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Three-dimensional transvaginal neurosonography of the fetal brain: 'navigating' in the volume scan

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ABSTRACT

Objectives *Fetal neuroscan by ultrasound has gained in importance over recent years. Two-dimensional (2D) transvaginal sonography was an important step in understanding the constantly changing and developing fetal brain. The objective of this article is to describe the use of three-dimensional ultrasound of the fetal brain enhanced by the transvaginal transfontanelle scanning technique.*

Methods *Thirty-four pregnant patients were referred to us because of a history of brain anomaly or suspected brain pathology. The fetuses were scanned transvaginally. Two-dimensional as well as three-dimensional (3D) images were generated. The volumes obtained by the 3D-ultrasound machine were displayed in the three conventional orthogonal planes (coronal, sagittal and axial).*

Results *Of the 34 fetuses 10 had normal brain anatomy and 24 had brain pathology. In all 34 cases the 2D images as well as the 3D volumes were of diagnostic quality and all three planes could be obtained. The axial sections could only be obtained by the 3D re-construction of the volume scans. The 2D images produced were acquired from a common point originating from the foot print of the transvaginal probe at the fetal anterior fontanelle or the sagittal suture, the sections 'radiate' from this point. Therefore, these sections are not parallel sections, but are oblique to each other. In contrast, the 3D volume could be examined using the classical parallel sections in all three orthogonal planes. The posterior fossa could be seen better if the footprint of the probe was placed over the posterior fontanelle or on the sagittal suture. The marker dot enabled a precise creation of anatomy and pathology. In the 'angio mode' it was possible to follow the anterior cerebral and pericallosal artery.*

Conclusions *The 3D-ultrasound technology using the transvaginal approach is effective and practical to perform during fetal neuroscan. The ability to 'navigate' in the volume and the 'marker dot' enables exact location of normal structures and evaluation fetal brain pathology. The volume can be reviewed over and over again, can be mailed to an expert, could be shown to consultants (pediatric neurology and neurosurgeons) and used for teaching.*

INTRODUCTION

Transvaginal sonography of the fetal brain, to either measure or to image the intracranial anatomy, was first described almost a decade ago[1,2]. During this decade the use of transvaginal neurosonography has evolved from a descriptive entity to one in which the biometry of the lateral ventricles as well as the planes delineating the anatomy have been standardized[3–6]. However, even though this imaging modality has become widely accepted and an increasing number of practitioners are experienced in this technique, many still seek to avoid its use and many more have not even heard or read about it. This is due to the fact, that despite the distinct advantage of its use, it is perceived as a cumbersome and time-consuming process.

The sections and/or planes obtained through the anterior fontanelle, using conventional 2-D transvaginal neurosonography, were adopted emulating the neonatal transfontanelle approach. All sections were obtained by placing the foot-print of the vaginal probe on the anterior fontanelle and the sections therefore 'radiate' from one point: the fontanelle. Almost every plane, except the median and one coronal plane, is angled or is oblique, and they are therefore are not parallel to each other. Fanning the probe from anterior-to-posterior to obtain the coronal sections and from side-to-side for the sagittal sections results in the desired planes[6]. In contrast to the 2D technique, when a volume of the fetal brain is obtained by using the 3D transvaginal ultrasound probes through the anterior fontanelle, the volume of the fetal brain can now be sequentially sectioned at demand in all three classical

