Simulated Diffusion-Weighted Imaging for the ITK Masses

Release 0.00

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Abstract

A recent article by Van Hecke et al. [3] describes a framework for creating simulated diffusion-weighted images (DWI). The methodology allows for modeling intersubject variability, regional pathology, and noise and is quite useful for evaluation purposes. This article describes our ITK implementation of this work which we provide to the community as open source.

Contents

1 Introduction

The popularity of diffusion tensor imaging (DTI) has resulted in a proliferation of corresponding analysis algorithms. The need for an evaluative framework for such algorithms motivated the developments of Van Hecke and colleagues in a recent paper [3] which encompasses modeling intersubject variability, regional pathology, and noise in creating tailored DWI from an existing DTI cohort. It should be noted that whereas

Van Hecke's paper also describes the registration processes to both align the DTI cohort to the common reference space and back to the individual subject space, we omit that part of the framework in this submission and allow the user to select their preferred method of image normalization. In addition, the user will need to reconstruct the DTI which can easily be performed with several publicly available packages such as Camino [2].[1]

2 General Overview of Simulated DWI Creation

The DWI simulation allows for the creation of a control group and experimental group consisting of an arbitrary number of directional image sets which can then be fitted to create individual DTI.

Intersubject variability is modeled using an eigendecomposition of the aligned sample DTI cohort. Specifically, for each aligned DTI, the first (i.e. longitudinal) eigenvalue and the average of the second and third (i.e. transverse) eigenvalues of each voxel within a specified brain mask are concatenated within a single vector. The matrix constituting the grouping of image vectors of eigenvalues is then decomposed to create the projections describing the variation found within the aligned cohort. These projections are used to add random intersubject variations to each of the control and experimental subject images.

Based on recent literature, pathology is introduced by Van Hecke using a simultaneous decrease in the longitudinal eigenvalues and an increase in the transverse eigenvalues. In propagating the change in transverse diffusion, we enforce that the ratio of the second to the third eigenvalues be the same before and after a transverse diffusion decrease.

Finally, the application of standard Rician noise is also included as a possibility for enhancing the realism of the simulated DWI data.

For further details, we encourage the reader to consult the paper on which this work is based.

3 Implementation

This work was originally developed within our Advanced Normalization Tools software package[2] and uses our ANTs command line classes. After compilation, one can invoke the help menu which will list the set of options and corresponding descriptions:

```
[ntustison@Nietzschean-Numerics] $ CreateDTICohort --help

COMMAND:
     CreateDTICohort
          CreateDTICohort implements the work of Van Hecke et al. (On the construction of
          a ground truth framework for evaluating voxl-based diffusion tensor MRI analysis
          methods, Neuroimage 46:692-707, 2009) to create simulated DTI data sets. The
          only difference is that all registrations (both for the input population and for
          the output population) are assumed to take place outside of this program.

OPTIONS:
     -d, --image-dimensionality 2/3
          This option forces the image to be treated as a specified-dimensional image. If
          not specified, the program tries to infer the dimensionality from the input
          image.

     -a, --dti-atlas inputDTIAtlasFileName
```

