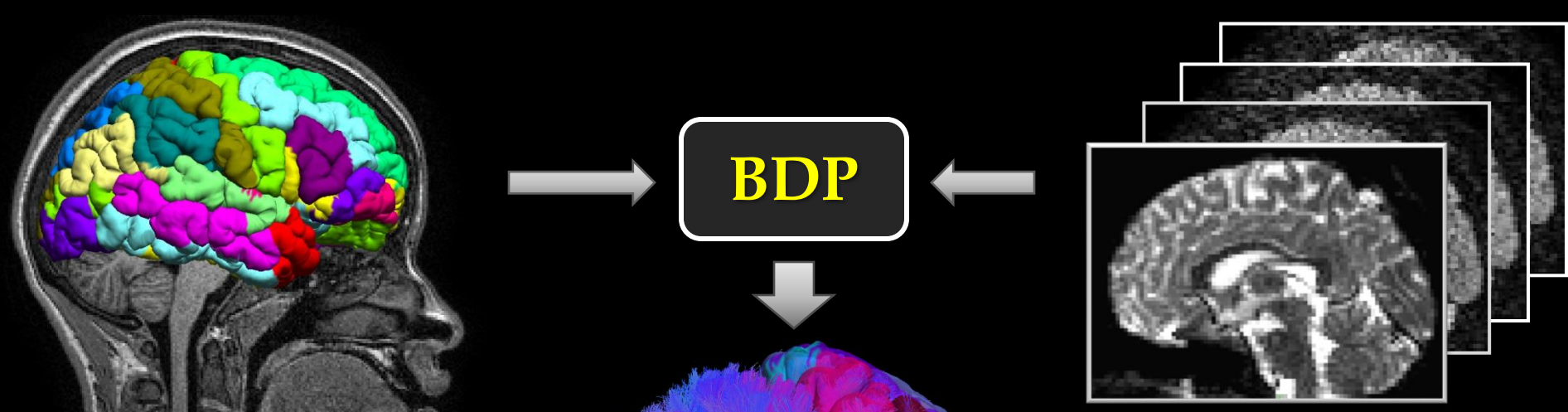


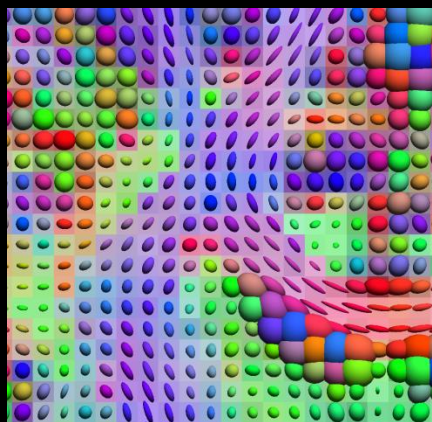
BDP: BrainSuite Diffusion Pipeline

Chitresh Bhushan

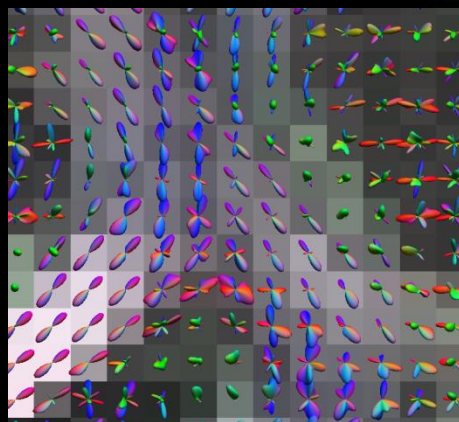


MPRAGE

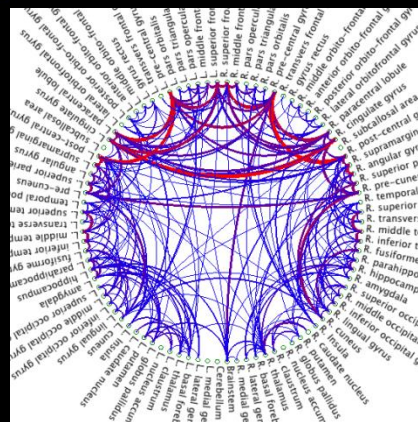
Diffusion dataset



Tensor



ODF

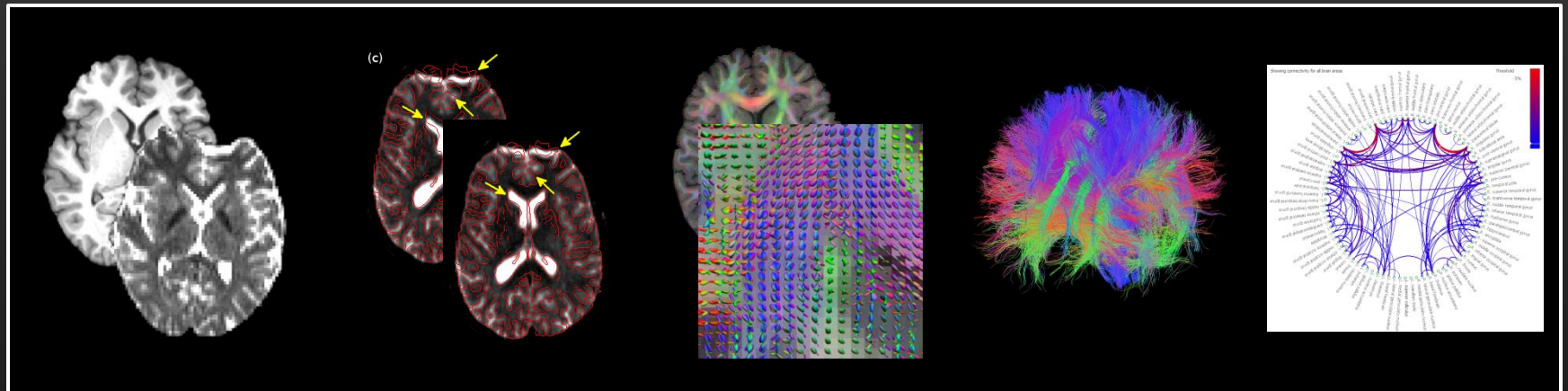


ROI Connectivity

	A	B	C	D
ROI_ID	Missing voxels	Mean (GM+WM)	Var (GM+WM)	
120	2076	0.193647623	0.157876641	
121	939	0.202837408	0.165470749	
130	0	0.183879077	0.152853325	
131	0	0.173550412	0.1415150764	
140	0	NaN	NaN	
141	0	NaN	NaN	
142	0	0.193445236	0.157581672	
143	0	0.212929964	0.172584817	
144	0	0.178581178	0.141114518	
145	0	0.180468515	0.149058774	
146	0	0.19012776	0.151103929	
147	0	0.190880433	0.143366888	
150	805	0.228198722	0.184615031	
151	1173	0.223954752	0.184945568	

ROI Statistics

Diffusion Pipeline



T1/DWI
coregistration

distortion
correction

diffusion
modeling

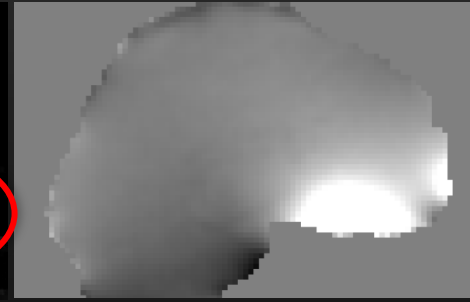
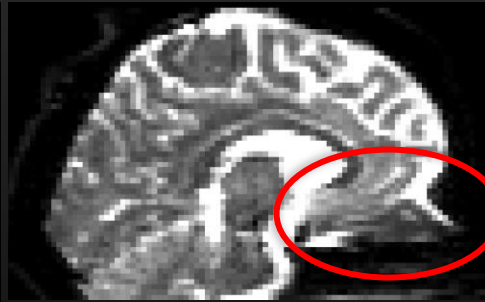
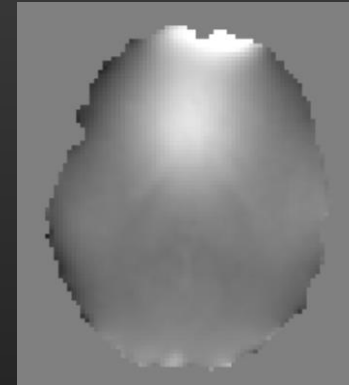
whole-brain
tractography

connectivity
analysis

Command line tool
(bdp.exe / bdp.sh)

