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Article:

Demonstration of normal and abnormal fetal brains using 3D printing from in utero MR imaging data.

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Summary

3D printing is a new manufacturing technology that produces high fidelity models of complex structures from 3D Computer Aided Design data. Radiology has been particularly quick to embrace the new technology because of the wide access to 3D data sets. Models have been used extensively to assist orthopedic, neurosurgical and maxillo-facial surgical planning. In this report we describe methods used for 3D printing of the fetal brain using data from in utero MR imaging.

Data acquisition for producing models of the fetal brain

The data used to produce the 3D printed fetal brain models was acquired using a 3D iuMR imaging volume acquisition. This was achieved by imaging the fetal brain using an ultrafast, fully balanced steady state sequence on a 1.5T whole body MR scanner as detailed in table 1

3D volume imaging has an inherently higher signal/noise ratio when compared to 2D imaging because the whole brain volume is excited at each repetition rather than slice In addition, the homogenous excitation across the imaging volume results in more uniform slice profiles when compared with 2D imaging, as partial saturation of signal between slices does not occur. These characteristics enable a smaller partition thickness and Field of View to improve anatomical resolution and the contiguous thin partitions permit post processing reconstruction for visualisation of the anatomy in different planes. The contrast mechanism of steady state imaging and Flip Angle determines the signal intensity from fluids providing good tissue contrast between the fluid and brain interfaces which assists the creation of surface projections. We currently use a flip angle of 60-70° as higher flip angles are associated with greater aliasing artefacts.[1] Scan time is kept short by optimising bandwidth (to permit shorter TR and TE) and by partial Fourier techniques. This allows acquisition during maternal suspended respiration leading to reduced movement artefact.

Post-acquisition image processing

The images from the 3D dataset are transferred onto a desktop PC and loaded into a free open source software package - 3D Slicer (http://www.slicer.org) for segmentation [2]. Once loaded into 3D Slicer, the brightness and contrast are user

selected to optimise visualisation of the CSF/brain interfaces (both external and ventricular). Each brain is manually segmented on a slice-by-slice basis in the plane used for acquisition (usually axial) with other anatomical planes and fetal brain atlases used for cross reference to improve accuracy.[3, 4] Manual outling of the fetal brain anatomy takes approximately 50-60 minutes for second trimester brains and 90-120 minutes for more mature fetuses, the longer time due to the increased complexity of sulcation/gyration.

3D Slicer identifies anatomical areas using labels each represented by an index value and associated colour. Once all the regions of interest have been annotated the software reconstructs electronic 3D surface models of the fetal brain using the resultant labels. The surface model data is then saved in the correct file format (.stl) required for 3D printing. The .stl file cannot be edited and the resultant 3D printed model is an exact representation of the generated 3D surface model, therefore the latter should be examined for any extraneous parts to ensure the contours are in keeping with anatomical detail. Laplacian smoothing can be applied at the model building stage in order to smooth contours if necessary.

3D Printing technique.

3D Printing is the collective term for a number of technologies which create parts in a layer-by-layer manner directly from 3D Computer Aided Design data without the need for tooling. The major benefits of 3D Printing stem from the ability to produce complex geometries, efficiently and effectively. The majority of 3D Printing systems use data in the .stl format, whereby the 3D object is reproduced as a triangulated surface.

The Laser Sintering process was chosen for models of the fetal brain described in this paper. This is a powder bed fusion process, whereby a layer of powder is deposited and selectively scanned by a CO^2 laser. Areas scanned by the laser melt and upon re-solidification form the layers of the part. Laser Sintering can produce parts from a range of materials including metals and ceramics. In our examples polymer material Nylon-12 was used to construct the models of the fetal brain.

Specifically, the models were produced using PA2200 material on an EOS Formiga P100 Laser Sintering system.

