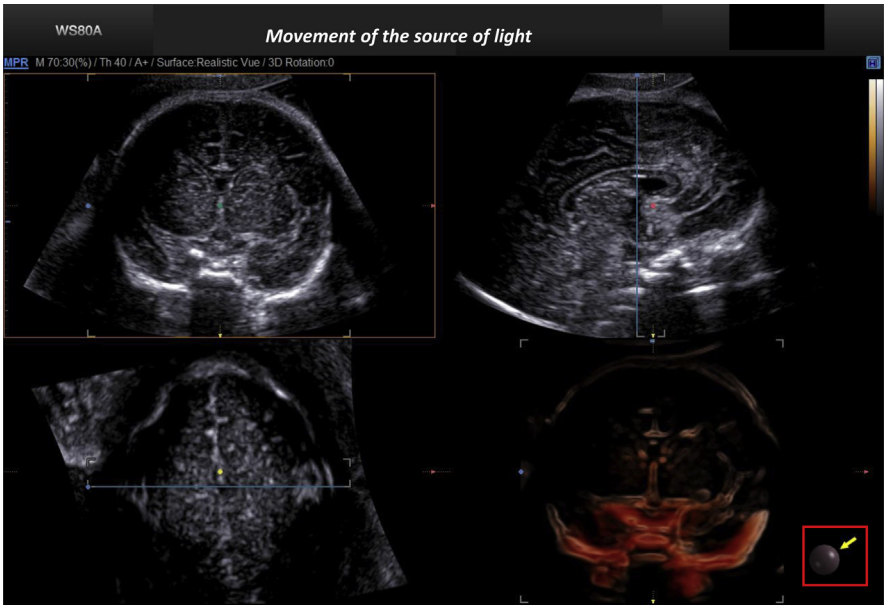
fissure, the fourth ventricle, and the Sylvian aqueduct could be obtained through an axial acquisition on the transcerebellar plane from a 30-week fetus.

Ultrasound midsagittal views of Case 2 (28 weeks, grade IV intraventricular hemorrhage) and Case 3 (34 weeks, cavum velum interpositum cyst) were reconstructed from a 3D dataset acquired on the midsagittal view and compared to MRI findings. In both cases, the best definition of the sulcal and gyral patterns, along with the corpus callosum, the cerebellar vermis, and, in

FIGURE 14
Adjustment of the light source allows one to obtain different views of the same diagnostic plane



In this example the light source is directed from right to left and from the top to bottom of the volume.

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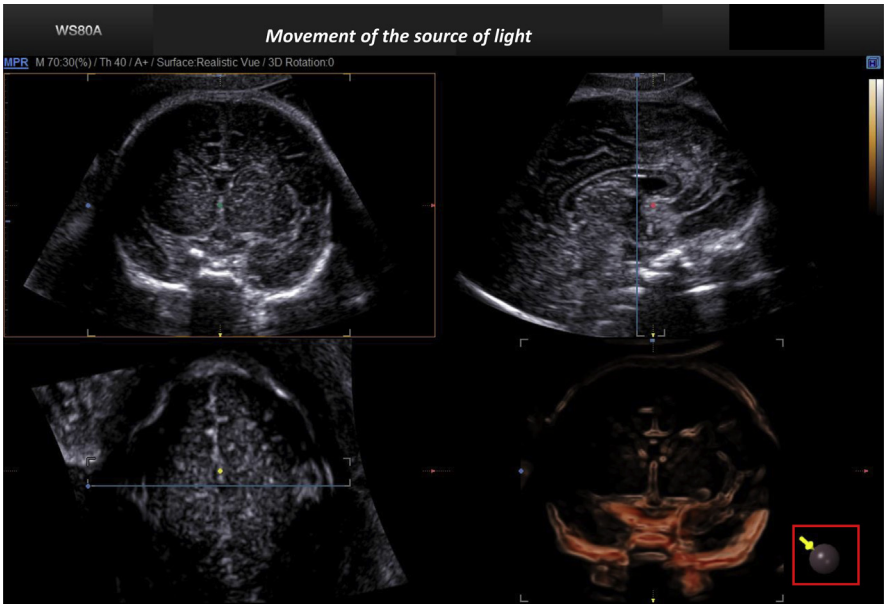
FIGURE 15
Adjustment of the light source allows one to obtain different views of the same diagnostic plane



