Computationally Assisted MRI and its application to Fetal Brain Studies

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Overview

1. Computational techniques in imaging:

   From Computational Photography to Computational MRI

2. Overview of Some Major Topics in Computational MRI

   - Contrast Domain Methods
   - Spatial Domain Methods

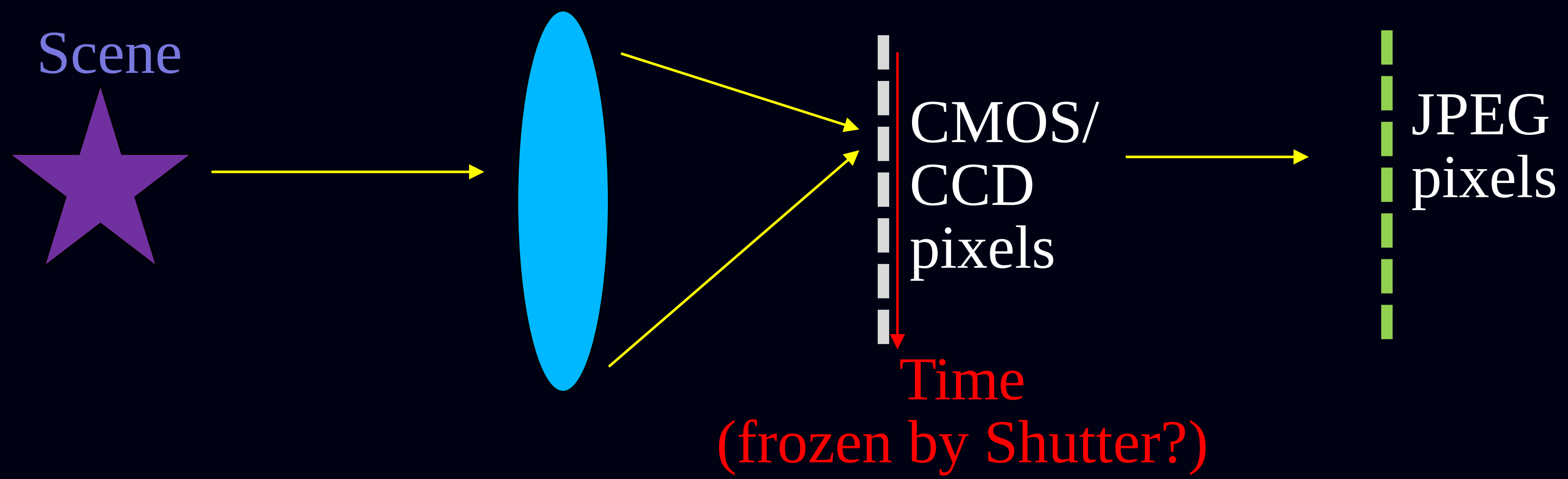
3. Fetal MRI

   Challenges of Fetal MRI

   Aspects of Computational MRI for Fetal Imaging

Traditional Photography extended:

1. Traditional Photography makes use of [directly] spatially indexed sensing



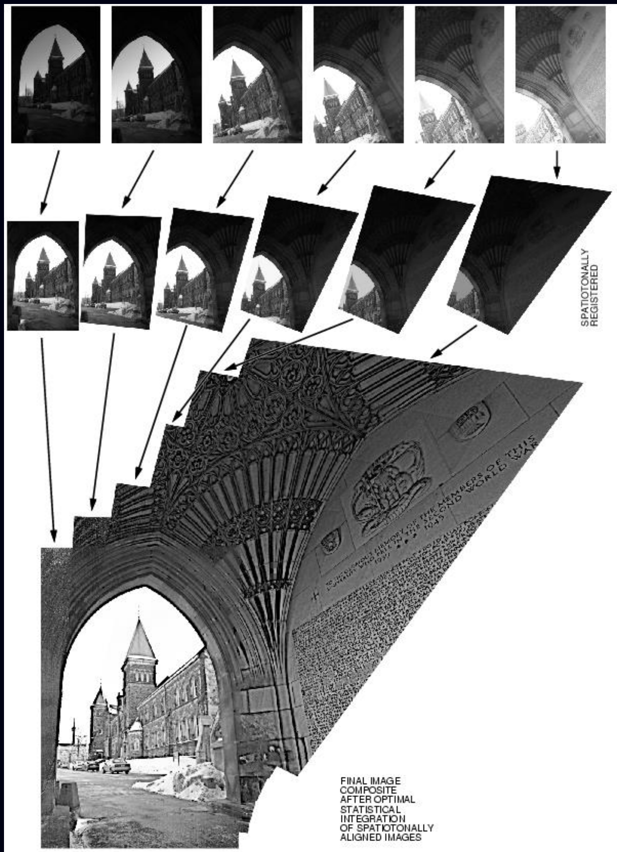
2. Computational Photography seeks to improve/expand imaging by combining potential changes in eg:

- Type and time of data collection
  (longer exposure, multiple exposure, filters, multiple sensors)

- Focus or aperture variation

With alternative image reconstruction techniques

Some Examples of Computationally Assisted Photography



- Increasing Field of View:

  Combining multiple smaller images

  Image mosaicing -> Panorama building

- Increasing Contrast:

  Combining multiple images with the same or different sensitivities:

  High Dynamic Range Photography

- Increasing Resolution:

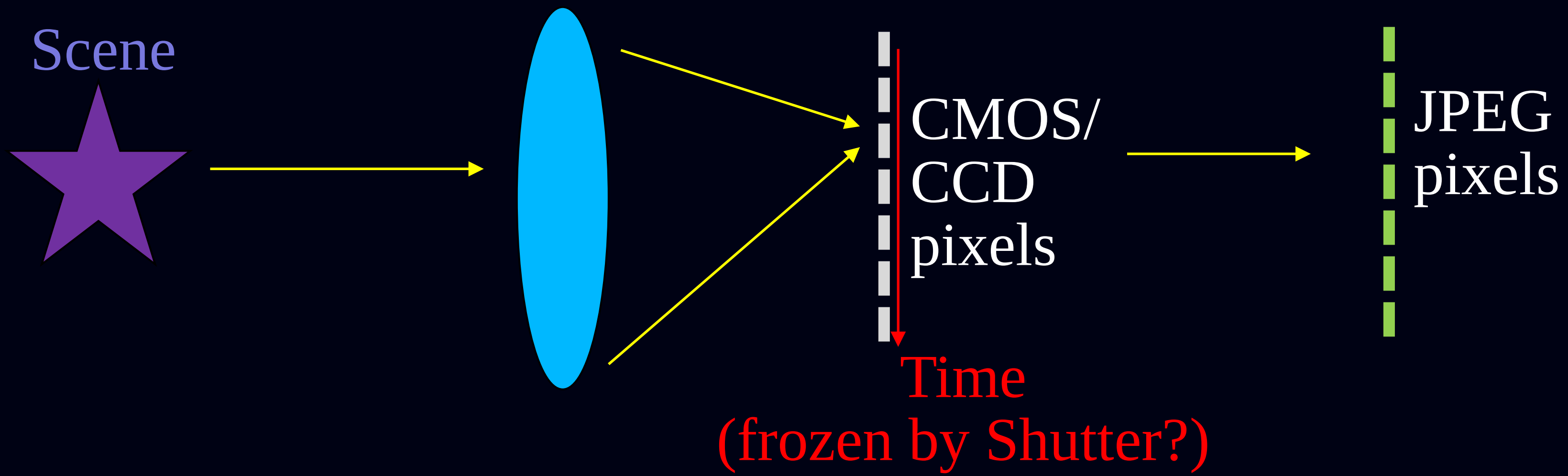
  Using Sensor or Object Motion/Shifting to enhance Resolution via PSF deconvolution

- Variable/Multiple Focusing/Depth of Field

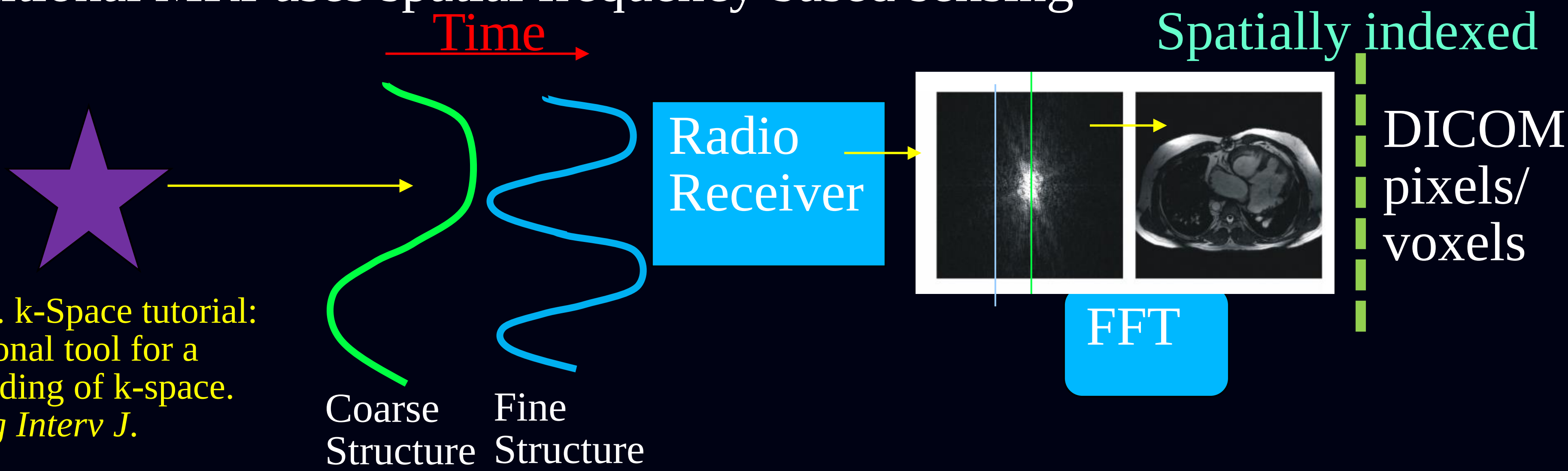
  Light Field Imaging

Traditional Photography vs Traditional MRI

1. Traditional Photography makes use of [directly] spatially indexed sensing



2. Traditional MRI uses spatial frequency based sensing



Moratal D, et al. k-Space tutorial: an MRI educational tool for a better understanding of k-space. *Biomed Imaging Interv J.* 2008;4(1)

Dimensionality and MRI

- Can Collect Spatial Frequencies by
  - 1. Encoding in 2D to form a slice:
    - And collect multiple slices over time to form a volume
  - 2. Encoding fully 3D to form a volume
- But each spatial frequency needs time to collect..

Computational Methods in MRI

- Many Techniques from computational photography translate directly to MRI.
- However… MRI also offers many different ways to create both contrast, spatial and temporal localization of signal.
  - These have motivated the development of very different approaches to computational imaging

Computational Contrast Estimation Methods in MRI

Detour… Quantitative Photography ideas…

- MRI and photography record raw signal intensities from a scene:

- In photography the brightness and colour of an object recorded are dependent variables like lighting of the scene.

- It is possible to use lighting/sensor/filter combinations to estimate the actual colour/surface material properties of an object.

-> Create ‘Quantitative Images’ of basic material properties

Detour… Quantitative MRI ideas…

1. In MRI contrast comes from many different measured properties
   (eg rate of relaxation of spins, motion of tissue, diffusion of water)

2. It can be varied by varying many parameters for an acqusition
   eg repetition time, echo time, flip angle etc etc…

3. In basic MRI acquisitions we record image intensities (providing weighted or relative contrast) dependent on factors such as:
   Excitation (magnetic field and coils generating it)
   Absorption of the signal (RF penetration effects)
   Received signal (receiver coil sensitivity, amplifier gain etc)

4. As with photography it is possible to combine acquisitions to estimate Basic material properties in quantitative form
   (eg spin relaxation time in 1/sec or flow in vol/sec)

5. These physical units should be consistent for a given tissue even in different scans and scanners

Computationally assisted MRI Topics (I)

- Increasing Contrast/Noise:

  Combining multiple acquisitions with the same or different parameters

[Hung AH, Liang T, Sukerkar PA, Meade TJ. High dynamic range processing for magnetic resonance imaging. PLoS One. 2013 Nov 8;8(11)]

Multiple Acquisitions With varying echo time:

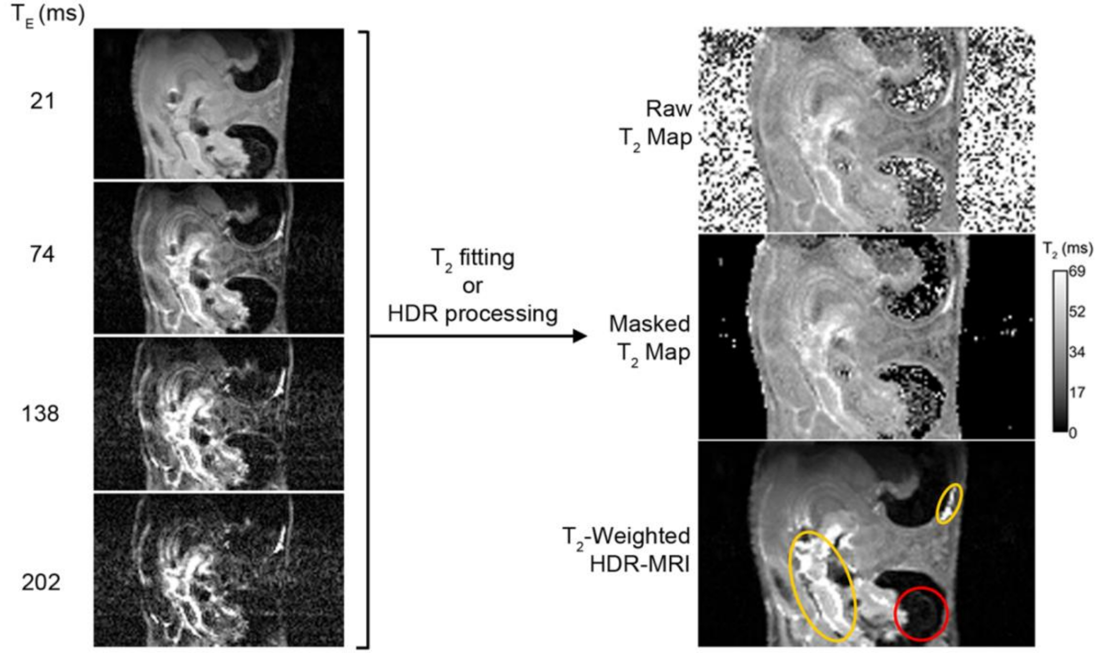


Figure 7. ***In vivo*** **HDR-MRI.** A series of images were acquired with constant T_R at 5632 ms and varying T_E as indicated. The same four LDR images were used to generate both the T_2 map and the HDR-MR image. Masking of the T_2 map was done by manual thresholding. In the HDR image, red and yellow outlines highlight features that were not captured in one or more of the individual LDR images. HDR-MRI captures the same features as T_2 mapping, but is less noisy in the low signal regions. Low signal features can be accurately depicted in HDR-MRI even when the features are only visible in a single LDR image.

