

Interest of the Steady State Free Precession (SSFP) sequence for 3D modeling of the whole fetus

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Abstract—Fetal magnetic resonance imaging (MRI) has been gaining interest over the last two decades. Current fast MRI sequences provide imaging data of the whole uterus in less than 20 seconds, avoiding fetal motion related artifacts without any maternal or fetal sedation. MRI has proved to be a useful adjunct to echographic screening for prenatal diagnosis. However, MRI volumetric data is still mainly interpreted on 2D slices and 3D applications remain limited. In this paper, we discuss the qualities of the SSFP MRI sequences to provide adequate data for 3D segmentation and modeling of the fetus. Potential exploitations of 3D segmentation and derived anatomical models cover several domains: biometric and morphologic clinical studies, quantitative longitudinal studies of normal and abnormal fetus developments, direct visualization of the overall fetus body and simulations in different fields (surgery, radiation dosimetry,...).

I. INTRODUCTION

Since the 1990s, MRI has played an increasing role in the diagnosis of fetal abnormalities, improving the confidence in the ultrasound diagnosis or enabling to identify additional pathologies [1].

However, current diagnoses are still mainly based on a slice by slice analysis. When 3D information about an organ is needed, multiple acquisitions with different orientations are performed. A tedious work is then necessary to reconstruct mentally the structure of interest. Three-dimensional reconstructions can, however, lead to a better understanding of complex organs.

Few research works have been dedicated to the segmentation and 3D modeling of fetal brains based on MR data. For instance, 3D models were developed with the aim of studying the morphogenesis [2], [3]. More recently, some studies have focused on 3D modeling of the lungs and have shown that volumetric information can be extracted to predict an abnormal development of this organ [4], [5].

Very little methodological work has been done for MRI-based 3D segmentation and modeling of the whole fetus, and this task is still challenging. In one of the few works providing whole fetal 3D reconstructions [6], [7], the fetus, the utero-placental unit, the fetus lungs and liver are segmented on several datasets. Nonetheless, this process requires a strong user interaction.

Recent improvements in MRI technology provide data with more appropriate visual quality to achieve fast and detailed 3D segmentation and modeling of the whole fetus,

and to overcome actual limitations. During a fetal MRI examination several MRI sequences can be used. Each sequence has specific characteristics highlighting some organs and pathologies better than others [8]. For 3D segmentation and modeling of the whole fetus, a sequence providing global anatomical information as well as good contrast should be judiciously selected.

In this paper we present our current conclusions on the selection of SSFP as an optimal MRI sequence for segmentation and 3D modeling of the fetus, based on the review of recent literature on the topic and on the evaluation of a large database of routine MRI exams, using several sequences, from a collaborating hospital highly specialized in obstetric screening. The feasibility of segmentation automation based on these data is then discussed, studying the image properties.

II. SSFP: AN OPTIMAL MRI SEQUENCE FOR 3D FETUS MODELING

To compute a high quality 3D fetal anatomical model, two main requirements have to be met. Firstly, the imaging data must preserve the fetus spatial coherence. If fetal motion occurs during data acquisition this coherence might be lost, degrading the fetus surface smoothness when the segmentation results are merged to obtain a 3D model [6]. To prevent such artifacts, the sequence acquisition time must be short enough to “freeze” fetal motion and avoid related artifacts. Moreover, high resolution is needed to precisely localize the organs boundaries.

Secondly, to enable fast and accurate segmentation and go toward automation of this process, high contrast is necessary between uterine wall, fetal soft tissues, placenta and amniotic fluid [9]. Additional organs should also show good contrast so as to provide a more detailed 3D model of the fetus. Besides, the data signal-to-noise ratio (SNR) must be high, with homogeneous response for a given tissue and sharp organ edges.

Several MRI sequences are available for fetal screening: echo-planar imaging (EPI), T1-weighted sequences and fast T2-weighted sequences constitute the basis of a fetal examination. For each sequence, parameters are tuned to optimize image quality, depending on the organ that is examined.