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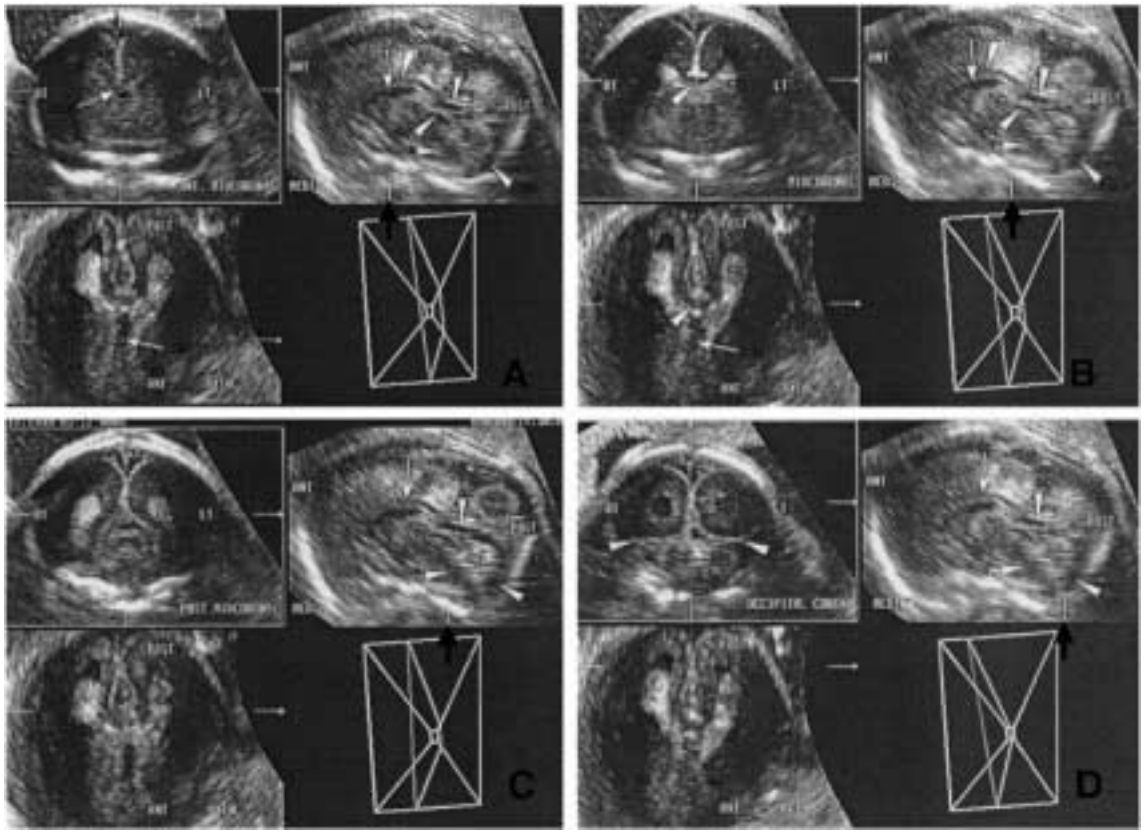

Figure 1 Normal fetal 3D brain scan at 22 weeks. Four screens are shown in panels A–D. In each panel the upper left box 'A' represents the coronal plane. The upper right (box 'B') displays the sagittal plane, the lower left (box 'C') the axial plane and in the lower right (box 'D') the actual volume and the plane used are displayed. The white upward pointing arrow in boxes 'D' in each panel shows the line utilized to create the coronal picture seen in all four boxes 'A'. The sidelines always highlight the 'active' box. Panel A: Box 'A'. Anterior coronal plane showing the anterior horns (AH), caudate nucleus (CN), interhemispheric tissue (IHF) and the superior sagittal sinus (SSS). Panel B: Box 'A'. Midcoronal plane showing the corpus callosum (CC) and the choroid plexus (CP) in addition to some of the structures seen on the previous plane. Panel C: Box 'A'. Posterior midcoronal plane showing the choroid plexus (CP) in the atrium of the lateral ventricle. Panel D: Occipital coronal plane depicting the posterior horns (PH), the tentorium (TE), and the cerebellum (C) with the cerebellar vermis (V) and the cisterna magna (CM). In box 'B' of all four panels the following structures are present: Superior sagittal sinus (SSS), cavum septi pellucidi (CSP), thalamus (T), corpora quadrigemina (CQ), quadrigeminal cistern (QC), fourth ventricle[4], cerebellum (C), and the cerebello-peduncular cistern or cisterna magna (CM).

orthogonal planes and these planes are parallel to each other. These planes are therefore comparable with those sections obtained using serial tomograms by computerized tomography or magnetic resonance imaging. Although, we use extensively the 2D fetal transfontanelle neuroscan initiated by us, we are increasingly aware of the new and more advanced technique for examination of the fetal brain by the 3D technique.

This article describes how to obtain and maximize the information stored as a 3D volume of the fetal brain by using the 3D ultrasound in general and the transvaginal approach in particular.

