Registration of Brain Resection MRI with Intensity and Location Priors

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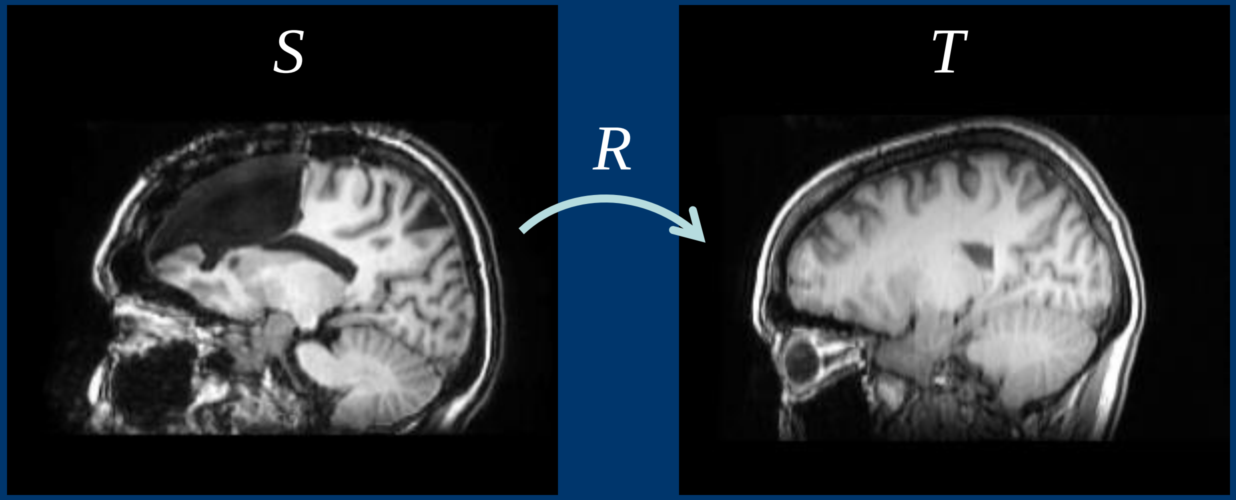
Image Registration Goal

- Align post-resection and preoperative brain MRI of epilepsy patients



- Challenge: Missing Correspondences
  - Cause misalignment of other actual corresponding features

Approaches to Handle Missing Correspondences

Previous Methods

- Biomechanical models + deformable registration for tumor/normal brain alignment[1]
- Point-based algorithm for pre-/intra-operative resection images[3]
- Estimate registration and missing data based on image similarity[4]
- Our recent simultaneous registration/correspondence estimation with intensity prior[5]

Our Approach

→ Jointly register and classify correspondences in statistical estimation framework[2]

→ Voxel-based, no feature pre-processing needed for images to be registered

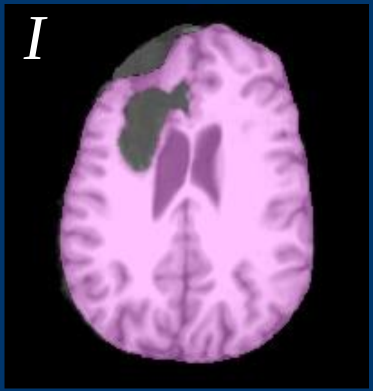
→ Consider other terms beside image similarity to determine missing correspondences

→ Include indicator map prior for location and smoothing

[1]Mohamed et al., MedIA 2006; [2]Pohl et al., Neuroimage 2006; [3]Liu et al., ISBI 2010; [4]Periaswamy and Farid, MedIA 2006; [5]Chitphakdithai and Duncan, MICCAI 2010

Registration and Indicator Map Estimation (RIME): Overview

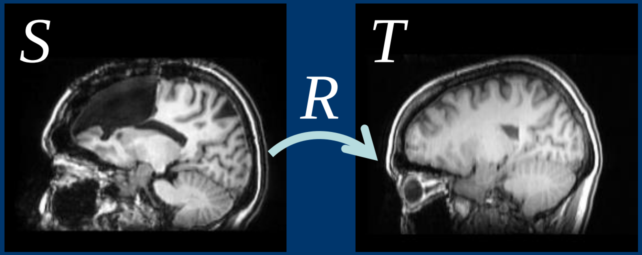
- Introduce "hidden" indicator map to segment valid tissue, resection, and background



- Given indicator map
  → easier to register
- Given correct alignment
  → easier to classify regions