BrainSuite GUI

EPI distortion



MPRAGE image

b=0 image (EPI)

Field inhomogeneity map

- Diffusion MRI uses fast acquisition – Echo planar Imaging (EPI)
- Susceptibility differences \Rightarrow Magnetic field (B_0) inhomogeneity
- EPI is sensitive to B_0 inhomogeneity \Rightarrow Localized geometric distortion

Distortion correction in BDP

1. Registration based

- Uses structural image to estimate distortion field
- Does not require any field inhomogeneity map

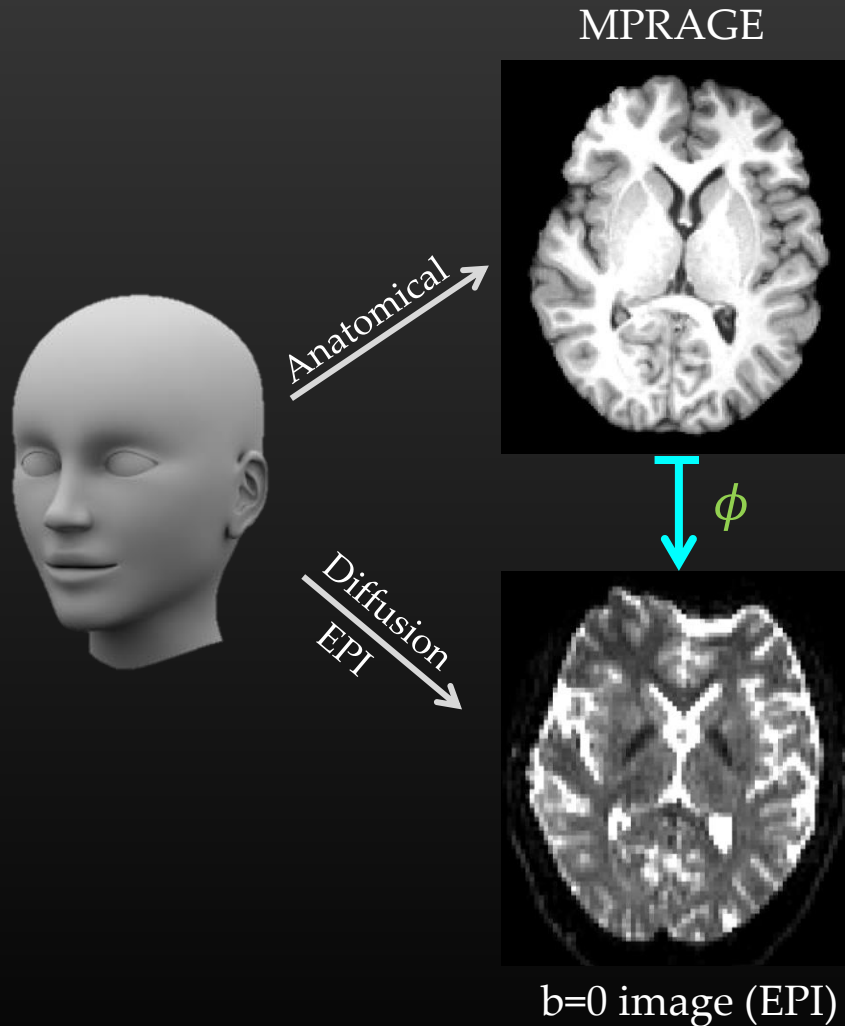
2. Fieldmap based

- Requires field inhomogeneity map
- Lower computational requirement

3. No distortion correction

- Only Rigid registration to MPRAGE
- Useful when some different technique is used for distortion correction

Registration based framework



Estimate deformation map ϕ

- Aligns MPRAGE and b=0 image
- Follows physics of EPI distortion
- Mutual-information based non-rigid registration

$$\phi : X_a \mapsto X_{\text{epi}}$$

$$\hat{\phi} = \arg \min_{\phi} \left(-I(F_a; F_c) + \alpha \mathcal{R}(\phi) \right)$$

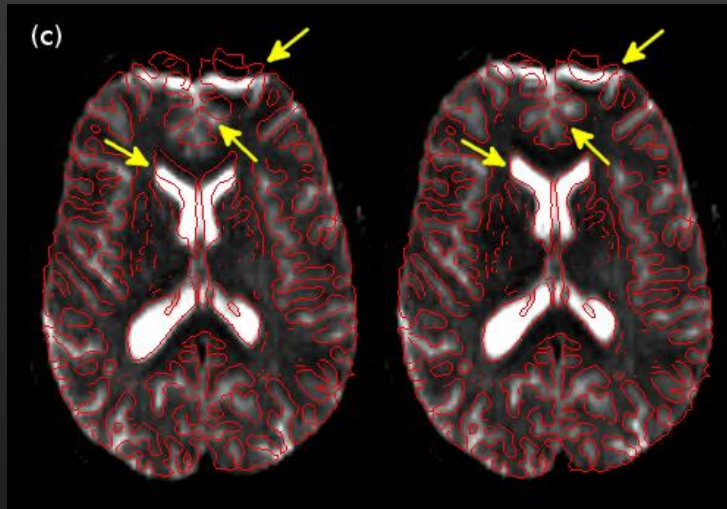
$$F_c(X_a) \approx F_{\text{epi}}(\phi(X_a)) \frac{\partial \phi_y(X_a)}{\partial y_a}$$

MPRAGE

Corrected Image

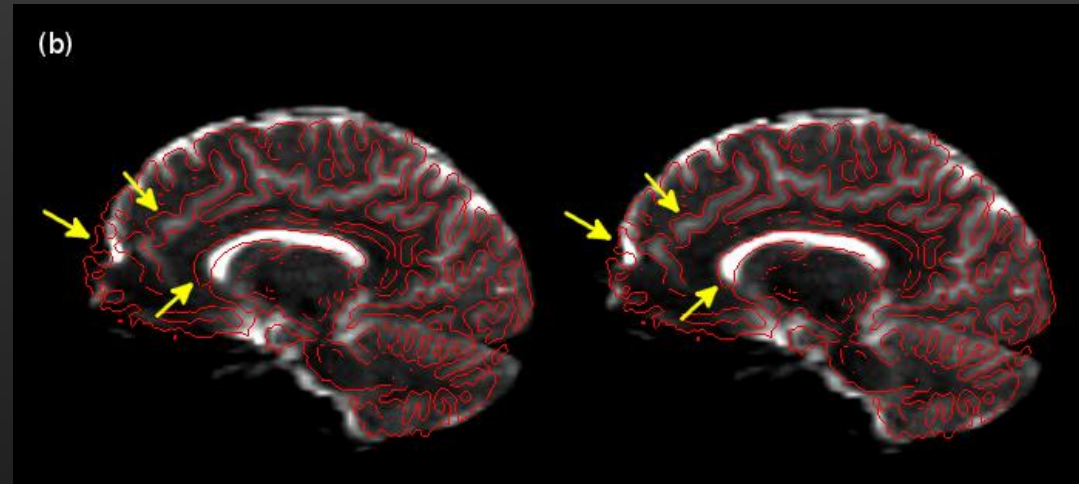
Normalized MI

Registration based correction



Before

After



Before

After

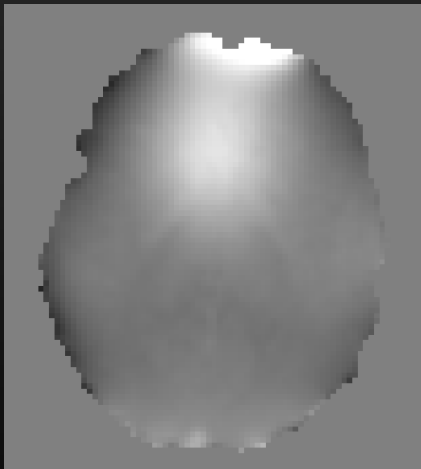
- No extra data (fieldmap) is required
- Similar performance to fieldmap method
 - Use anatomical information in images