In this example, the light source is directed from left to right and from top to bottom of the volume, which accounts for the different chromatic features of the rendered view (bottom right) of the same diagnostic plane that is shown in Figure 14.

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Case 3, the cyst walls, were obtained with Crystal Vue.

A comparison among multiplanar, Crystal Vue, and MRI on the coronal plane is shown in Case 4 (34 weeks, grade 3 intraventricular hemorrhage). As can be seen (images 4b and 4e), Crystal Vue provided a detailed view of the intraventricular clots and the ventricular walls. Finally, on the axial plane, clear definition of the cystic walls, together with the midline shift, was shown using Crystal Vue (Case 5, 28 weeks, interhemispheric arachnoid cyst with midline shift). In all of the abnormal cases, the antenatal

FIGURE 16
Selection of the "Inversion Mode" from the control panel

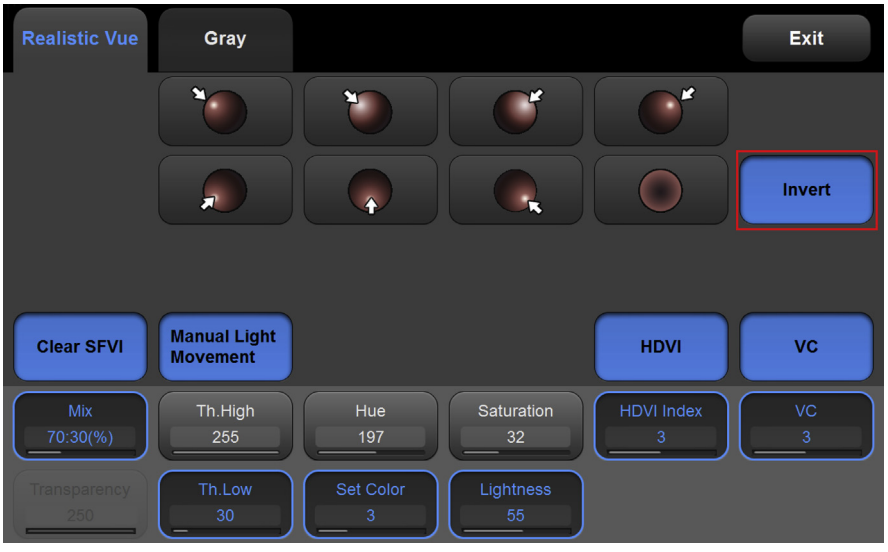

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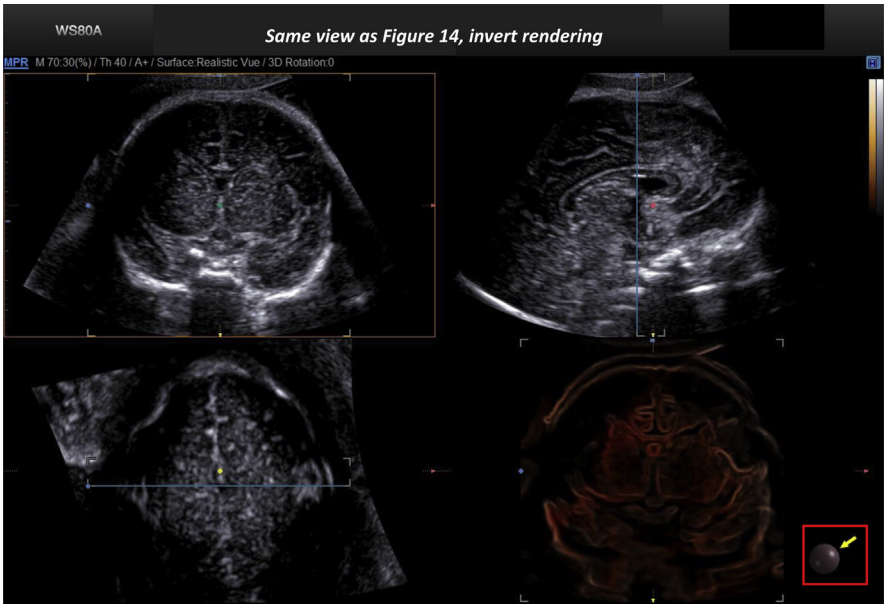
FIGURE 17
Selection of the "Inversion Mode" allows one to obtain different views of the same diagnostic plane