METHODS

A total of 34 pregnant women with fetuses in cephalic presentation were scanned transvaginally using the conventional 2D transvaginal probe of the ATL 3000 or 5000 (ATL, Bothell, WA, USA) and using the vaginal 3D probe of the Medison 530 Digital 3D ultrasound machine (Medison America, Inc. Cypress, CA, USA). Four fetuses with suspected intracranial pathology underwent external cephalic version under continuous ultrasound guidance since they were in a breech presentation. All patients included in this prospective observational study were between the gestational age of 11–37 weeks and had been referred to our center either for a history of a previous fetus/infant with a brain anomaly or having had a transabdominal scan that was suspicious for a fetal brain malformation. All subjects were scanned by two of the three authors (A.M. and I.E.T.-T.). All images were optimized and the volumes saved by one of the authors (P.M.). All patients first underwent 2D-transvaginal fetal neurosonography using the ATL 3000 or 5000 ultrasound machine. Subsequently, they were changed to the Medison machine and 2D dimensional transvaginal sonography of the fetal brain was performed to identified the region of the anterior fontanelle. The fetal head was gently manipulated and controlled by the free hand of the examiner. Once the ultrasound beam had been aligned with the longitudinal axis of the fetal brain through the anterior fontanelle or the sagittal suture and a clear and diagnostically good 2D

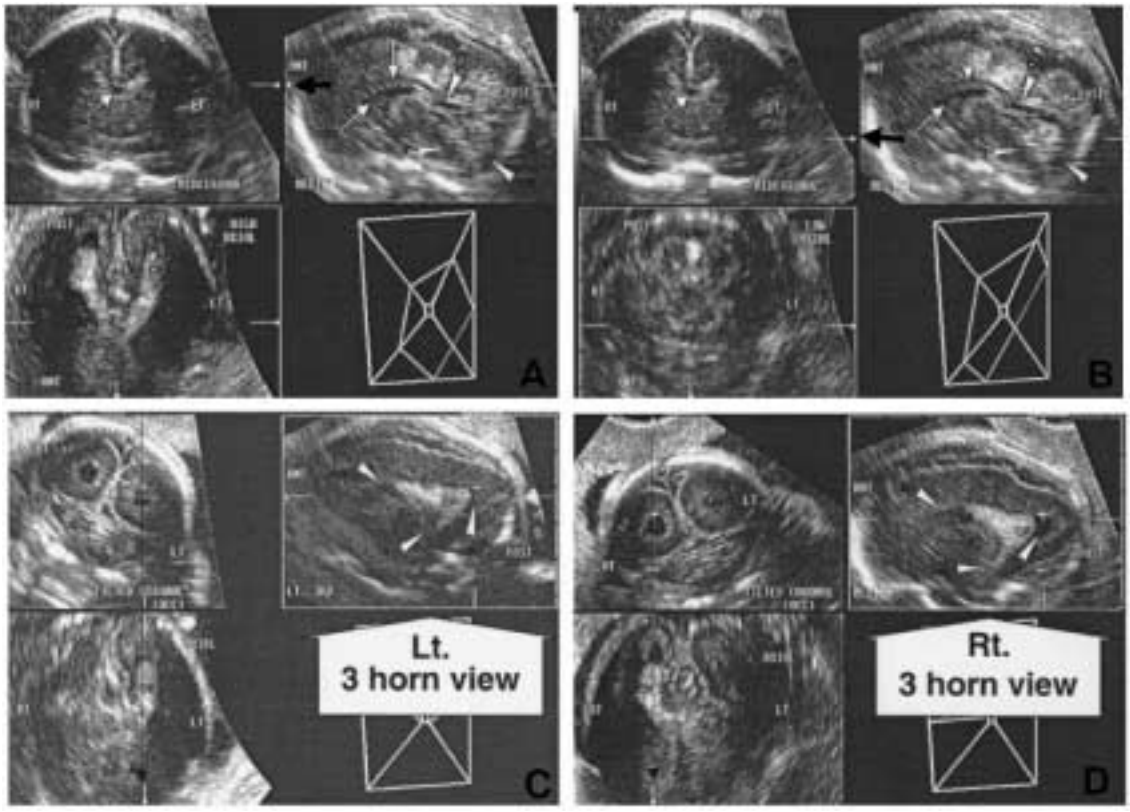

Figure 2 Continuation of the same normal brain seen in Figure 1 with the same general comments. Panel A: The active box is box 'C' in which a mid-axial plane is seen generated at the level indicated by the large white arrow in box 'B'. The choroid plexus (CP) is seen stretching from the anterior horns (AH) to the posterior horns (PH). The marker dot is on the corpus callosum (CC). Panel B: Box 'C' (the active box) depicts a low axial plane showing the posterior fossa with the cerebellar hemispheres (C), the hyperechoic vermis and the cerebello-pedunclular cistern or cisterna magna (CM). Panel C and D: The active boxes are box 'B' which show the normal right and left three horn views (3 HV), respectively. Note that the coronal views in boxes 'A' of panel C and D are titled first to the left and then to the right to obtain the left and the right three horn views and that the lateral ventricles are kept relatively 'straight' in boxes 'C'. The thalamus (T) and the inferior horn (IH) as well as the anterior horn (AH), the posterior horn (PH), the choroid plexus (CP) and the cerebellar hemisphere (C) are also seen.

image of the fetal brain was seen, a volume scan of the brain was obtained using the sweep modality of the ultrasound machine. A second volume with the fetal head in the short axis was also obtained by rotating the probe 90° from the median section of the fetal brain.

