Deformable Slice-to-Volume Registration for Motion Correction of Fetal Body and Placenta MRI

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I. Supplementary Data

This supplementary data section presents the preliminary results of the assessment of DSVR reconstruction quality for fetal body MRI on a large number of datasets.

A. Fetal MRI Data

The set of fetal MRI cases used for preliminary evaluation of DSVR reconstruction quality contains 100 randomly selected iFIND[1] T2-weighted datasets of fetuses from 20-34 weeks GA range. The iFIND acquisitions were performed on a 1.5T MRI using ssFSE sequence with TR = 15000 ms, TE = 80 ms, voxel size = 1.25 x 1.25 x 2.5 mm, slice thickness 2.5 mm and slice spacing 1.25 mm. Each of the datasets contains 7-10 stacks acquired under different orientations with respect to the fetal body and uterus. Fig. 1 shows GA distribution of the analysed cases.

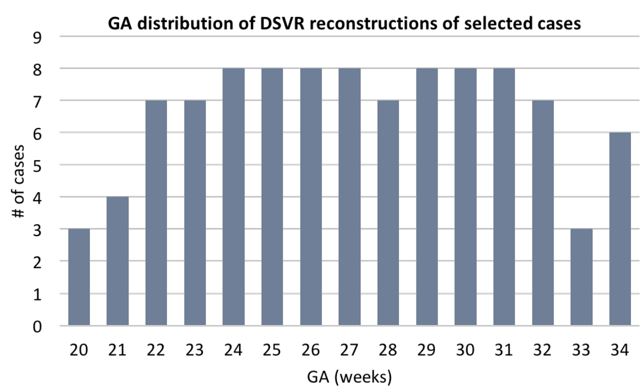

Fig. 1. Selected iFIND cases: distribution of subject GA.

B. DSVR pipeline

The diagram of the main processing steps of the DSVR pipeline described in the main article is presented in Fig. 3.

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[1]iFIND Project: http://www.ifindproject.com

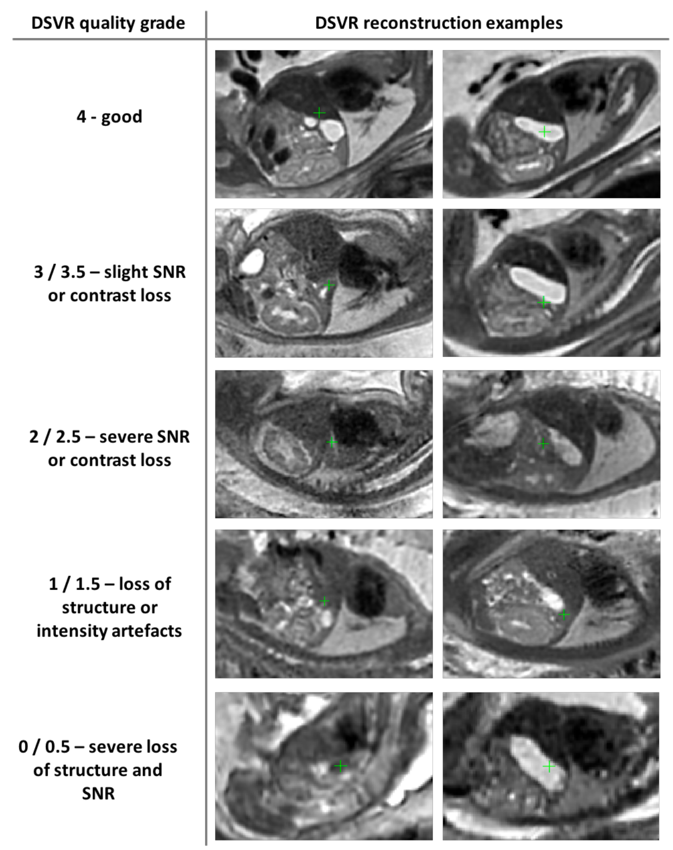

Fig. 2. DSVR reconstruction quality grading scheme examples: [0; 4].

C. DSVR Reconstruction Quality Grading

Each of the selected datasets was reconstructed based on the standard DSVR pipeline with structural outlier rejection. On average, we used 5-8 stacks selected with respect to the amount of motion and intensity artefacts. If the output quality was lower than expected, reconstructions were repeated with a different template and combinations of stacks.

