Super-resolution Reconstruction of Fetal Brain MRI

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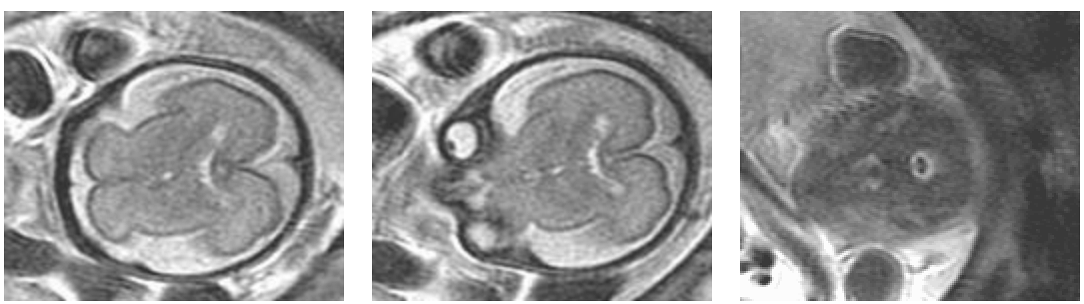
Workshop on Image Analysis for the Developing Brain (IADB)
MICCAI'09, London, UK
September 24, 2009

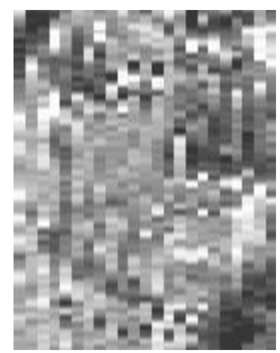
What is the current fetal MRI practice?

- Single-shot fast spin echo (SSFSE) imaging is used to acquire fast fetal MRI slices.
  - The quality and resolution of SSFSE slices is normally good despite intermittent fetal motion.
  - But motion artifacts and thick slices needed for high SNR severely affect the out-of-plane views, and make the 3D evaluation and analysis difficult.

