Evaluation of Brain Atrophy Estimation Algorithms using Simulated Ground-Truth Data

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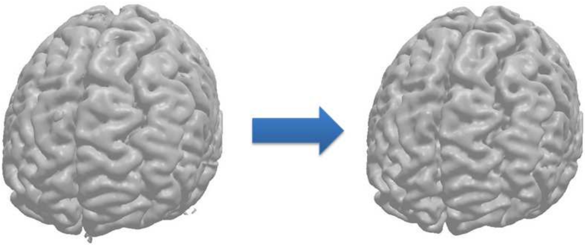
Outline

- Simulation of atrophy
- Experimental Results : Simulation of Atrophy
- Overview of popular atrophy estimation approaches
  - SIENA, SIENAX and BSI
- Evaluation of Atrophy Estimation Approaches
- Conclusions and Future perspectives

Brain Atrophy in Multiple Sclerosis

- Brain Atrophy - A sensitive marker of disease progression
- Growing need for methods to estimate brain atrophy
- Popular methods for brain atrophy estimation
  - Boundary Shift Integral (BSI) and SIENA for longitudinal analysis
  - SIENAX for cross-sectional analysis
- Validation of these tools important but complicated
  - Ground-truth unavailable

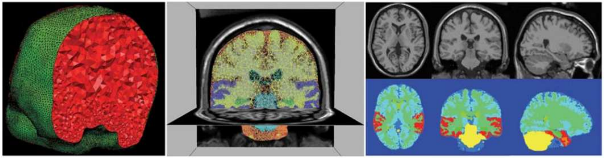
Simulation of Atrophy



- A way to generate ground-truth for evaluation of atrophy estimation methods
- Realistic simulation of atrophy
  - Pathology specific considerations : annual atrophy rate, atrophy in various regions of brain
  - Constraints : Skull should not be deformed, etc.

Simulation of Atrophy: Related Works

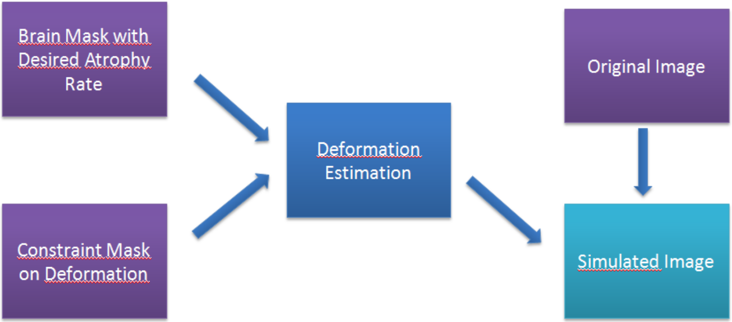
- Camara *et al.* (IEEE TMI 2006)
  - Biomechanical model
  - Finite-element approach



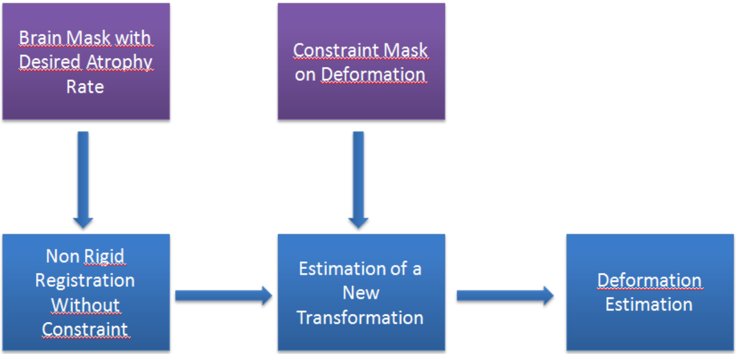
- Karacali *et al.* (IEEE TMI 2006)
  - Non-rigid registration framework
  - Topology preserving deformation field

$$H(h) = \frac{1}{2} \sum_{\omega \in \mathcal{B}} \left(\frac{1}{n(\omega)} \sum_{i=1}^{n(\omega)} J_i(\omega) - V(\omega) \right)^2 + \gamma \sum_{\omega \in \Omega} \sum_{i} 1_{J_i(\omega) < \epsilon} \left(\frac{J_i(\omega)}{\epsilon} + \frac{\epsilon}{J_i(\omega)} - 2 \right)$$