[1] http://camino.org.uk/
[2] http://www.picsl.upenn.edu/ANTS/

```
     A diffusion tensor atlas image is required input for creating the cohort.

-x, --label-mask-image maskImageFileName
                       lowerThresholdValue
     A mask image can be specified which determines the region(s). to which the
     simulated pathology operations are applied. See also the option '--pathology'.
     If no mask is specified one is created by thresholding the atlas FA map at 0.2
     unless a lower threshold is specified.

-n, --noise-sigma <noiseSigma=18>
     This parameter characterizes the Rician noise in the original DWIimages. Van
     Hecke uses the noise-estimation method of Sijbers et al. "Automatic estimation
     of the noise variance from the histogram of a magnetic resonance image", Phys.
     Med. Biol. 52:1335-1348, 2007.

-p, --pathology label[<percentageChangeEig1=-0.05>,<percentageChangeAvgEig2andEig3=0.05>,
                      <numberOfVoxels=all or percentageOfvoxels>]
     The user can specify the simulated pathology in a given area using a label mask.
     If no label is prepended to parameters, the specified parameters are applied to
     all labels.Pathology is simulated by changing the eigenvalues. Typically this
     involves a decrease in the largest eigenvalue and an increase in the average of
     the remaining eigenvalues. Change is specified as a percentage of the current
     eigenvalues. However, care is taken to ensure that diffusion direction does not
     change. Additionally, one can specify the number of voxels affected in each
     region or one can specify the percentage of voxels affected. Default is to
     change all voxels. Note that the percentages must be specified in the range
     [0,1]. For dimension=3 where the average transverse diffusion eigenvalues are
     altered, this change is propagated to the distinct eigenvalues by forcing the
     ratio to be the same before the change.

-w, --dwi-parameters [B0Image,directionFile,bvalue]
                     [B0Image,schemeFile]
     This option specifies the parameters of the output diffusion-weighted images
     including the directions and b-values. The directions are specified using a
     direction file which has as its first line the number of directions.Each
     successive three lines contains the x, y, and z directions, respectively, and a
     single b-value. Note that several direction files of this format are distributed
     with the Camino DTI toolkit
     (http://web4.cs.ucl.ac.uk/research/medic/camino/pmwiki/pmwiki.php).
     Alternatively, one can specify a scheme file where each direction is specified
     followed by a b-value for that direction, i.e. <x1> <y1> <z1> <bvalue1> ...
     <xN><yN><zN><bvalueN>.

-r, --registered-population textFileWithFileNames.txt
     If one wants to introduce inter-subject variabilitya registered DTI population
     to the DTI atlas is required. This variability is modeled by a PCA decomposition
     on a combination of the first eigenvalue image and the average of the second and
     third eigenvalues.The registered image file names are specified using a text
     file where each line is the name of an individual DTI.

-o, --output [outputDirectory,fileNameSeriesRootName,
              <numberOfControls=10>,<numberOfExperimentals=10>]
     The output consists of a set of diffusion-weighted images for each subject. Each
     file name is prepended with the word 'Control' or 'Experimental'. The number of
     control and experimental subjects can be also be specified on the command line.
     Default is 10 for each group.

-h
     Print the help menu (short version).
     <VALUES>: 0

--help
     Print the help menu.
```

Listing 1: CreateDTICohort long command line menu which is invoked using the '--help' option. The short command line menu is obtained by typing '-h'.

4 Simulated DWI Example

We have included a sample data set derived from the NKI/Rockland INDI[3] data set consisting of 10 DTI from normal subjects, a B0 image, and a label mask modified from the popular ICBM template consisting of 52 regions where the additional 2 regions are 1) unlabeled regions from the original ICBM mask where FA ≥ 0.2 and 2) the remainder of the brain.[4] This allows for pathology to be individually prescribed for each labeled region. All images are aligned to the MNI152 template space [1].