- Maximum a posteriori framework:

$$\hat{R} = \arg\max_{R} \log \sum_{I} p(R, I \mid S, T)$$



Registration and Indicator Map Estimation (RIME): EM Algorithm

- E-Step: Indicator Map Weights $p\left(I(\mathbf{x})=l \mid S,T,R^k\right)=$

$$\frac{\overbrace{p\left(T\left(R^k(\mathbf{x})\right)\mid S,I(\mathbf{x})=l,R^k\right)}^{\text{Similarity Term}}\overbrace{p\left(S(\mathbf{x})\mid I(\mathbf{x})=l\right)}^{\text{Intensity Prior}}\overbrace{p\left(I(\mathbf{x})=l\right)}^{\text{Indicator Map Prior}}}{\sum_{l'} p\left(T\left(R^k(\mathbf{x})\right)\mid S,I(\mathbf{x})=l',R^k\right)p\left(S(\mathbf{x})\mid I(\mathbf{x})=l'\right)p\left(I(\mathbf{x})=l'\right)}$$

- M-Step: Update registration $R^{k+1}=$

$$\arg\max_R\left[\sum_{\mathbf{x}\in S}\sum_{l\in L}\overbrace{p\left(I(\mathbf{x})=l \mid S,T,R^k\right)}^{\text{E-Step Weights}}\log\overbrace{p\left(T\left(R(\mathbf{x})\right)\mid S,I(\mathbf{x})=l,R\right)}^{\text{Similarity Term}}+\log\underbrace{p(R)}_{\text{Transformation Prior}}\right]$$

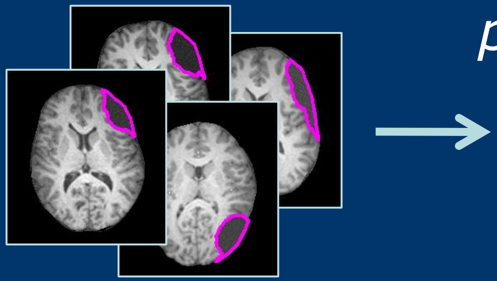
Similarity Metric, Intensity Prior, and Transformation Prior

- Similarity Metric

$$P\left(T\left(R\left(\mathbf{x}\right)\right)\right) \mid S, R, I\left(\mathbf{x}\right) = l \sim \begin{cases} Unif\left(\frac{1}{c} \right) & , l = \text{resection} \\ N\left(S\left(\mathbf{x}\right), \sigma_1\right) & , l = \text{valid tissue} \\ N\left(S\left(\mathbf{x}\right), \sigma_2\right) & , l = \text{background} \end{cases}$$

- Intensity Prior
  - Different distribution for intensities given indicator label

Training set



Resection class parameters

μ_r, σ_r

- Transformation Prior
  - Prior constrains B-spline control points for uniform cubic B-spline FFD model

For more detail: Chitphakdithai and Duncan, MICCAI 2010

Indicator Map Prior: MRF and Mean Field Approximation

- Impose Markov random field onto indicator map

$$p(I) = \frac{1}{Z} \exp\left[-\beta \sum_c V_c(I) \right]$$

← *Problem: Intractable calculation*

- Approximate using mean field theory

$$p(I) \approx \prod_{\mathbf{x}} \frac{1}{Z'_{\mathbf{x}}(\beta)} \exp\left[-\beta \sum_c V'_c\left(I(\mathbf{x}), \bar{I} \right) \right]$$

where $\bar{I} \approx I^k = \arg\max_l p\left(I(\mathbf{x}) = l \mid S, T, R^k \right)$

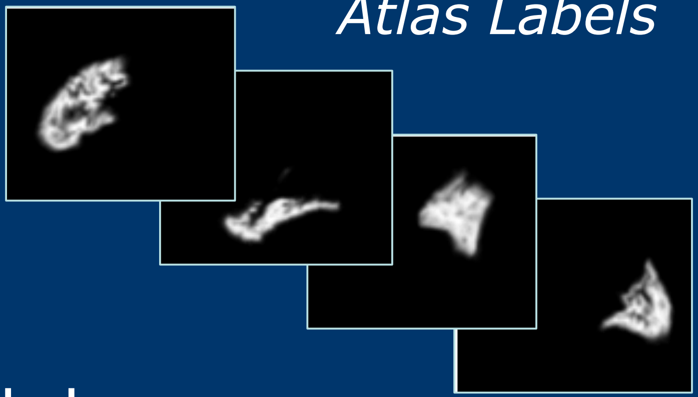
- Prior probability at an indicator map voxel:

$$p\left(I(\mathbf{x}) = l \mid \beta_L, \beta_S \right) \approx \frac{1}{Z'_{\mathbf{x}}(\beta_L, \beta_S)} \exp\left[\beta_L V'_L\left(l, I^A(\mathbf{x}) \right) + \beta_S \sum_{\mathbf{n} \in N(\mathbf{x})} V'_S\left(l, I^k(\mathbf{n}) \right) \right]$$