The volume was manipulated as follows:

- Coronal sections of the brain were restored and displayed in the 'active box', box 'A' in the upper left side of the monitor (recognizable by the rectangular frame), while the plane of the sections could be seen moving from anterior to posterior on the sagittal image on the upper right side (box 'B') of the quartered screen field of the monitor (Figure 1A–D). Transferring the 'active box' to the sagittal image (box 'B') in the upper right side of the monitor it was possible to view all sagittal sections from side-to-side following the planes of the sections seen (box 'A') on the upper left coronal image. Finally, by moving the 'active box' to the lower right image (box 'C') it was possible to obtain successive horizontal (axial) views of the brain from the base of the skull to the 'top-of-the-head' by looking at the changing planes which were moving as observed in boxes 'A' and 'B' of the two upper images (Figure 2A,B).
- A view of the three horns was simultaneously accomplished by: (1) placing the coronal plane in the upper left (box 'A'), the sagittal (median) plane in the upper right (box 'B') and the axial (horizontal) plane in the lower left (box 'C'); (2) placing the 'active box' on box 'A' this brain section was rotated in the 'Y' axis to image the right lateral ventricle (the sagittal sinus should move to the right); (3) activating box 'B' and using the main 'section control knob' the sagittal plan in box 'A' was moved to the right, keeping the left lateral ventricle in the vertical position in box 'C'. Following these steps the three horn view was seen in box 'B' (Figure 2C,D).

The sections obtained by the stored volume were compared with those obtained by conventional 2D transvaginal transfontanelle neurosonography and the information obtained from the volume was compared to that obtained by the conventional scan. The structures we sought included: the corpus callosum, cavum septi pellucidi, lateral ventricles, third ventricle, corpora quadrigemina, fourth ventricle, cerebellar hemispheres, vermis, cisterna magna and cisterna ambiens as well as other midbrain structures.

RESULTS

In all 34 cases the volume obtained was of high diagnostic quality. All three conventional planes were imaged in all

Table 1 Pathology cases examined with 3D sonography

Case	*Sonographic Findings*	*GA*	*Outcome*
1	Arachnoid cyst; Size/dates discrepancy	26	TOP; no autopsy
2	Arachnoid cyst	24	46 XX; Delivery at term; peritoneal shunt placed; alive and well
3	Arachnoid cyst	31	Delivery term; arachnoid cyst; hydrocephalus
4	Arnold Chiari malformation	16	46 XX; TOP; no autopsy
5	Exencephaly (Twin A; Twin B normal)	18	Selective reduction of Twin A
6	Anencephaly	18	TOP; no autopsy
7	Exencephaly; amniotic bands	13	TOP; no autopsy
8	Intraparenchymal bleed; porencephaly	23	TOP; no autopsy
9	Semilobar holoprosencephaly	11	TOP; no autopsy
10	Alobar holoprosencephaly	17	TOP; no autopsy
11	Semilobar holoprosencephaly; ventriculomegaly (lateral ventricles 1.4 cm)	26	46 XX; TOP; no autopsy
12	Alobar holoprosencephaly; Size/dates discrepancy; echogenic kidneys	18	TOP; no autopsy
13	Agenesis corpus callosum; DW variant	21	46XX; delivery at term; AGCC; DW variant; infant dysmorphic
14	Agenesis corpus callosum; borderline ventriculomegaly (lateral ventricles 1.5 cm)	22	46 XX; TOP; autopsy confirm findings; horseshoe kidney
15	Partial agenesis corpus callosum; bilateral hydrocephalus; abducted thumb (MASA syndrome)	22	46 XY; TOP; no autopsy; L1CAM gene identification is pending
16	Dandy–Walker malformation	32	Lost to follow-up
17	Borderline ventriculomegaly (10.4 cm) at 22 weeks; normal scan at 26 weeks	22	46 XX; normal neonate
18	Nuchal translucency; subsequently cystic hygroma	16	46XY; TOP; no autopsy
19	Bilateral choroid plexus cysts	17	47XY + 18; right club foot and clenched hands
20	Choroid plexus cyst	22	Normal neonate
21	Choroid plexus cyst	17	Lost to follow-up
22	Agenesis corpus callosum	21	Lost to follow-up
23	Right posterior encephalocele; diaphragmatic hernia; oligohydramnios	31	Refused amnio; undelivered
24	Agenesis corpus callosum; bilateral ventriculomegaly (lateral ventricle 1.6 cm)	31	46 XX; undelivered