The output 3D isotropic volumes with 0.85 mm resolution were assessed by clinicians trained in fetal MRI with respect to the image quality and information content. The reconstruction quality grading scheme together with examples is presented in Fig. 2. It has [0; 4] range with 4 corresponding to high quality volumes with well defined organ structure and preserved tissue

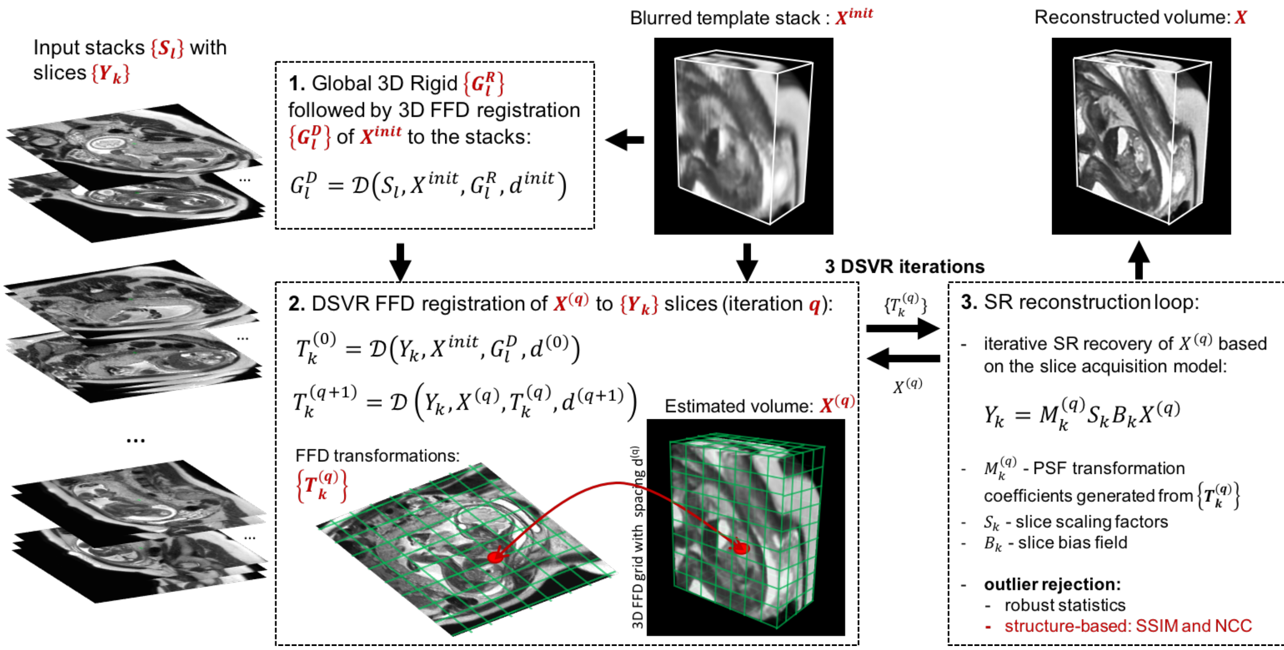

Fig. 3. DSVR processing pipeline: visual representation of the main modules.

texture. Output volumes with slight SNR or contrast loss are graded as 3 or 3.5. Severe SNR or contrast loss cases correspond to 2 or 2.5. This type of reconstruction quality issues is generally related to the low quality of the original data (e.g., low SNR). Reconstructed volumes with severe loss of structural information or intensity artefacts are graded between 0 and 1.5 and this is primarily caused by severe motion and large rotations or bending of fetal body.

Volumes with grades ≥ 2 are considered to have sufficient quality for further analysis and interpretation. This grading scheme follows the general structure of the scheme currently employed at St Thomas' Hospital for grading fetal brain SVR reconstructions [1].

The distribution of all grades of the reconstructed cases is shown in Fig. 4 with 69% being in high quality range [3; 4], 25% with severe SNR and contrast loss and 6% of the cases are in the "failed" category.

The average grade values per GA are given in Fig. 5. In addition, Tab. I shows the proportions of primary causes of low reconstruction quality for 20-24, 25-29 and 30-34 GA ranges.

TABLE I
PRIMARY CAUSES OF LOW QUALITY FOR DIFFERENT GA RANGES.