Fieldmap based correction

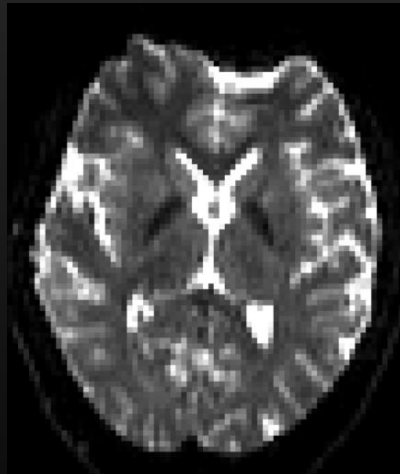
- Acquire the fieldmap $\Delta B_0(x, y)$

Deformation map $\rightarrow \phi_y = y + \frac{\Delta B_0(x, y) T_{es}}{G_y \tau}$ ← Echo spacing

Corrected Image $\rightarrow F_c(X_a) \approx F_{\text{epi}}(\phi(X_a)) \frac{\partial \phi_y(X_a)}{\partial y_a}$



Fieldmap



Distorted
image



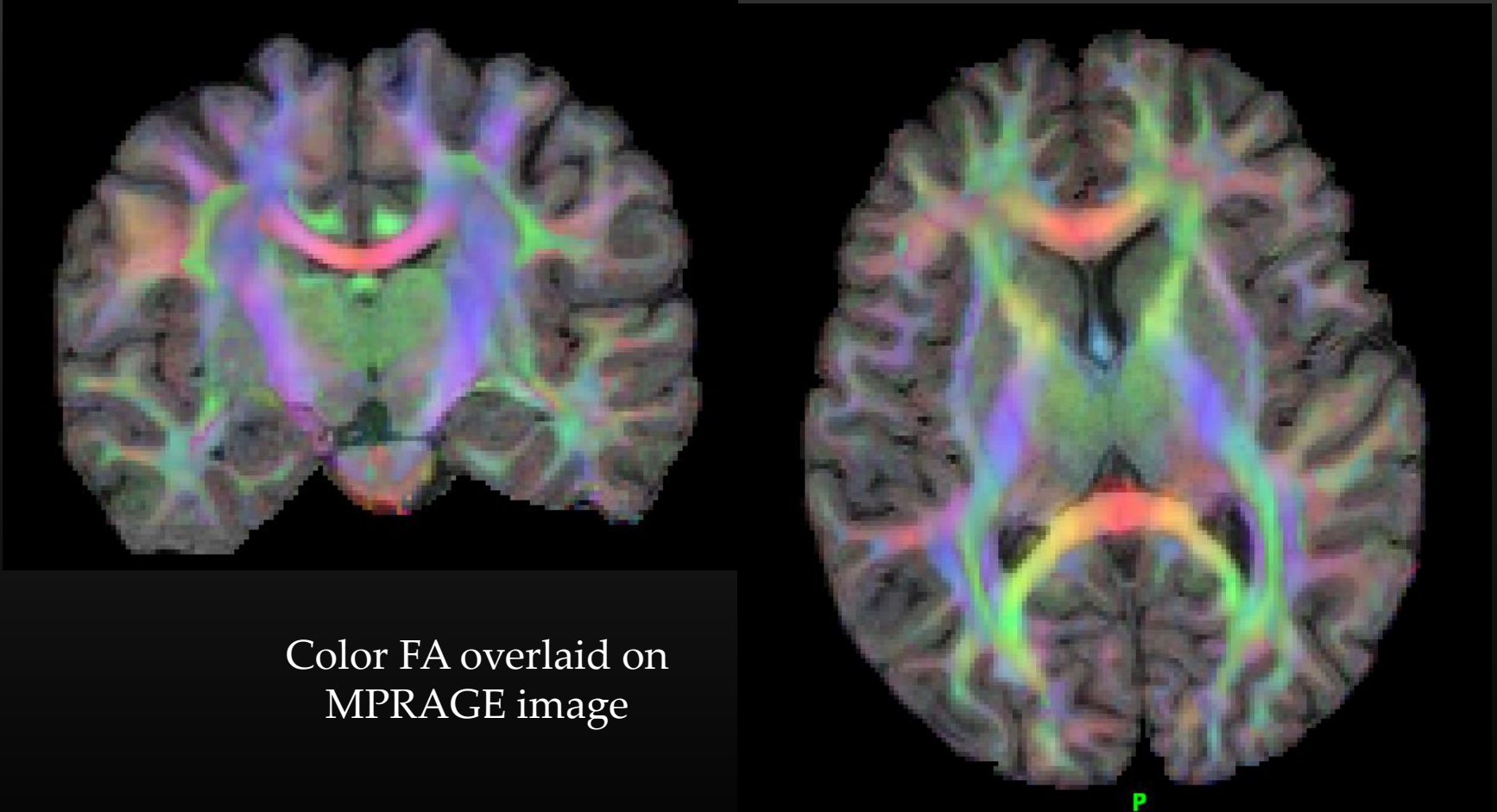
Corrected
image



MPRAGE

Co-registered output

- Accurate alignment after diffusion modelling



Color FA overlaid on
MPRAGE image

Syntax

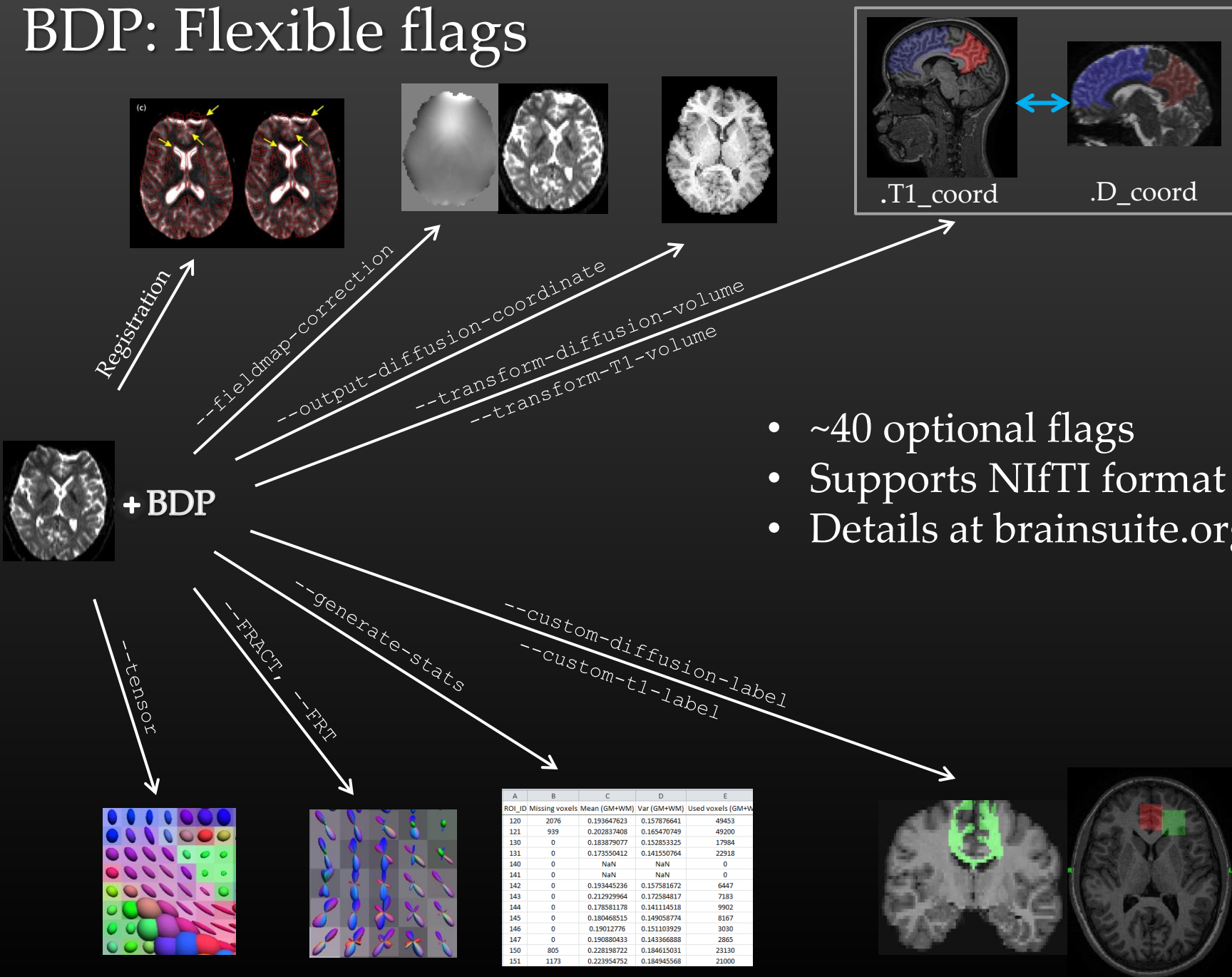
NIfTI input (.nii or .nii.gz)

```
bdp.sh <BFC File> [Optional Flags] --nii <4D DWI NIfTI>  
--bvec <Gradient file> --bval <b-value file>
```

