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FetalSurfer: Automated Fetal Cortical Surface Reconstruction

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Synopsis

Keywords: Fetal, Data Processing

Motivation: The cerebral cortex of the fetus is undergoing intricate development. Abnormal cortical development may potentially alter brain function. However the methods for processing fetal MRI images, especially cortical reconstruction, are still far behind those used for adults.

Goal(s): To develop an accurate cortical surface reconstruction method and perform morphological calculations for fetal MRI.

Approach: Trustworthy AI segmentation and refined Freesurfer were used to process T_2-weighted fetal brain image.

Results: The proposed mothod (FetalSurfer) allows for trustworthy reconstruction of the cortical surfaces of the fetal brain and calculation of indicators to measure the morphology of fetal development.

Impact: FetalSurfer implements a novel fetal cerebral cortex reconstruction method without manual refinement by professional doctors, filling the gap of fetal image processing methods. Calculated indicators as curvature, thickness and sulcal depth can be used to perform morphological analysis.

Introduction

Fetuses develop rapidly during the second-to-third trimesters of pregnancy[1, 2]. The morphological properties of cerebral cortex, such as the thickness and folding are important biomarkers for investigating the healthy and diseased fetal brains in neuroscientific and clinical applications. Unfortunately, tools for automated cortical surface reconstruction and cortical morphometry are lacking, in contrast to several such software packages for adults and newborns and adults, such as FreeSurfer[9,10] and its infant version[3]. This is partially because high isotropic resolution images are challenging to acquire on continuously moving fetuses and the commonly used T_1-weighted contrast for differentiating gray and white matter in adult brains is poor in fetal brains which are still undergoing myelination[3].

Recent efforts performed fetal cortical reconstruction and analysis using atlas-based tissue segmentation results, which might be sub-optimal. Wu et al.[4] used ANTs software package for the co-registration. Xu et al.[5] used the refined structural MRI processing pipeline for Developmental Human Connectome Project (herein referred to as dhcp-structure-pipeline) originally designed for infants to perform segmentation and cortical analysis.

To address this challenge, we developed a new pipeline entitled “FetalSurfer” (Fig. 1) for automatically and more accurately reconstructing fetal cortical surfaces. FetalSurfer leveraged accurate and efficient tissue segmentation based on deep-learning models to replace time-consuming registration-based segmentation. FetalSurfer pipeline consists of slice-to-volume motion correction and high-resolution image volume reconstruction (SVR), brain tissue segmentation, cortices parcellation, and cortical surface reconstruction by refining FreeSurfer’s procedures. Compared to dhcp-structural-pipeline, FetalSurfer demonstrated superior accuracy and robustness in segmentation and cortical reconstruction.

Method and Materials

Data Acquisition. Fourteen pregnant women (22-36 weeks gestation) with normal fetal brains were scanned with written informed consent forms and IRB approval on a 1.5-T MRI scanner (PHILIPS Achieva Nova Dual hp) with spine and 16-channel body coils to obtain 2D T_2-weighted turbo spin echo images, along axial, coronal, and sagittal directions, with 4 mm slice thickness and 0.8×0.8 mm^2 in-plane resolution.

High-resolution reconstruction. NiftyMIC[6] (https://github.com/gift-surg/NiftyMIC) was employed to perform slice-to-volume motion correction and combine stacks of thick-slice images acquired along three directions for super-resolving 0.8 mm isotropic high-resolution T_2-weighted image volume for each subject.

AI and Atlas segmentation. The trustworthy AI segmentation framework[7] was used to segment each fetal brain volume into eight structures: extra-axial CSF, cortical gray matter, white matter, intra-axial CSF, deep gray matter, cerebellum, brainstem and corpus callosum. This approach offers a practical system to enhance the backbone AI system, leveraging the Dempster-Shafer theory. nnUnet[8] model was chosen as the primary AI segmentation model. Specifically, when the primary model encounters challenges or is unable to produce reliable results, the fallback system can intervene to provide more dependable outcomes.

FBA is the structural fetal brain atlases[4] for Chinese population ranging from 23w to 35w. The brain region labels including those for cortices were propagated from the atlas to each individual brain using a non-linear co-registration tool NiftyReg (https://github.com/KCL-BMEIS/niftyreg).

Surface reconstruction. Surface reconstruction followed Freesurfer[9, 10] (https://surfer.nmr.mgh.harvard.edu/) which was designed for adult T_1-weighted data. Briefly, AI model was used to replace Freesurfer's segmentation process for reconstructing the gray-white surface, which was subsequently expanded to find the boundary with the greatest contrast between gray matter and CSF. Steps such as white matter filling, hemispherical smoothing, and surface inflation are as standard. Cortical properties including the surface area, convexity, curvature, regional volume, sulcal depth, and thickness were quantified.

Results

Fig. 2 show successful super-resolution reconstruction, AI segmentation, atlas-based parcellation for 14 fetuses aging between 22 to 36 weeks.

Fig. 3 shows cortical surfaces reconstructed from each individual brain volume. The cortex becomes more folded as fetuses age. The central sulcus appears around 28 weeks.

Fig. 4 compares gray-white and pial surfaces reconstructed from an exemplar brain volumeusing FetalSurfer and the dhcp-structural-pipeline. The dhcp-structural-pipeline misclassified the germinal matrix as gray matter (Fig. 4i), presumably due to atlas-based segmentation, and produced erroneous cortical folding (Fig. 4ii, iii). FetalSurfer improved upon these results by leveraging more accurate AI segmentation. All results were visually inspected by expert radiologists.