GA range	Low SNR	Motion	Low CNR
20-24 weeks GA	2.94 %	61.76 %	35.29 %
25-29 weeks GA	15.15 %	42.42 %	42.42 %
30-34 weeks GA	45.83 %	29.17 %	25.00 %

While the average grade for all cases is 3.090 ± 0.799, the grades for younger GA cases are generally lower. Motion is the predominant reason of low reconstruction quality for the cases from ≤ 24 weeks GA range, which is in agreement with the corresponding expected higher motion amplitude range. On the other hand, for the older cases (≥ 30 weeks GA), SNR loss becomes the primary cause.

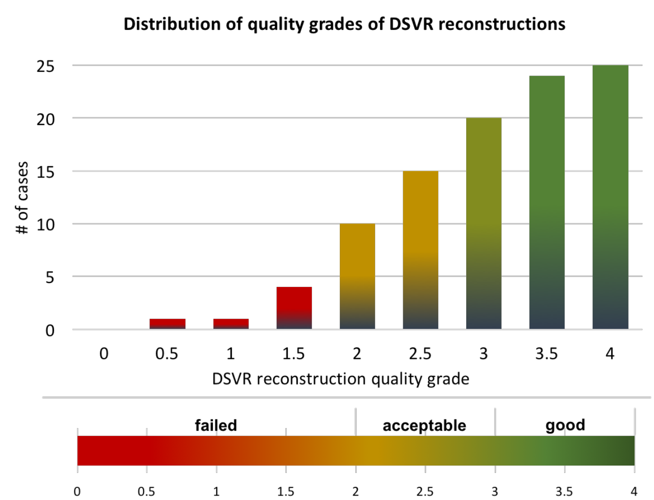

Fig. 4. Distribution of quality grades of all DSVR reconstructions.

D. DSVR Reconstruction Examples

This section presents examples of reconstructions from the investigated set of cases.

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- High quality reconstruction

Fig. 6 presents examples of high quality reconstructed volumes for healthy and abnormal cases for 20, 24, 28 and

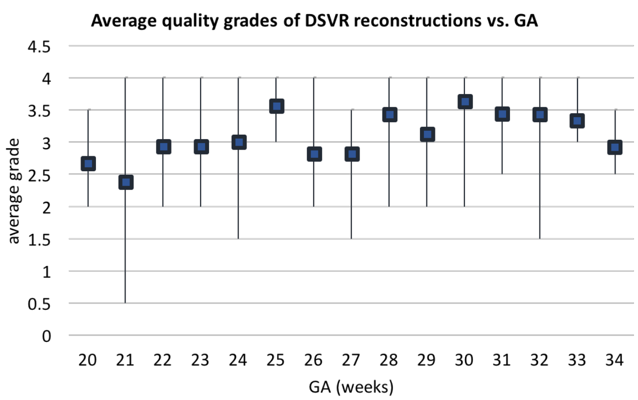

Fig. 5. Average DSVR reconstruction quality grades per GA.

32 weeks GAs. Despite the smaller feature size with respect to resolution of the original stacks, DSVR is generally capable of reconstruction of young GA cases ($\leq$ 25 weeks) with minor to average motion corruption degree.

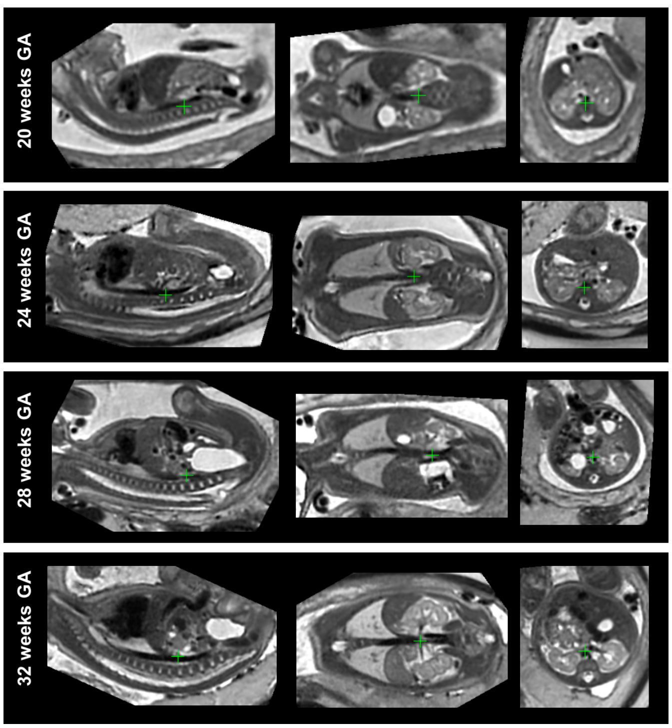

Fig. 6. DSVR reconstruction examples: $\{20, 24, 28, 32\}$ weeks GA cases.