Below we give the first few lines of the terminal output from a sample call to the routine `CreateDTICohort` contained in the script `createDWI.sh`, which is also included.

```
[ntustison@Nietzschean-Numerics] $ sh createDWI.sh

Creating DTI cohort for 3-dimensional images.

--- Modeling intersubject variability ---

Processing DTI/dti_01.nii.gz (1 of 10).
Processing DTI/dti_02.nii.gz (2 of 10).
Processing DTI/dti_03.nii.gz (3 of 10).
Processing DTI/dti_04.nii.gz (4 of 10).
Processing DTI/dti_05.nii.gz (5 of 10).
Processing DTI/dti_06.nii.gz (6 of 10).
Processing DTI/dti_07.nii.gz (7 of 10).
Processing DTI/dti_08.nii.gz (8 of 10).
Processing DTI/dti_09.nii.gz (9 of 10).
Processing DTI/dti_10.nii.gz (10 of 10).

--- Calculating regional average FA and MD values (original and pathology) ---

   Region FA (original)  FA (path.)     FA (%change)   MD (original)  MD (path.)     MD (%change)
   1      0.426666       0.392867       -0.0792165     0.0010568      0.00101915     -0.0356265
   2      0.387891       0.385816       -0.00534951    0.000799096    0.000827288    0.0352805
   3      0.610309       0.618394       0.013248       0.00087893     0.000985969    0.121783
   4      0.562708       0.572108       0.0167038      0.000992207    0.00111096     0.119684
   5      0.641522       0.646897       0.00837787     0.00091601     0.00103919     0.13448
   6      0.450288       0.462858       0.0279156      0.00154076     0.00185622     0.204742
   7      0.504297       0.562074       0.114571       0.000824662    0.00090193     0.0936977
   8      0.455938       0.452463       -0.0076219     0.0008713      0.000884652    0.0153244
   9      0.458622       0.447742       -0.0237231     0.000859755    0.000851439    -0.00967258
   10     0.553985       0.568811       0.0267624      0.000894992    0.000954038    0.0659738
   11     0.560088       0.57298        0.0230185      0.000869192    0.000948747    0.0915286
   12     0.455487       0.440347       -0.0332389     0.00151854     0.00143839     -0.0527812
   13     0.450941       0.436025       -0.0330789     0.00232649     0.00220849     -0.050718
   14     0.531836       0.555623       0.0447257      0.00104972     0.00119604     0.139394
   15     0.558183       0.57513        0.0303612      0.000980834    0.00110763     0.129277
   16     0.604708       0.619218       0.023996       0.000831829    0.000947156    0.138643
   17     0.620054       0.649983       0.0482687      0.000799265    0.00089297     0.117239
   18     0.44215        0.455869       0.0310285      0.000782263    0.00085731     0.0959354
   19     0.468299       0.495326       0.0577122      0.000743647    0.000816076    0.0973973
   20     0.59195        0.63697        0.0760543      0.000770545    0.000860518    0.116765
   21     0.603748       0.645064       0.0684337      0.000746336    0.000831687    0.114361
   22     0.509597       0.554742       0.0885913      0.000837227    0.000934504    0.11619
   23     0.359127       0.397746       0.107537       0.000830458    0.000907076    0.0922604
   24     0.37626        0.419576       0.115122       0.000813638    0.000879125    0.080486
   25     0.401218       0.440621       0.098208       0.000789715    0.000861153    0.0904596
   26     0.392857       0.426172       0.0848036      0.000757251    0.000823564    0.0875718
   27     0.367774       0.427039       0.161146       0.000873593    0.000956149    0.0945015
   28     0.395989       0.449048       0.133992       0.000865832    0.000947765    0.0946285
   29     0.467424       0.483241       0.0338396      0.000879305    0.00097071     0.103951
   30     0.459866       0.486898       0.058784       0.000899325    0.000982584    0.0925787
```