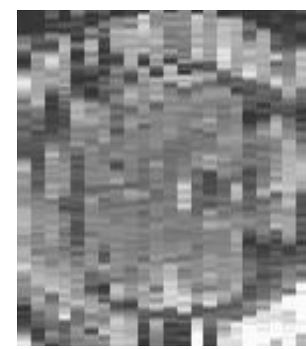
Inter-slice motion



Adjacent slices of an axial SSFSE scan



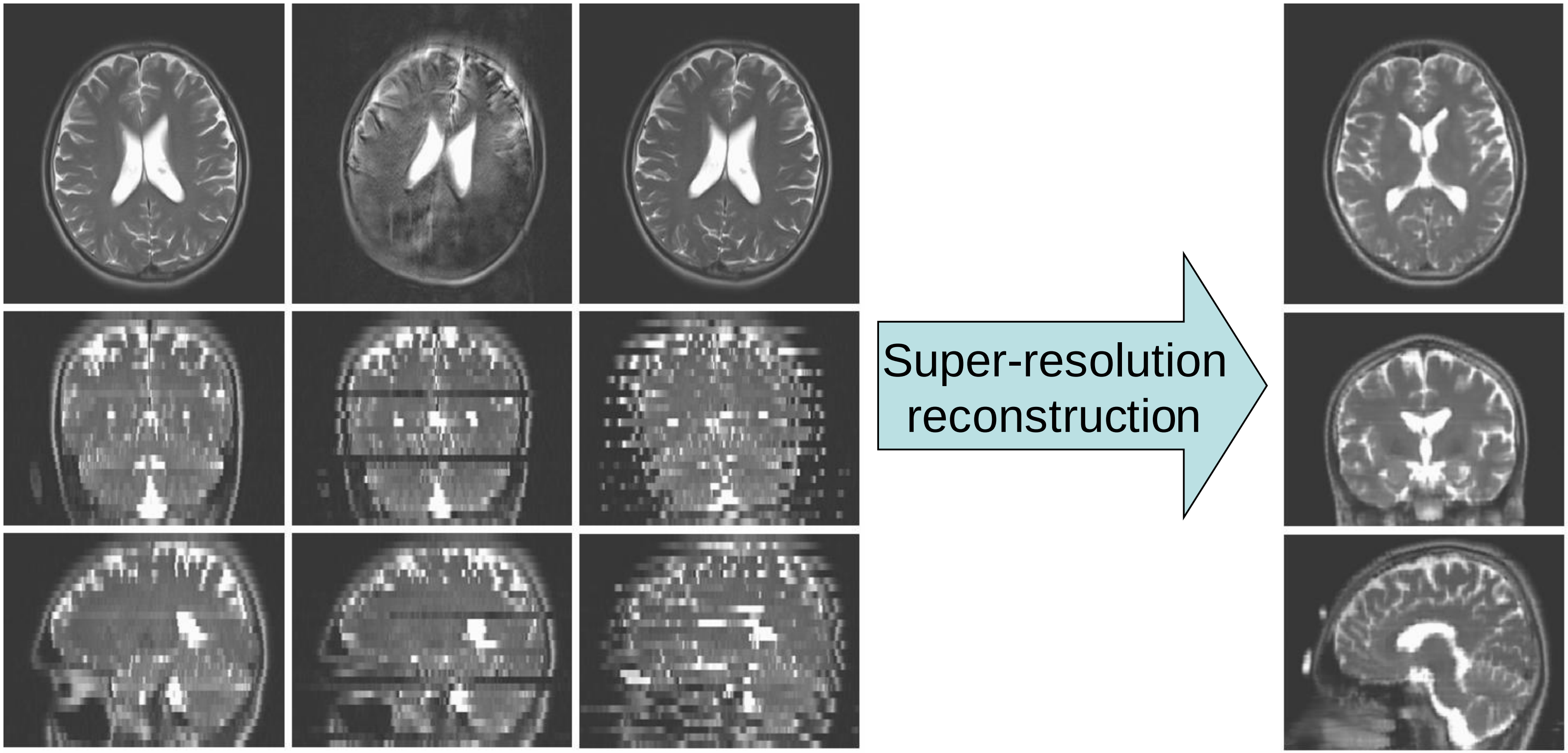
sagittal



coronal

Volumetric MRI reconstruction

- State-of-the-art image processing technology allows reconstruction of volumetric MRI from multiple sets of thick-slice motion-corrupted SSFSE scans.



What is new in this study?

- The previous reconstruction techniques rely on iterations of slice-to-volume registration and scattered data interpolation (SDI);
  - These techniques do not present an explicit mathematical framework for convergence to at least a local optimum solution in the sense of minimum reconstruction error.
- The developed technique is based on a slice acquisition model, and refines the reconstructed image through maximum likelihood error minimization.

Slice acquisition model

- k^{th} 2D slice: $\underline{Y}_k$
- Imaged object: $\underline{X}$
- Noise: $\underline{V}_k$

number of slices

$$\underline{Y}_k = \mathbf{D}_k \mathbf{B}_k \mathbf{S}_k \mathbf{M}_k \underline{X} + \underline{V}_k \quad , \quad k = 1, \ldots, n$$

Motion (3D)

Down-sampling

Slice selection profile (3D)

PSF blur

Slice selection profile

- A simple and relatively accurate model for slice selection profile is a box-car function:

$$\left|\vec{\mu}_{sk}.\vec{r}-s_{0k}\right|<\Delta s_k/2$$

slice orientation (normal vector of the slice plane equation)

distance of the slice from the origin

slice thickness

- This model is formulated as region selection, signal averaging, and resampling.