Example

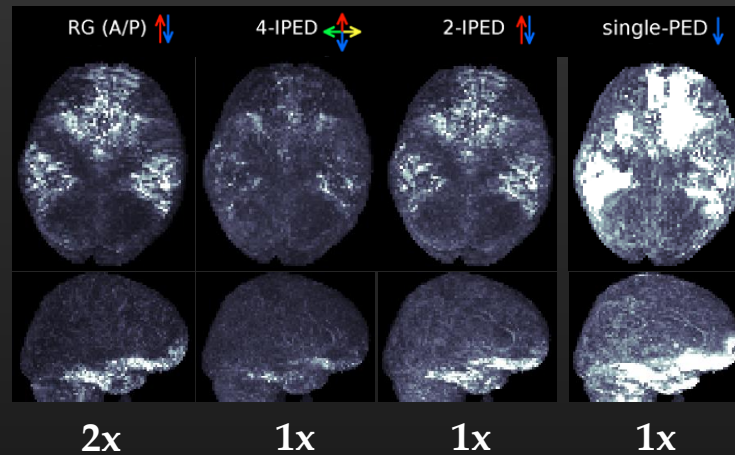
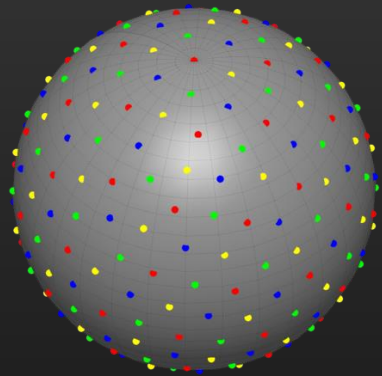
```
bdp.sh 2467264.bfc.nii.gz --tensor --odf  
--nii 2467264.dwi.nii.gz --bvec 2467264.dwi.bvec  
--bval 2467264.dwi.bval
```

BDP: Flexible flags

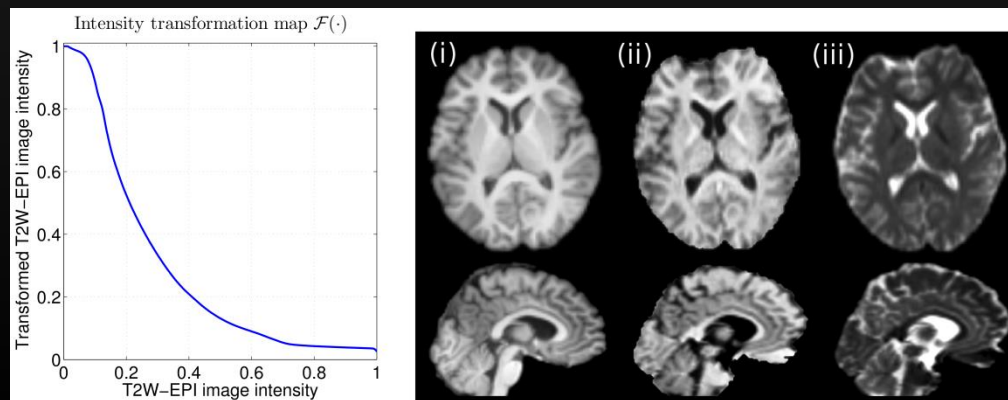


More...

- Interleaved Phase encoding (Bhushan et al. 2013)
 - superior distortion correction without any time penalty



- INVERSION (Bhushan et al. 2014)
 - Robust co-registration





Download hands-on dataset

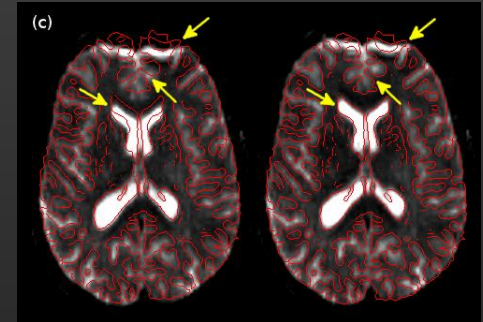
<http://brainsuite.org/NITP2014/>

Running BDP

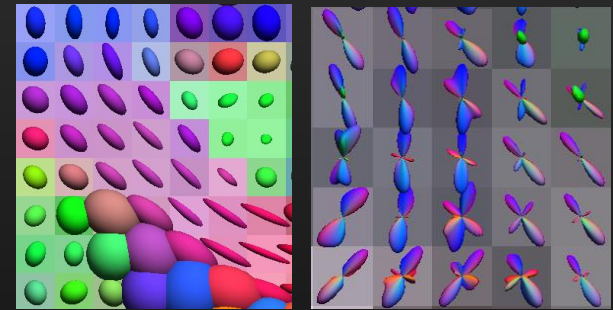
{ or bdp.exe

bdp.exe – overview

- Co-register diffusion and MPRAGE scan
 - Distortion correction – multiple methods



