Reconstruction Methods for *in-utero* Fetal Brain MRI

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Résumé— **In this paper we present methods for reconstructing anatomical and diffusion-weighted MRI data on regular grids from scattered data. We investigate the use of a super-resolution technique for anisotropic anatomical fetal brain MR data reconstruction without modifying the data acquisition protocol. The approach, which consists of iterative motion correction and high resolution image estimation, is compared with a previously used interpolation-based reconstruction method. Concerning the diffusion-weighted data, the proposed method has the advantage that no specific diffusion model needs to be assumed. We propose the use of a groupwise registration method, and a dual spatio-angular interpolation by using radial basis functions. Evaluation on *in-utero* fetal data show significant improvements in performance provided by the reconstruction approaches.**

Mots-Clés
fetal MRI, brain imaging, image reconstruction, tractography

I. INTRODUCTION

Brain maturation is one of the most captivating aspects of neuroimaging, particularly in the earliest phases of maturation during fetal development and childhood. The development of the human central nervous system (CNS) begins in utero and continues until the end of adolescence. The maturation process is characterized by a spatio-temporal and very complex heterogeneity which is likely to reflect the successive steps of psycho-motor and cognitives learning of the child.

The non-invasive nature of magnetic resonance imaging (MRI) provides unique opportunities for *in vivo* investigation of the developing human brain. In the context of fetal brain analysis, MRI is a complementary method to routine ultrasound. Fetal MR imaging is a valuable complement to prenatal sonography to confirm and characterize suspected brain abnormalities. Fetal brain maturation can be studied by in utero MRI from the 18th gestational week (GW) to term, and relies primarily on T2-weighted and diffusion-weighted (DW) images. 3D detailed evaluation of the developing brain is crucial since the assessment of sulcation is often critical in identifying abnormalities. In addition, visualization of cortical development and maturational steps of the brain may benefit from information provided by DW sequences.

The development of ultrafast 2D acquisition sequences has led to significant improvements in the clinical utility of fetal MRI [1]. However, the slice acquisition time is still very critical and has to be as short as possible to reduce the impact of fetal motion on the exam. As a result, sets of thick 2D slices are generally acquired in clinical studies, with motion commonly occurring between slices. Overall, the resulting image is limited in its geometric integrity between slices due to motion, and in its through plane spatial resolution. As a consequence, the main current studies focus on brain development and morphology changes from childhood to adolescence. Working out the development of fetal and neonatal brain remains an open issue. In this paper, we present reconstruction methods for anatomical (Section II.2) and diffusion-weighted (Section II.3) fetal brain MRI.

II. MATERIAL AND METHODS

II.1. Image Acquisition

Fetal MRI was performed on a 1.5 T Siemens Avanto MRI Scanner (SIEMENS, Erlangen, Germany) at the Hautepierre Hospital (Strasbourg, France) using an 6-channel phased array coil combined to the spine array positioned around the mother abdomen. Concerning anatomical data, the SR reconstruction algorithm has been applied to T2 weighted HASTE sequences (TE/TR = 147/3190 ms), resolution : $0.74 \times 0.74 \times 3.45$mm. Concerning diffusion-weighted images, an axial spin echo single-shot echo-planar sequence was acquired along 30 non-collinear diffusion gradient encoding directions with a b value of $700 s/mm^2$. The following pulse sequence parameters were used : TR=6800 ms ; TE=99 ms ; FOV=250×250 mm^2 ; matrix = 128×128 ; 41 contiguous axial slices of 3.5 mm thickness covering the whole fetal brain ; no gap ; number of excitations = 2.

II.2. Anatomical Image Reconstruction

The first approach to forming high resolution MR images of the fetal brain has been recently proposed by our research team [2] without modifying the acquisition protocol used in routine. This retrospective method is based on a registration refined compounding of multiple sets of orthogonal fast 2D MRI slices to address the key problem of fetal motion. This is achieved by first globally registering the low resolution images, and then applying an iterative slice alignment scheme which seeks to refine the 3D positioning of each slice to the current combined high resolution volume. This is driven by normalized mutual information to provide robustness to contrast variation induced by motion of the fetal brain with respect to the imaging coil in the magnet. As a final step, a relative intensity correction is applied between the low resolution images to remove the differences in relative signal strength across the different acquisitions in each region of the fetal brain.