- Low quality reconstruction

The essential requirements for good reconstruction quality are that the magnitude of deformations should be within FFD capture range and the ROI is oversampled with a sufficient number of stacks (5-8). The current version of DSVR implementation is not designed for correction of large amplitude motion.

An example of a failed 21 weeks GA case (0.5 grade) is given in Fig. 7 with SVR [1], PVR [2] and DSVR reconstructions from five stacks. The primarily causes of low reconstruction quality are large rotations of fetal body between the stacks (Fig. 7.a-b) as well as severe motion and small feature size with respect to resolution of the input stacks.

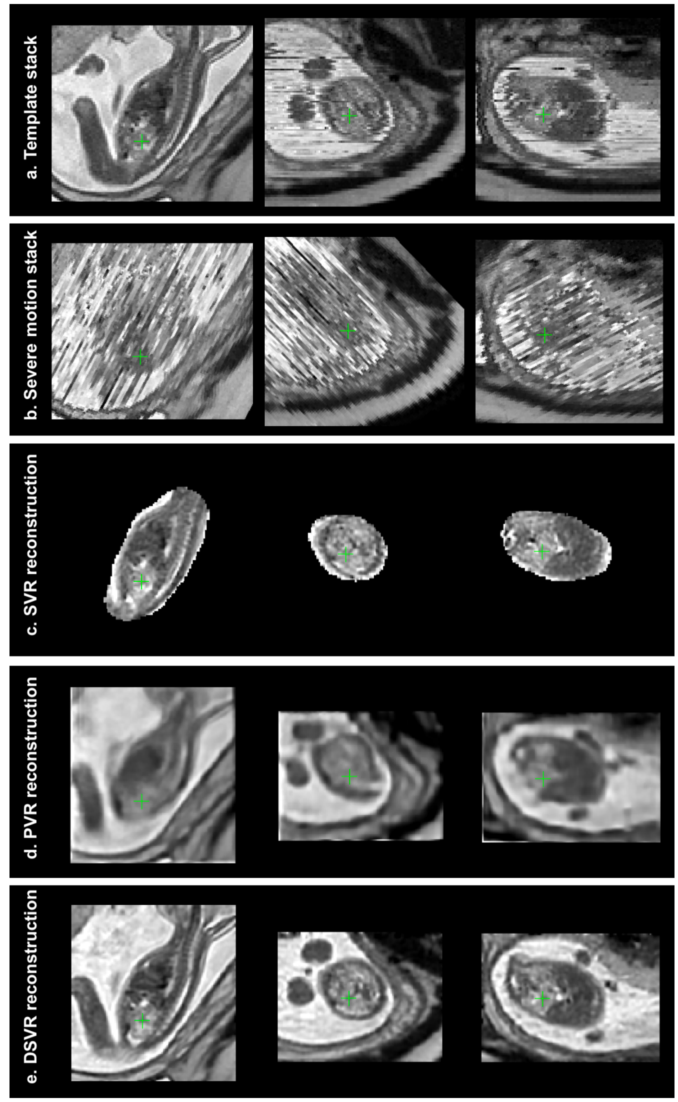

Fig. 7. Reconstruction examples: severe motion 21 weeks GA case.

- Twin pregnancy reconstruction

Fig. 8 shows an example of a twin pregnancy reconstructions for a 29 weeks GA minor motion dataset. The reconstruction of the entire uterus from six stacks was performed using GPU accelerated SVR [3], PVR [2] and DSVR. Unlike PVR, neither SVR or DSVR are designed for large FoV motion correction but rather focus of a particular ROI. However, in this case, PVR could not resolve the impact of limb movement and produced significant smoothing of structural features. This is primarily caused by the reconstruction target initialisation strategy employed in both SVR and PVR that is based on average of global stack registration. DSVR was capable of producing relatively good reconstruction quality for the fetal bodies and placenta. However, in general, DSVR performs better when the bodies of each of the twins are reconstructed separately since it decouples their motion patterns.