Indicator Map Prior: Location Prior Term

$$p\left(I(\mathbf{x})=l \mid \beta_L,\beta_S\right) \approx \frac{1}{Z'_{\mathbf{x}}\left(\beta_L,\beta_S\right)} \exp\left[\beta_L V'_L\left(l, I^A(\mathbf{x})\right) + \beta_S \sum_{\mathbf{n}\in N(\mathbf{x})} V'_S\left(l, I^k(\mathbf{n})\right)\right]$$

- $V'_L\left(l, I^A(\mathbf{x})\right) =$ probability voxel $\mathbf{x}$ takes on label l as given by atlas I^A
- User chooses atlas region (e.g. left temporal lobe) which best corresponds to resection location


Atlas Labels

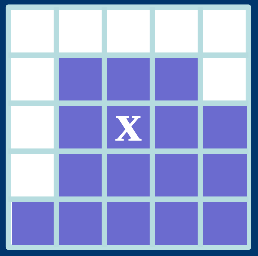
→ Helpful for CSF voxels which have similar intensity to resection voxels

Indicator Map Prior: Smoothing Prior Term

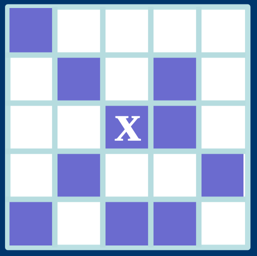
$$p\left(I(\mathbf{x}) = l \mid \beta_L, \beta_S\right) \approx \frac{1}{Z'_{\mathbf{x}}\left(\beta_L, \beta_S\right)} \exp\left[\beta_L V'_L\left(l, I^A(\mathbf{x})\right) + \beta_S \sum_{\mathbf{n} \in N(\mathbf{x})} V'_S\left(l, I^k(\mathbf{n})\right)\right]$$

- Depends on values of neighbors $N(\mathbf{x})$ of $\mathbf{x}$ in current indicator map estimate I^k
- Use Potts model:

$$V'_S\left(l, I^k(\mathbf{n})\right) = \delta\left(l, I^k(\mathbf{n})\right)$$



Higher $\sum_{N(\mathbf{x})} V'_S$



Lower $\sum_{N(\mathbf{x})} V'_S$

→ Helpful for eliminating small mislabeled regions

Indicator Map Prior: Weighting Parameters

$$p\left(I(\mathbf{x})=l \mid \beta_L,\beta_S\right) \approx \frac{1}{Z'_{\mathbf{x}}\left(\beta_L,\beta_S\right)} \exp\left[\beta_L V'_L\left(l, I^A(\mathbf{x})\right) + \beta_S \sum_{\mathbf{n}\in N(\mathbf{x})} V'_S\left(l, I^k(\mathbf{n})\right)\right]$$

Location weight (β_L) — Smoothing weight (β_S)

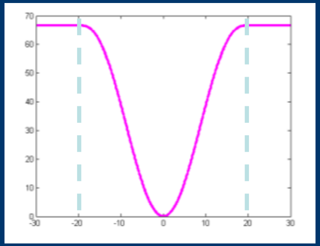
- In M-step, estimate $\beta_L^{k+1}, \beta_S^{k+1} =$

$$\arg\max_{\beta_L,\beta_S}\left[\sum_{\mathbf{x}}\sum_{l} p\left(I(\mathbf{x})=l \mid S,T,R^k\right)\log p\left(I(\mathbf{x})=l \mid \beta_L,\beta_S\right) + \log p\left(\beta_L,\beta_S\right)\right]$$

- Assign normal dist with small mean on β_L, β_S
  → Constraint so indicator map estimation not overly dependent on prior

Experiments: Methods Compared

- "Standard" non-rigid registration[1] (*SNRR*)
- Robust similarity[2] (*RSR*)
  - Reduce influence of outliers based on data term



Tukey Function

- Registration and indicator map estimation with only intensity prior[2] (*RIME-int*)
- Proposed approach (*RIME-imp*)

