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3D printing of complex surgical cases: Spina bifida

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Abstract: Spina Bifida is a congenital defect that exposes the spinal cord to fluids in the womb. Severe cases of Spina Bifida can result in partial or complete paralysis, inability to walk, and/or bladder and bowel dysfunction. Surgeons perform in utero Spina Bifida repair to prevent the progressive damage to the exposed neural tissue before birth. As in utero Spina Bifida repair becomes the standard of care, pediatric neurosurgeons are exploring novel diagnostic and planning tools, like 3D segmentation and 3D printing, to prepare for the procedure and educate expecting parents.

I. Introduction

Spina Bifida is a congenital defect in which the vertebral column does not enclose properly, exposing the spinal cord. The most severe defects, Myelomeningocele (MMC) and Myeloschisis (MS), can result in partial or complete paralysis below the level of the spinal opening, inability to walk, and/or bladder and bowel dysfunction. The gravity of these symptoms is associated with the continuous exposure of the neural tissues *in utero*. For this reason, fetal surgery was sought as the most effective way of preventing irreversible damage to the patient. In 2010, an NIH-funded study demonstrated that 42% of patients that underwent *in utero* Spina Bifida repair were walking independently within 30 weeks of birth. Conversely, only 21% of patients in the postnatal repair group reached the same milestone. While fetal surgery has proven effective, this procedure leads to the risk of premature births and possible thinning of the mother's uterine wall [1].

Given the high-stakes nature of *in utero* Spina Bifida repair, pediatric neurosurgeons are exploring novel planning tools to best prepare for the procedure. In the present work, Digital Anatomy Simulations for Healthcare, LLC (DASH) partnered with the Orlando Health Fetal Care Center (OHFCC) to develop a workflow for the segmentation and 3D printing of patient-specific Spina Bifida models.

II. Material and methods

II.I. 3D Segmentation of Fetal MRI

The OHFCC MRI protocol consisted of three (3) sequences: Echo Planar Imaging (EPI), fast imaging with steady-state free precession (True-FISP), and half-Fourier acquisition single-shot turbo spin-echo (HASTE). Each sequence was pre-processed and segmented using 3D Slicer [2]. At the surgeon's request, the body of the fetus, ventricular system, spinal cord, and spina bifida defect were segmented. Resampling through B-spline interpolation generated isotropic voxel volumes from each MRI sequence. Noise reduction and edge enhancement was achieved through an implementation of the gradient anisotropic diffusion filter [3]. Tissues were segmented through a manual sequence of operations, including intensity thresholding, masking, and painting [2]. The segmentation process yielded coarse 3D models representative of the shape and volume of each tissue of interest.

II.II. 3D Modeling and Refinement

Refined 3D models of each tissue of interest were generated by digitally sculpting high-quality surfaces and volumes that preserved the shape of the segmented tissues. Pixologic's Zbrush was used to generate high-quality surface geometries that conformed to the coarse segmentation of a specific tissue.

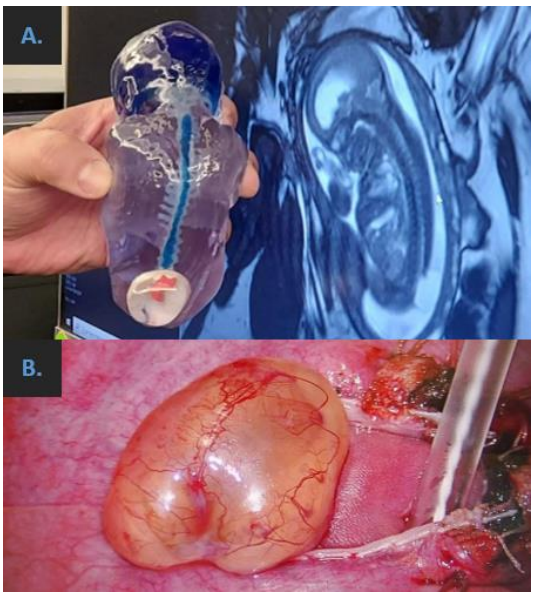

Figure 1: Comparison of 3D Printed Spina Bifida Model and Sagittal View of Fetal MRI (A), Photograph of myelomeningocele during surgery (B)

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High-quality models were also used as volumetric masks in 3D Slicer to generate a secondary, more accurate segmentation of the corresponding tissue. In cases with MRI sequences severely affected by motion artifacts, entire anatomical structures, such as the body and limbs of the fetus, were generated by blending tissue models from a similar case (reference case) and the segmented structures of the affected case (incomplete case) (Figure 2).