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diagnosis was confirmed by further imaging after birth.

Comment

There are several proprietary post-processing 3D techniques including HDlive Silhouette,[68–71] TrueVue,[72] Luminance,[73] and others, all of which have particular and specific attributes to different imaging applications over which we have deferred to the manufacturers' descriptions in the absence of a "head to head" comparison in this area. In this article, we do not compare the techniques but, rather, describe how to process a 3D volume and optimize its rendering using Samsung Crystal Vue technology.

Rendering optimization

Manipulation in the multiplanar mode is a prerequisite for any 3D post-processing technique; hence the quality of the acquired volumes, in common with any other 3D rendering technique, depends on the time spent on obtaining the ideal plane. Using Crystal Vue, several steps or "clicks" are needed on the ultrasound machine keyboard, and the user interface requires time and experience for familiarization of all of the features, although many are common to conventional multiplanar imaging.

Qualitative assessment of rendered views obtained with Crystal Vue and comparison with MRI

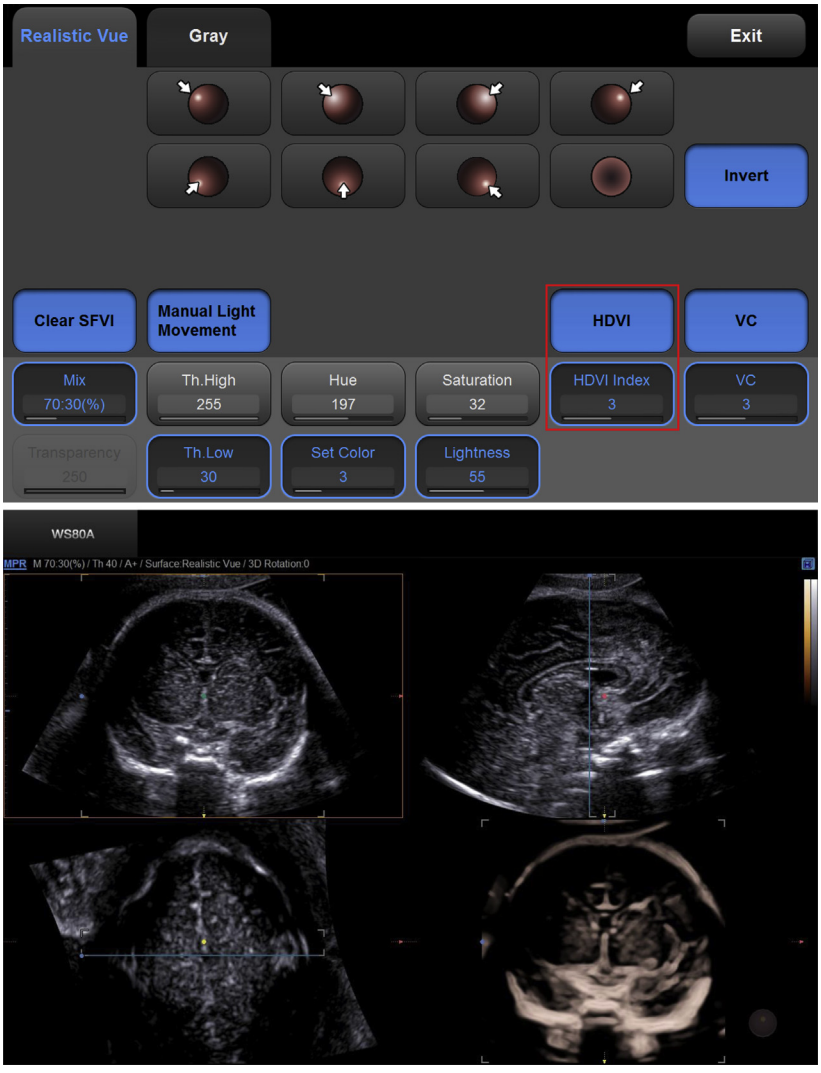
The qualitative evaluation of Crystal Vue in the assessment of the fetal CNS and its comparison to multiplanar imaging and MRI highlights different properties for each technique. Multiplanar imaging is a useful modality for evaluation of the fetal CNS.[7–22,63] Crystal Vue appears to give high-resolution imaging in the assessment of the developing cortical gyri and sulci in the coronal and sagittal planes and for the delineation of the wall of cystic lesions. MRI seems to provide more information particularly in the axial plane, whereas the assessment of the cortical folding may be performed with 3D US and Crystal Vue.