Let us now discuss existing sequences with respect to these requirements. A large database of routine MRI exams acquired at Cochin hospital (Paris, France) on two 1.5 Tesla superconducting units (Magnetom, Siemens , Erlangen, Germany and Avanto, General Electrics , Milwaukee (Wis.), United States). This database was analyzed

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to identify the sequence best fitting our requirements. EPI can be discarded because of the low SNR and insufficient data quality due to susceptibility artifacts, field distortion, chemical shift artifacts and poor spatial resolution [10], [11] affecting data quality. T1-weighted sequences are also inadequate because of the weak contrast existing between the utero-placental unit, the fetus and the amniotic fluid, and the presence of motion artifacts (Figure 1). It is also clear that sequences dedicated to one specific organ provide poor global information.

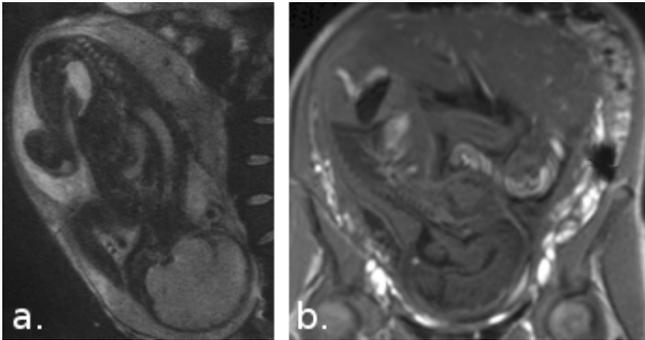


Fig. 1. (a) EPI data with insufficient image signal-to-noise ratio and contrast. (b) T1-weighted data with inadequate contrast to localize the fetus boundaries.

Fast T2-weighted sequences present adequate characteristics for our application. It is possible to acquire a field of view including the whole uterus in about 20 seconds with high spatial resolution and high signal to noise ratio, while “freezing” fetal motion. The amniotic fluid response being strikingly higher than the fetal soft tissues and uterine wall ones, an easy delineation of the fetus is possible [12]. Besides, highly aqueous or amniotic fluid-filled tissues provide high signal responses, due to the T2-weighting component. Additional organs can thus be identified, such as:

- fetal brain, contrasting with the cerebrospinal fluid,
- fetal lungs, fluid-filled,
- gastrointestinal structures because of the fetus swallowing amniotic fluid, contrasting with the low intensity of the adjacent soft tissues.

Two fast T2-weighted sequences are often used: single-shot fast spin-echo (SSFSE by GE©, or HASTE, with half-Fourier plane acquisition, by Siemens©) and SSFP (FIESTA by GE©, or true FISP by Siemens©). Sharing T2-weighting characteristics listed below, they also present few differences [13]. SSFSE/HASTE were the first sequences introduced in fetal MR examination and have been used for 3D modeling [7],[5]. However, the sequences present one main limitation considering our aim; the fetus motion can be small enough to leave the boundaries fixed at the image resolution, but generates flow in amniotic fluid, leading to stripes visible on reconstructed orthogonal plane as shown in Figure 2. Such tissue heterogeneity greatly reduces the chances of segmentation automation.

SSFP sequence provides equivalent or even better data quality than SSFSE/HASTE, with a significantly lower spe-

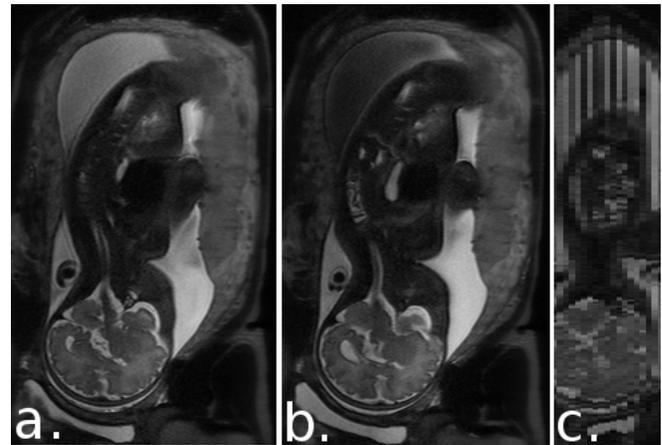


Fig. 2. Flow artifacts on SSFSE/HASTE data. (a and b) Amniotic signal intensity differs on two consecutive slices. (c) Resulting stripes are visible in the reconstructed orthogonal plane.

