A novel approach for high-resolution image reconstruction for in-vivo fetal brain MRI

Cedric Clouchoux[1, 2], Pierrick Coupé[2], Jose Manjon[3], Nicolas Guizard[2], Marine Bouyssi-Kobar[3], Mylene Lefebvre[3], Adre Du Plessis[4], Alan Evans[2], Catherine Limperopoulos[4]

[1]Montreal Children Hospital, McGill University, Montreal, Quebec
[2]McConnell Brain Imaging Center, Montreal Neurological Institute, McGill University, Montreal, Canada
[3]ITACA, Valencia, Spain
[4]Fetal-Neonatal Neurology, Children Hospital, Boston, United States

Introduction:

In the present study, we propose an automatic framework for obtaining an accurate representation of the in-vivo fetal brain for the quantification of cerebral volume and cortical surface. One of the biggest challenges in performing non-sedated fetal MRI studies is fetal motion, resulting in motion artifact and poor image quality [Limperopoulos09, Prayer06]. To date, most conventional fetal MRI acquisitions will have a 1x1x2mm3 resolution. The challenge is then to recover a high image quality from such volumes, in order to reliably characterize cortical development during intra-uterine life. Typically, three fetal scans are acquired, one in each direction, providing high in-plane resolution slices in each direction. The problem is then to create a single, isotropic high-resolution volume. This reconstruction is detailed herein, as well as results based on synthetic and real fetal data. An example of fetal cortical surface rendering is also presented.

Method:

The input data is composed of three low-resolution (LR) T2-weighted volumes (1.2x1.2x2 mm3 voxel resolution), acquired in each direction (coronal, sagittal and axial). After the normalization and the co-registration of the three input volumes, a high-resolution (HR) reconstruction is achieved. This step consists of reconstructing one isotropic HR volume from 3 LR anisotropic volumes (fig.1). In order to optimize the information derived from the input volumes, we propose an iterative super-resolution method based on bilateral filtering [Tomasi98], without any HR reference image. This process takes into account important and specific issues including: LR volumes with different anisotropic resolution, volumes not perfectly registered and, inconsistent image contrast. The algorithm proceeds as follows: first, a nearest-neighbors interpolation is performed on the three input volumes, in order to have the same voxel size as the desired HR output. An initial volume is then computed, which is the average of these input volumes. Each interpolated volume is then used to compute an estimation of the reconstructed value by bilateral filtering along the HR axis. For each voxel, the local mean of its 2D neighborhoods in the HR plane is matched with their corresponding local means within the reconstructed volume in order to be robust to normalization error between the LR volumes. Finally, the estimations obtained from each direction are aggregated within a robust function to be less sensitive to misalignments. The resulting HR volume is then considered as the reference volume for the next iteration, and the process is repeated until convergence has been reached.

Results:

The HR reconstruction method was evaluated on simulated T2 data from the Brainweb database [Cocosco97], before being applied to clinical data. We first down-sampled a HR volume (1mm3) according to the three directions, to recover similar inputs that have the same resolution as the clinical data. Different reconstruction methods were then applied (fig.2). The proposed method achieved better reconstruction than the other techniques, without the blurring induced by a cubic interpolation or block artifacts

introduced by a nearest neighborhood interpolation. The cubic interpolation method showed greater differences with the ground truth than the proposed method, which was particularly evident with the contours (fig.2). Peak signal-to-noise ratio (PSNR) was measured for the different methods. The PSNR for each direction of the LR images was as follows: axial=22.93 dB; sagittal=21.37 dB; coronal= 21.89 dB. For the reconstructed HR volumes, the results of the three methods are presented below:
- Nearest-neighbors interpolated volume average: 25.14 dB
- Cubic interpolated volume average: 26.02 dB
- The proposed method volume average: 28.47 dB.

In other words, in an ideal case (no registration or contrast errors) where interpolation-based methods [Rousseau06, Jiang07] should be optimal, the proposed method produced better results. The method was then applied to data from a 30-week gestation age (GA) fetus. Three single shot fast spin echo T2-weighted imaging sequences were acquired, one for each direction (sagittal, coronal and axial) using the following parameters: TEeff=120ms;TR=12500ms, number of signal averages 0.625; field of view 330mm; slice thickness 2mm with no interslice gap, acquisition matrix 256x204 (1.5T scanner, 5-channel phased array cardiac coil). Figure 3 shows the resulting HR volume, and figure 4 illustrates the resulting cortical surface mesh extraction in a 28-week GA fetus.