TOP, termination of pregnancy; AGCC, agenesis of the corpus callosum; DW, Dandy–Walker; GA, gestational age.

fetuses. Each patient was its own control and all anatomic structures that were sought (as described in the methods), in the coronal and sagittal sections using the conventional 2D transvaginal neurosonography were also seen with the 3D scan. However, in the latter the axial section was also imaged. In the 24 cases (Table 1) with intracranial pathology 'navigating' within the volume allowed us to simultaneously view the pathology in all three orthogonal scanning planes. The 2D images were used to make the diagnosis of the pathology or to ascertain a normal scan.

It is impossible and impractical to present all or even most of the pathologic brain scans obtained. We selected to show only the following pathologies: (1) partial agenesis of the corpus callosum (Figure 3) in a fetus with MASA syndrome; (2) partial agenesis of the corpus callosum with ventriculomegaly (Figure 4); and (3) right occipital encephalocele (Figure 5).

The main difference between the 2D and the 3D studies were:

1 the axial section could be seen in all cases transvaginally using the 3D technique; this was an advantage since when using the 2D technology the axial section is rarely seen. However, the images of the axial sections were less sharp than those of the coronal and sagittal sections, especially as gestational age increased.

2 The sections obtained from the saved 3D volume were parallel to each other and not oblique to each other as is the case with conventional 2D transvaginal neurosonography.

3 the posterior fossa was seen the best in the coronal and sagittal sections when the 3D volume was examined. In addition, by scanning through the posterior fontanelle or the posterior section of the sagittal suture, the image of the posterior fossa is much clearer (Figures 1 and 2).

When the 2D studies were compared with the 3D, the main advantage of 'navigating'-within-the-volume in these pathologic cases was being able to follow the 'marker dot' that indicated the same anatomical spot on all three orthogonal planes. It was possible to know the exact location of any structure or any pathology in each plane. Some of the figures depict the functionality of the 'marker dot':