Super-resolution reconstruction

- The maximum likelihood (ML) estimation is formulated by assuming an exponential model of PDF as a function of a distance *d* between the model and the acquired slices;

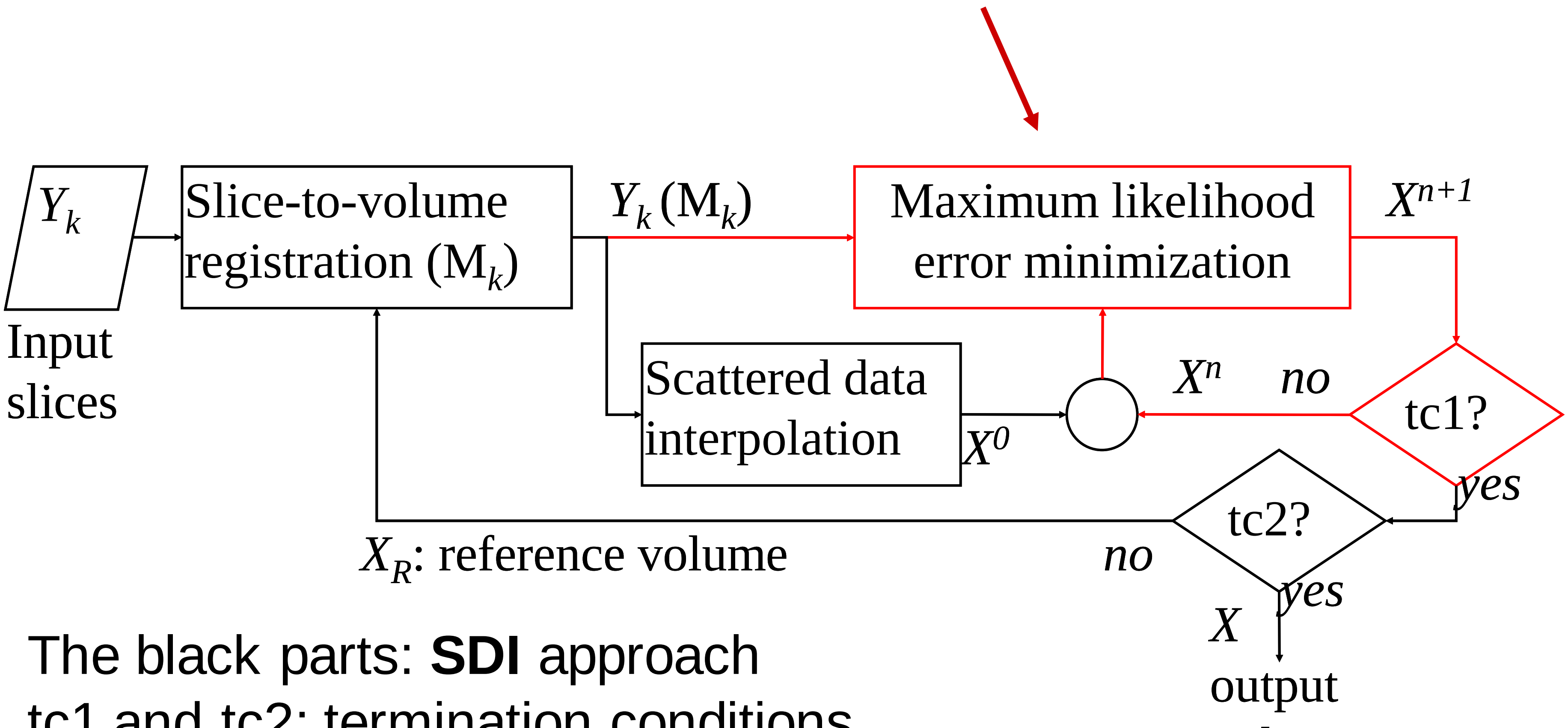
$$\underline{\hat{X}} = \underset{\underline{X}}{ArgMin}\left[\sum_{k=1}^{N} d\left(\underline{Y}_k, \mathbf{D}_k \mathbf{B}_k \mathbf{S}_k \mathbf{M}_k \underline{X}\right)\right]$$

$$\underline{\hat{X}} = \underset{\underline{X}}{ArgMin}\left[\sum_{k=1}^{N} \left\|\mathbf{D}_k \mathbf{B}_k \mathbf{S}_k \mathbf{M}_k \underline{X} - \underline{Y}_k\right\|_2^2 + \lambda \left\|\mathbf{C}\underline{X}\right\|_2^2\right]$$