- Placenta reconstruction

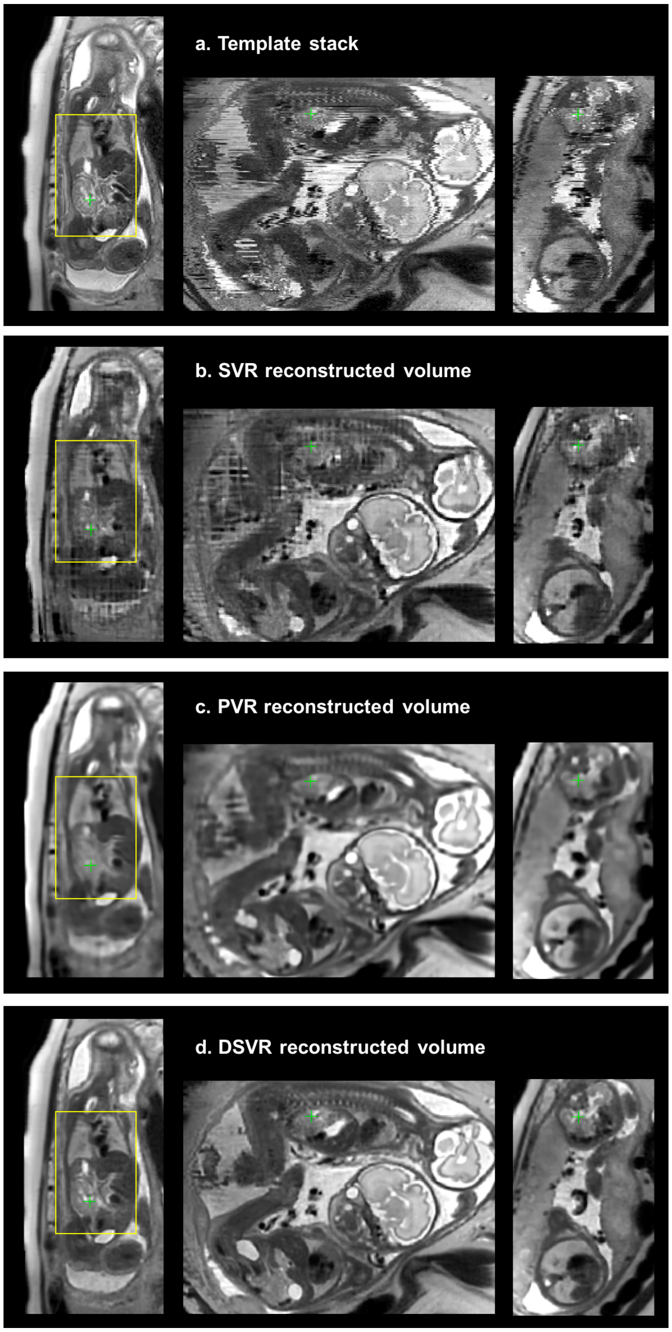

Fig. 8. Reconstruction examples: 29 weeks GA twin pregnancy case.

With respect to placenta reconstruction, Fig. 9 shows a reconstruction example for one of the minor motion iFind datasets using SVR [1], PVR [2] and DSVR methods from five stacks. The output DSVR volume provides sufficiently high resolution and contrast for local structural features and tissue texture. On the other hand, due to local non-rigid deformations, SVR and PVR produced blurring of local features (e.g., vessels).

It has to be taken into account that unlike fetal body, placenta does not preserve global shape due to its tissue elasticity properties and is characterised by low tissue contrast. This introduces an additional challenge for physiologically-accurate motion correction. However, for minor to average motion datasets, DSVR provides sufficiently good reconstruction quality in comparison to the alternative methods. Development of a pipeline for severe motion cases would potentially require decoupling of maternal motion (including both respiratory motion and random movements) and introducing model-based constrains on deformation fields.