Conclusion:

This novel and robust automatic methodological framework enables the quantification of fetal brain volumes using an innovative HR fetal MR image reconstruction. This methodology was developed specifically to address the unique obstacles of non-sedated fetal MR image acquisitions, validated on synthetic data and tested on clinical data. The proposed reconstruction method successfully overcame the inherent challenge of LR images resulting from ultra fast imaging sequences and fetal motion, and demonstrated a superior PSNR compared to existing interpolation-based techniques. The pipeline is entirely automated, allowing for the processing of large fetal MRI datasets. The quantification of fetal cortical brain development in healthy and high-risk fetuses over the second and third trimester is currently underway.

References

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Figures:

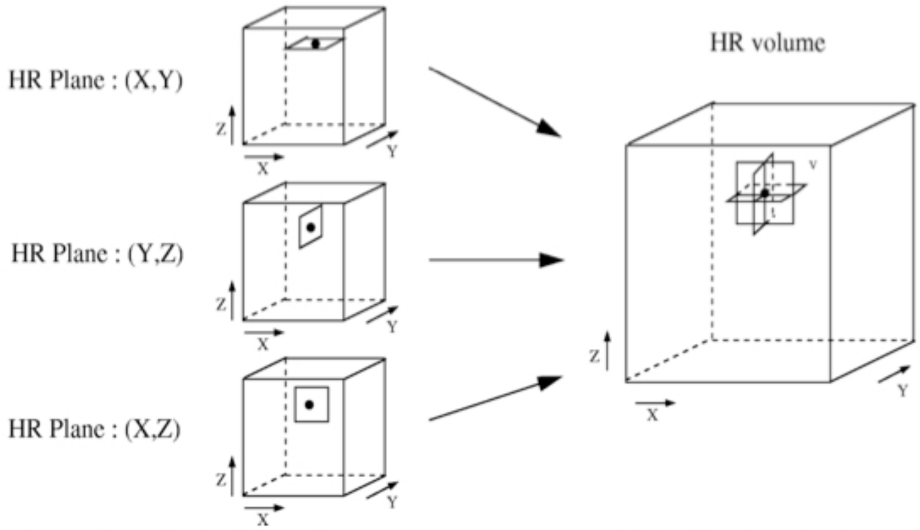

Fig. 1. Illustration of the HR volume reconstruction, using 2D local neighborhoods in the HR dimension, from each original LR volume.