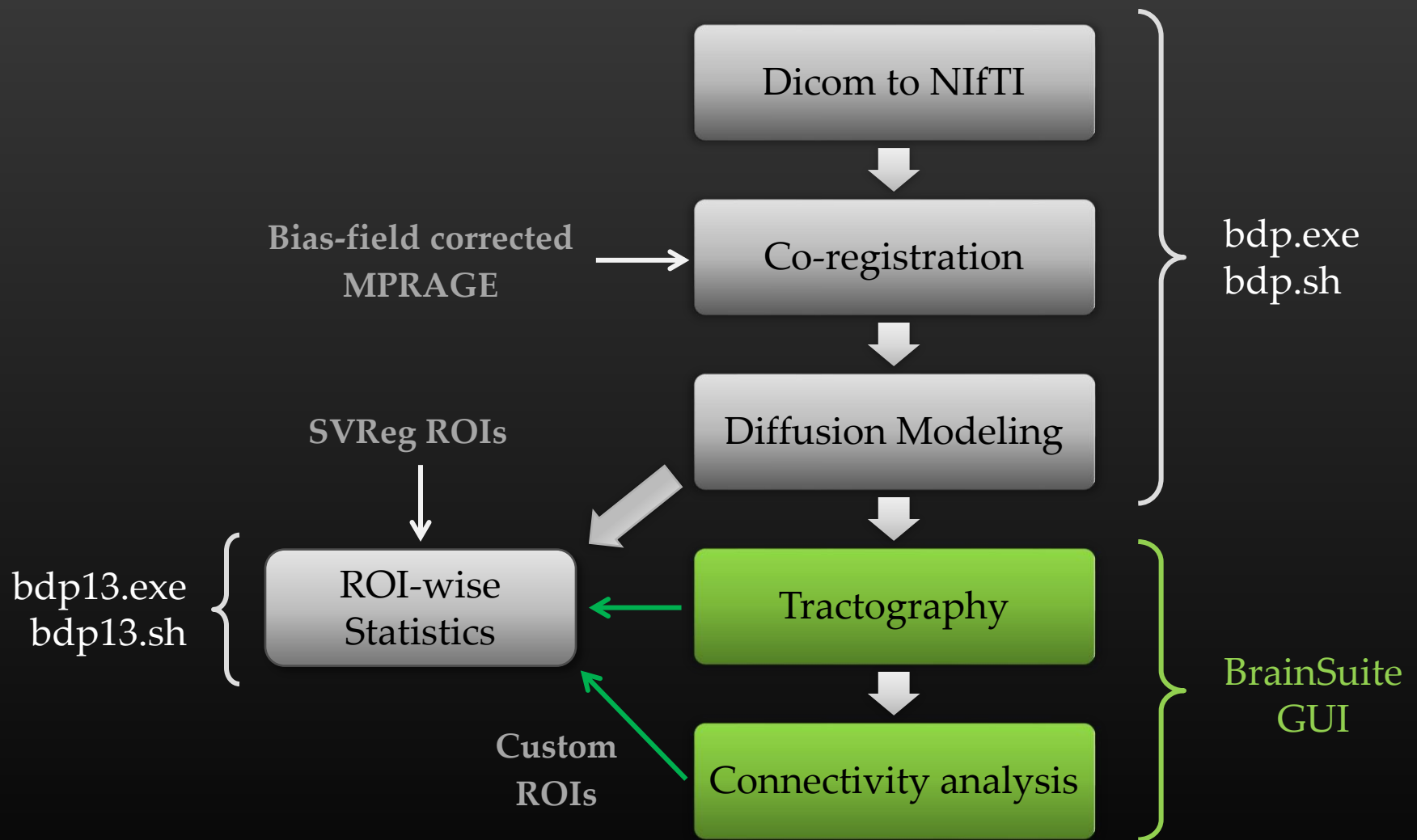
- Fit diffusion model
 - Multiple models – Tensor, ODFs



- Compute *basic* ROI-wise statistics
 - Custom ROIs, track based ROIs etc.

A	B	C	D	E	F	G
ROI_ID	Missing voxels	Mean (GM+WM)	Var (GM+WM)	Used voxels (GM+WM)	Mean (WM)	Var (WM)
120	2076	0.193647623	0.157876641	49453	0.367816687	0.158458
121	939	0.202837408	0.165470749	49200	0.384492725	0.163745
130	0	0.183879077	0.152853325	17984	0.371818811	0.152749
131	0	0.173550412	0.141550764	22918	0.347554863	0.142177
140	0	NaN	NaN	0	NaN	NaN
141	0	NaN	NaN	0	NaN	NaN
142	0	0.193445236	0.157581672	6447	0.394196153	0.124804
143	0	0.212929964	0.172584817	7183	0.414764017	0.14748
144	0	0.178581178	0.141114518	9902	0.345779568	0.12801
145	0	0.180468515	0.149058774	8167	0.353723109	0.141367
146	0	0.19012776	0.151103929	3030	0.36529085	0.157643
147	0	0.190880433	0.143366888	2865	0.348852992	0.136231
150	805	0.228198722	0.184615031	23130	0.397928327	0.16902
151	1173	0.223954752	0.184945568	21000	0.423291534	0.159717

Diffusion Pipeline



bdp.exe / bdp.sh

- Command line tool
 - Highly extensible using your batch/shell scripts
- Flexible – numerous flags for custom processing
- Requires
 - Matlab 2012a MCR
 - Visual C++ runtime package (windows only)

- Documentation

<http://brainsuite.org/processing/diffusion/>

- Detailed flag description

<http://brainsuite.org/processing/diffusion/flags/>

Syntax

DICOM

```
bdp.exe <BFC File> [Optional Flags] -d <DICOM path> [DICOM path ...]
```

- Limited support
- BDP extracts (most) relevant diffusion scan parameters

NIfTI (.nii or .nii.gz)

```
bdp.exe <BFC File> [Optional Flags] --nii <4D DWI NIfTI> --bvec <Gradient file> --bval <b-value file>
```

- BDP expects diffusion gradient direction in voxel coordinates
- BDP uses NIfTI header matrix extensively for registration

Linux and Macintosh

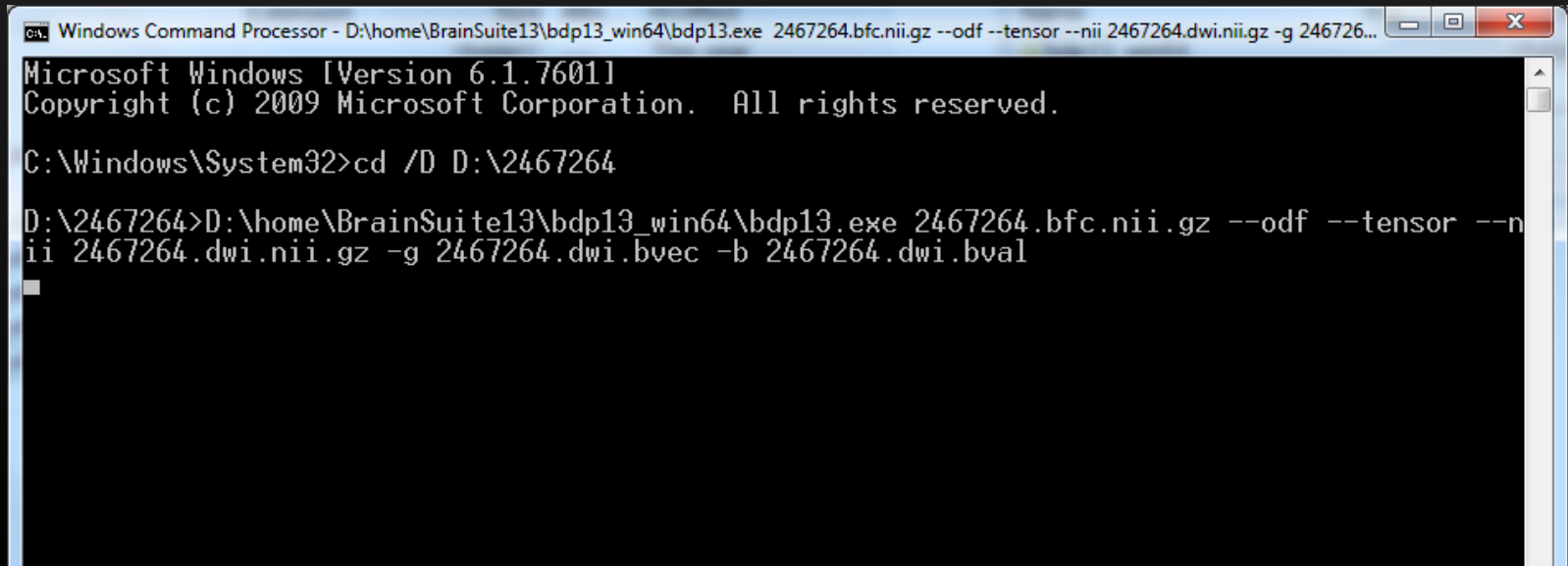
Replace `bdp.exe` by `bdp.sh`

Syntax

NIfTI input (.nii or .nii.gz)

```
bdp.exe <BFC File> [Optional Flags] --nii <4D DWI  
NIfTI> --bvec <Gradient file> --bval <b-value file>
```