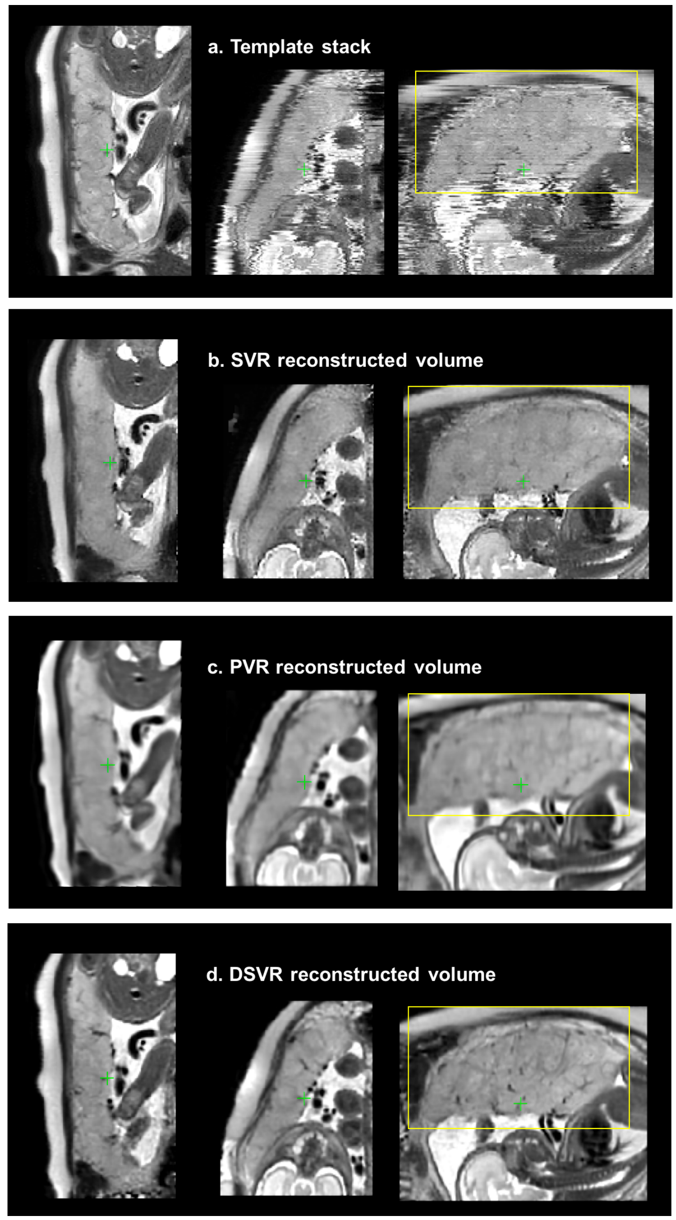

Fig. 9. Reconstruction examples: 30 weeks GA placenta case.

F. Reconstruction Examples from Quantitative Evaluation Study

The full versions of the images from the leave one out quantitative evaluation of reconstruction methods are presented in Fig. 10- 11. They include examples of the template stacks and the corresponding SVR, PVR and DSVR reconstructed volumes.

The full version image of the simulated experiment results example is given in Fig. 12.

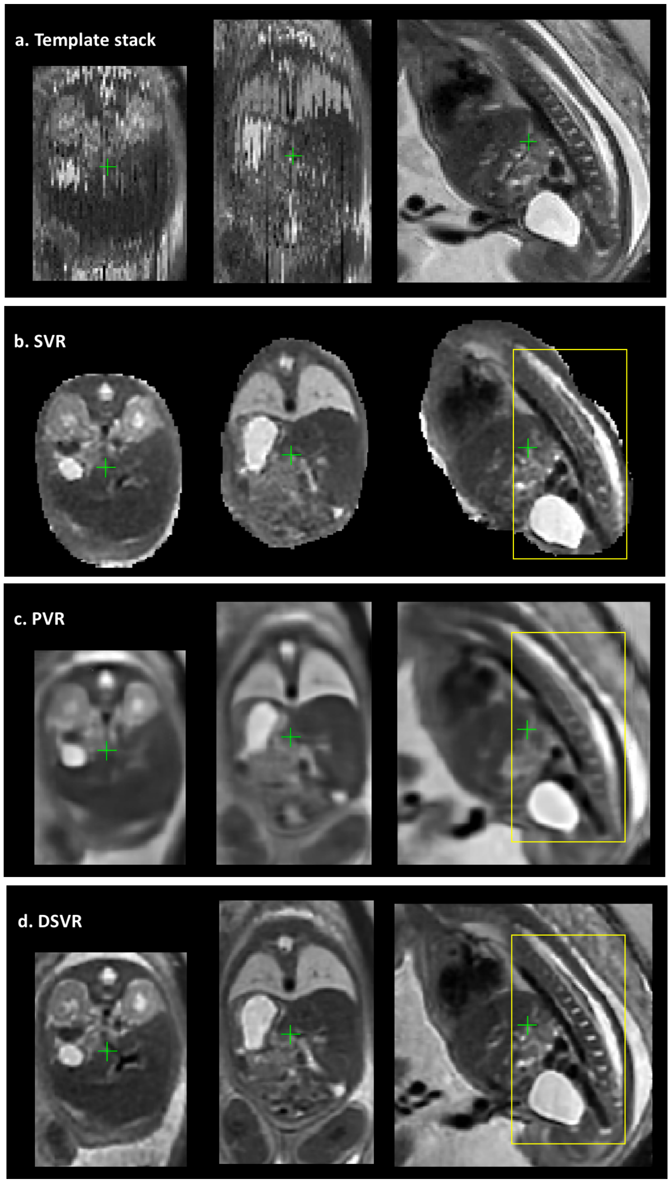

Fig. 10. Example of motion correction for a minor motion dataset (29 weeks GA): template stack, SVR, PVR and DSVR reconstructed volumes.