Computationally assisted MRI Topics (II)

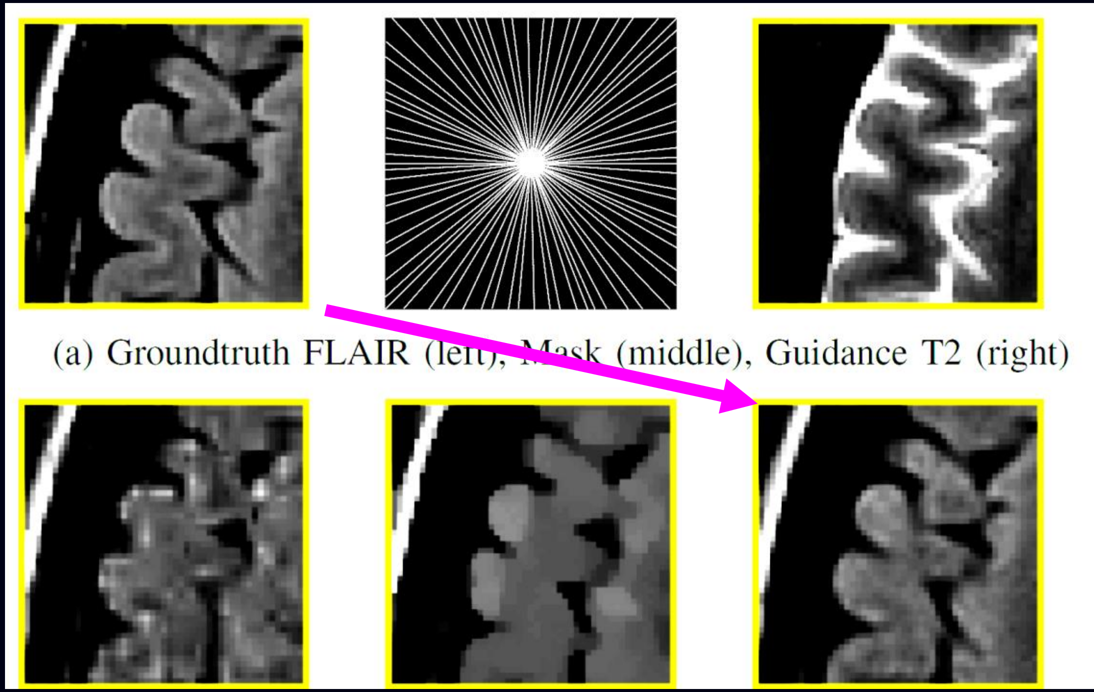
Simulating one contrast from another:

To reduce total imaging time

[P. Song, L. Weizman, J. F. C. Mota, Y. C. Eldar and M. R. D. Rodrigues, "Coupled Dictionary Learning for Multi-Contrast MRI Reconstruction," 2018 25th IEEE International Conference on Image Processing (ICIP), 2018.

FLAIR (fluid attenuated inversion recovery) from T2W images:

High resolution
FLAIR contrast
From a T2
Contrast MRI



Spatial Domain Methods in Computational MRI

Computationally assisted MRI Topics (III)

- Increasing Field of View:

Because of the size of the main magnet and receiver coils MRI scanners have a limited field of view.

Volume Stitching:

Multiple Partial Scans -> Whole Body Volume Surveys

[Glocker B. et al. (2009) MRI Composing for Whole Body Imaging. In: Bildverarbeitung für die Medizin 2009.]

Fig. 3. Composing of 3 spine volumes. Top: initial average. Bottom: result. Gray bars indicate overlap.

Deformable Volume matching of parts

Computationally assisted MRI Topics (IV)

- Increasing Dimensionality/Motion Correction

  Stitching 2D slices to 3D Volumes

B. Kim and J. L. Boes and P. H. Bland and T. L. Chenevert and C. R. Meyer,"Motion correction in fMRI via registration of individual slices into an anatomical volume",Magn. Reson. Med.,1999,41

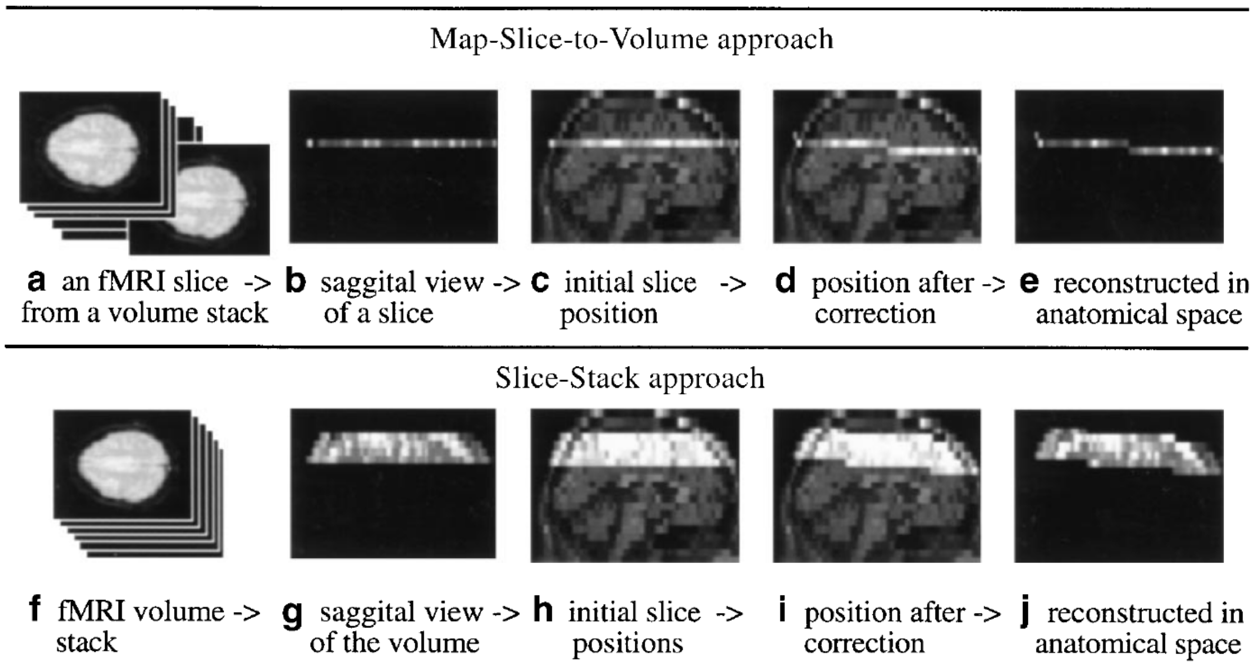
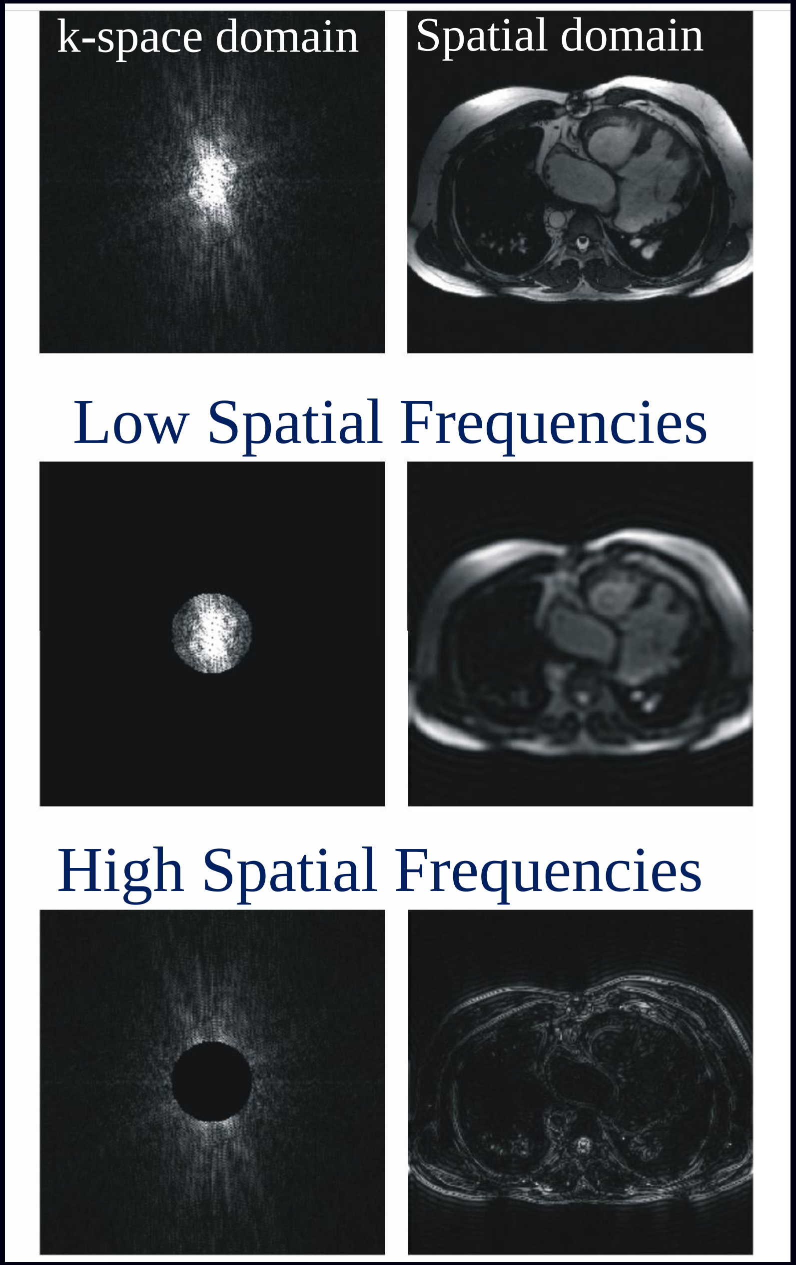


FIG. 3. Motion correction scheme depicting map-slice-to-volume (top row) and slice-stack (bottom row) approach by sagittal view of a brain. The far left column represents (**a**) an fMRI slice and (**f**) volume of stacked slices in an activation cycle. The next two columns show (**b**,**c**) the fMRI slice and (**g**,**h**) volume as positioned by the slice selection pulse during acquisition. Spatially corrected positions representing 5° rotation of head in saggital plane are shown for (**d**) the slice and (**i**) volume, and the last column presents reconstructed fMRI volumes from (**e**) the slice and (**j**) volume in the anatomical reference space. In the map-slice-to-volume approach, an individual slice is repositioned into the anatomical volume space as each is subject to different motion parameters and the procedure is repeated for each slice in a time series fMRI. In the slice-stack approach, accurate relocation of slices is compromised by overlooking the time interval between slices and assuming all the slices in one activation cycle are subjected to the same motion parameters.

Detour: Partial Acquisitions beyond spatial stitching

- Rather than simply acquire a <u>spatial subset</u> of a scene
  - (like photographic mosaicing from smaller images)
- MRI allows acquisition of a <u>spatial frequency subset</u>
- Potential Speedup:

Form an image by collecting only parts of k-space



Computationally assisted MRI Topics (V)

- Increasing [Super] Resolution:

Combine Multiple Low Resolution images

Using Acquisition characteristics or Patient Motion to deconvolve system PSF blur: Fill out HR k-space

[Plenge, E. and Poot, et al, "Super-resolution methods in MRI: Can they improve the trade-off between resolution, signal-to-noise ratio, and acquisition time?", Magnetic Resonance in Medicine,2012.]