We extend this previously used scattered data interpolation-based reconstruction method by applying a super-resolution technique for anisotropic fetal brain MR data reconstruction without modifying the data acquisition protocol. As in most of common SR approaches, we model the physical problem and then compute a solution by inverting this observation model :

$$\mathbf{y_{r,s}} = S_r B_r W_s W_r \mathbf{x} + \mathbf{n_r} \quad for \quad 1 \leq r \leq n, \ 1 \leq s \leq m_r \tag{1}$$

where n is the number of LR images and m_r is the number of slices of the LR image r, $\mathbf{y_{r,s}}$ denotes the slice s of the LR image r, $\mathbf{x}$ is the HR image, $\mathbf{n_r}$ represents the observation noise, S_r is the subsampling matrix, B_r a blur matrix, W_s and W_r are geometric transformations of sth slice of the $\mathbf{y_{r,s}}$ and of the rth low resolution image respectively. The purpose of super-resolution is to remove the effects of the blurring convolution and to increase the voxel grid density. To estimate the high resolution image, the observation model is introduced into an inverse problem framework which is solved using a variational approach.

II.3. 3D Diffusion Tensor Image Reconstruction

The purpose of the proposed technique is to extend the developed method dedicated to T2-weighted MR images to correct geometrical distortions, fetal motion and to reconstruct a high resolution 3D diffusion tensor image. The goal is to obtain isotropic images with resolution lower or equal to the in-plane resolution of the data currently acquired in routine. The proposed method has the advantage that no specific diffusion model needs to be assumed. Previous work assume the tensor model, but this is not suitable under certain conditions like intravoxel orientational heterogeneity. We propose the use of a groupwise registration method, and a dual spatio-angular interpolation by using radial basis functions (RBF).

The method takes advantage of the intensity dependence between DW images to first obtain their joint alignment. To this end, we first register the diffusion-weighted images S_i to an arbitrary chosen reference (S_r) by using a transformation model (A^z) consisting of a set of full affine transformations applied to each slice independently (denoted by the superscript z), and mutual information as similarity metric. The spatial transformation A^z_{ri} from S_i to S_r is defined as

$$A^z_{ri}(X) = M(X) \cdot X + O(X) \tag{2}$$

where $M(X)$ is a 3×3 matrix and $O(X)$ is the offset. Differently from a global affine transform, M and O depend on the spatial position X, more specifically on the k-component of the corresponding image coordinates. Then, a new reference $\overline{S}^{(1)}$ is computed by averaging the transformed images S_i and the process is repeated until the mean squared error (MSE) between $\overline{S}^{(k-1)}$ and $\overline{S}^{(k)}$ for consecutive iterations $k-1$ and k is lower than a given threshold ϵ. Finally, $\overline{S}^{(k)}$ is registered to S_0 and the resulting transformation A_{0r} is composed with A^z_{ri} to obtain the final transformation between S_i and S_0 :

$$A^z_{0i}(X) = (A_{0r} \circ A^z_{ri})(X) \tag{3}$$

The image $\overline{S}^{(k)}$ is characterized by a higher signal-to-noise ratio (SNR) than images S_i, and provides a better depiction of the anatomical structure of the brain. These properties allow an accurate registration to S_0, necessary to map all the sequence in its space of coordinates.

In our case, each point contains spatial and angular coordinates which must be considered separately because of the difference in scale between both types of coordinates. This situation is different from the usual problem addressed DTI interpolation where only an interpolation in the sphere is required. To take into account these differences, we propose to replace the single RBF with the product of a spatial (ϕ) and an angular (ψ) RBF :

$$y((X, \Theta)) = \sum_{i=0}^{N-1} w_i \phi(|X - X'_i|) \psi(|\Theta - \Theta'_i|) \tag{4}$$

where $X = (x, y, z)$ are the spatial coordinates, and $\Theta = (\phi, \theta)$ the spherical coordinates of the sampling vector U_i. Equation 4 allows a dual interpolation in two different unrelated spaces. In Equation 4, $|X - X'_i|$ represents the Euclidean distance, whereas $|\Theta - \Theta'_i|$ is the geodesic distance over the unit sphere.