G. Conclusions

The results of this preliminary evaluation show that DSVR provides sufficient reconstruction quality for fetal body MRI for 20-34 weeks GA range cases. Furthermore, the examples of twins and placenta reconstructions indicate that it can be employed for a wider range of applications.

Since it is based on classical registration methods, DSVR is not designed for correction of large amplitude movement which can lead for a certain proportion of failed reconstructions for younger GA cases that are prone to severe motion.

In addition to the main software development plan, future investigation will focus on quantitative assessment of reconstructed volumes with respect to measurements of organ shape and volume and intensity variations.

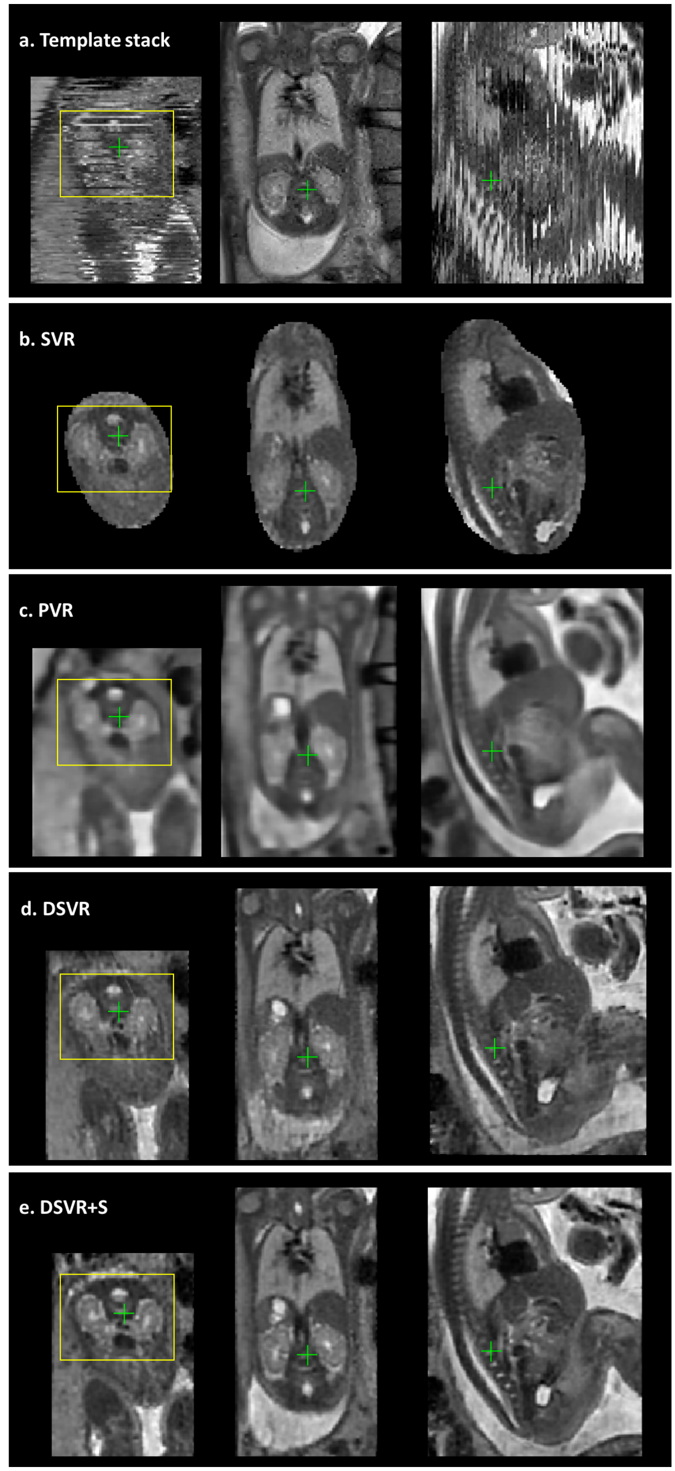

Fig. 11. Example of motion correction for a severe motion dataset (30 weeks GA): template stack, SVR, PVR, DSVR and DSVR+S reconstructed volumes.