Regularization term

ML solution: iterative error minimization

$$\underline{\hat{X}}^{n+1} = \underline{\hat{X}}^{n} + \alpha\left[\sum_{k=1}^{N}\mathbf{M}_k^{\mathbf{T}}\mathbf{S}_k^{\mathbf{T}}\mathbf{B}_k^{\mathbf{T}}\mathbf{D}_k^{\mathbf{T}}\left(\underline{Y}_k - \mathbf{D}_k\mathbf{B}_k\mathbf{S}_k\mathbf{M}_k\,\underline{\hat{X}}^{n}\right) - \lambda\mathbf{C}^{\mathbf{T}}\mathbf{C}\,\underline{\hat{X}}^{n}\right]$$



The black parts: **SDI** approach

tc1 and tc2: termination conditions

Scattered data interpolation (SDI)

- B-Spline scattered data interpolation
  - Lee et al., IEEE Trans Visual Comp Graph. 1997; 3(3):228-244.
  - Jiang et al., IEEE Trans Med Imag. 2007, 26(7):967-980.
- Local-neighborhood interpolation injection based on oriented Gaussian kernels
  - Rousseau et al., Acad Radiol. 2006; 13(9):1072-1081.
- In this study: weighted local intensity injection based on cubic B-Spline kernels.