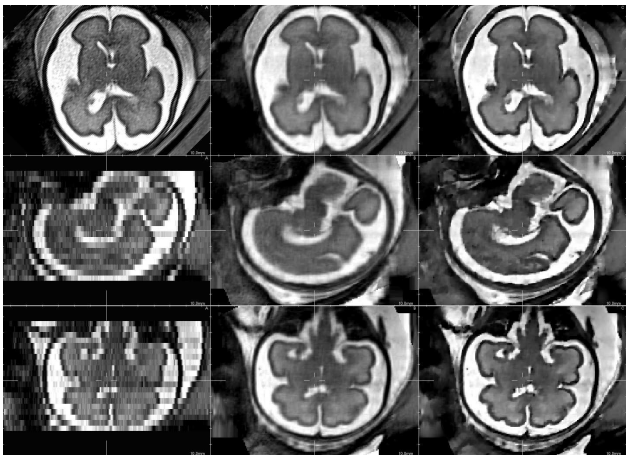

FIGURE 1 – Details of a reconstructed fetal brain T2w MR image using 3 orthogonal LR images. From left to right : A) original low resolution image, B) reconstructed image using local sparse interpolation [2], C) SR reconstruction.

III. RESULTS

Figure 1 shows one original low resolution image compared to the high resolution reconstructed images for axial, coronal, sagittal views. Results obtained with the SR approach compare favorably with the local sparse interpolation approach proposed by Rousseau *et al.* in [2]. It can be especially noticed that the boundaries of brain structures (like the cortex) are better recovered. Moreover, the noise present in the LR image has no major impact on the reconstructed images. The result shown in Figure 1 has been obtained using 3 LR images.
The tractography was performed by applying a particle filtering framework using an analytical Q-ball model for the diffusion data. Regions of interest were used for seeding the tractography after propagation to the T_2^{epi} image by using affine registration, and to assess the presence/absence of these specific bundles in the analyzed cases. Figures 2 and 3 shows examples of the obtained results, where the region of interest corresponds to the splenium of the corpus callosum.

IV. CONCLUSION

The presented reconstruction methods allow potentially to recover fine image details compared to the existing approaches. This study shows that such reconstruction techniques allow to perform tractography on fetal brain MRI. Visual analysis of the obtained results on real data are very encouraging. Such high resolution image reconstruction algorithm represents an important step towards analysis of fine scale anatomical details.
Acknowledgment : The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013 Grant Agreement no. 207667).

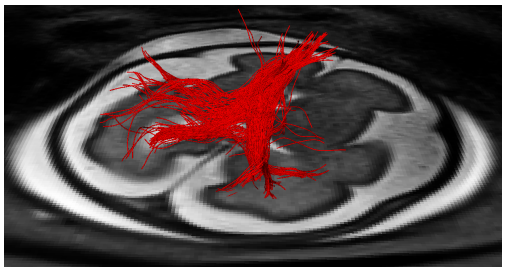

FIGURE 2 – Fibers obtained using a probabilistic tractography algorithm in conjunction with Q-ball diffusion modeling. The splenium of the corpus callosum has been used as seeding region.

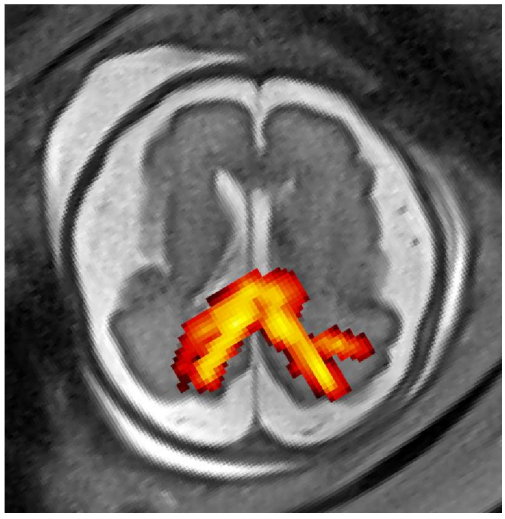

FIGURE 3 – Probabilistic map obtained using the same tractography algorithm in conjunction with Q-ball diffusion modeling. The splenium of the corpus callosum has been used as seeding region.

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