References

[1] M. Kuklisova-Murgasova, G. Quaghebeur, M. A. Rutherford, J. V. Hajnal, and J. A. Schnabel, "Reconstruction of fetal brain MRI with intensity matching and complete outlier removal," *Medical Image Analysis*, vol. 16, no. 8, pp. 1550–1564, 2012.

[2] A. Alansary *et al.*, "PVR: Patch-to-Volume Reconstruction for Large Area Motion Correction of Fetal MRI," *IEEE Transactions on Medical Imaging*, vol. 36, no. 10, pp. 2031–2044, 2017.

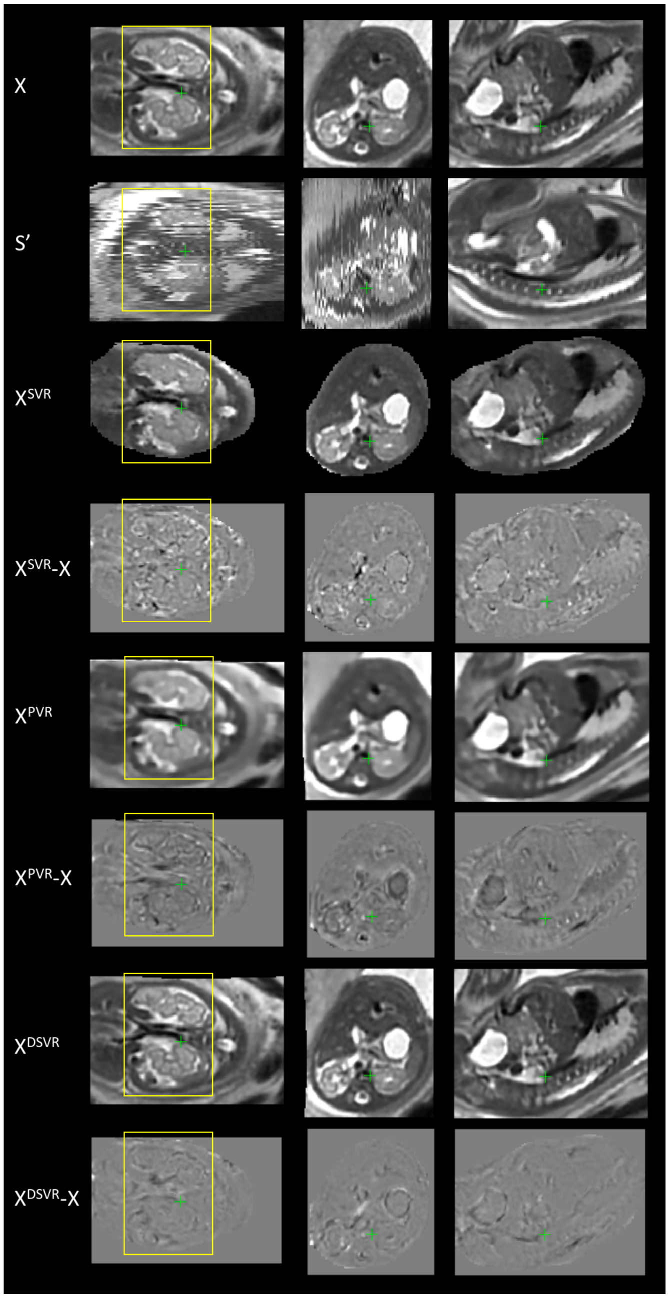

Fig. 12. Simulated experiment: original reference volume ($\boldsymbol{X}$), one of the generated motion-corrupted stacks ($\boldsymbol{S'}$), SVR ($\boldsymbol{X}^{\boldsymbol{SVR}}$), PVR ($\boldsymbol{X}^{\boldsymbol{PVR}}$) and DSVR ($\boldsymbol{X}^{\boldsymbol{DSVR}}$) reconstruction results and their difference with the reference.

[3] B. Kainz *et al.*, “Fast Volume Reconstruction from Motion Corrupted Stacks of 2D Slices,” *IEEE Transactions on Medical Imaging*, vol. 34, no. 9, pp. 1901–1913, 2015.