Even though a very recent Randomized Controlled Trial suggests that MRI does add to prenatal ultrasound,[74] the genuine contribution of MRI compared to US in fetal CNS imaging has been subject of controversies among experts in neurosonology.[75–78] Furthermore, costs and limited availability represent major disadvantages of MRI, which can also be negatively affected by fetal movements.[79] On the other hand, multiplanar imaging has high reproducibility among operators and is able to identify small lesions (<4 mm) that cannot be detected at MRI and to provide simultaneous visualization of the same structure in the 3 planes.[7,8,14]

Crystal Vue rendering in the evaluation of the fetal CNS: which perspectives?

We do not envisage that Crystal Vue can substitute for MRI as a second-level examination for the assessment of the fetal CNS especially, although it appears capable of providing additional information compared to 2D US.[80–82] Very recent evidence has shown that advanced US and MRI assessment of the fetal CNS may yield information that may not be obtainable through other

FIGURE 18
Adjustment of the transparency of the HD Volume Imaging (HDVI) (icon "HDVI index")



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investigations,[80,83] and within this scenario Crystal Vue could be complementary to other imaging techniques in the advanced neuroimaging of the fetus.

Cortical folding becomes more complex with advancing gestational age[15,16,84]; thus we have included only third-trimester fetuses, as we believe that this represents the ideal timeframe in which Crystal Vue imaging should be undertaken. It is worth noting that structures that may be suboptimally visualized on 3D US could be clearly seen using Crystal Vue, the resolution of which appeared greater for subtle brain structures such as sulci, fissures, and cyst walls, the latter being difficult (if not impossible) sometimes to see on MRI. This may suggest a use in the longitudinal assessment of fetuses where disorders of the neuronal migration are suspected.

Conclusion

In conclusion, we describe how to obtain Crystal Vue rendered views by focusing on CNS imaging, and we compare our images with those of conventional multiplanar mode and MRI. We previously reported the features of Crystal Vue imaging of the skeletal system[43] and the oropalatal structures[32] and how this may provide additional diagnostic information. By showing views of the normal and the abnormal fetal brain, we suggest that Crystal Vue rendering may similarly play a role in complementing the antenatal imaging of different CNS structures. We believe that an important message for neurosonologists and fetal medicine specialists is not that one technique is better than another but the combination of several techniques—in this case, Crystal Vue with multiplanar imaging and MRI—could be complementary in