Fig. 5 demonstrates the quantified gray-CSF surface curvature and sulcal depth values, as well as the cortical thickness.

Discussion and Conclusion

An automated, accurate and efficient fetal cortical reconstruction pipeline FetalSurfer is proposed, which leverages state-of-the-art AI based brain segmentation. This tool has a high potential to advance fetal brain morphometry, aiding in the early diagnosis of neurological and developmental brain disorders and investigating fetal development assessment. Future work will systematically validate FetalSurfer and quantitatively compare it with other methods.

Acknowledgements

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Figures

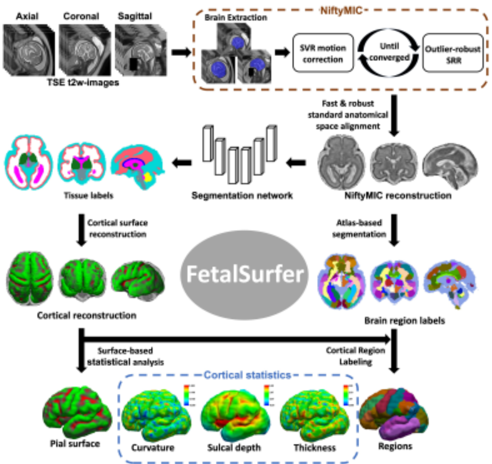

Figure 1. FetalSurfer Pipeline. High isotropic resolution image volumes are first reconstruction from stacks of thick-slice T_2-weighted images using NiftyMIC. A trustworthy nnUnet model is then utilized for brain tissue segmentation. Cortical surfaces are reconstructed by refining Freesurfer procedures to extract cortical features as

curvature, sulcal depth, thickness. Brain region labels are also propagated from the FBA atlas to each individual brain volume using non-linear co-registration for cortical parcellation.

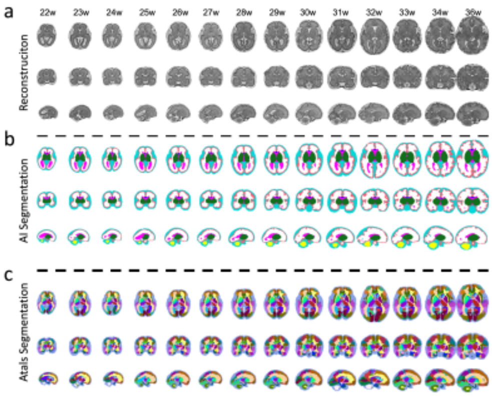

Figure 2. Reconstruction and segmentation. (a) High isotropic resolution T_2-weighted image volume reconstruction results of NiftyMIC, (b) brain tissue segmentation results using the trustworthy nnUnet model, and (c) atlas based segmentation results using NiftyReg non-linear co-registration for fetuses aging between 22 to 36 weeks are displayed.

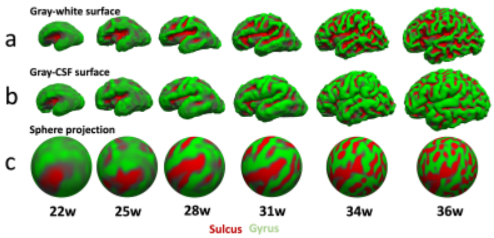

Figure 3. Cortical surfaces. (a) Gray–white interface surfaces, (b) gray–cerebrospinal fluid (CSF) interface surfaces, and (c) spherical projection reconstructed from high-resolution fetal brain image volumes for fetuses aging between 22 to 36 weeks are displayed.

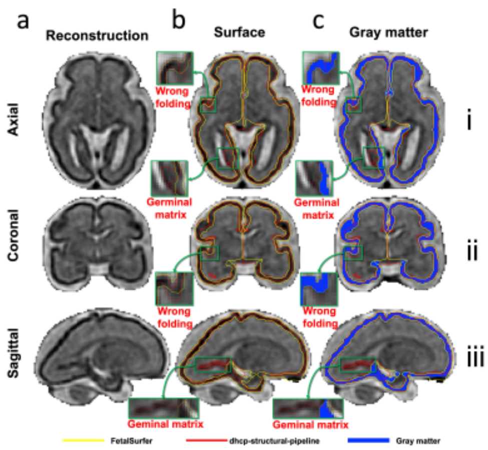

Figure 4. FetalSurfer vs. dhcp-structural-pipeline comparison. Gray–white and gray–cerebrospinal fluid (CSF) surfaces reconstructed from an exemplar fetal brain image volume using FetalSurfer and dhcp-structural-pipeline are displayed for comparison.

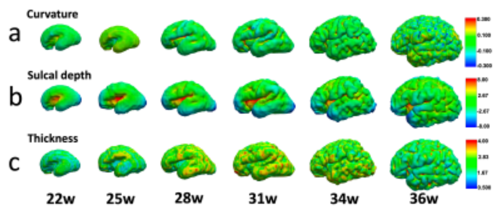

Figure 5. Quantification of morphological properties. Gray–cerebrospinal fluid (CSF) surface curvature and sulcal depth values, as well as the cortical thickness values of fetuses ranging between 22 to 36 weeks are displayed.

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