[3] http://fcon_1000.projects.nitrc.org

[4] http://www.loni.ucla.edu/Atlases/Atlas_Detail.jsp?atlas_id=5

```
   31     0.468384      0.520791      0.111889       0.000892105   0.000971572   0.0890779
   32     0.475016      0.504796      0.0626932      0.000931563   0.00104899    0.126052
   33     0.330981      0.372975      0.12688        0.000834499   0.000914815   0.0962437
   34     0.335543      0.372813      0.111073       0.000800139   0.000874732   0.0932242
   35     0.474078      0.510758      0.0773704      0.000793743   0.000879568   0.108127
   36     0.406761      0.459163      0.128828       0.000771591   0.000858159   0.112193
   37     0.305497      0.314823      0.0305267      0.000867374   0.00097527    0.124394
   38     0.320879      0.34981       0.0901605      0.000847713   0.00095333    0.124591
   39     0.476671      0.483099      0.0134837      0.000928494   0.0010066     0.0841179
   40     0.474913      0.495017      0.042332       0.000925391   0.00102012    0.102363
   41     0.378974      0.409393      0.0802644      0.000779719   0.000843773   0.0821508
   42     0.398861      0.420382      0.0539565      0.000765444   0.000833252   0.0885867
   43     0.360756      0.36034       -0.00115312    0.000769285   0.00083562    0.0862293
   44     0.367618      0.386133      0.0503644      0.000755733   0.000823069   0.089101
   45     0.408336      0.432339      0.0587838      0.000865836   0.000952377   0.09995
   46     0.450344      0.473607      0.0516559      0.000839035   0.000934961   0.114329
   47     0.352407      0.335938      -0.046734      0.000862954   0.000947891   0.0984256
   48     0.479243      0.482496      0.00678764     0.000806836   0.000892731   0.106459
   49     0.390706      0.409486      0.0480653      0.00127162    0.00148426    0.167222
   50     0.420062      0.456485      0.0867099      0.00140615    0.00156606    0.11372
   51     0.296425      0.326624      0.101875       0.000876206   0.000949146   0.0832462
   52     nan           nan           nan            0.00901245    0.00884544    -0.0185311

--- Writing images ---

Writing control 1 (of 11) DWI images.
  Applying direction 0 (of 30): [0 0 0], bvalue = 0
  Applying direction 1 (of 30): [-0.546405 0.619202 0.563943], bvalue = 1000
  Applying direction 2 (of 30): [-0.398931 -0.600006 0.693432], bvalue = 1000
  Applying direction 3 (of 30): [0.587973 0.521686 0.618168], bvalue = 1000
  Applying direction 4 (of 30): [0.055894 -0.991971 -0.113444], bvalue = 1000
  Applying direction 5 (of 30): [-0.666933 -0.677984 0.309094], bvalue = 1000
  Applying direction 6 (of 30): [0.163684 0.533013 0.830123], bvalue = 1000
  Applying direction 7 (of 30): [0.542826 0.133898 0.829102], bvalue = 1000
  Applying direction 8 (of 30): [-0.074751 -0.350412 0.933608], bvalue = 1000
  Applying direction 9 (of 30): [0.845751 -0.478624 -0.235847], bvalue = 1000
  Applying direction 10 (of 30): [0.767148 -0.610673 0.196372], bvalue = 1000
  Applying direction 11 (of 30): [-0.28381 0.381633 0.879663], bvalue = 1000
  Applying direction 12 (of 30): [0.537228 -0.616249 0.575868], bvalue = 1000
  Applying direction 13 (of 30): [-0.711387 0.197778 0.674398], bvalue = 1000
  Applying direction 14 (of 30): [0.886511 0.219025 0.407586], bvalue = 1000
  Applying direction 15 (of 30): [0.296061 0.842985 0.449136], bvalue = 1000
  Applying direction 16 (of 30): [-0.93754 -0.34099 0.068877], bvalue = 1000
  Applying direction 17 (of 30): [0.398833 0.917023 0.000835], bvalue = 1000
  Applying direction 18 (of 30): [0.097278 -0.711949 0.69546], bvalue = 1000
  Applying direction 19 (of 30): [-0.311534 0.908623 -0.278121], bvalue = 1000
  Applying direction 20 (of 30): [-0.432043 -0.089758 0.897375], bvalue = 1000
  Applying direction 21 (of 30): [-0.94998 0.03081 0.310788], bvalue = 1000
  Applying direction 22 (of 30): [0.146722 -0.811981 -0.564942], bvalue = 1000
  Applying direction 23 (of 30): [-0.172201 -0.908573 0.38058], bvalue = 1000
  Applying direction 24 (of 30): [0.507209 -0.848578 -0.150513], bvalue = 1000
  Applying direction 25 (of 30): [-0.730808 -0.654136 -0.194999], bvalue = 1000
  Applying direction 26 (of 30): [0.077744 0.094961 0.992441], bvalue = 1000
  Applying direction 27 (of 30): [0.383976 -0.293959 0.8753], bvalue = 1000
  Applying direction 28 (of 30): [0.788208 -0.213656 0.57713], bvalue = 1000
  Applying direction 29 (of 30): [-0.752333 -0.301447 0.585769], bvalue = 1000
  Applying direction 30 (of 30): [-0.975732 0.165497 -0.143382], bvalue = 1000
Writing control 2 (of 11) DWI images.
  Applying direction 0 (of 30): [0 0 0], bvalue = 0
  Applying direction 1 (of 30): [-0.546405 0.619202 0.563943], bvalue = 1000
  Applying direction 2 (of 30): [-0.398931 -0.600006 0.693432], bvalue = 1000
  Applying direction 3 (of 30): [0.587973 0.521686 0.618168], bvalue = 1000
    .                .                .                .                .
    .                .                .                .                .
    .                .                .                .                .
```

References

[1] D. L. Collins A. C. Evans and B. Milner. An MRI-based stereotactic atlas from 250 young normal subjects. In *Society for Neuroscience Abstracts*, volume 18, page 408, 1992. 4

[2] P. A. Cook, Y. Bai, S. Nedjati-Gilani, K. K. Seunarine, M. G. Hall, G. J. Parker, and D. C. Alexander. Camino: Open-source diffusion-MRI reconstruction and processing. In *Proceedings of the 14th Scientific Meeting of the International Society for Magnetic Resonance in Medicine*, 2006. 1

[3] Wim Van Hecke, Jan Sijbers, Steve De Backer, Dirk Poot, Paul M Parizel, and Alexander Leemans. On the construction of a ground truth framework for evaluating voxel-based diffusion tensor mri analysis methods. *Neuroimage*, 46(3):692–707, Jul 2009. (document), 1