1 In Figure 1A the 'marker dots' are all in the cavum septi pellucidi (CSP).

2 In Figure 1B the marker dots are all on the corpus callosum (CC).

3 In Figure 2A the dot is on the splenum of the corpus callosum (CC).

4 In Figure 2C,D the dot is in the left and right posterior horn, respectively.

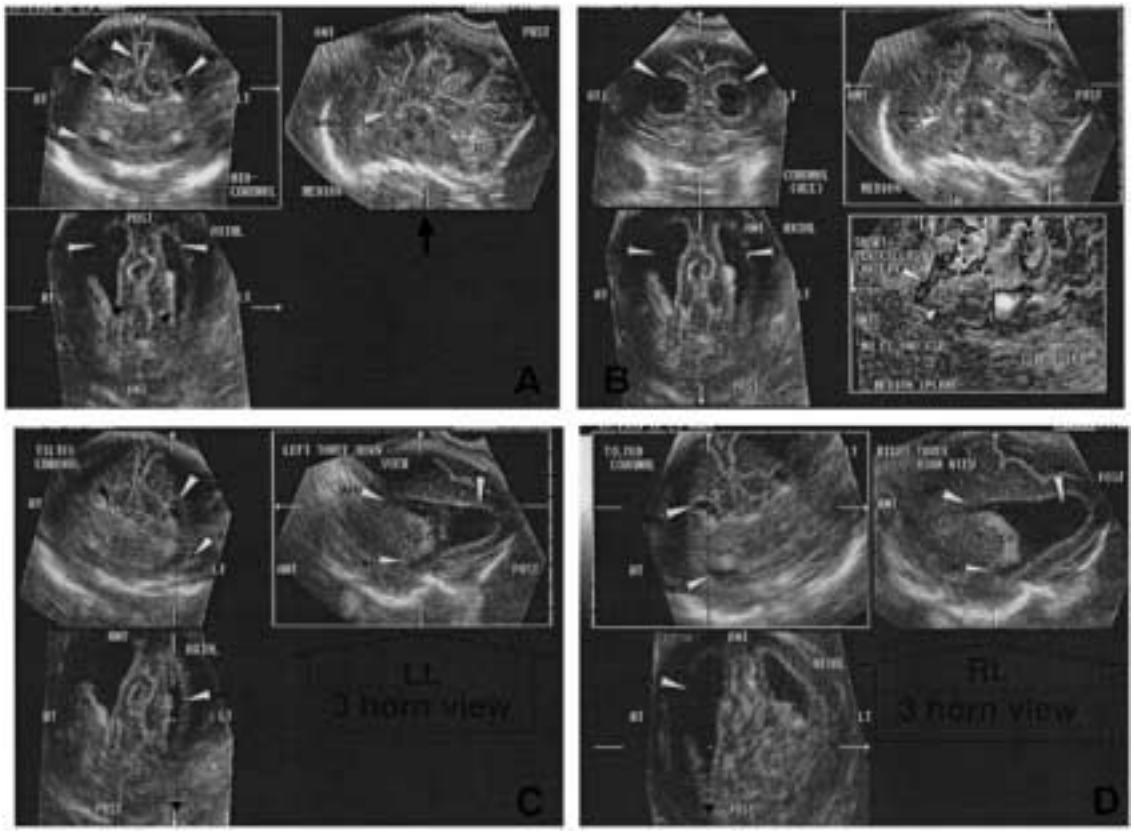

Figure 3 Neuroscan of a fetus with partial agenesis of the corpus callosum and borderline ventriculomegaly at 22 weeks. Panel A: On the midcoronal plane (box 'A') the third ventricle[3] is displaced upward almost confluent with the inter-hemispheric tissue (IHF). Note also the laterally displaced and almost vertical anterior horns (AH). In box 'B' the sagittal plane reveals that there is no cavum septi pellucidi and no corpus callosum leave alone a small portion of the genu. The caudate nucleus (CN), thalamus (T) and the cerebellum (C) are present. In box 'C' the teardrop-shaped lateral ventricle is seen with the anterior horns (AH) and the dilated posterior horns (PH). Panel B: On this occipital coronal plane (box 'A') the dilated posterior horns (PH) are seen above the cerebellum (C). In box 'C' the teardrop-shaped lateral ventricles with the dilated posterior horns (PH) are seen. In box 'D' (lower right) a colour study of the pericallosal artery in the median plane was inserted to show that only the anterior segment of the artery is present confirming the diagnosis. Panel C and D: show the left and right three horn views, respectively. Note the slightly wider than usual anterior horns (AH), the dilated posterior horns (PH) and the open inferior horns (IH).

5 In Figure 3C,D the dot is in the anterior horns (AH).

6 In Figure 4B the dot is on the area of the missing corpus callosum.

7 In Figure 5 the dot marks the spot where the brain tissue protrudes through the cranial defect.

DISCUSSION

To obtain a good volume of the fetal brain one must first get a good 2D image. At times, in order to access the fontanelles transabdominal flexion of the fetal head using the abdominally placed hand of the examiner is needed. This maneuver will allow access to fontanelles, which serve as an acoustic window allowing sharp and clear images of the intracranial anatomy. Furthermore, this maneuver stabilized the fetal head so the volume obtained is free of movement artifact.

Navigating through the coronal planes in an anterior to posterior fashion enabled a thorough examination of the intracranial anatomy in the coronal plane. This navigation allowed us to obtain the three horn view (3HV). This view is comparable to the right and left Oblique-1 views that are obtained by the 2D transvaginal scan[6]. This plane is also the same as the oblique planes obtained by the neonatal transfontanel brain scanning. In the normal fetal brain the anterior horn is narrow, the posterior horn has a more or less triangular shape with the apex pointing posteriorly and the inferior horn is barely seen or not seen at all (Figure 2C,D). In Figures 3C,D and 4C,D the posterior horn is dilated and the inferior horns are visible, which means that there is a significant degree of ventriculomegaly (compared to Figure 2C,D in which the lateral ventricles are normal in size).