cific absorption rate [14]. Banding artifacts due to field heterogeneity were limiting the use of SSFP in the past, but new advances in gradient coil and shimming technologies reduce greatly their influence [13]. The need for a large field of view with this sequence is a limitation for small organs studies [11], but has no consequences for a region of interest including the whole uterus. Moreover, flowing fluids response is not affected with SSFP thanks to gradient refocusing and very short echo times [15], overcoming the main limitation of SSFSE/HASTE sequences. For these different reasons, SSFP seems to be the most suitable MRI sequence for 3D segmentation (Figure 3).

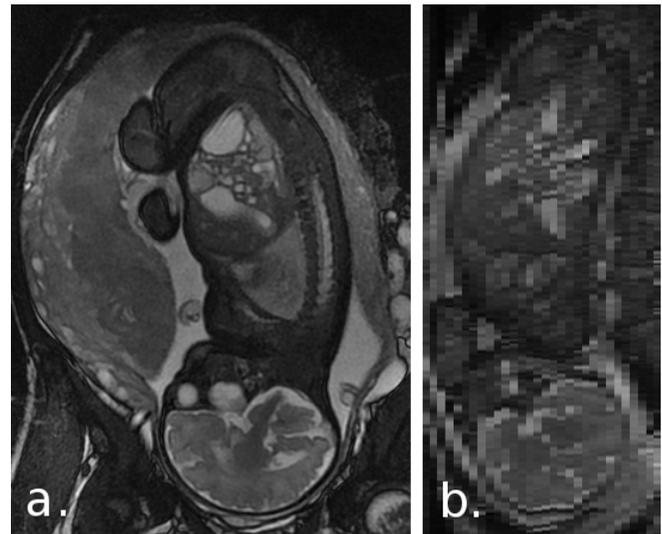


Fig. 3. (a) An SSFP slice and (b) a reconstructed orthogonal slice. Fetal motion is frozen, and high inter-organ contrasts are available.

SSFP can be acquired in 2D or 3D. 3D SSFP is used for placenta studies at the Cochin hospital. Because of the longer acquisition time, the data frequently present fetal motion and maternal breathing artifacts (the acquisition is performed without breath-hold, for patient comfort concern), making it

inadequate for our purpose.

2D SSFP data are currently obtained with the GE Avanto high-performance whole-body 1.5 Tesla superconducting unit. A twelve-channel, phased array surface coil is used to optimize the signal-to-noise ratio over the whole uterus. Patients are scanned in the supine or lateral decubitus position, without sedation or breath-hold. SSFP data are acquired sagittal to the fetus (TR/TE = 4.2/1.8 ms, flip angle = 60°, FOV = 380, slice thickness/gap = 5/0 mm, matrix = 256×256, number of signals acquired = 1) optimizing the number of slices needed to encompass the entire uterine volume, and thus the acquisition time. Despite the voxel anisotropy (1.5 x 1.5 x 5 mm³), the set of slices build a sufficiently precise and spatially consistent 3D volume. These are the data used in the following.