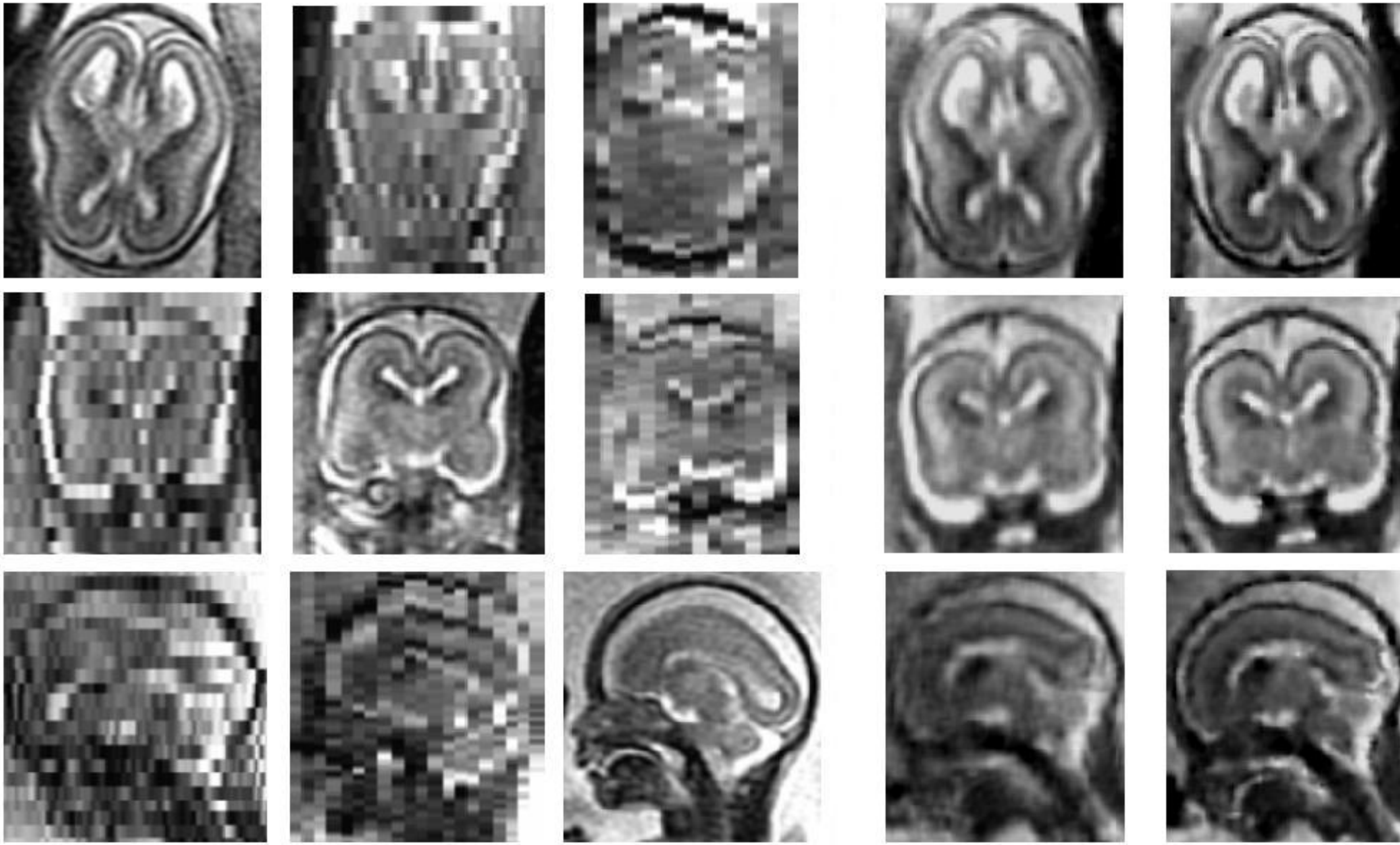
Data acquisition

- Data was obtained from clinical MRI of patients with diagnosed or suspected cases of fetal anomalies after diagnostic ultrasonography.
  - 1.5-T TwinSpeed Signa system (GE healthcare) and an 8-channel phased-array cardiac coil.
  - without maternal sedation or breath-hold.
  - SSFSE with TR varying between 1000 and 4500 ms; TE varying between 80 and 100 ms; variable matrix size between 160 and 512; and slice thickness of 3 or 4 mm.

Datasets and comparison

- Ten fetal MRI datasets
  - Gestational age range of 19.28 to 35.43 weeks (mean 26.33 $\pm$ 6.34).
  - The number of input scans used in reconstruction (*N*) was between 3 and 11 (mean 6.1 $\pm$ 2.5).
- Comparing methods:
  - Averaging (initial estimation) (AVE)
  - Scattered data interpolation (SDI)
  - The developed ML estimation (MLE)