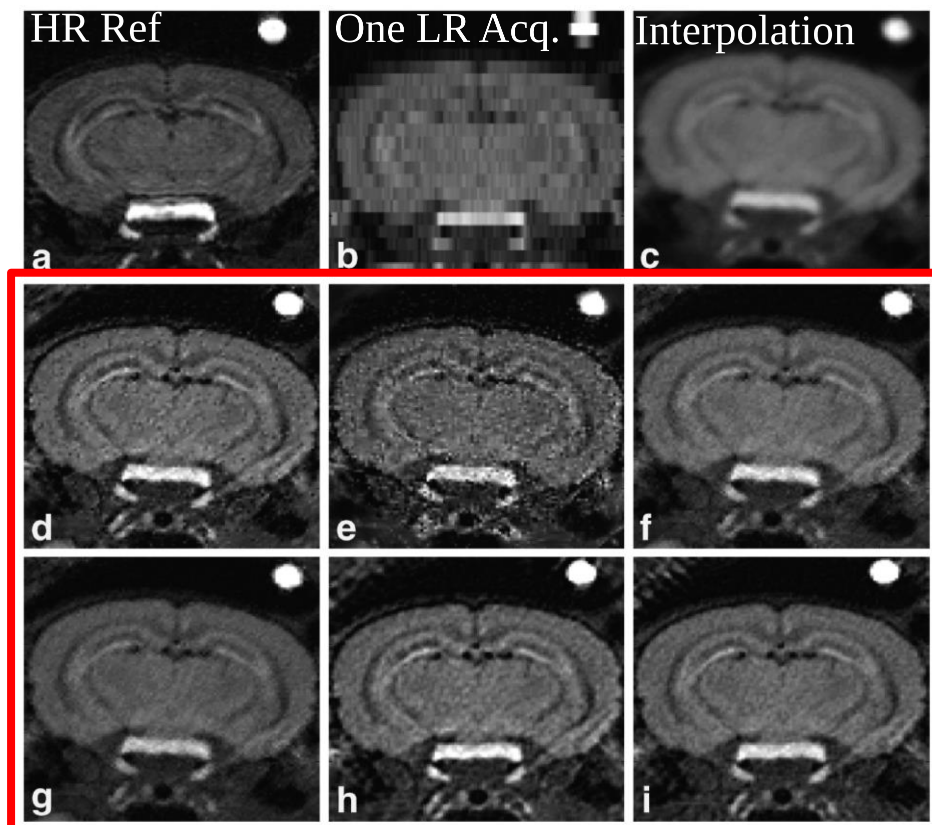


FIG. 9. Axial slices of in vivo mouse brain. The images show: (**a**) a direct HR 3D acquisition, (**b**) one of the eight LR acquisitions, and reconstructions with (**c**) INT, (**d**) IBP, (**e**) RSR, (**f**) ART, (**g**) POCS, (**h**) TIK, and (**i**) LASR, using eight LR images.

Computationally assisted MRI Topics (VI)

Decreasing Acquisition Time via Reconstruction from Partial Acquisitions:

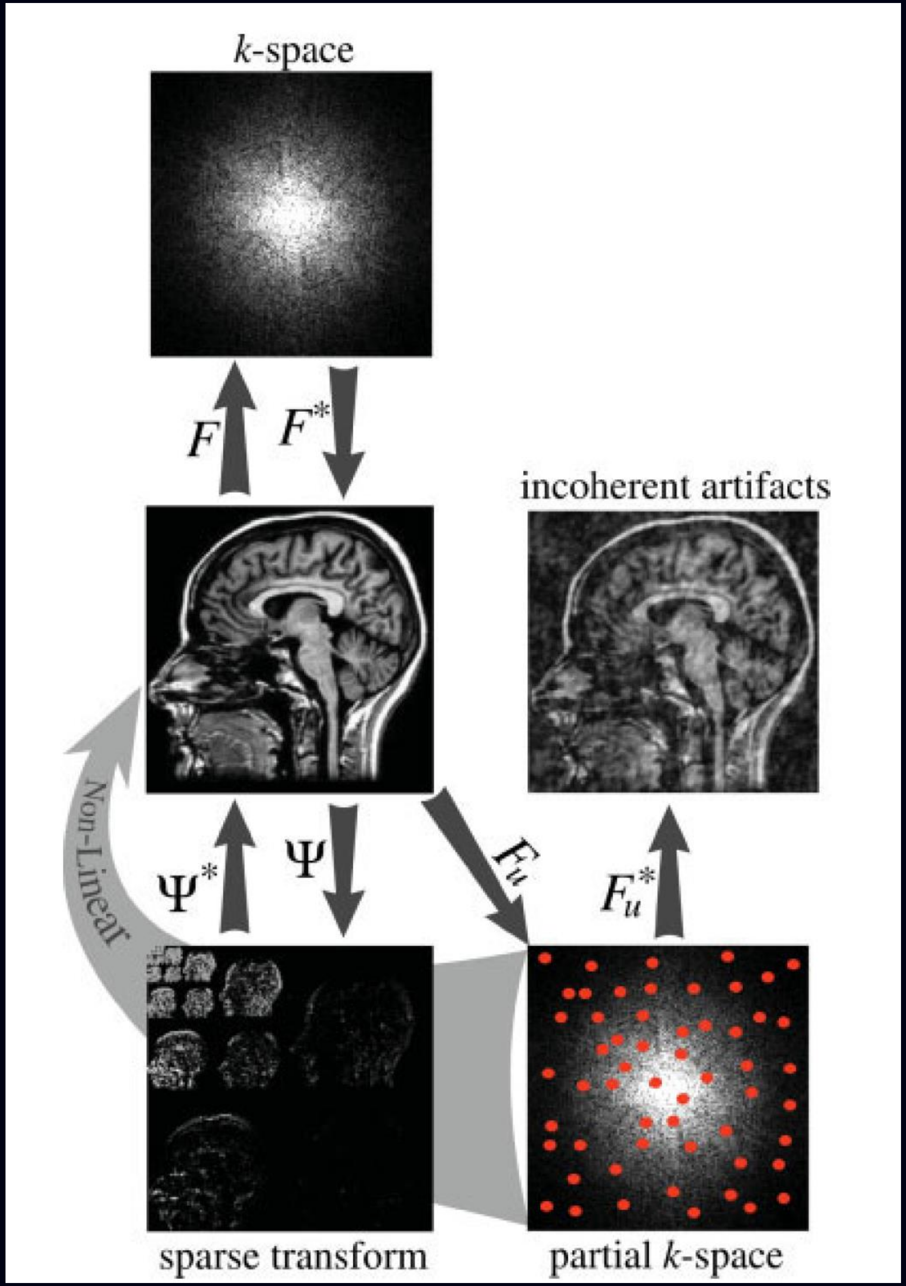
Compressed Sensing -> Sparse MRI Acquisitions

Find a representation/data collection domain that is optimally sparse

-> Collect only the parts of the signal that are important for a scene:

Use a non-linear reconstruction which enforces sparsity

Lustig, M., Donoho, D. and Pauly, J.M. (2007), Sparse MRI: The application of compressed sensing for rapid MR imaging. Magn. Reson. Med., 58: 1182-1195



Computationally assisted MRI Topics (VII)

Newer Techniques aim to exploit different forms of data redundancy/sparsity:

a) Spatial
b) Temporal
c) Multi-channel (spatially localized multi-coil acquisition)

[Ye, J.C. Compressed sensing MRI: a review from signal processing perspective. *BMC biomed eng* **1,** 8 (2019)]

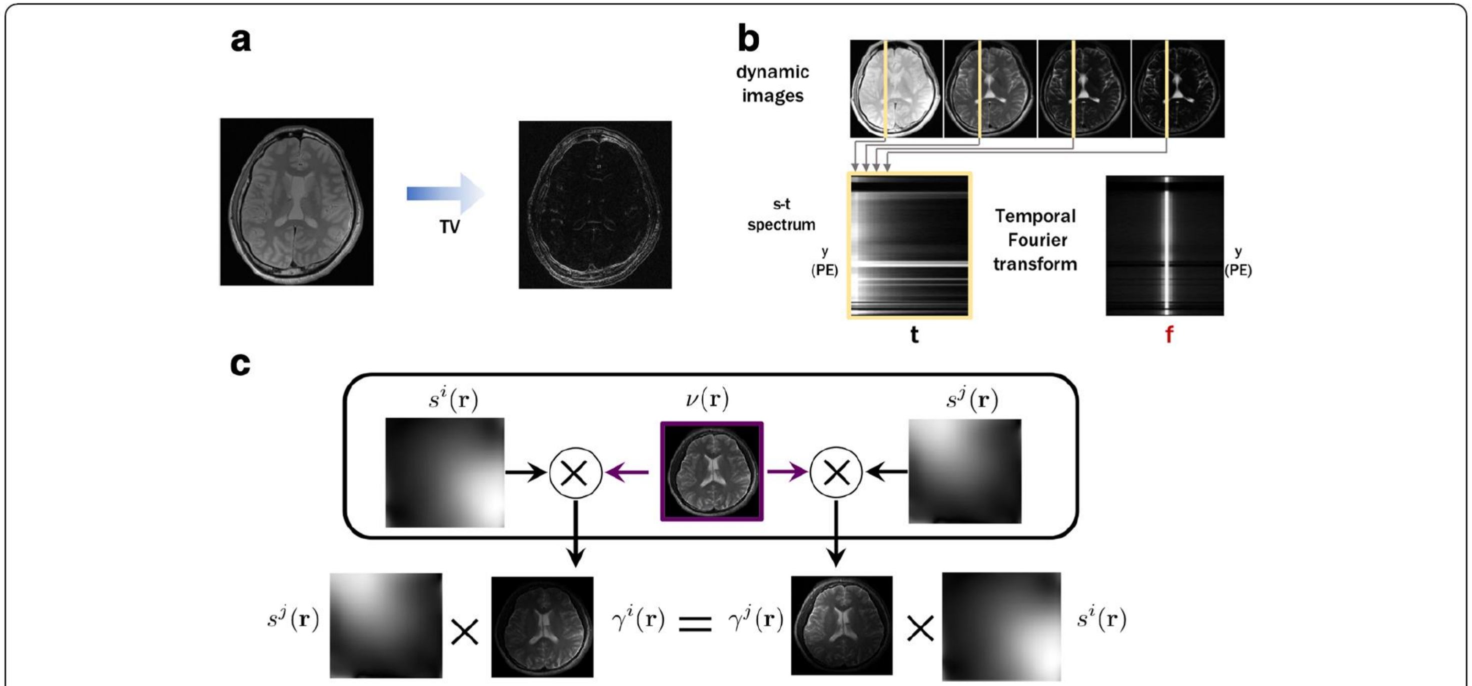


Fig. 1 Various types of sparsity in MRI. (**a**) Sparsity from spatial domain redundancy, (**b**) Sparsity from temporal redundancy, and (**c**) sparsity from mu.ti-channel redundancy

Computationally assisted MRI Topics (VIII)

[Fully] Quantitative: MRI Fingerprinting

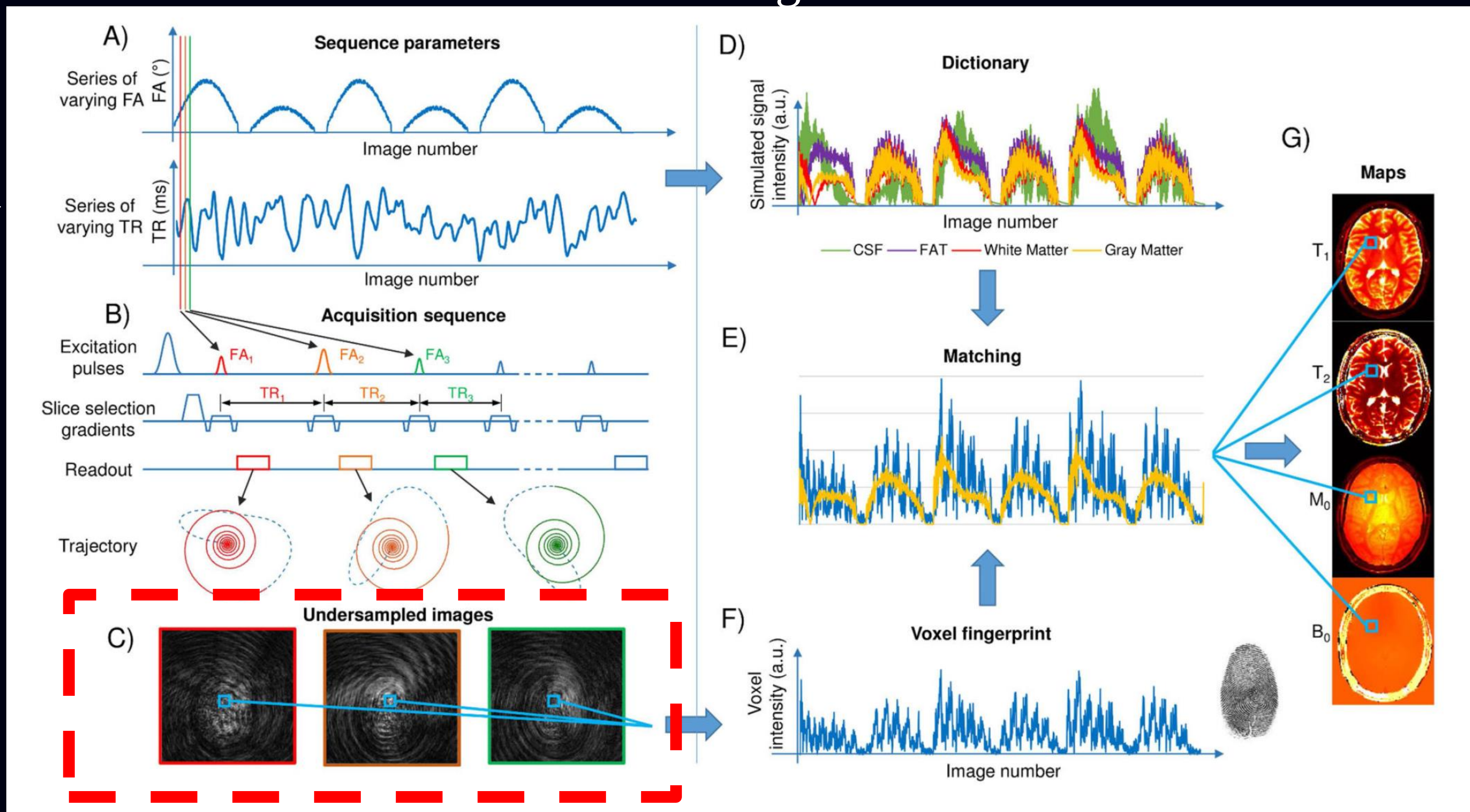
Aiming to synthesize ANY contrast sensitivity..
From partial acquisition of all possible contrasts