Similarly to our previously published article describing the planes and sections obtained by the transfontanelle fetal neurosonography scan[6], we could have arbitrarily decided on any given number of representative sections in each plane obtained by the 3D scan. These sections could easily be placed at the level of predetermined anatomic structures as we did in using the 2D transvaginal fetal neuroscan. However, since it is so easy to 'navigate' within the volume and to 'move' through multiple sections at will in all three planes, there is little or almost no need to have a finite number of predetermined standard sections that need to be imaged. A finite number of predetermined sections when scanning with 2D transvaginal sonography was felt

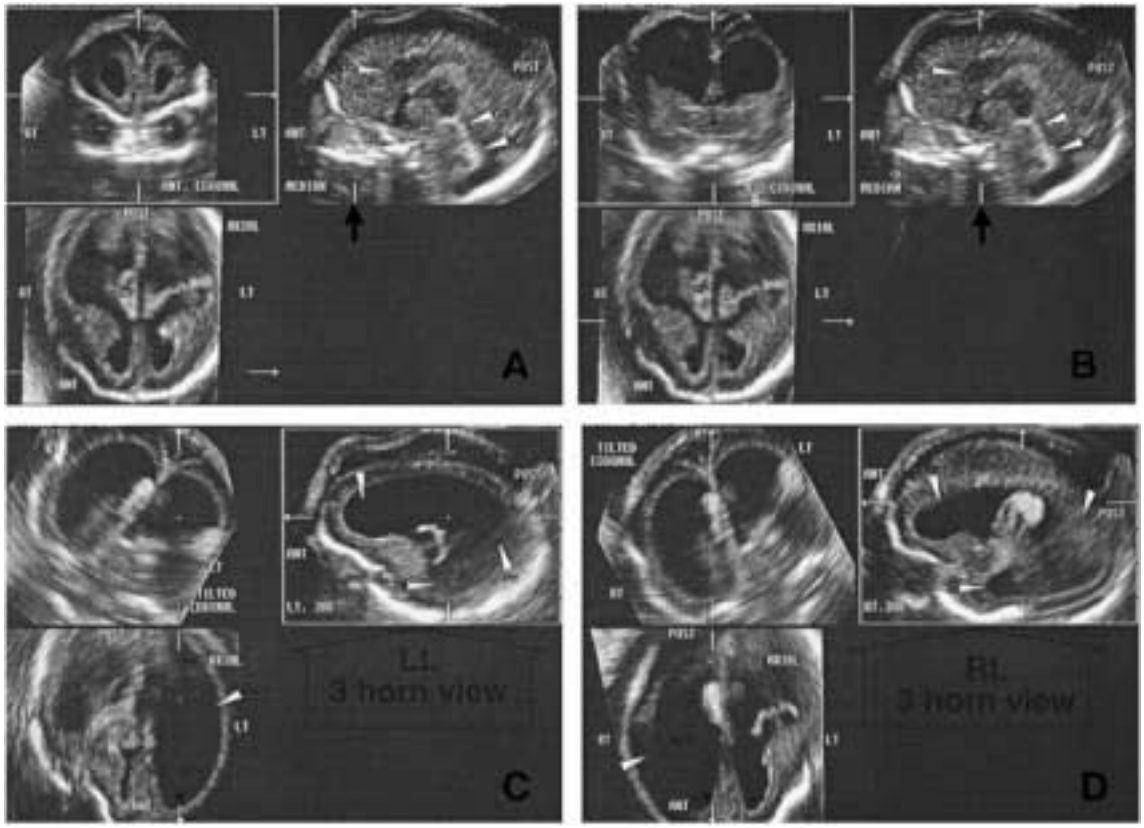

Figure 4 Partial agenesis of the corpus callosum and ventriculomegaly at 21 weeks. Panel A: The anterior coronal plane (box 'A') obtained at the level of the orbits (O) clearly shows enlarged anterior horns (AH). This is also evident on the axial plane (box 'C') where the teardrop-shaped lateral ventricles are evident (CP, choroid plexus; PH, posterior horn). In box 'B' only the genu of the corpus callosum (CC) can be seen on this median plane. (T, thalamus; CQ, corpus quadrigemina; C, cerebellum). Panel B: On the midcoronal plane the corpus callosum is missing. The lateral ventricles are dilated. The 'marker dot' is on the spot where the CC is missing. Panel C and D: The right and left three horn views are shown in boxes 'B', respectively. Note that all three horns are distended and clearly visible is the inferior horn (IH). Due to the increased amount of fluid in the lateral ventricles some disturbing side-lobe artifacts are seen in the posterior horns (PH).