III. SUITABILITY OF SSFP ACQUISITIONS FOR SEGMENTATION

A preliminary work has focused on the study of SSFP data properties. The uterus was first manually segmented on ten datasets, to compute the intensity histograms of the uterine structures. The different histograms exhibited two well-delimited modes, in agreement with the high visual contrast of these data. Figure 4 shows the histogram of the 3D data displayed in Figure 3. Signal intensities of fetal soft tissues belong to the hypo-intense mode, while highly aqueous and amniotic fluid-filled tissues constitute the hyper-intense mode. The minimum intermodal value has been used to threshold the images (Figure 5 a.). The segmentation result shows a very good separation of the two tissue types. This shows the feasibility of segmentation methods based on an initial threshold, although more work has to be carried out in order to automate the process, in particular to cope with potential heterogeneities.

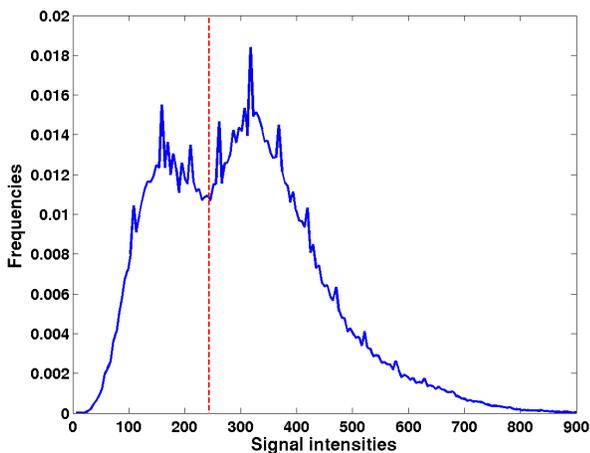


Fig. 4. Histogram of the image shown in Figure 3.

A second segmentation step was performed using 3D Slicer software tools (<http://www.slicer.org>) (Figure 5 b.). A 30 slices volume can be segmented in about five minutes.

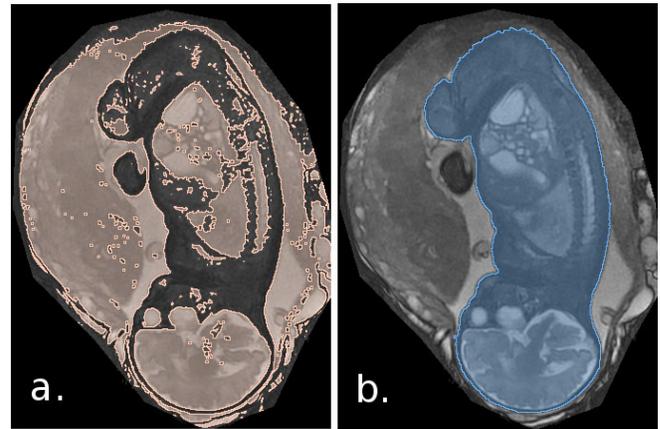


Fig. 5. (a) Thresholding result using the minimum intermodal value extracted from the histogram. (b) Semi-automatized segmentation result of the fetus.

In order to provide more detailed models, fetal organs were also segmented using the same method, including the brain, the eyes, the lungs, the heart and the urinary bladder. 3D models were reconstructed with 3D slicer. Figure 6 shows a reconstruction result. The smoothness of the organ contours shows that no fetal motion occurred during the acquisition.

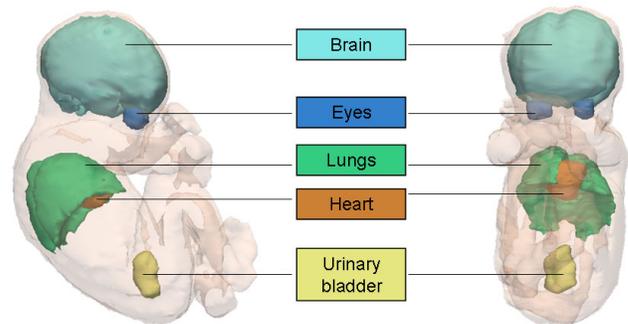


Fig. 6. Two different views of a fetus 3D model, including the brain, the eyes, the lungs, the heart, and the urinary bladder.