[Panda A, Mehta BB, Coppo S, et al. Magnetic Resonance Fingerprinting-An Overview. *Curr Opin Biomed Eng*. 2017;3:56-66]

Pre-Acquired Dictionary of signals from different tissues

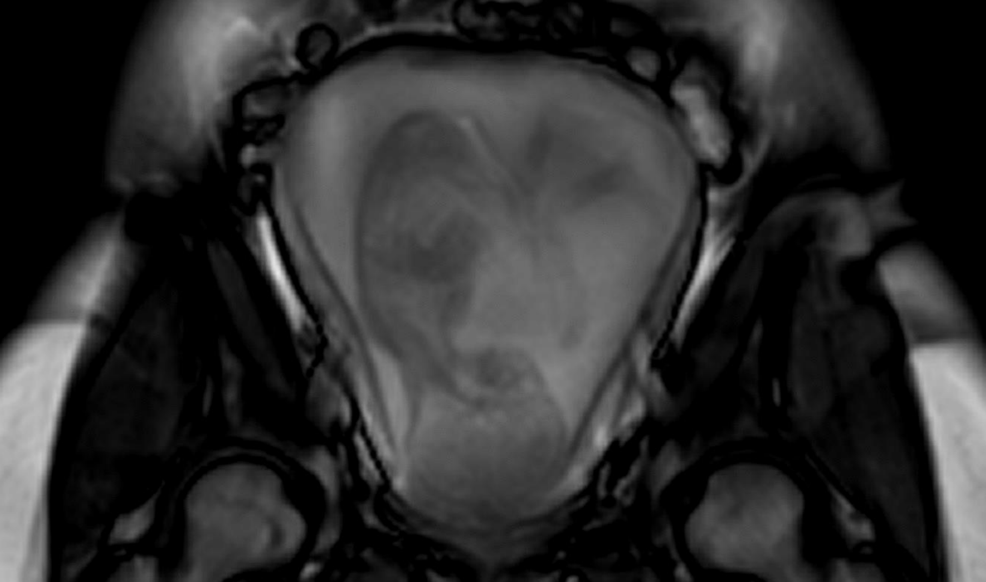
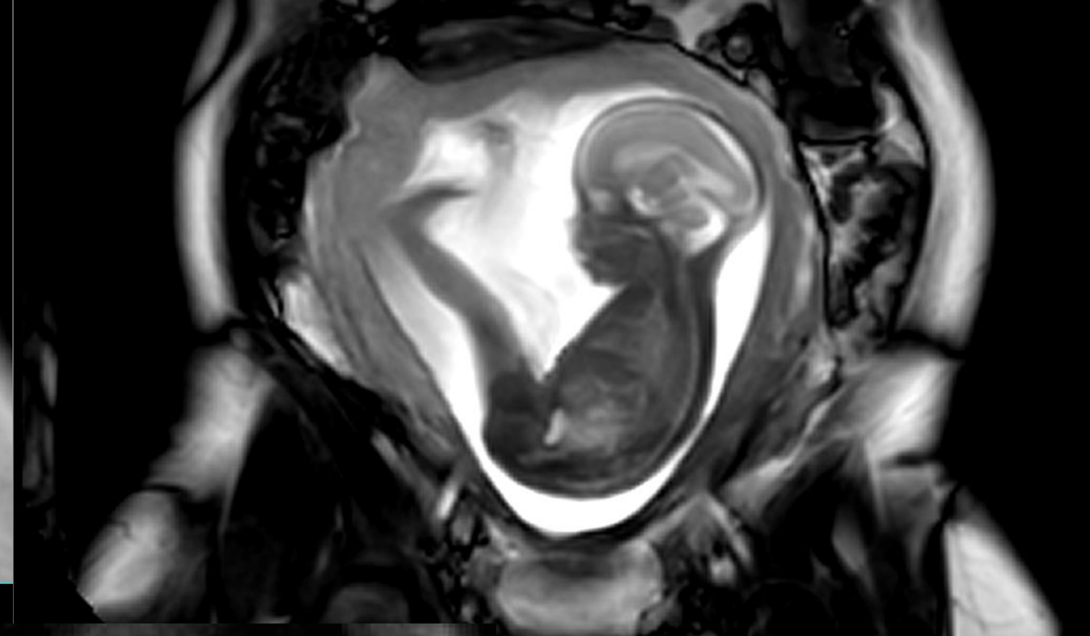
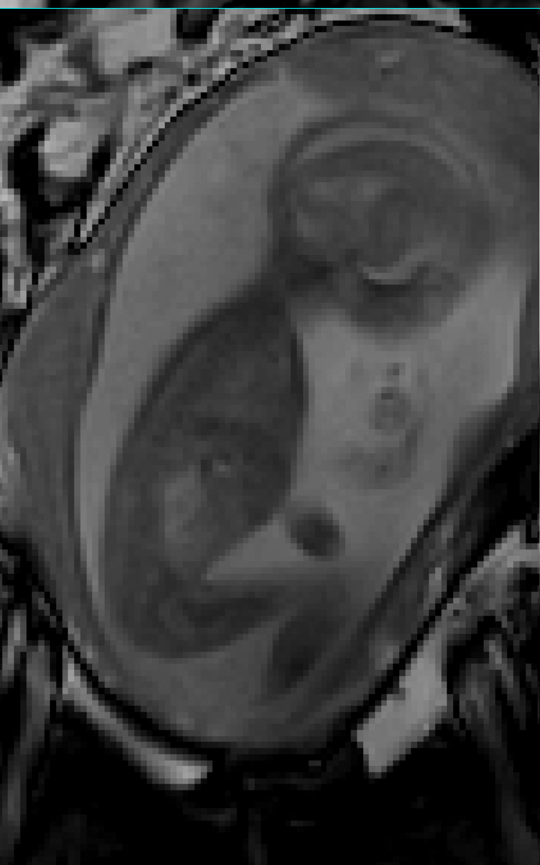
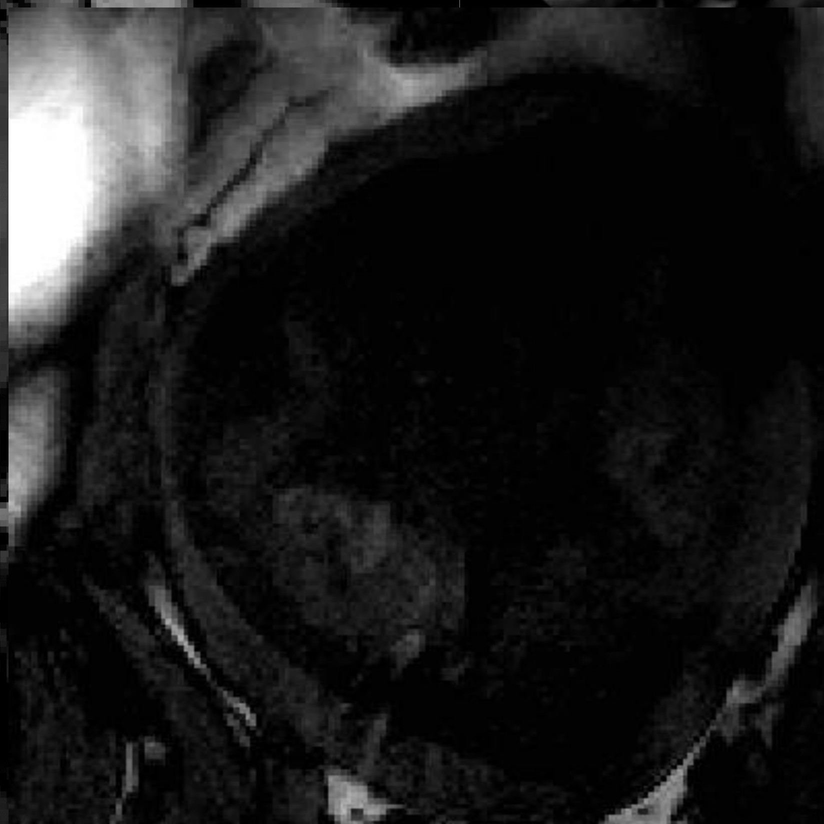
Flip Angles

Repetition Times



Create Images of ANY MRI Tissue Property..
T1 relaxation
T2 relaxation
Etc..

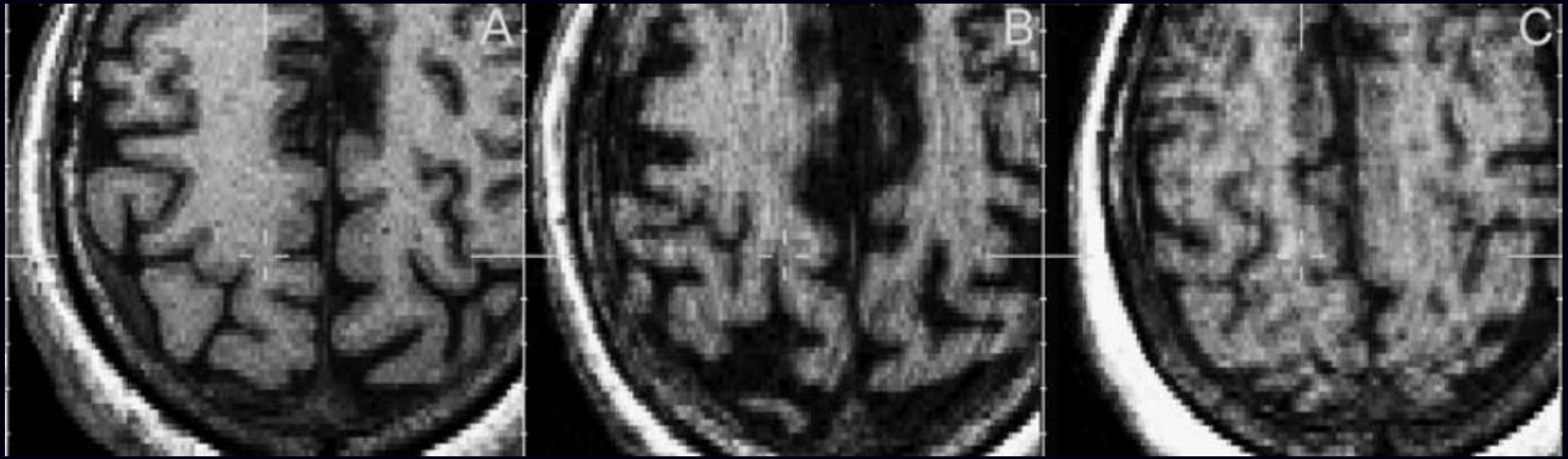
Fetal Brain MRI


Fetal MRI vs Adult MRI

- Adults (generally) can be told to remain still during an MRI study
- Fetuses move and (generally) respond less well to requests than adults
  - Smaller fetuses have more space and move more
- Typical 3D adult structural MRI scans take 2-12min
  - Motion artifacts occur if head motion during study
- To acquire full 3D MR image during motion without significant artifact:
  - whole study would have to take fraction of a second

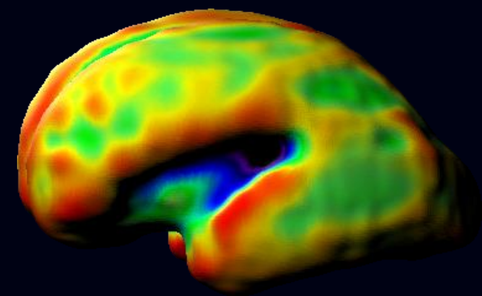
Adult 3D MR Imaging with varying motion artifact

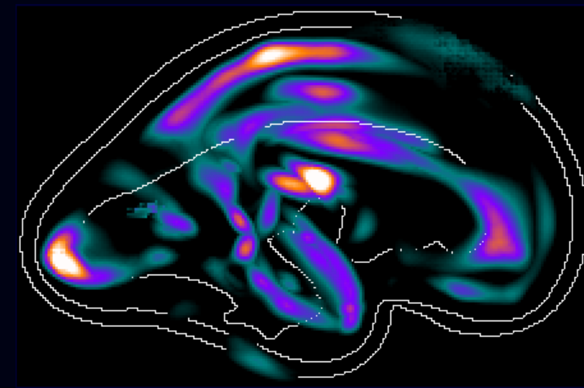


From Clinical Radiology To Quantitative Neuroscience

2D slices

3D Measures





– A Number of 3D Fetal Studies have used MR

- However often limited to studying a fraction of cases
  -> Where motion does not occur

– For realistic clinical use + research studies we need
  - data from **most** cases not **some** cases