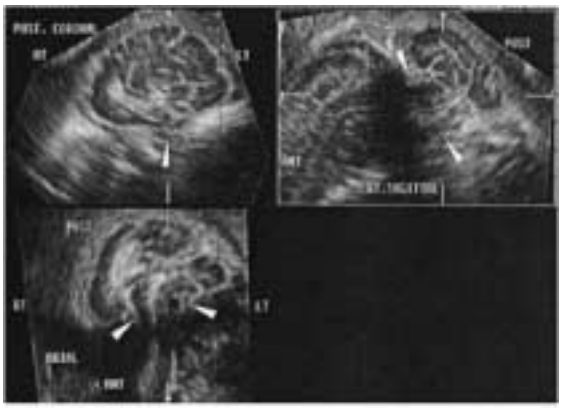

Figure 5 Right posterior parietal encephalocele at 31 weeks. This example is presented to demonstrate the ease with which the 3D orthogonal display enables pin-pointing of the location of the bony gap in the skull through which the brain protrudes. Panel A: In box 'B' which is a right parasagittal plane we are able to see clearly the center of the lesion and the protruding brain. The arrows mark the edges of the gap in the bone. In box 'C' the axial plane-reveals that the bony gap (between the two arrowheads) is indeed to the right of the middle axis of the skull marked by the vertical line. Here too two arrows mark the bony edges of the lesion in the skull.

by us to be important, since these are single 'snapshots' of the fetal brain in either the 'coronal', 'sagittal' or the 'axial' plane. The sonologist or sonographer must use these single images to mentally 'reconstruct' the anatomy or the location of the pathology. Lastly, at the time of the volume acquisition it is important to have on the screen the clearest, most resolute image depicting the normal anatomy or the pathology of interest.

The last but probably most significant attribute of the 3D fetal neuroscan using the digital ultrasound equipment is the use of the 'marker dot'. This dot is generated by the intersection of three planes freely movable by the user and marks the same spot (or technically the same voxel) within the volume. In our hands the liberal use of this 'marker dot' constituted the most valuable feature of the software in the machine without which it would have been extremely hard to pinpoint exactly the same structure on the three orthogonal and simultaneously displayed planes. Even more so it would have been almost impossible to pinpoint the exact locations of pathological structures. For example, in the case of agenesis of the corpus callosum (Figure 3) we were able to trace in all three planes the location of the upwardly displaced third ventricle and assure ourselves that the corpus callosum was indeed missing.

In several cases we obtained volume scans with the

power angio feature turned on to obtain the image of various main vessels in the brain. The vessels we were mostly interested were the anterior cerebral artery and its branch: the pericallosal artery. On a median 2D image one can see these arteries if one stays within the strict median plane. If, however, the artery deviates to one or another side due to pressure from a structure such as a cyst, the course of the displaced artery can only be followed with great difficulty or not at all. Using the 3D volume in which the artery was captured one can relatively easily follow the course of any artery through its deviant course using the 'marker dot'.

In the case of partial agenesis of the corpus callosum the marker dot was instrumental in following the anterior cerebral artery and its branch: the pericallosal artery. This was obtained by the angio (power) mode. The short first part of the artery was followed using the 'dot' (Figure 3B).

In one of our cases of arachnoid cyst the use of the 'marker dot' was even more important since it enabled us to detect and follow the severely displaced pericallosal artery. By finding it we could exclude the more devastating form of the interhemispheric arachnoid cysts that straddles and 'destroys' the corpus callosum. Postnatal imaging confirmed our findings (Case 2 in Table 1).

Another distinct advantage of the 3D multiplanar imaging using the orthogonal display is the ease with which any existing pathology can be conveyed to the pediatric neurologist or neurosurgeon. Having experienced the customary approach of the neurologist and neurosurgeon in the past it was astounding to see the change in their attitude after they were presented with a volume scan and we were able to demonstrate to them the multiplanar 'navigation' within the volume at their own will. Their understanding of the pathology was better and faster. They were able to provide a more focused and precise post-natal management based upon the objective evaluation of the pathology.

In conclusion, the 3D ultrasound technology can effectively be used to examine the fetal brain. The ability to simultaneously view and review a brain volume in all three scanning planes, by 'navigating' back and forth through the digitally stored data and using the 'marker dot' was found to be clinically important. The unparalleled clinical application of the 3D technology is that the information within the 3D volume can be reviewed over and over again, a diskette containing the volume can be mailed or sent via the Internet to a distant expert in the field for review. It can also be used for teaching. Tomographic sections can be generated in all three conventional planes. Comparison with neonatal ultrasound, magnetic resonance imaging or computerized tomography studies or pathology specimens can now be more accurately obtained. We are confident that it will find its way into the daily scanning armamentarium of the perinatologist and the imaging specialist.

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