- BDP expects diffusion gradient direction in voxel coordinates
- BDP uses NIfTI header matrix extensively for registration



```
Windows Command Processor - D:\home\BrainSuite13\bdp13_win64\bdp13.exe 2467264.bfc.nii.gz --odf --tensor --nii 2467264.dwi.nii.gz -g 246726...  
Microsoft Windows [Version 6.1.7601]  
Copyright (c) 2009 Microsoft Corporation. All rights reserved.  
  
C:\Windows\System32>cd /D D:\2467264  
  
D:\2467264>D:\home\BrainSuite13\bdp13_win64\bdp13.exe 2467264.bfc.nii.gz --odf --tensor --nii 2467264.dwi.nii.gz -g 2467264.dwi.bvec -b 2467264.dwi.bval
```

Example

- `C:\bdp13p17_win64\bdp.exe C:\5934\5934.bfc.nii.gz -
-nii C:\5934\5934.dwi.nii.gz --bvec
C:\5934\5934.dwi.bvec --bval C:\5934\5934.dwi.bval`
- Flags are separated by space
- If required file are not in current working directory, then specify full path to files
- Any number of flags can be added
- Output files:
 - Many many files.... (see documentation for all details)
 - `<fileprefix>.BDPSummary.txt`
 - Summary of all the processing with references
 - The command used for future reference

<fileprefix>.BDPSummary.txt

BrainSuite Diffusion Pipeline: Processing Summary

BDP Version: 13p17

Processing finished: 19-Sep-2013 12:03:26

Scan: D:\BrainReg_Git\data\BDP_test_data\6067JH\5934JH

Diffusion MRI data was co-registered to the anatomical T1-weighted image and corrected for susceptibility-induced distortions using an acquired B0 fieldmap [Bhushan 2012].

Diffusion tensors were estimated using a weighted linear least squares method, and scalar diffusion parameters such as fractional anisotropy (FA), mean diffusivity (MD), radial diffusivity, and axial diffusivity were computed based on an eigendecomposition of the tensors as described in [Kim 2009].

Orientation distribution functions (ODFs) were computed using the Funk-Radon Transform and the Funk-Radon [Halдар 2013].

REFERENCES:

[Bhushan 2012] C. Bhushan, J. "susceptibility-induced distortion nonrigid registration", Asia-Pacific Annual Summit and Conference

[Halдар 2013] J. P. Halдар, R. the sphere: Application to high NeuroImage, Volume 71, Pages

[Kim 2009] J. H. Kim, J. Halдар imaging of mouse brain stem at Methods, Volume 176, Issue 2,

COMMAND USED:

```
bdp13.exe D:\BrainReg_Git\data\BDP_test_data\6067JH\5934JH.bfc.nii.gz
--threads=4
--dir=y-
--odf
--tensor
--output-subdir windows_complied_v13p17_fieldmap
--output-diffusion-coordinate
--nii D:\BrainReg_Git\data\BDP_test_data\6067JH\6067JH.DWI.00.nii.gz
--bvec D:\BrainReg_Git\data\BDP_test_data\6067JH\6067JH.DWI.00.bvec
--bval D:\BrainReg_Git\data\BDP_test_data\6067JH\6067JH.DWI.00.bval
--fieldmap-correction D:\BrainReg_Git\data\BDP_test_data\6067JH\6067JH.fieldmap.rad
--echo-spacing=0.00036
```

Approximate processing time: 18.07 minutes

Command line output

```
Reading input flags...

Output sub-directory already exists:
D:\BrainReg_Git\data\BDP_test_data\6067JH\windows_complied_v13p17_fieldmap
The files in the output folder can be overwritten.
Checking input files...
Successfully generated b-matrices file.

BDP could not find any .mask.nii.gz file. BDP will use input bfc file itself as
brain mask. You can specify a custom head mask by using flag --t1-mask
<maskfile_name>. The custom mask must overlay correctly with input BFC image in
BrainSuite.

Reading the input parameters for co-registration...
Checking orientation information...Done
Extracting 0-diffusion (b=0) image from input DWIs...Done

DWI mask is not defined in input flags. BDP will generate (pseudo) mask from
0-diffusion (b=0) image. Automatic mask generation may not be accurate in some
situations and can affect overall quality of co-registration. In case
co-registration is not accurate, you can define a DWI mask by using flag
--dwi-mask <mask_filename>. The mask can be generated and hand edited in
BrainSuite interface. This mask would be used only for registration purposes
(and not for statistics computation).
Saved (pseudo) mask: D:\BrainReg_Git\data\BDP_test_data\6067JH\windows_complied_v13p17_fieldmap\5934JH.dwi.RAS.mask.nii.gz

Distortion correction using fieldmap started...
Field of view (FOV) of Fieldmap and EPI (diffusion) scan seems to be different.
PNG images showing overlay will be generated with name:
D:\BrainReg_Git\data\BDP_test_data\6067JH\windows_complied_v13p17_fieldmap\5934JH.dwi.RAS.correct.fielmap_overlay

WARNING: Fieldmap and EPI (diffusion) data do not share same field of view
(FOV), but it seems that EPI data is totally included in fieldmap FOV. BDP will
only use information from overlapping FOV. It is *highly* recommended to check
the overlay images to make sure fieldmap and EPI data overlap correctly.
Fieldmaps should be pre-registered to EPI image in order to work correctly.

[=====>] 21/21 volumes done

Saving file...Done
Correcting DWI mask...
Field of view (FOV) of Fieldmap and EPI (diffusion) scan seems to be different.
PNG images showing overlay will be generated with name:
D:\BrainReg_Git\data\BDP_test_data\6067JH\windows_complied_v13p17_fieldmap\5934JH.dwi.RAS.correct.mask.fielmap_overlay
```

Command line
output – Always
verbose with
relevant important
information

Default flags

When no optional flag is defined:

- `--tensor`
- `--dir=y`
- Registration based distortion correction
- Only T1-coordinate outputs
- Outputs are saved in same directory as bfc file
- `--threads=4`

```
C:\bdp13p17_win64\bdp.exe C:\5934\5934.bfc.nii.gz -  
-nii C:\5934\5934.dwi.nii.gz --bvec  
C:\5934\5934.dwi.bvec --bval C:\5934\5934.dwi.bval
```


Help!

`--help` or `-h`

- Prints out description of all BDP flags
- Also reports the version of BDP executable being run

`--check-for-updates`

- Connects to BrainSuite server to check if a new version of BDP is available

All other flags and options are ignored and BDP terminates after printing help or checking for updates.

Of course online documentation:

<http://brainsuite.org/processing/diffusion/>

Diffusion models

Multiple 'model' flags can be used at once:

➤ Diffusion Tensor

- `--tensor`
- `<name>.eig.nii.gz` – saves all eigen value/vectors
- FA, colorFA, axial, radial, L2, L3, MD

➤ ODFs

- `--FRT`
- `--FRACT`
- `<name>.odf` – Load saved Spherical harmonic coefficients

➤ Coordinate filename suffix

- `.T1_coord` : In T1/MPRAGE coordinates
- `.D_coord` : In diffusion coordinates

Distortion direction

--dir=<direction>

Define phase encoding direction

x : increases along the Right side of the subject

x- : increases along the left side of the subject.

y : increases along the Anterior direction of the subject

y- : increases along the posterior direction of the subject

z : increases along the Superior direction

z- : increases along the inferior direction

Example

--dir=y-

- -ve sign is important only for fieldmap based correction

Fieldmap based correction

Required

```
--fieldmap-correction <fname.nii.gz> (in rad/sec)  
--echo-spacing=<t> (in sec)
```

Example

```
--fieldmap-correction fieldmap.radians.nii.gz  
--echo-spacing=0.00036
```