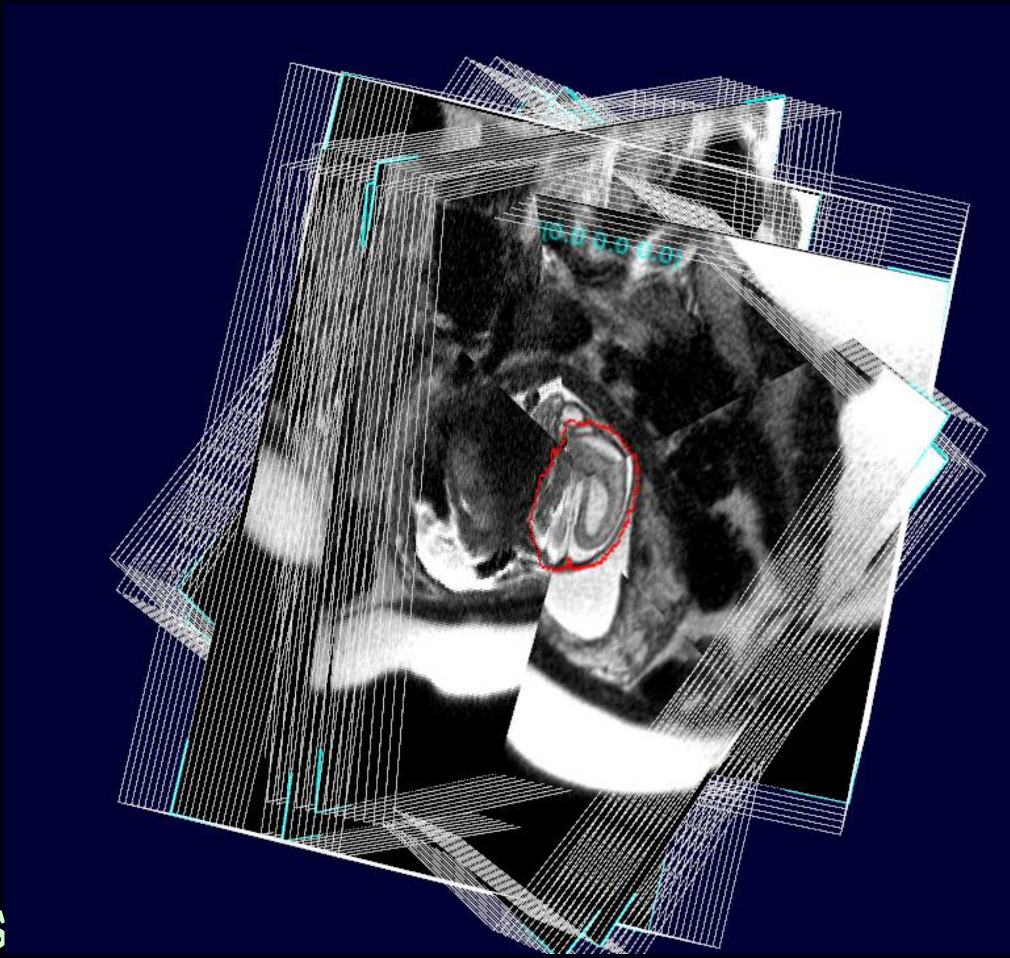
- Clinical 2D -> true 3D imaging data

Fetal MRI for 3D image Formation

- Acquire multiple 2D slices using
  - partial k-space acquisition
  - Parallel receiver coils (SENSE)

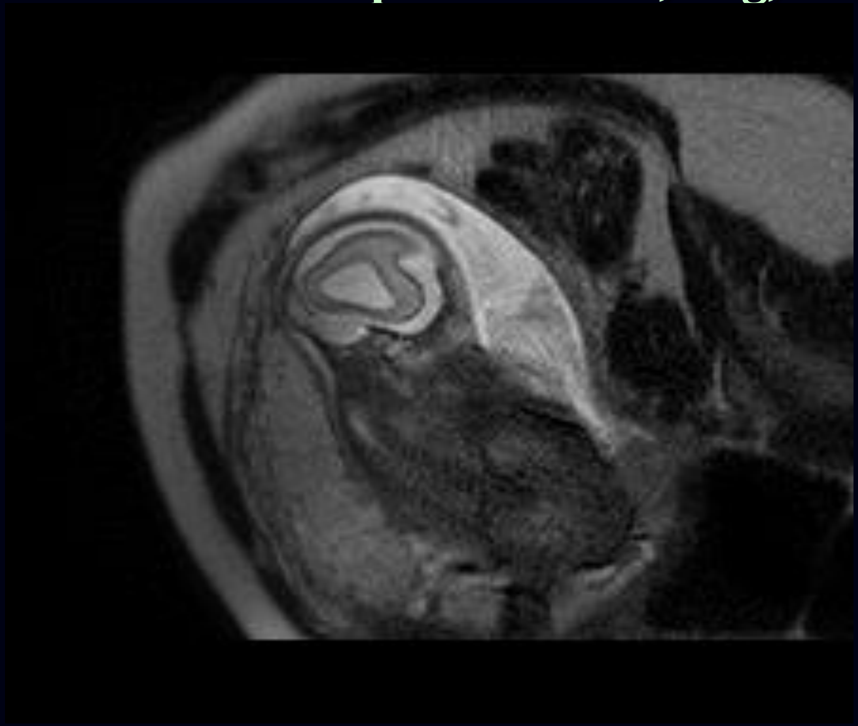
Increase speed and freeze motion in a slice.

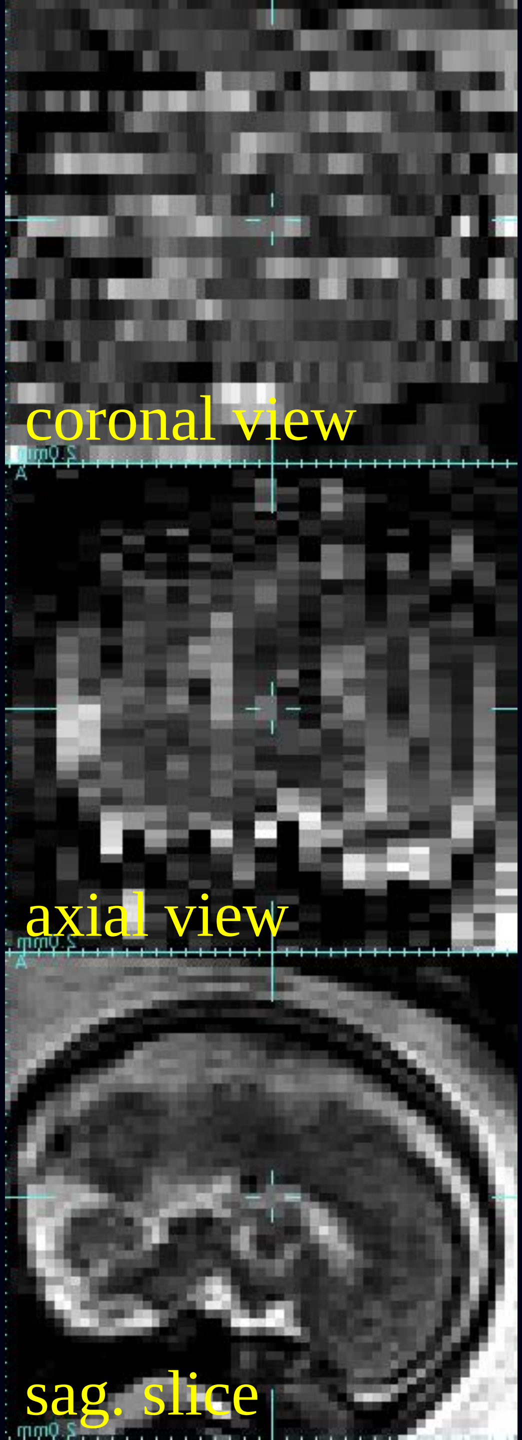
- Collect thick slices but in different anatomical planes
  - Provide high resolution in all 3 spatial dimensions.



Example Slice Images

- **T2W Multi Slice**
  - Single shot fast spin echo (SSFSE; 2D)
  - T2 weighted
  - TR = 4500 ms, TE = 90 ms
  - Approximately 1x1x3 mm^3 voxel dimension
  - 15~30 slices in each stack
- **Anisotropic resolution with thick slices**
- **Often Acquired using Real Time Planning tools**
- **Multiple Slice stacks Acquired: Axial, Sag, Coronal**

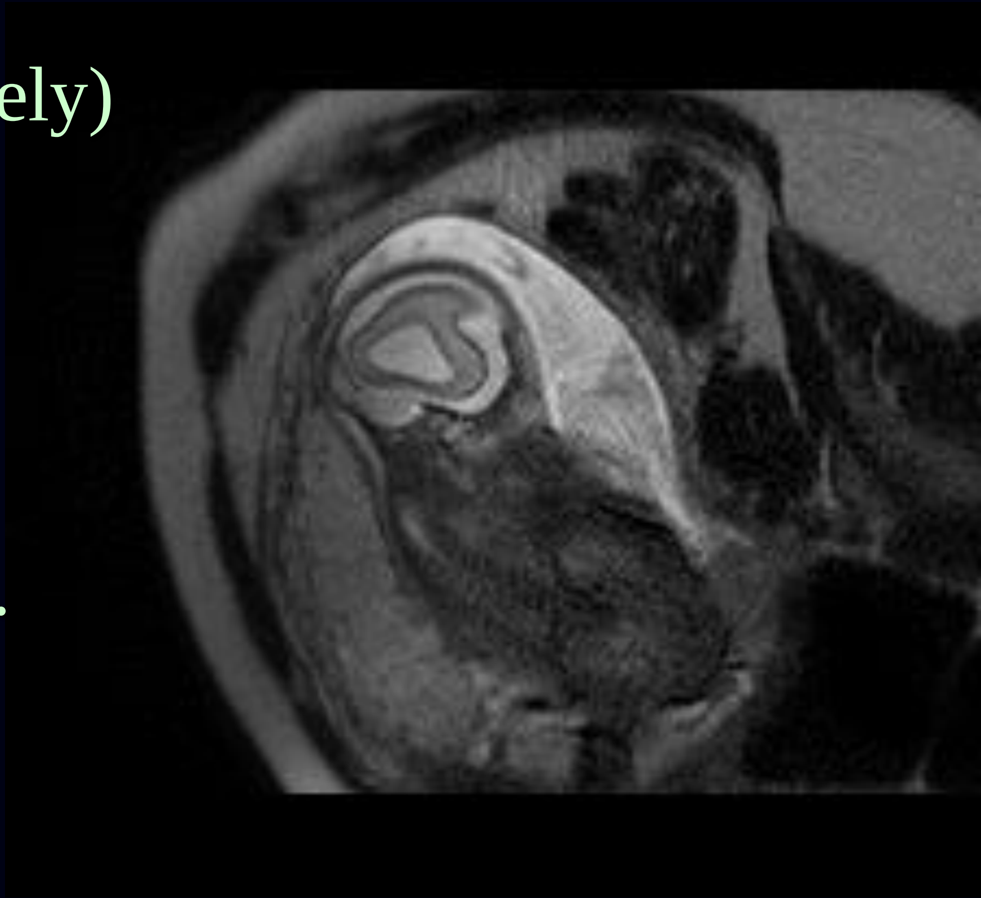




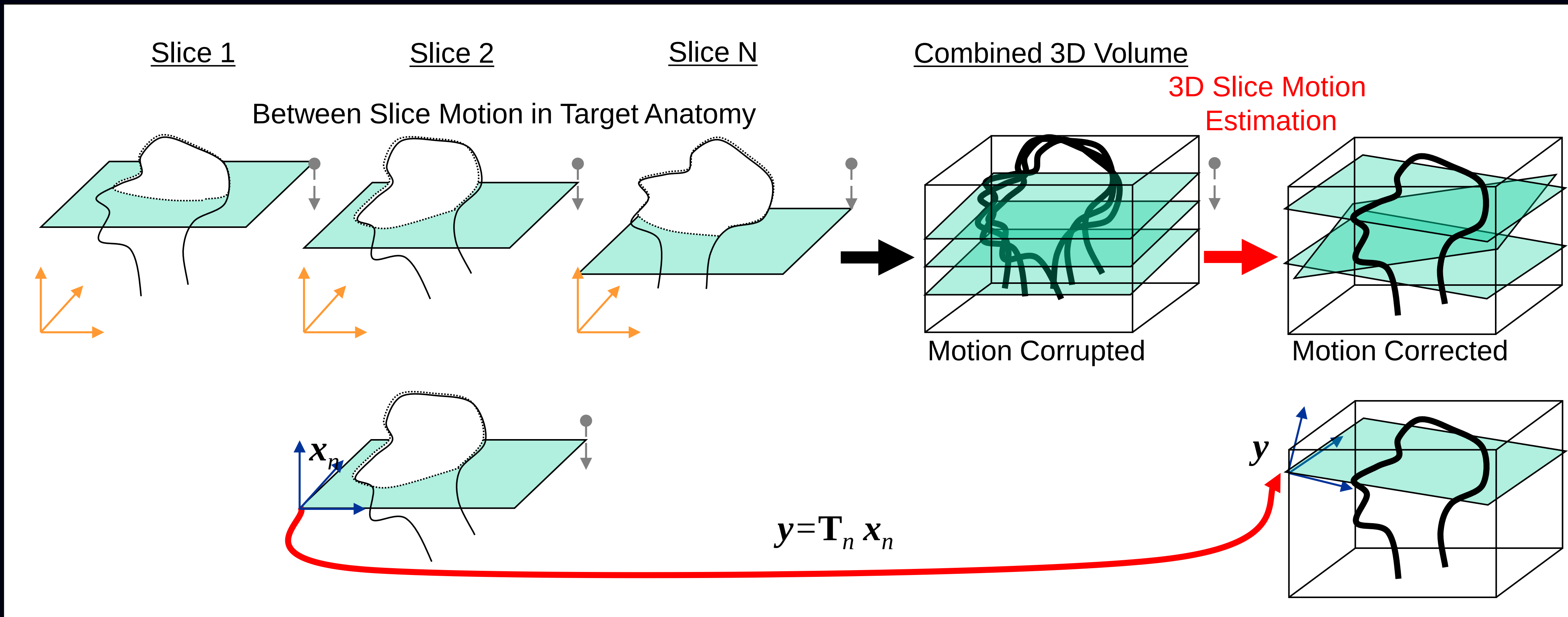
Object Motion Correction not **Whole Image** Motion Correction

- Object of Interest Moving within
  Surrounding Tissues during scan
- Object moving rigidly (approximately)
- Surrounding tissues/fluids
  Deforming/flowing
- Motion Within Slice Frozen
  Small % of corrupted slices
- Between Slice: Full 3D rot. + trans.
  significant fraction of object size
  (unlike eg cardiac motion)
- Motion is not repetitive