Based on the encouraging results obtained with this preliminary analysis of SSFP images, our current work aims at developing segmentation methods for different organs in these images, taking into account the partial volume effect induced by the slice thickness. Good results have already been obtained for the eyes, for which an automated segmentation has been designed.

The segmentation task relies on both the organ morphology and its response to the SSFP sequence. On the one hand, the algorithm assumes that the eye is also almost spherical, with a stable diameter. On the other hand, it is filled with vitreous humor, which is 99% water, and has therefore a very high grey level with the SSFP sequence. The surrounding soft tissues presenting a low response, great contrast is available to localize the organ. A pattern matching based method has been used to extract spherical intense objects on a dark background. The eyes were segmented successfully on ten

datasets, for fetus of various ages (in the range of 26-34 gestational weeks) using this method. A segmentation result is illustrated in Figure 7.

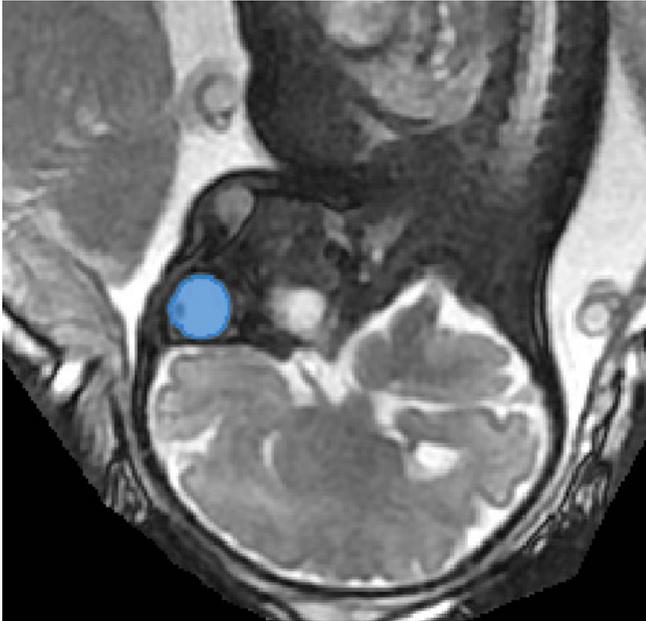


Fig. 7. Automated eye segmentation result.

The eyes identification constitutes an anchor in the fetus anatomy and provides the plane of symmetry of the head. An initial location of the brain can be easily deduced from the eyes position. Using this information, we developed a preliminary segmentation method aiming at segmenting this organ with a deformable model. Promising results were obtained for two brains. Using anatomical spatial relationships between neighboring organs, it is possible to attempt a segmentation of additional structures of interest such as the spine, the lungs, the urinary bladder and the stomach. This is the aim of our future work.

IV. MRI AND FETAL BIOMETRY ASSESSMENT

As a conclusion, we briefly mention the potential of MRI acquisitions for fetal biometry assessment. Once a 3D segmentation is obtained, a set of measurements can be performed. They conveniently complement measurements that can be derived from traditional ultrasound acquisitions. Among the useful measures, biometric ones are particularly useful for diagnosis, such as the brain volume and diameter, the abdomen perimeter, the length of the femur, the lung volume, etc. The 3D nature of the acquisitions, the spatial resolution and the quality of the segmented volumes are important features of MRI data for providing precise, reliable and unbiased measures. Until now such measures were mostly performed manually [6], [7]. This paper shows that automated measures can now be foreseen, and will undoubtedly be available in a near future. As an example, eye biometric data have been evaluated, such as the mean diameter (14.2 mm). However, this value is computed on

only ten datasets and more data are needed to make this study statistically significant.

Potential exploitations of 3D segmentation and derived anatomical models cover several domains: biometric and morphologic clinical studies, quantitative longitudinal studies of normal and abnormal fetus developments, direct visualization of the overall fetus body and simulations in different fields (surgery, radiation dosimetry,...).