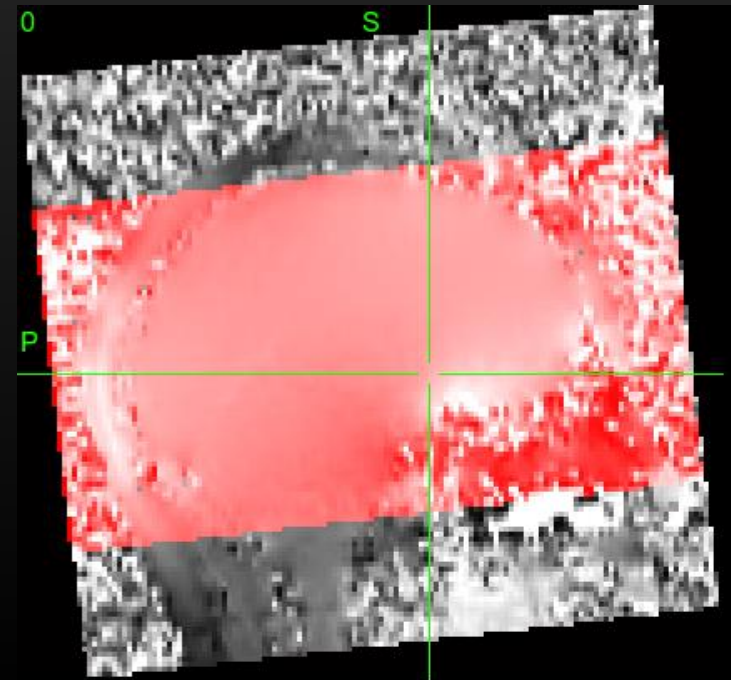
Optional

```
--fieldmap-smooth3=<S> (in mm)  
--ignore-fieldmap-fov
```

- BDP checks for overlap of field of view (FOV) of diffusion scan and fieldmap scan
- Overrides FOV check

Example:

```
--fieldmap-smooth3=0.75
```



Some (more) useful flags

`--output-subdir <directory_name>`

- allows to specify a sub-directory name in which output files would be written
- Example:

```
--output-subdir BDPv17
```

`--output-diffusion-coordinate`

- Enables estimation of diffusion tensors and/or ODFs in the native diffusion coordinate
- All native diffusion coordinate files are saved in a separate folder named “diffusion_coord_outputs”
- Outputs in MPRAGE coordinates are always saved

Statistics flags

--generate-stats

- Requires extraction (& SVReg) output files
- Writes statistics for white matter(WM), grey matter(GM), and both WM and GM combined
- Outputs in .csv format

A	B	C	D	E	F	G	H	I	J	K
ROI_ID	Missing voxels	Mean (GM+WM)	Var (GM+WM)	Used voxels (GM+WM)	Mean (WM)	Var (WM)	Used Voxels (WM)	Mean (GM)	Var (GM)	Used voxels (GM)
120	2076	0.193647623	0.157876641	49453	0.367816687	0.158458	13550	0.12791613	0.095325	35903
121	939	0.202837408	0.165470749	49200	0.384492725	0.163745	14200	0.12913822	0.093767	35000
130	0	0.183879077	0.152853325	17984	0.371818811	0.152749	4789	0.11566798	0.076836	13195
131	0	0.173550412	0.141550764	22918	0.347554863	0.142177	5907	0.1131282	0.076227	17011
140	0	NaN	NaN	0	NaN	NaN	0	NaN	NaN	0
141	0	NaN	NaN	0	NaN	NaN	0	NaN	NaN	0
142	0	0.193445236	0.157581672	6447	0.394196153	0.124804	1873	0.11123998	0.073218	4574
143	0	0.212929964	0.172584817	7183	0.414764017	0.14748	2233	0.12188043	0.082116	4950
144	0	0.178581178	0.141114518	9902	0.345779568	0.12801	2914	0.1088594	0.069754	6988
145	0	0.180468515	0.149058774	8167	0.353723109	0.141367	2412	0.10785522	0.072814	5755
146	0	0.19012776	0.151103929	3030	0.36529085	0.157643	764	0.13106996	0.091235	2266
147	0	0.190880433	0.143366888	2865	0.348852992	0.136231	768	0.13302445	0.093814	2097
150	805	0.228198722	0.184615031	23130	0.397928327	0.16902	8681	0.12622583	0.098437	14449
151	1173	0.223954752	0.184945568	21000	0.423291534	0.159717	7044	0.12334342	0.091737	13956
160	0	NaN	NaN	0	NaN	NaN	0	NaN	NaN	0
161	0	NaN	NaN	0	NaN	NaN	0	NaN	NaN	0

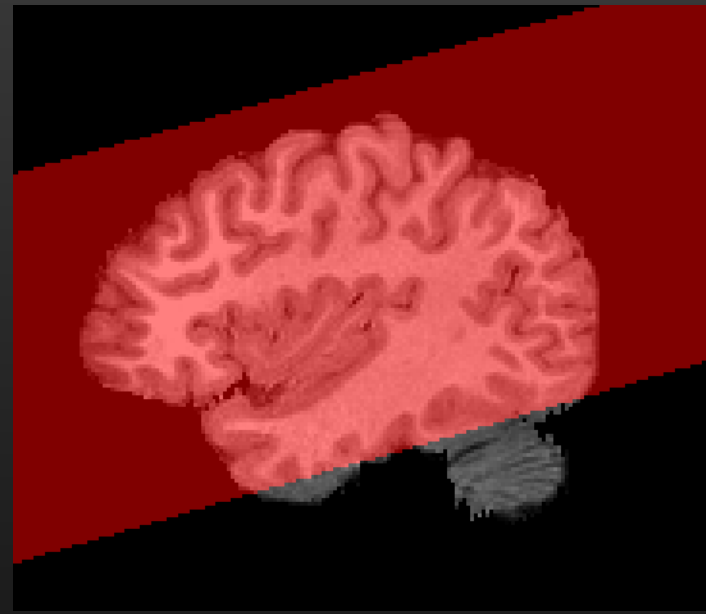
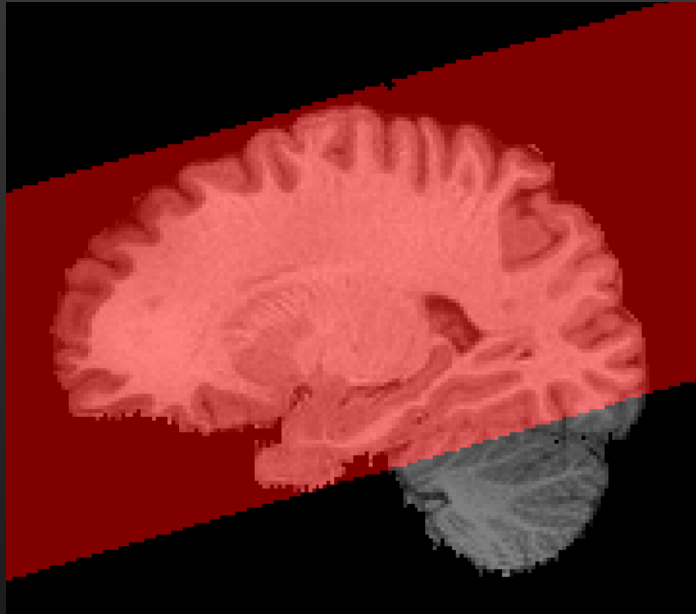
Statistics flags