  But can be continuous (inc maternal breathing, heart)

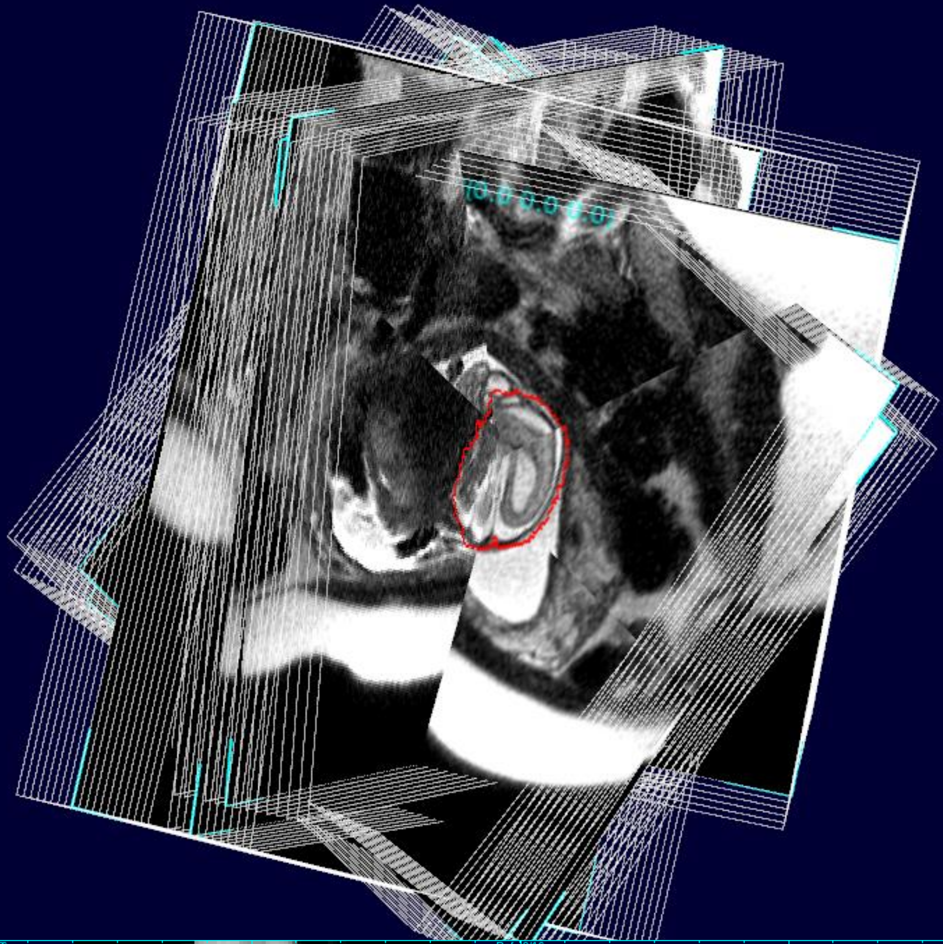


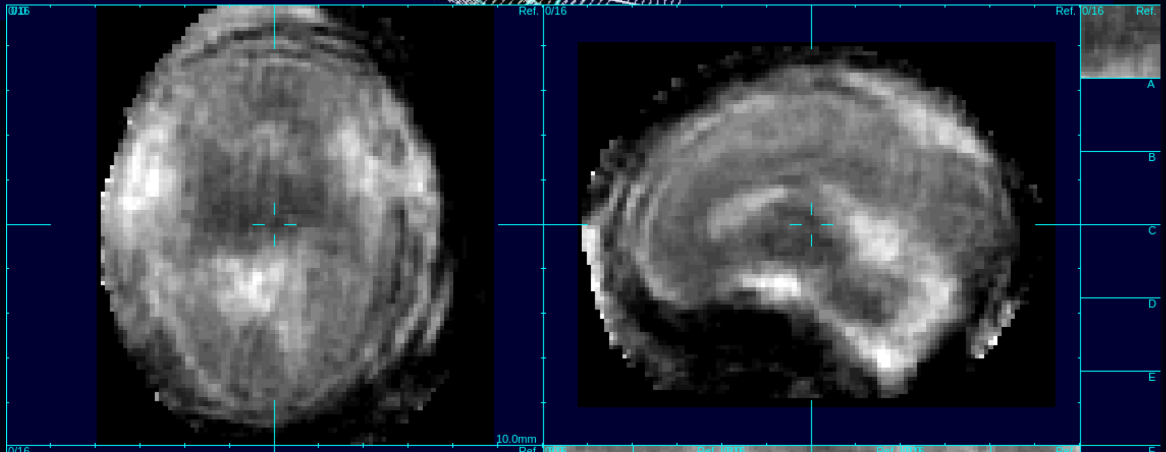
Combining fast MRI with Computer Vision: Building a volume image from component parts (slices)



$\mathbf{T}_n(t_x, t_y, t_z, \theta_x, \theta_y, \theta_z)$

6 rigid transformation parameters estimated for EACH SLICE….
Large set of numbers..





3D MRI during Motion:

Fast 2D Imaging

+ 2D->3D Mosaicing

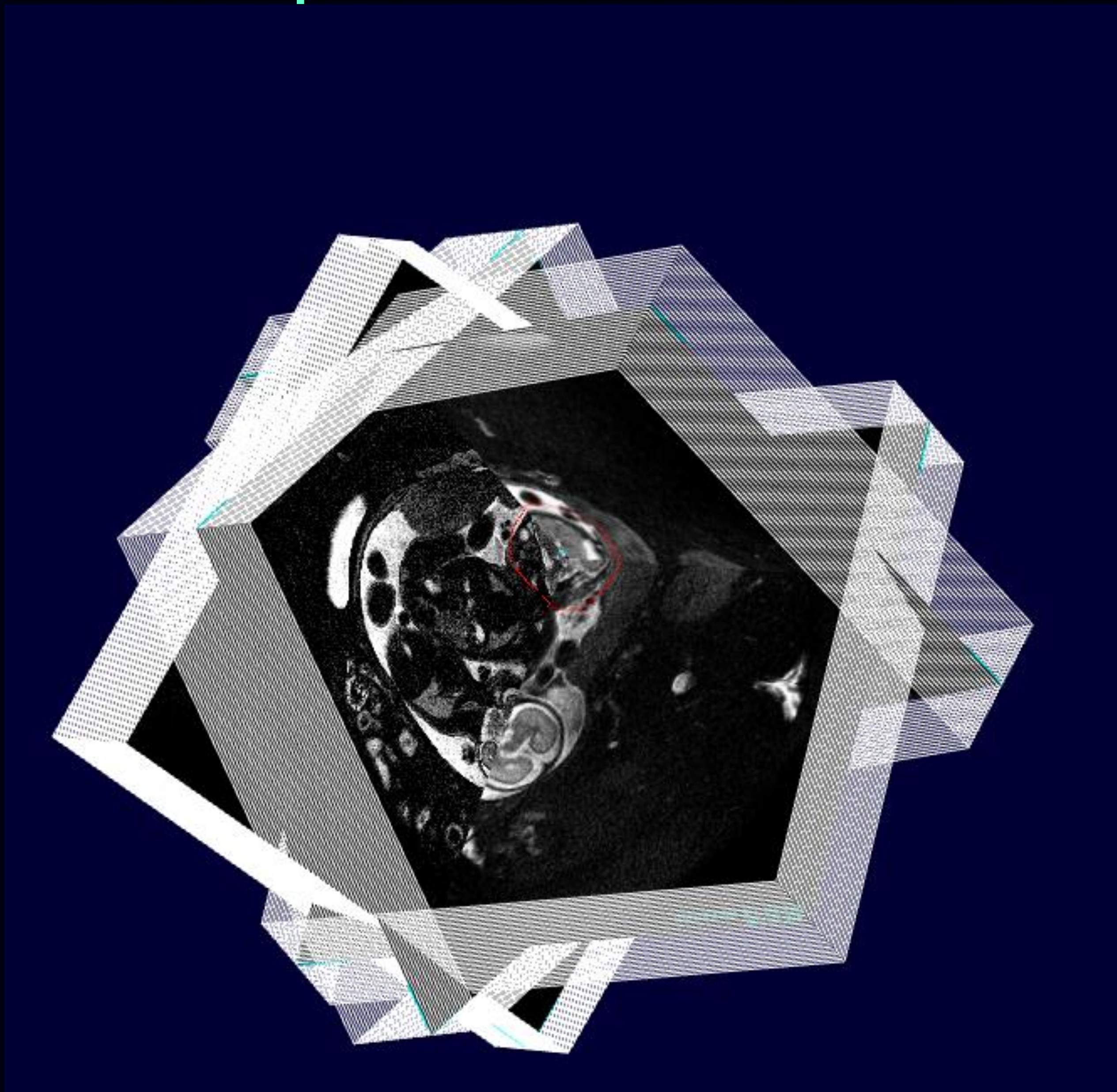
Reconstruction based:

- Rousseau et al [MICCAI 2005]
- Jiang et al [TMI 2007]

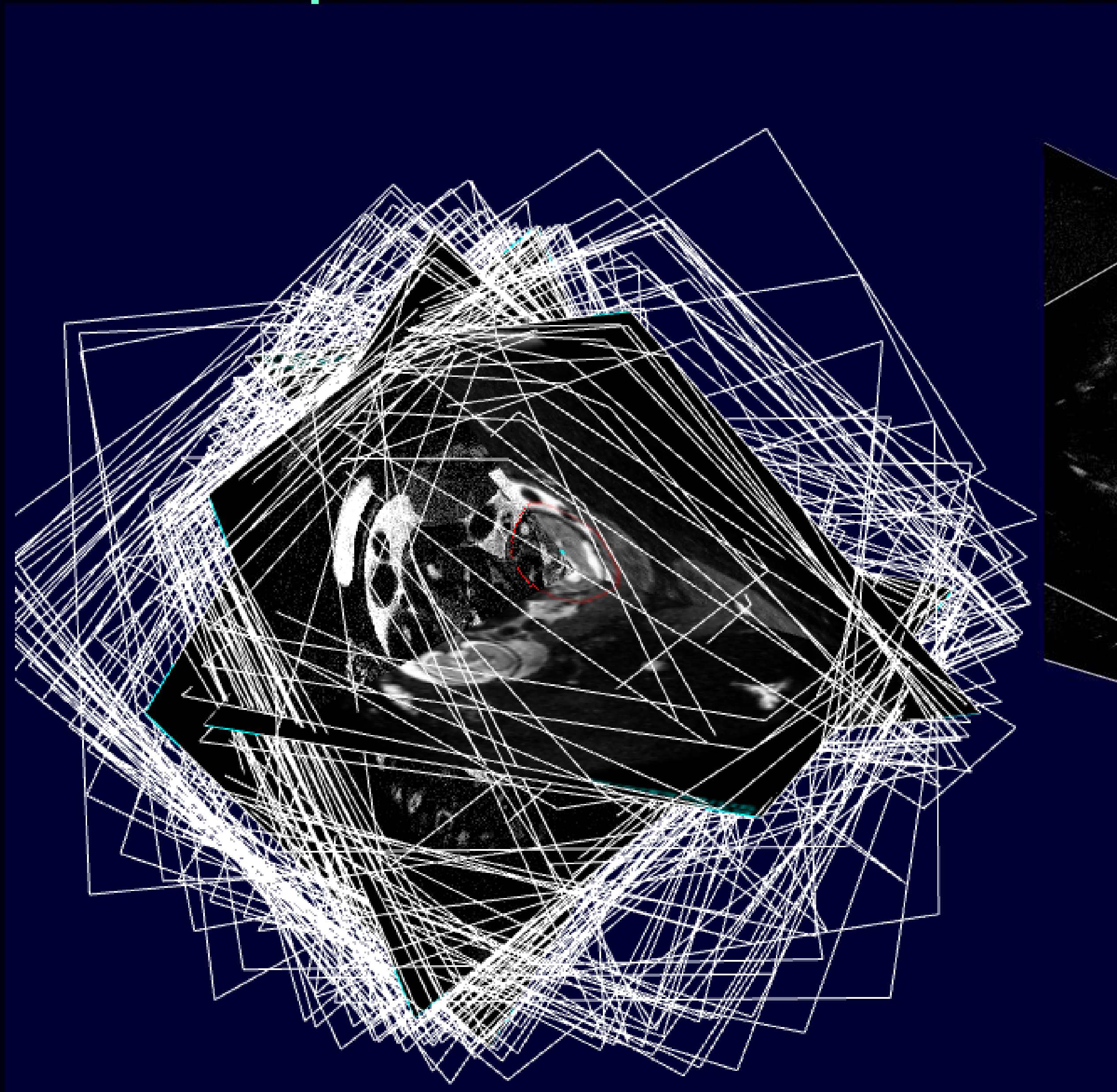
Intersection based:

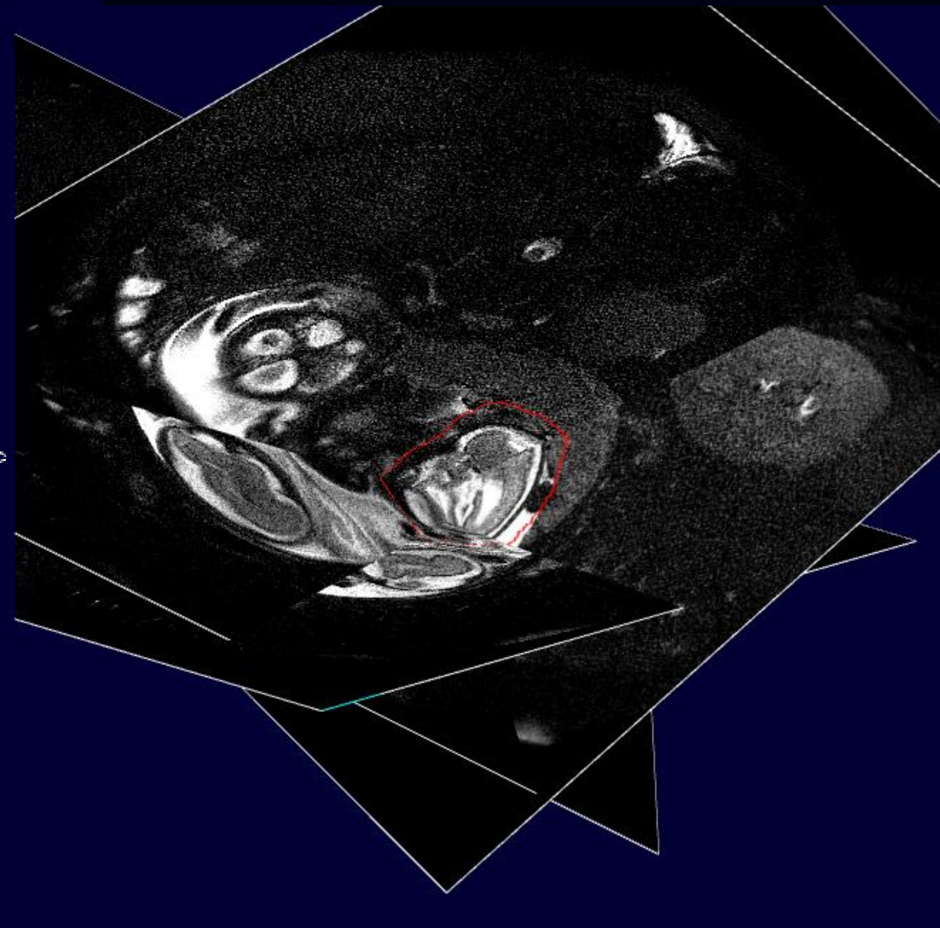
- Kim et al [TMI 2010]

Example Extreme Motion Recovery

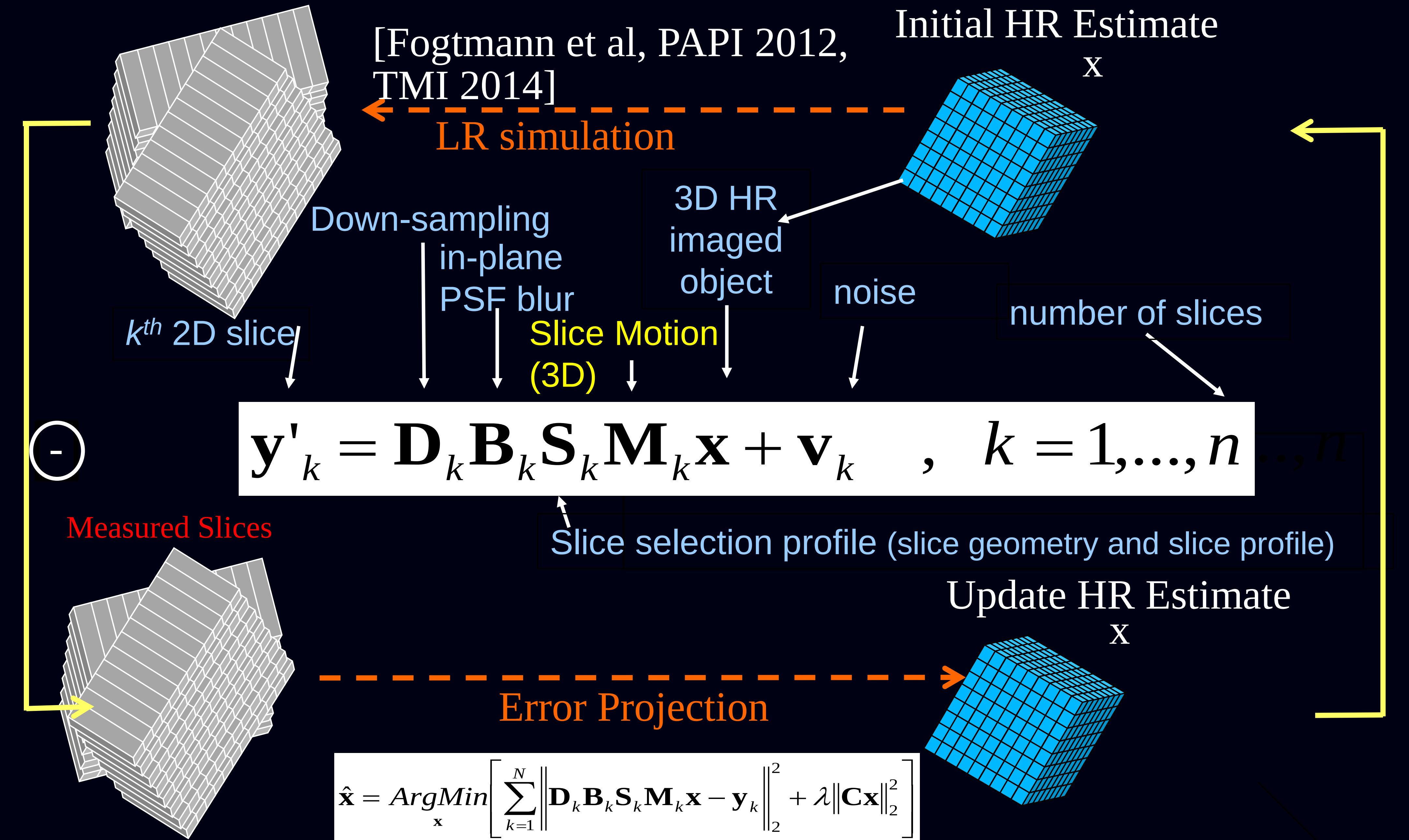


Example Extreme Motion Recovery





Iterative 3D reconstruction



$$\mathbf{y}'_k = \mathbf{D}_k \mathbf{B}_k \mathbf{S}_k \mathbf{M}_k \mathbf{x} + \mathbf{v}_k \quad , \quad k = 1, \ldots, n$$

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

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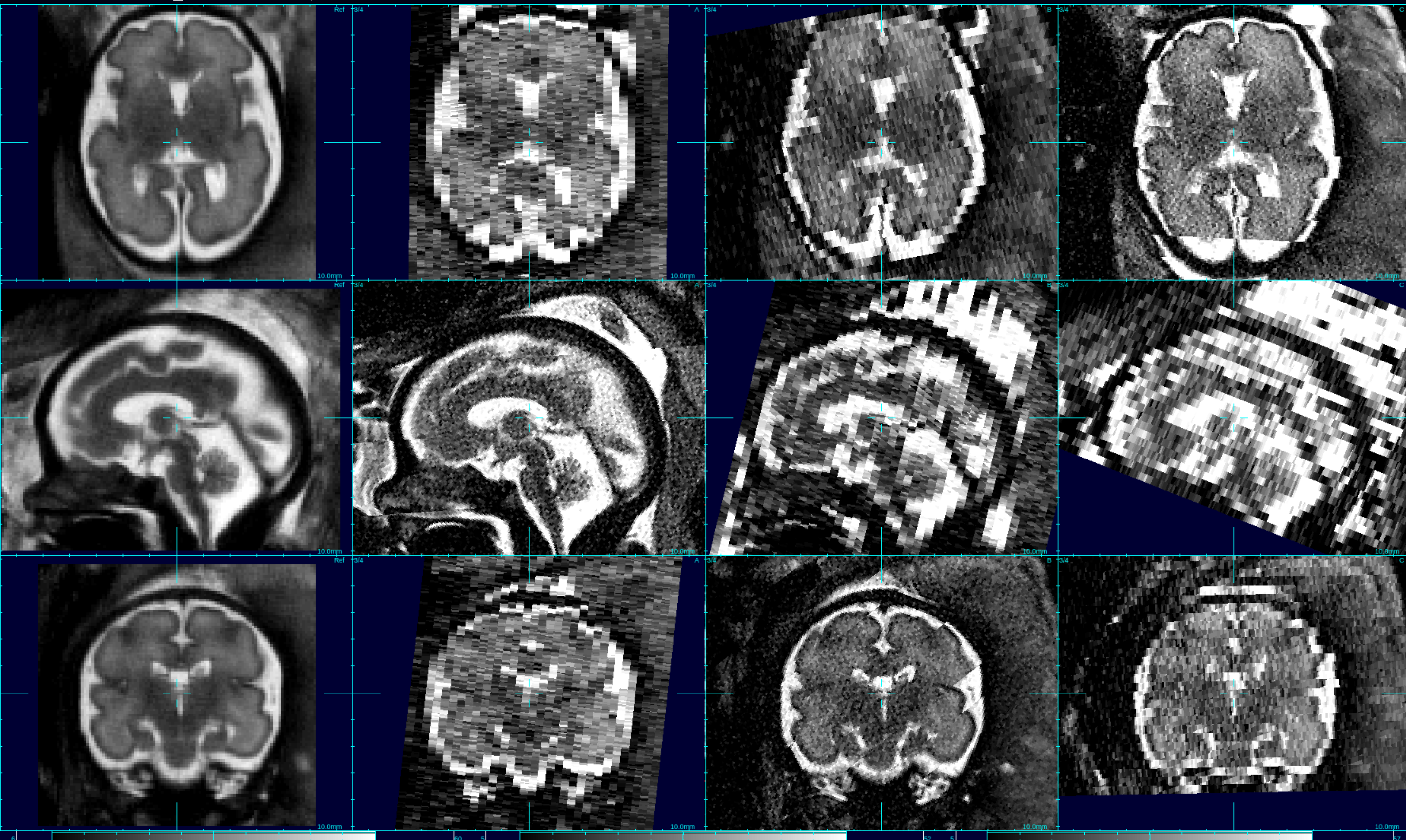
Combined Volume (interpolation) | Slice Stack 1 | Slice Stack 2 | Slice Stack 3



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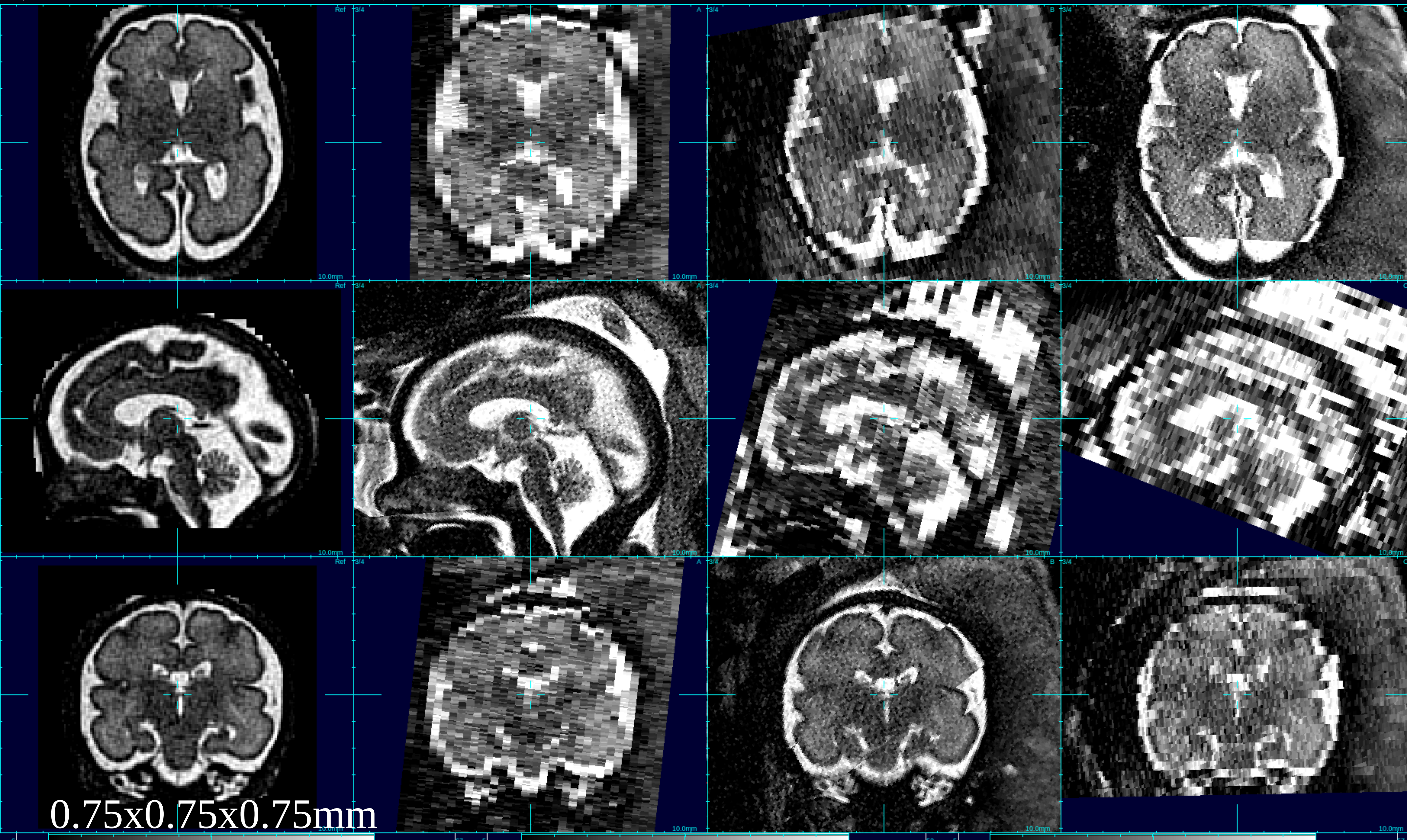
Combined Volume (robust deconvolution)