Results: visual inspection



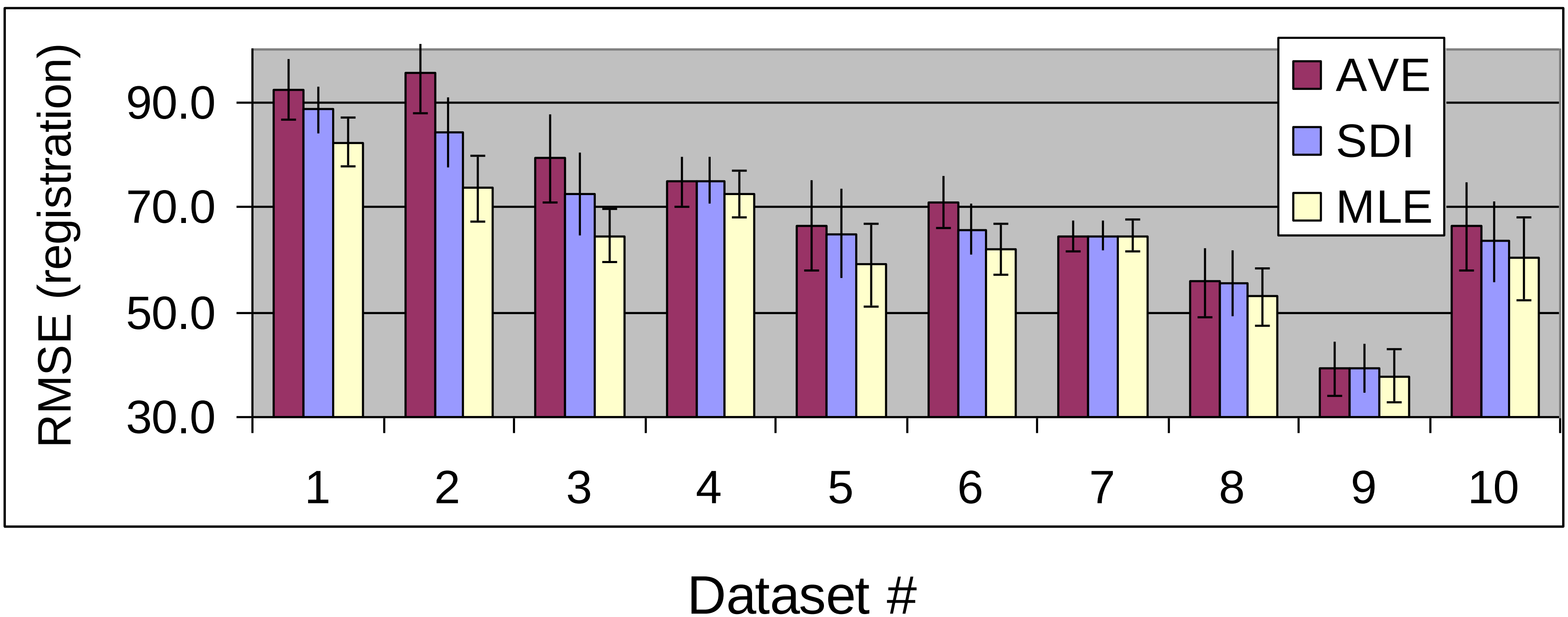
3 out of 5 input SSFSE scans SDI MLE

Results: Qualitative assessment

- The visual inspection shows that good-quality uniformly-sampled volumetric reconstructed images were obtained for 9 datasets.
  - Mis-registration artifacts were observed in the reconstructed images for the 10th dataset (GA 35.43, N=6) using both techniques, and for the 2nd dataset (GA 19.28, N=5) using the SDI technique only.
  - In all cases the images obtained by the MLE technique present higher contrast and sharper edges than the images obtained by SDI.

Quantitative evaluation (1)

- Obtained RMSE of intensity values between the reconstructed images and the acquired slices
  - Lower RMSE Indicates better slice-to-volume registration which in-turn indicates better reconstructed volumes used as reference for registration iterations.



Quantitative evaluation (2)

- Image sharpness measures:
  - When the motion is more effectively estimated and corrected and the motion-corrected images are more accurately fused in the reconstruction process, sharper structures appear in the reconstructed image.
  - *M*1 (the intensity variance measure): sum of square differences (SSD) between each voxel intensity value and the mean image intensity value.
  - *M*2 (the energy of image gradient measure).

	mean(AVE)	mean(SDI)	mean(MLE)	SDI > AVE	MLE > AVE	MLE > SDI
M1	4.06E+04	4.14E+04	4.38E+04	80% (8/10)	100% (10/10)	100%
M2	1.67E+10	1.62E+10	1.92E+10	40% (4/10)	100% (10/10)	100%

Conclusion

- An iterative ML error minimization approach based on a slice acquisition model has been developed for fetal brain MRI super-resolution reconstruction.
- This approach is intuitive, flexible, and guarantees the convergence to at least a local optimum solution.
- Visual inspection and the quantitative evaluation results indicate improved reconstruction.
- Improved reconstruction enhances the capacity of research studies on early brain development, clinical evaluation, 3D fetal cerebral biometry, and brain mapping.

Acknowledgements

- This research was supported in part by NIH grants R01 RR021885, R01 GM074068 and R01 EB008015.

- The clinical fetal MRI data were collected at the Advanced Fetal Care Center (AFCC) at Children's Hospital Boston.

- The authors would like to thank Dr. Judy Estroff, Dr. Ellen Grant, Dr. Carol Barnewolt, and Dr. Omar Khwaja at AFCC.

Thank you!

Questions?