Whilst high strength is not a key requirement for production of most models, they must be strong enough to endure handling by potentially large numbers of users. Parts produced via Laser Sintering generally possess relatively high mechanical strength when compared with other 3D Printing processes, again making this a suitable process. Whilst it is possible to build the model in two separate materials the majority of 3D Printing processes only allow the production of parts in a single color. However, there are a number of processes which allow the production of multiple colors and/or materials within a single part as demonstrated later. Additionally, the lack of requirement for tooling allows the production of small volumes (including production of single units) at no cost penalty. This can provide major advantages in personalization for medical use, whereby every individual may have different geometric or functional needs from a similar part. The ability to produce one-off models economically makes 3D printing highly suitable for the production of training models and demonstrators as discussed in this paper. More comprehensive discussions of methods for, and applications of, 3D printing within the medical sector can be found elsewhere.[5, 6]

Application of 3D models of the fetal brain

One of the major applications we envisage for this technology is trying to improve anatomical understanding and training of radiologists keen to develop their skills in fetal neuroimaging. We have created a fetal brain teaching file that consists of a number of cases with sample reports and background to the condition with both images from the 2D studies and 3D printed models produced via Laser Sintering available for review. The abnormal brain models consist of several of the commoner brain malformations at various gestational ages along with age-matched controls (see figures 1 and 2). It also possible to transpose 2D images from iuMR studies onto 3D models to enhance the understanding of fetal anatomy further. The 3D volume images can be manipulated into the same plane as the 2D images and those

images are copied onto clear plastic with adhesive on one side to produce 'transfers'. The .stl file of the matched sections from the 3D printed model can be exported to produce a limited print of the model to produce discrete 3D printed sections of the fetal brain as shown in figure 3. A further possibility is the production of models from multiple materials. For example in the case of the fetal brain models it can be useful for showing clear differentiation of the ventricular system compared with the remainder of the brain parenchyma as shown in Figure 4. This is a two-color part produced on a Connex multi-material system.

In summary, we have outlined a method that can be used to produce 3D printed models and described our approach to constructing 3D models of the fetal brain. The field is developing rapidly and presents a wide range of therapeutic and teaching opportunities for medicine and radiology in particular.

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Figure 1. Images of the 3D printed model produced via Laser Sintering from an iuMR study performed at 30 weeks' gestational age on a fetus with ventriculomegaly and an inter-hemispheric cyst recognised on ultrasonography, compared with an age-matched fetus with no brain abnormality. A 2D single shot fast spin echo image in the axial plane of the normal brain is shown in figure 2a along with superior (fig 1b) and left lateral views (fig 1c) of the 3D printed model. The matching images from the fetus with agenesis of the corpus callosum and extra-axial cysts, which do not communicate with the ventricular system (Barkovich type II cysts) [7] are shown in figs 1d-1f. Please note that the orientation of the 2D images has been altered to match the 3D model for ease of interpretation. The left hemisphere contains widespread heterotopia, a feature that was confirmed at autopsy.

Figure 2. Images of the 3D printed models produced via Laser Sintering from two iuMR studies performed at two gestational ages in a fetus with lissencephaly compared with an age-matched fetus with no brain abnormality. A 2D single shot fast spin echo image in the axial plane of the normal brain at 22 weeks' gestation is shown in figure 3a along with superior (fig 2b) and left lateral views (fig 2c) of the 3D printed model. The same format is shown for a normal 30 week fetus (fig 2d-2f) and the fetus with lissencephaly (fig 2g-2i).

Figure 3. A 3D printed model produced via Laser Sintering with the internal anatomy of the brain shown from an attached 2D single shot fast spin echo image to produce a 'section' of the fetal brain – superior (fig 3a) and oblique (fig 3b) projections.

Figure 4. Dual material 3D printed brain produced on a Connex 500 jetting system (manufactured courtesy of Professor Richard Bibb, Loughborough Design School). Separate .stl files were exported from 3D Slicer, one consisting of the segmented entire ventricular system and the other of part of the brain parenchyma. The ventricular system is printed in the same white material as the other brains whilst the parenchyma is printed in a clear material. The superior (fig 4a), inferior (fig 4b) and left lateral (fig 4c) show the relationship between the ventricles and brain to advantage.

Table 1.

3D FIESTA	Steady State Balanced Gradient Echo
Repetition Time (ms)	4.2
Time to Echo (ms)	2.1
Flip Angle (degrees)	60
Bandwidth (Hz)	125
Number of Excitations	0.75
Slice thickness/gap (mm)	2.2/0
Number of Partitions	26
Field of View (mm)	340 x 270
Matrix size	320/256
Interpolation – Phase/ Secondary Phase	ZIP 512/ ZIP 2
Scan Time (sec)	21