Simulation of Atrophy : Proposed Approach



Proposed Approach: Deformation Estimation



Proposed Approach: Deformation Estimation

- Non-rigid registration framework [Noblet IEEE IP 2005]
  - B-spline based multi-resolution deformable model
  - Let $\mathbf{s} \triangleq [x, y, z]^t \in \Omega \subset \mathbb{R}^3$ and $\Omega_J \subset \Omega$ be the area where the desired simulated atrophy level $J(\mathbf{s})$ is user-specified. We minimize :

$$E_{\mathbf{u},J,\lambda} = \int_{\Omega_J} \left|\log\left(J_{\mathbf{u}}(\mathbf{s})\right) - \log\left(J(\mathbf{s})\right)\right|^2 d\mathbf{s} + \lambda\, C \int_{\Omega} E_{Reg}\left(\mathbf{u}(\mathbf{s})\right) d\mathbf{s}$$

  where $\mathbf{u}$ is the transformation to be estimated, $J_{\mathbf{u}}$ stands for the Jacobian of $\mathbf{u}$, E_{reg} is a regularization term, λ is a weighting factor and C is a scaling factor.

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Experimental Results : Simulation of Atrophy I

- Simulation of atrophy on Brainweb database for normal subject
- Simulated atrophy range: 0-1% and 1-10% of total brain volume
- Constant atrophy simulated over brain

Experimental Results : Simulation of Atrophy II

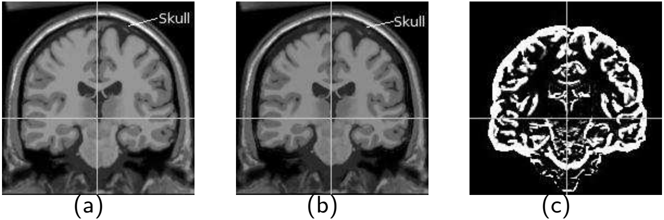

Figure: (a) Original BrainWeb image (b) Image (a) simulated for 10% of atrophy using our algorithm (c) Difference between images (a) and (b). Note that there is no deformation on the skull between (a) and (b).

Experimental Results : Simulation of Atrophy III

Table: Results of simulation of atrophy using the proposed approach: overall desired atrophy, mean Jacobian with the corresponding standard deviation.

	Using Jacobian values		Using Log of Jacobian values	
Desired Atrophy(%)	Mean Jacobian ($\mathbf{u}_{merged}^{-1}$)	Simulated Atrophy(%)	Mean Jacobian ($\mathbf{u}_{merged}^{-1}$)	Simulated Atrophy(%)
1	1.0091 ± 0.0028	0.9023	1.0091 ± 0.0030	0.9050
2	1.0189 ± 0.0043	1.8509	1.0190 ± 0.0046	1.8630
3	1.0291 ± 0.0045	2.8268	1.0294 ± 0.0034	2.8564
4	1.0396 ± 0.0049	3.8062	1.0399 ± 0.0039	3.8346
5	1.0503 ± 0.0056	4.7936	1.0506 ± 0.0047	4.8192
6	1.0613 ± 0.0067	5.7766	1.0616 ± 0.0057	5.8057
7	1.0726 ± 0.0080	6.7678	1.0728 ± 0.0070	6.7895
8	1.0842 ± 0.0098	7.7628	1.0844 ± 0.0082	7.7853
9	1.0960 ± 0.0099	8.7598	1.0963 ± 0.0096	8.7806
10	1.1081 ± 0.0120	9.7558	1.1083 ± 0.0121	9.7755

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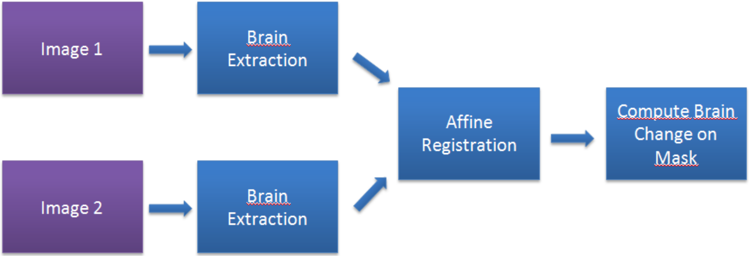
Brain Atrophy Estimation Approaches

Evaluated methods:

- Boundary Shift Integral (BSI) [Freeborough IEEE TMI 1997]
- Structural Image Evaluation, using Normalisation, of Atrophy (SIENA) [Smith JCAT2001]
- Segmentation-based algorithm (SIENAX) [Smith Neuroimage2002]

Brain Atrophy Estimation Approaches : SIENA overview

SIENA [Smith2002]: Motion estimation at the brain surface

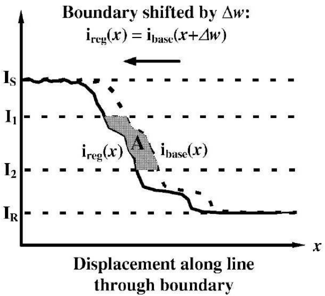


Brain Atrophy Estimation Approaches : BSI overview

BSI: Boundary shift integral [Freeborough1997]

- Brain mask extraction
- Volume change computation

$$\Delta v = \frac{1}{I_1 - I_2} \iiint_{boundary} clip(i_{base}(x, y, z), I_1, I_2) - clip(i_{reg}(x, y, z), I_1, I_2) dxdydz$$



"Boundary Shift Integral" [Freeborough1997].