Slice Stack 1

Slice Stack 2

Slice Stack 3



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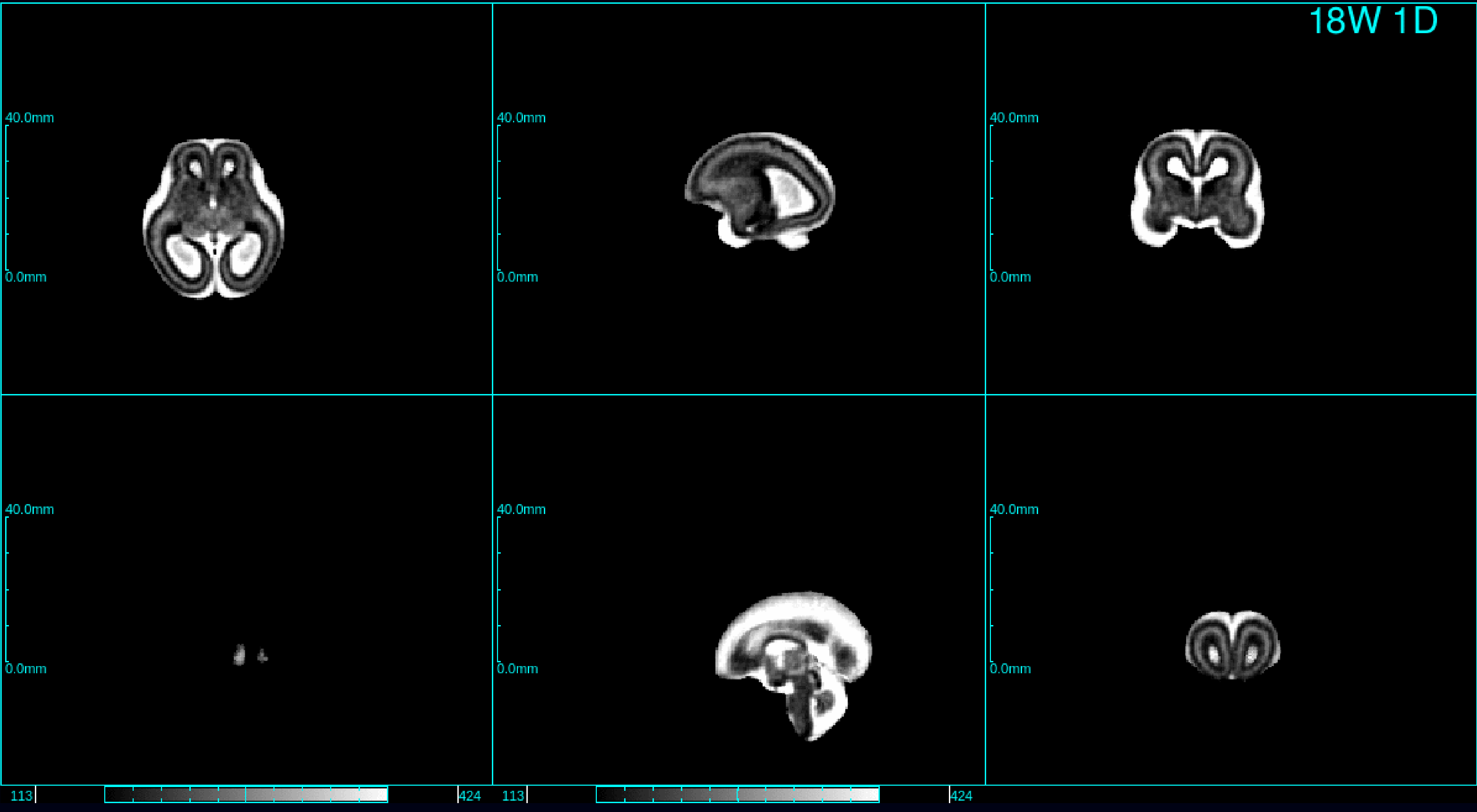
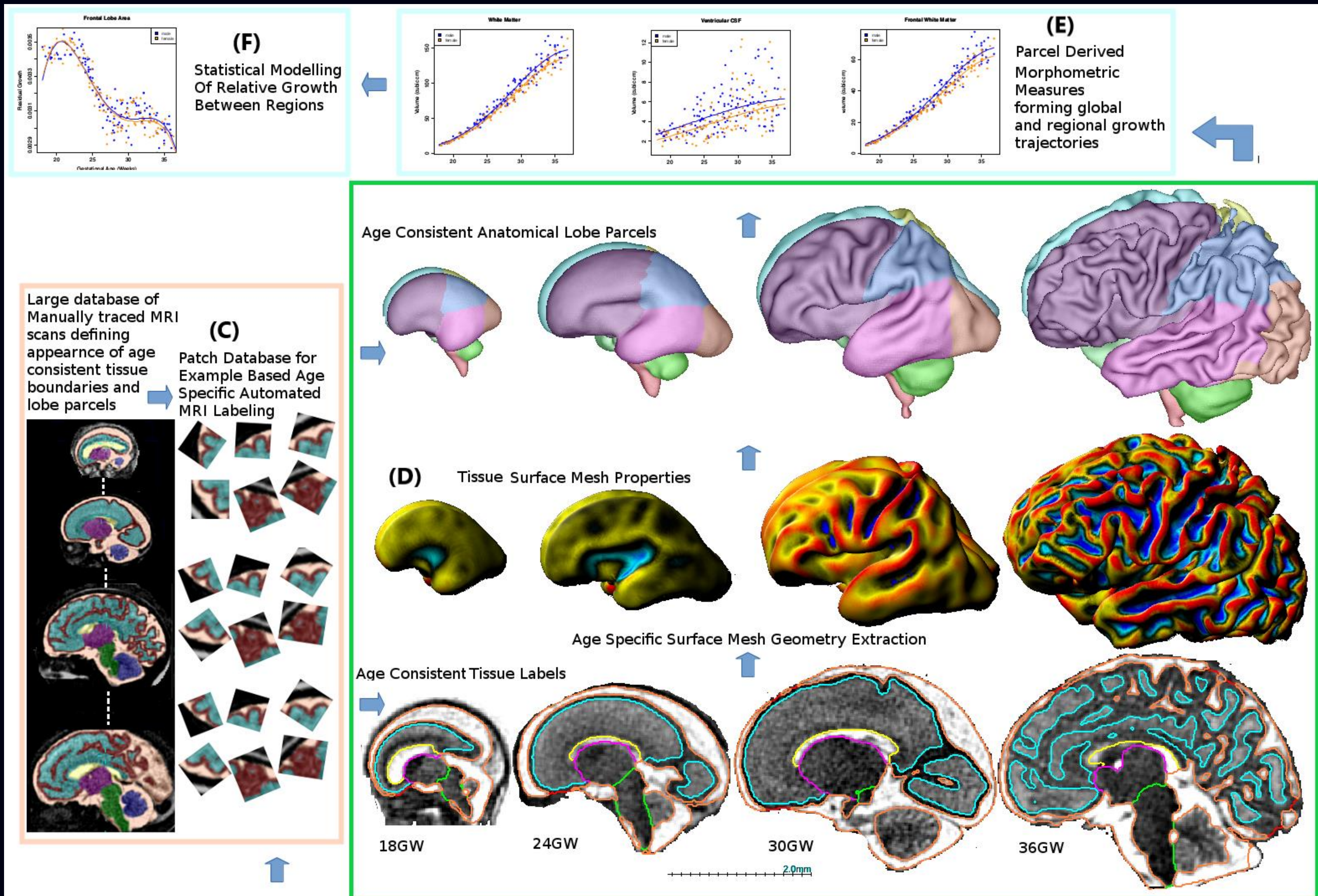
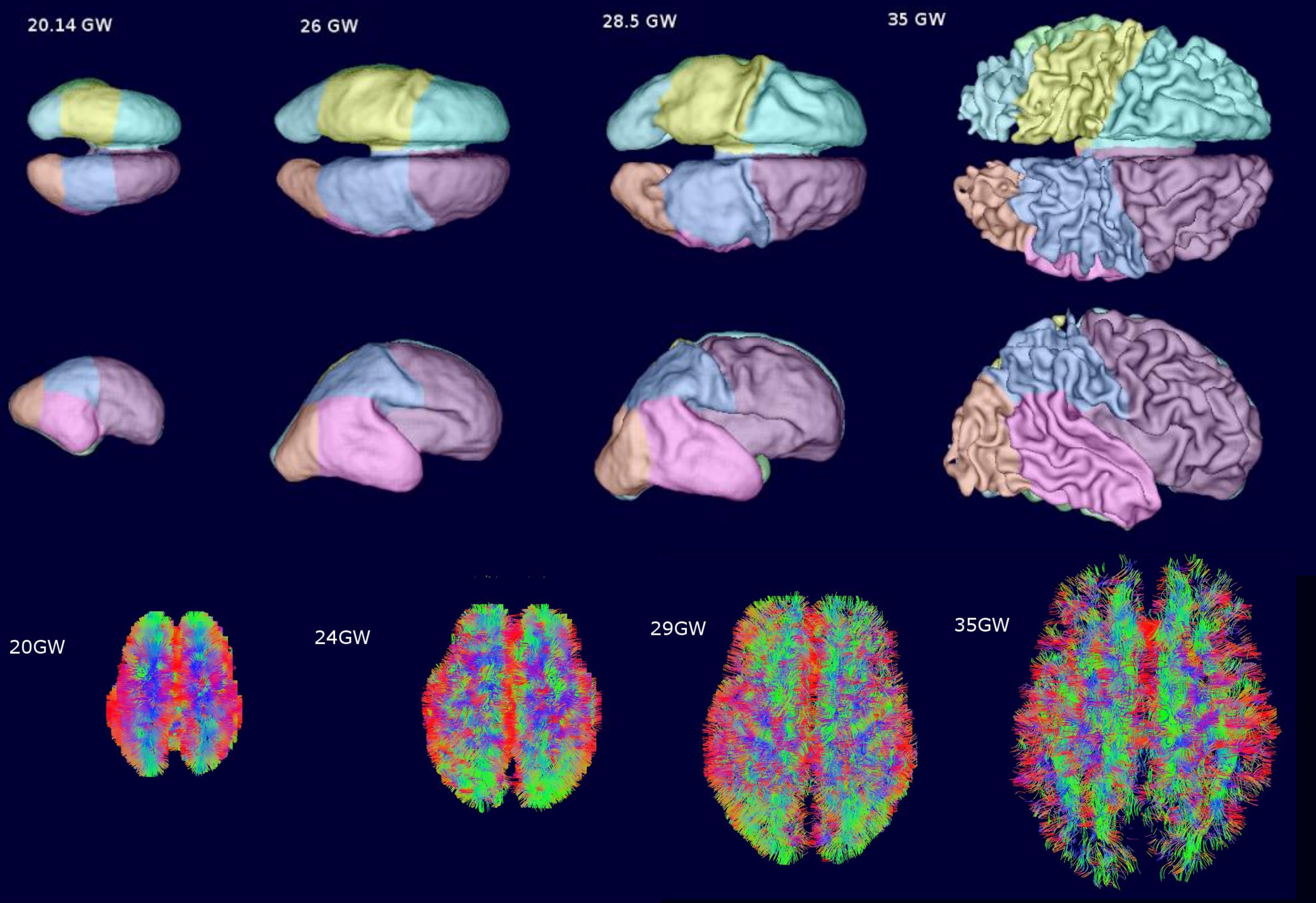
Daily Brain Growth Derived from 246 Fetal Brain Scans 18-36GW




(F)
Statistical Modelling
Of Relative Growth
Between Regions
Frontal Lobe Area
White Matter
Ventricular CSF
Frontal White Matter
(E)
Parcel Derived
Morphometric
Measures
forming global
and regional growth
trajectories
Age Consistent Anatomical Lobe Parcels
Large database of
Manually traced MRI
scans defining
appearnce of age
consistent tissue
boundaries and
lobe parcels
(C)
Patch Database for
Example Based Age
Specific Automated
MRI Labeling
(D)
Tissue Surface Mesh Properties
Age Specific Surface Mesh Geometry Extraction
Age Consistent Tissue Labels
18GW
24GW
30GW
36GW
2.0mm


20.14 GW
26 GW
28.5 GW
35 GW
20GW
24GW
29GW
35GW

Progression of Fetal MRI brain studies

- 2007-2012
  - Motion correction of clinical radiology imaging with additional acquisitions
  - Initial smaller scale studies of (clinically) normal brain development (~20-50 scans)
- 2012-present
  - Development and Use of more quantitative Neuroscience specific: computational imaging protocols
  - More robust, fine scale and automated image reconstruction and analysis pipelines
  - Large scale (Many 100’s scans) + Longitudinal imaging studies in volunteer pregnancies

Some Recent papers using Computational Fetal MRI techniques

- Waldorf, Kristina M Adams, Nelson, Branden R, Stencel-Baerenwald, Jennifer E, Studholme, Colin and Kapur, Raj P, Armistead, Blair, Walker, Christie L, Merillat, Sean, Vornhagen, Jay, Tisoncik-Go, Jennifer et al," Congenital Zika virus infection as a silent pathology with loss of neurogenic output in the fetal brain", Nature medicine,2018,

- Xiaojie Wang, Verginia C. Cuzon Carlson, Colin Studholme, Natali Newman, Matthew M. Ford, Kathleen A. Grant, and Christopher D. Kroenke, In utero MRI identifies consequences of early-gestation alcohol drinking on fetal brain development in rhesus macaques, Proceedings of the National Academy of Science of the United States of America, 117(18), May 2020,

- C. Studholme, C Kroenke, M. Dighe, Motion corrected MRI differentiates male and female human brain growth trajectories from mid-gestation, Nature Communications, 11, 3038, June 2020.