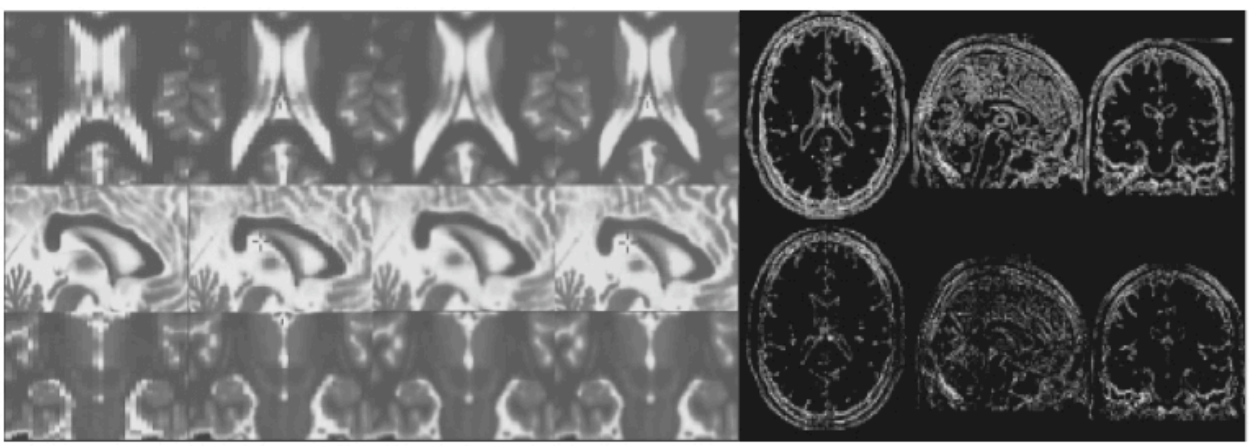

Fig. 2. HR reconstruction on simulated data, zoomed in a specific region for visualization purpose. Left, First column: downsampled volume in one direction (HR: sagittal plane). Second column: HR reconstruction by averaging interpolated input volumes (Nearest Neighbors algorithm). Third column: HR reconstruction by averaging interpolated input volumes (Cubic interpolation algorithm). fourth column: HR reconstruction using the proposed method. Right, the three right columns show the differences between ground truth and resulting HR volume. Top row: cubic interpolation. Bottom row: proposed method.

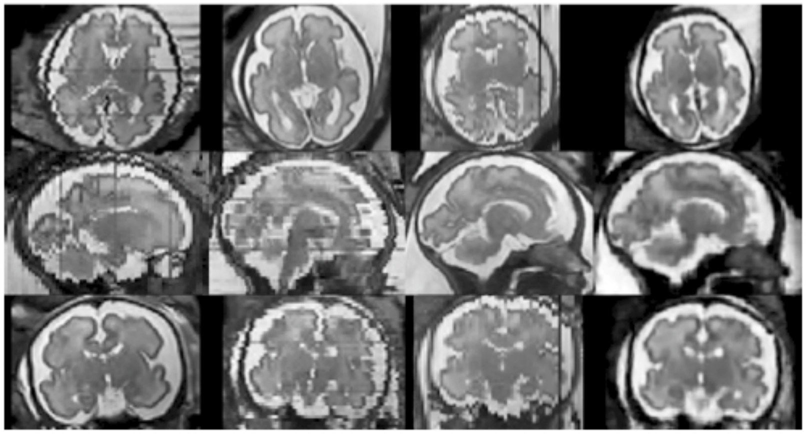

Fig. 3. HR reconstruction of a 30 week GA fetus. Three columns on the left: original data, each row being a low-resolution scan in one direction. Right column: resulting HR isotropic volume.

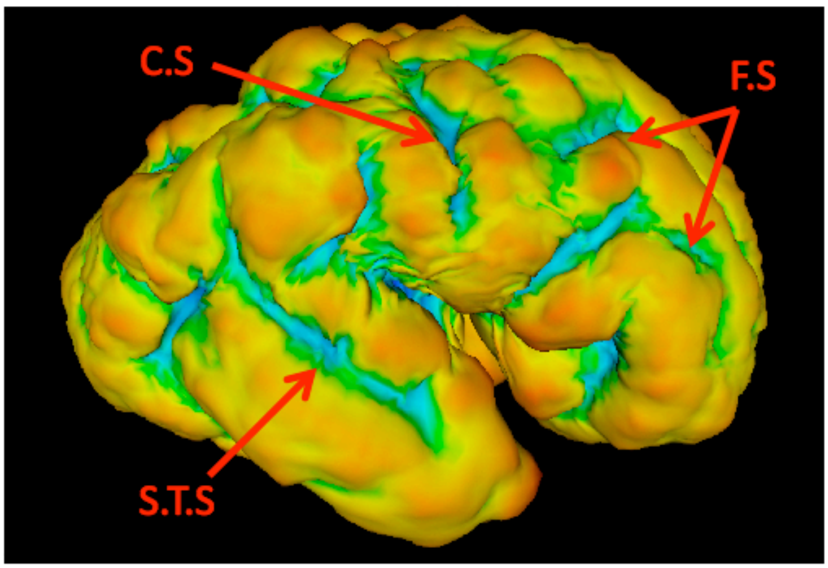

Fig. 4. Extracted cortical surface from of a 28 week GA fetus. The mesh represents the average of grey and white matter surfaces). Primary sulci are clearly visible, such as the Central Sulcus (C.S), the Frontal (F.S) and the Superior Temporal Sulci. Colormap stands for the cortical depth (red: superficial cortex, blue: deep cortex).