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Evaluation of the brain atrophy estimation methods

- Robustness to image artefact
  - Gaussian Noise (SNR of 15dB)
  - Intensity Brainweb non-uniformity (INU) fields (20% INU)
- Evaluation using Percentage Brain Volume Change (PBVC)
- For BSI, we provide the ground truth of the gray-white matter mask instead of manual segmentation

Atrophy rates between 0-1%

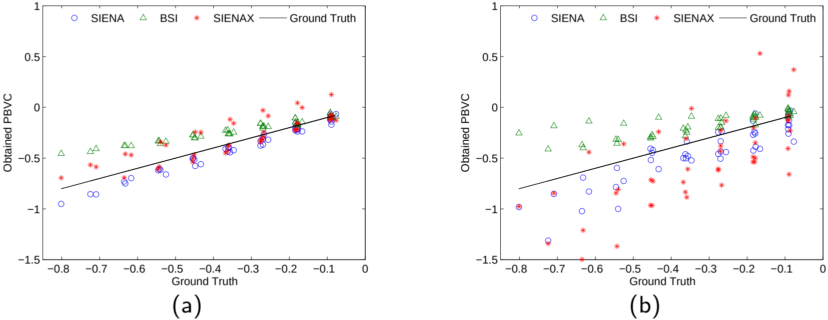

Figure: PBVC: (a) perfect images (b) "noisy" images for atrophy rates between 0-1%

Atrophy rates between 1-10%

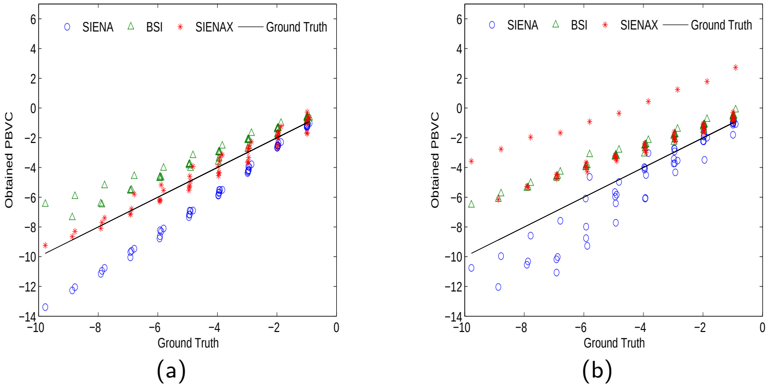

Figure: PBVC: (a) perfect images (b) "noisy" noise (SNR=15dB) for atrophy rates between 1-10%

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Conclusions : Simulation of Atrophy

- Simulation of brain atrophy : facilitates evaluation of brain atrophy estimation methods
- Proposed non-rigid registration based approach to simulate atrophy; method can accurately simulate the desired atrophy
- Method is flexible; can be easily used to simulate regional atrophy in the brain

Conclusions : Evaluation of atrophy estimation approaches

- SIENA
  - Overestimates atrophy
  - Performance can be improved using a better brain extraction; SIENA not as sensitive to brain extraction as SIENAX
  - Results depend on accuracy of segmentation and registration algorithm

Conclusions : Evaluation of atrophy estimation approaches

- BSI
  - Underestimates atrophy
  - Affected by noise and bias field inhomogeniety
  - Manual extraction of brain restricts reproducibility
  - Results depend on accuracy of registration algorithm

Conclusions : Evaluation of atrophy estimation approaches

- SIENAX
  - Underestimates atrophy (for simulations between 1 and 10%)
  - Quality of brain extraction decides performance; BET sensitive to the applied bias field inhomogeniety

Future Perspectives

- Simulation of atrophy more adapted to MS : non-uniform atrophy, gray-white matter atrophy
- Evaluation of these methods based on other sources of error : mis-registration, partial volume, geometrical distortion
- Statistical analysis of trends (under or over-estimation)

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