TABLE 1
Recommended steps for volume collection and postprocessing

	General considerations	Specific recommendations
Patient selection	All patients potentially eligible	Limitation represented by high body mass index, oligohydramnios, fetal movements, unfavorable fetal lie
	Ideally gestation between 28 and 34 wk	Development of all gyri and sulci that can be antenatally evaluated
Volume acquisition	Insonation for 3D transabdominal acquisition	All scanning planes potentially suitable for the brain:
		- Axial plane for 3D imaging of the posterior fossa
		- Coronal through the anterior fontanelle for the visualization of the CSP, the thalami, and the optic chiasm
		- Midsagittal view through the metopic/midsagittal suture or the anterior fontanelle for the corpus callosum, sulci, and gyri
	ROI Position and ROI Size	Need to be adjusted based on the depth and the size on the index structure
	Scan Angle sweep width of the 3D acquisition	Needs to be adjusted based on the size of the index structure
	Scan Quality	Needs to be set at "Extreme"
Once the volume is acquired (see also dedicated PowerPoint)	Volume has to be oriented along the x, y and z axis	Use the multiplanar mode.
	ROI to be adjusted to obtain the thinnest slice	Select "ROI" through the dedicated button on the keypad
	Select the rendering plane through the icon "Render Setup"	Manual or automated selection of the rendering plane; automated selection may be helpful for experts but misleading for first users
Postprocessing (see also dedicated PowerPoint)	Selection of Crystal Vue ± Realistic Vue	Dedicated icon(s) on the control panel
	Optimization of Crystal Vue rendering	- HDVI needs to be set based on the index structure
		- Selection of "Crystal Vue Setup" or "Realistic Vue Setup" on the control panel to change automatically or manually the source of the light
		- Consider inverted mode
		- HDVI index needs to be set at 3
		- Contrast may be further adjusted through the functions "Th. Low" and "Bias"; these controls, in our experience, are not critical to imaging quality

Note: We refer to the fetal central nervous system (CNS) by way of example; however, the principles apply to other organs and systems.

CSP, cavum septum pellucidum; *3D,* 3-dimensional; *ROI,* region of interest.

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the antenatal assessment of the fetal anatomy, thus providing a better diagnostic performance than each technique alone. ■

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All of the authors have contributed to the work and take responsibility for the content.

CONTRIBUTING AUTHORS

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Glossary

Multiplanar mode—Ultrasound modality for volumetric imaging that displays and allows navigation of the ultrasound volume. Multiplanar mode allows images to be created from the original plane of acquisition (ie, the axial plane) in any other plane of the space (coronal, sagittal, or oblique one).

Postprocessing—Consists of the manipulation of the raw data after acquisition and includes all the adjustments in terms of transparency, contrast, light source, and rendering modality performed to optimize image quality from the original volume.

Rendering—Rendering technologies consist of dedicated software that can be applied to the stored 3-dimensional volumes to obtain the desired mixture of contrast, light, and transparency and retrieve additional information such as the surface of the index volume or the skeleton that is underlying the fetal skin.

HD Volume Imaging (HDVI)—HDVI encompasses a subsets of organ/tissue-specific presets available on the Samsung WS 80 ultrasound machine that aims to deliver clearer contrast by enhancing tissue differentiation and edge depiction.

Crystal Vue—Context preserving post processing rendering technology for 3-dimensional ultrasound volumes introduced in 2015 by Samsung Medison and based on image-contrast enhancement.

Realistic Vue—Postprocessing rendering technique for three-dimensional volumes developed by Samsung Medison which can be compared to HDlive Silhouette, TrueVue and Luminance.

Inversion mode—Rendering technique that inverts anechogenic structures that are displayed as black on the customary 2-dimensional gray-scale ultrasound image into a white (or colorized), cast-like appearance.

Region of interest (ROI)—The ROI represents a subset of the 3-dimensional volume dataset that is identified for volume rendering by means of a dedicated volume box that can be adjusted on the ultrasound machine.