REFERENCES

- [1] C. Adamsbaum, A. Gélot, C. André, and J.M. Baron, *Atlas d'IRM du cerveau fœtal (Atlas of foetal brain MRI)*, Masson, Paris, 2001.
- [2] A. Cachia, J. F. Mangin, D. Riviere, F. Kherif, N. Boddaert, A. Andrade, D. Papadopoulos-Orfanos, J. B. Poline, I. Bloch, and M. Zilbovicius, "A primal sketch of the cortex mean curvature: a morphogenesis based approach to study the variability of the folding patterns," *Medical Imaging, IEEE Transactions on*, vol. 22, no. 6, pp. 754-765, 2003.
- [3] L. Schierlitz, H. Dumanli, J. N. Robinson, P. E. Burrows, A. G. Schreyer, R. Kikinis, F. A. Jolesz, and C. M. Tempny, "Three-dimensional magnetic resonance imaging of fetal brains," *Lancet*, vol. 357, no. 9263, pp. 1177-1178, 2001.
- [4] H. Osada, K. Kaku, K. Masuda, Y. Iitsuka, K. Seki, and S. Sekiya, "Quantitative and qualitative evaluations of fetal lung with MR imaging," *Radiology*, vol. 231, no. 3, pp. 887-892, 2004.
- [5] G. Kasprian, C. Balassy, P. C. Brugger, and D. Prayer, "MRI of normal and pathological fetal lung development," *European Journal of Radiology*, vol. 57, no. 2, pp. 261-270, 2006.
- [6] R. A. Kubik-Huch, S. Wildermuth, L. Cettuzzi, A. Rake, B. Seifert, R. Chaoui, and B. Marincek, "Fetus and uteroplacental unit: fast MR imaging with three-dimensional reconstruction and volumetry-feasibility study," *Radiology*, vol. 219, no. 2, pp. 567-573, 2001.
- [7] T. M. Keller, A. Rake, S. C. Michel, B. Seifert, J. Wisser, B. Marincek, and R. A. Kubik-Huch, "MR assessment of fetal lung development using lung volumes and signal intensities," *European Radiology*, vol. 14, no. 6, pp. 984-989, 2004.
- [8] D. Prayer and P. C. Brugger, "Investigation of normal organ development with fetal MRI," *European Radiology*, 2007.
- [9] D. Levine, "Three-dimensional fetal MR imaging: will it fulfill its promise?," *Radiology*, vol. 219, no. 2, pp. 313-315, 2001.
- [10] T. A. Huisman, E. Martin, R. Kubik-Huch, and B. Marincek, "Fetal magnetic resonance imaging of the brain: technical considerations and normal brain development," *European Radiology*, vol. 12, no. 8, pp. 1941-1951, 2002.
- [11] D. Prayer, P. C. Brugger, and L. Prayer, "Fetal MRI: techniques and protocols," *Pediatric Radiology*, vol. 34, no. 9, pp. 685-693, 2004.
- [12] W. Y. Guo and T. T. Wong, "Screening of fetal CNS anomalies by MR imaging," *Child's Nervous System*, vol. 19, no. 7-8, pp. 410-414, 2003.
- [13] H. W. Chung, C. Y. Chen, R. A. Zimmerman, K. W. Lee, C. C. Lee, and S. C. Chin, "T2-weighted fast MR imaging with true FISP versus HASTE: comparative efficacy in the evaluation of normal fetal brain maturation," *American Journal Roentgenology*, vol. 175, no. 5, pp. 1375-1380, 2000.
- [14] B. Ertl-Wagner, A. Lienemann, A. Strauss, and M.F. Reiser, "Fetal magnetic resonance imaging: indications, technique, anatomical considerations and a review of fetal abnormalities," *European Radiology*, vol. 12, no. 8, pp. 1931-1940, 2002.
- [15] W. R. Nitz, "Fast and ultrafast non-echo-planar MR imaging techniques," *European Radiology*, vol. 12, no. 12, pp. 2866-2882, 2002.