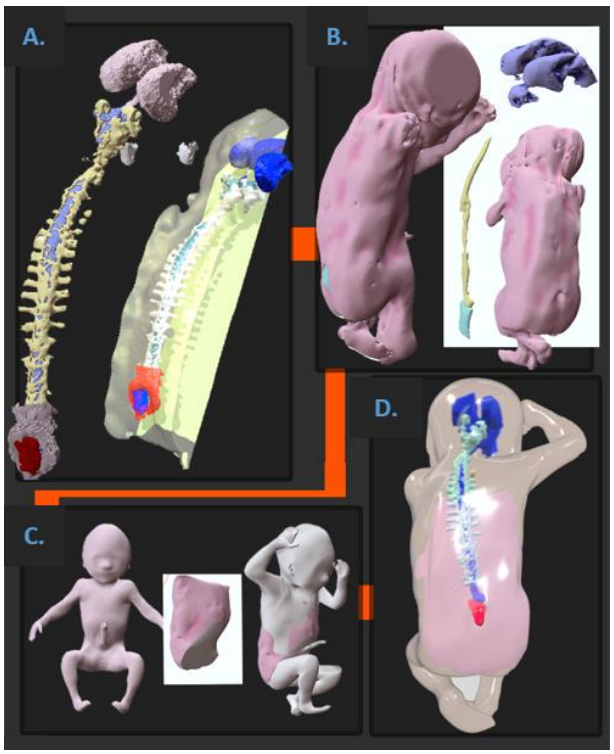

Figure 2: 3D Refinement of Fetal Body. Tissue segmentations from multiple MRI sequences (A-B). Simulated model of fetal body based on prior case data and posed to match incomplete data (C). Combined segmented and simulated fetal body (E).

II.III. 3D Printing

High-quality tissue models were exported as STL assemblies for 3D printing. The files were prepared in GrabCAD Print and printed using a Stratasys PolyJet J750 (Figure 3).

III. Results and Discussion

In collaboration with OHFCC, our team 3D printed seven (7) spina bifida cases: four (4) MMC and three (3) MS defects. True-FISP MRI sequences were used for the segmentation of the ventricular system, spinal cord, spinal opening, fluid-filled sac (cele), and herniated spinal nerves (placode). HASTE sequences were useful for reconstructing the body and limbs of the fetus.

Resampling, noise reduction, and edge enhancement of MRI sequences accelerated the manual segmentation process. Refined models were used as volumetric masks in 3D Slicer [2] to generate a secondary, more accurate segmentation of each tissue. Volumetric masking created a discrete separation between tissues with similar intensity values, allowing for other segmentation approaches to be used. This approach generated more detailed models of the features internal to MMC and MS defects. High-quality surface models from prior cases (reference models) were used to segment tissues and structures affected by motion artifacts (incomplete model). Through 'character rigging', reference models can be articulated and posed to match the few segmented landmarks of the incomplete model (Figure 2). This approach allowed for the generation of a full fetal body for every case.

The color and material for each tissue was chosen based on the function of the model. Surgical planning models accentuated pathological features by means of transparent and flexible materials. Patient education models, on the other hand, used matte colors, rigid, and flexible materials to dull-out pathological features. For almost all reconstructed cases, both surgical planning and educational models have been 3D printed. Depending on the geometry, models were 3D printed in 14-17 hours. If multiple copies were printed at the same time, the build time was approximately 20-22 hours (Figure 3). Thus far, our team is capable of segmenting, 3D printing, and delivering patient-specific Spina Bifida models in less than 48 hours.

IV. Conclusions

In partnership with OHFCC, DASH has developed a workflow for the 3D segmentation and 3D printing of surgical planning and educational models for *in utero* Spina Bifida repair. As we continue to fabricate models, our team will work with pediatric neurosurgeons to improve upon the workflow in order to benefit their preparation for surgery.

Figure 3: 3D Printed Spina Bifida Models. Myelomeningocele models (A). Myeloschisis models (B)

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AUTHOR'S STATEMENT

Conflict of interest: F. Lobo Fenoglietto, R. Sims, J. Inziello, J. Stubbs, and K. Stubbs are owners and employees of Digital Anatomy Simulations for Healthcare, LLC (DASH). DASH is a privately-owned, for-profit company.

REFERENCES

[1] A. J. Copp, *Spina Bifida*, Nat Rev Dis Primers.; 1: 15007. Doi:10.1038/nrdp.2015.7.

[2] Fedorov, Andriy, et al. *3D Slicer as an image computing platform for the Quantitative Imaging Network.* Magnetic resonance imaging 30.9 (2012): 1323-1341.

[3] P., Pietro, T. Shiota, and J. Malik, *Anisotropic diffusion*. Geometry-driven diffusion in computer vision. Springer, Dordrecht, 1994. 73-92.