A	B	C	D	E	F	G	H	I	J	K
ROI_ID	Missing voxels	Mean (GM+WM)	Var (GM+WM)	Used voxels (GM+WM)	Mean (WM)	Var (WM)	Used Voxels (WM)	Mean (GM)	Var (GM)	Used voxels (GM)
120	2076	0.193647623	0.157876641	49453	0.367816687	0.158458	13550	0.12791613	0.095325	35903
121	939	0.202837408	0.165470749	49200	0.384492725	0.163745	14200	0.12913822	0.093767	35000
130	0	0.183879077	0.152853325	17984	0.371818811	0.152749	4789	0.11566798	0.076836	13195
131	0	0.173550412	0.141550764	22918	0.347554863	0.142177	5907	0.1131282	0.076227	17011
140	0	NaN	NaN	0	NaN	NaN	0	NaN	NaN	0
141	0	NaN	NaN	0	NaN	NaN	0	NaN	NaN	0
142	0	0.193445236	0.157581672	6447	0.394196153	0.124804	1873	0.11123998	0.073218	4574
143	0	0.212929964	0.172584817	7183	0.414764017	0.14748	2233	0.12188043	0.082116	4950
144	0	0.178581178	0.141114518	9902	0.345779568	0.12801	2914	0.1088594	0.069754	6988
145	0	0.180468515	0.149058774	8167	0.353723109	0.141367	2412	0.10785522	0.072814	5755
146	0	0.19012776	0.151103929	3030	0.36529085	0.157643	764	0.13106996	0.091235	2266
147	0	0.190880433	0.143366888	2865	0.348852992	0.136231	768	0.13302445	0.093814	2097
150	805	0.228198722	0.184615031	23130	0.397928327	0.16902	8681	0.12622583	0.098437	14449
151	1173	0.223954752	0.184945568	21000	0.423291534	0.159717	7044	0.12334342	0.091737	13956
160	0	NaN	NaN	0	NaN	NaN	0	NaN	NaN	0
161	0	NaN	NaN	0	NaN	NaN	0	NaN	NaN	0

Default information:

- WM/GM from <name>.cortex.dewisp.mask.nii.gz
- SVReg labels from <name>.svreg.corr.label.nii.gz
- ROI_ID from brainsuite_labeldescription.xml
 - `--custom-label-xml <filename.xml>`

Statistics – FOV issues



- BDP detects overlap of field of view (FOV) of MPRAGE and diffusion scan
- Computes missing voxels in each ROI
- By default does *not* compute stats for ROI missing *any* voxel
- `--force-partial-roi-stats`
 - Force stats computation in all ROIs

Custom labels

```
--custom-diffusion-label <name>
```

```
--custom-t1-label <name>
```

- Define custom labels in either coordinates
- <name> can be either NIfTI filename or directory name
- Custom labels can be painted in BrainSuite13

```
--custom-label-xml <filename.xml>
```

- Example:

```
--custom-diffusion-label ROI26.nii.gz
```

```
--custom-t1-label T1_labels
```

- When `--custom-label-xml` is not used:
 - BDP generates 5-digit ROI IDs for each label found
 - Saves ROI ID maps (to labels found) in an .xml file
`<fileprefix>.BDP_ROI_MAP.xml`

Re-compute statistics

`--only-generate-stats`

`--generate-stats-only`

- Refined/manually corrected labels – re-run BDP to only compute statistics
- Skip all of the processing (co-registration, distortion correction and tensor/ODF estimation)
- All of the other flags **MUST** be used in the same way as they were in the initial BDP run
(`<fileprefix>.BDPSummary.txt`)

Transform image volumes

`--transform-diffusion-volume <name>`

`--transform-t1-volume <name>`

- To-and-fro from diffusion and T1-coordinates
- `<name>` can be either NIfTI filename or directory name
- This does *not* perform any distortion correction

`--transform-interpolation <method>`

- Define interpolation method
- `linear`, `nearest`, `cubic` or `spline`

`--transform-data-only`

- Skip all of the processing (co-registration, distortion correction and tensor/ODF estimation)
- All of the other flags **MUST** be used in the same way as they were in the initial BDP run (`<fileprefix>.BDPSummary.txt`)

Error!

```
C:\Windows\System32>D:\bdp13p17_win64\bdp13.exe zxdfasd.nii.gz
```

```
Reading input flags...
```

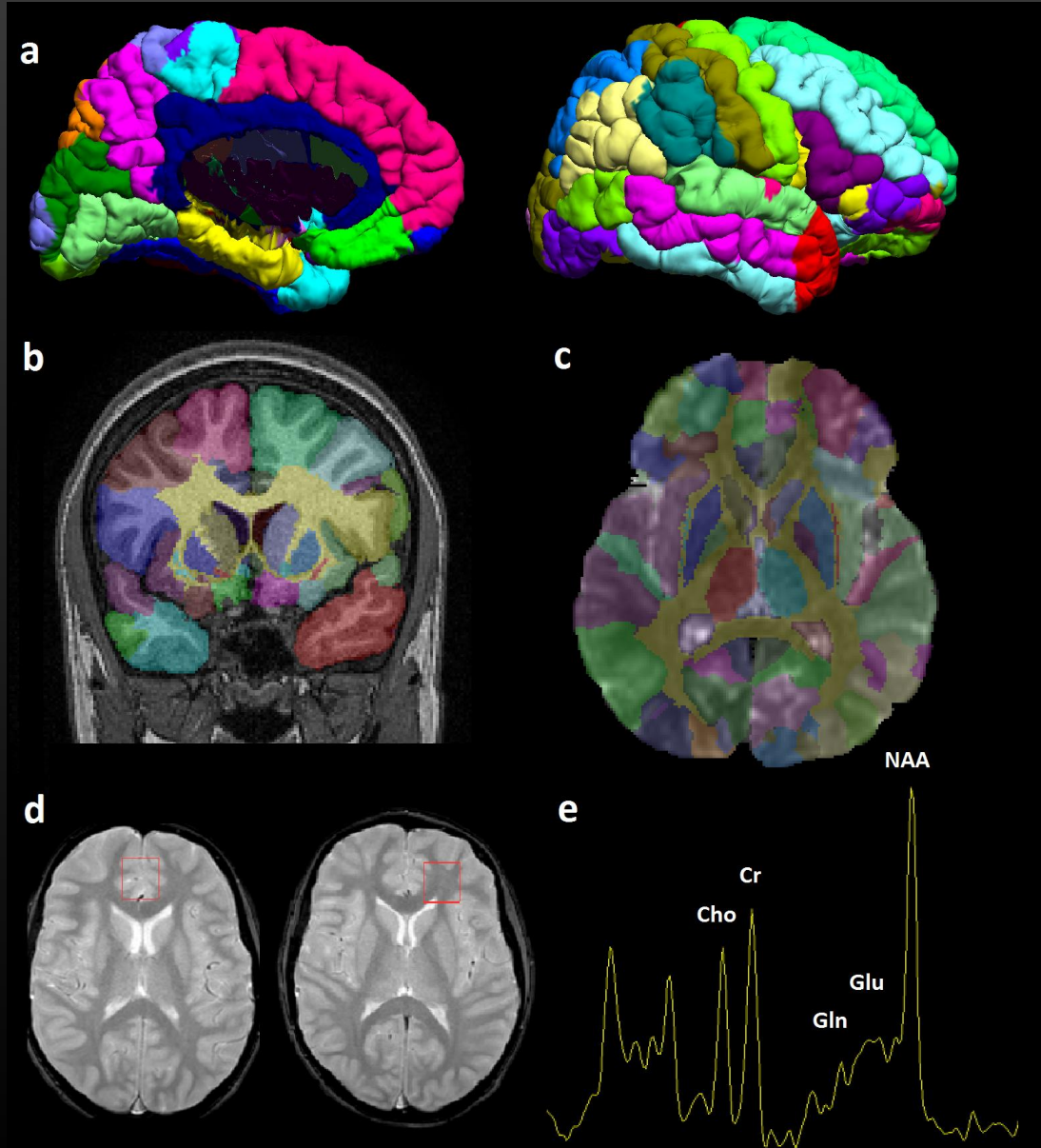
```
*****  
*                                                    *  
*          Error running BDP                          *  
*                                                    *  
*          FILE DOES NOT EXIST                        *  
*                                                    *  
*****
```

```
BDP could not find the file:  
zxdfasd.nii.gz
```

```
Check to make sure that the file exists and that you spelled  
its filename and path correctly
```

```
*****
```


Example multimodal study



Choi et al., "A Multimodal Investigation of Neuronal/Axonal Integrity Using Structural T1-weighted Imaging, Diffusion Tensor Imaging, and H1 MR Spectroscopy", ISMRM 2013, Salt Lake City, p. 1951



BDP Documentation:

<http://brainsuite.org/processing/diffusion/>

Detailed flag description:

<http://brainsuite.org/processing/diffusion/flags/>