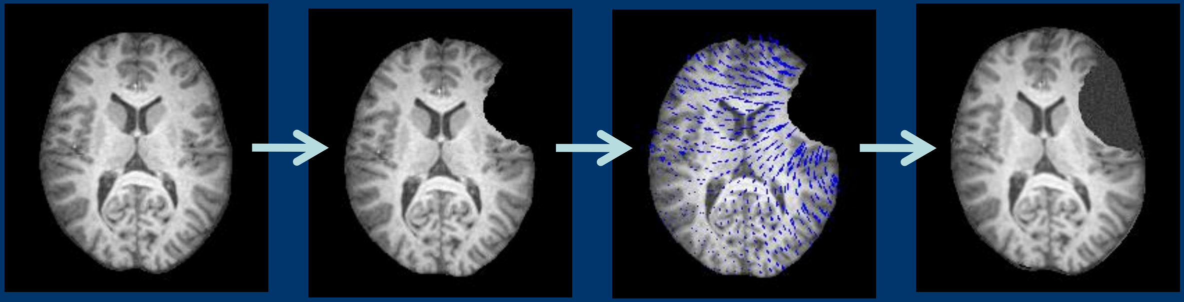
*All methods use:

- Voxel intensity-based similarity
- FFD transformation model

[1]Rueckert et al., TMI 1999; [2]Chitphakdithai and Duncan, MICCAI 2010

Synthetic Data: Setup

- Synthetic post-resection image creation

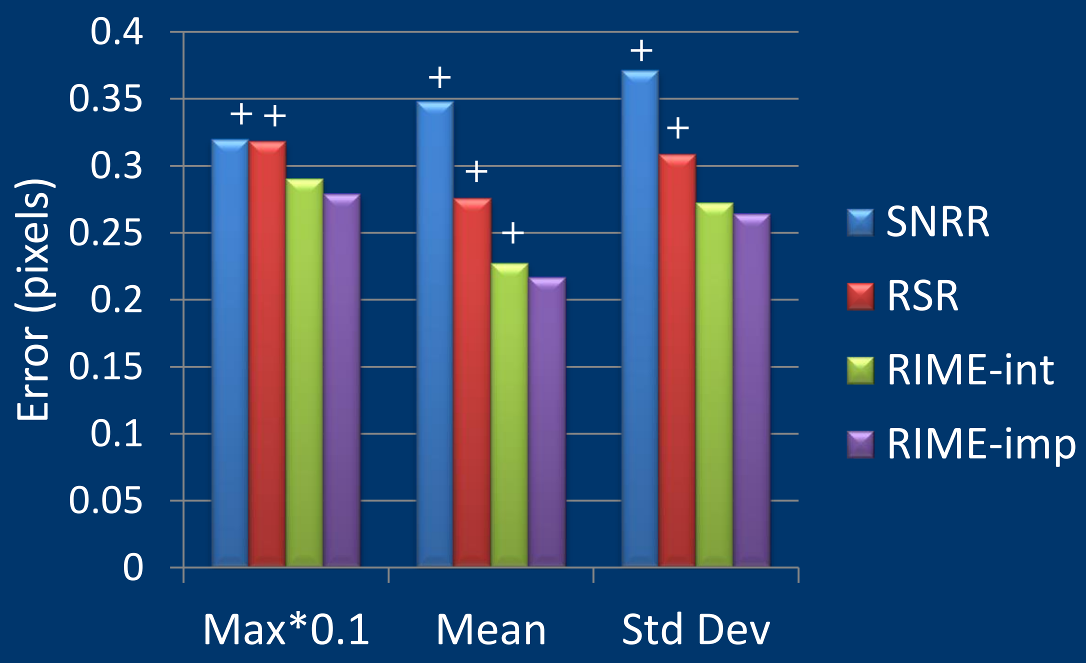


- Probabilistic atlas labels

- For intensity prior: leave-one-out method, trained on 10 images

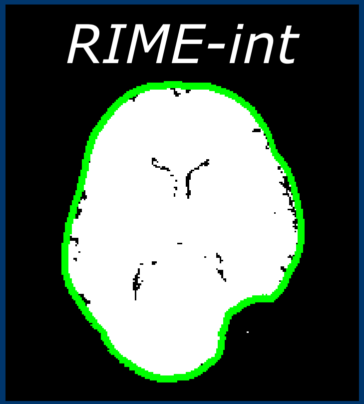
Synthetic Data: Results

Average Displacement Field Errors

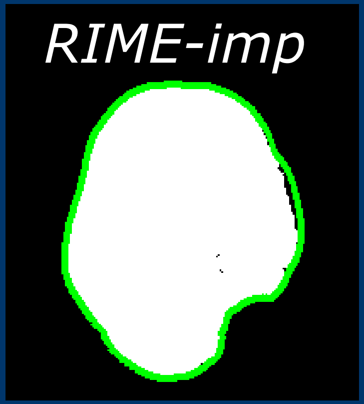


+ Significantly higher compared to *RIME-imp* ($p < 0.05$)

Valid Tissue Map



Dice: 0.98

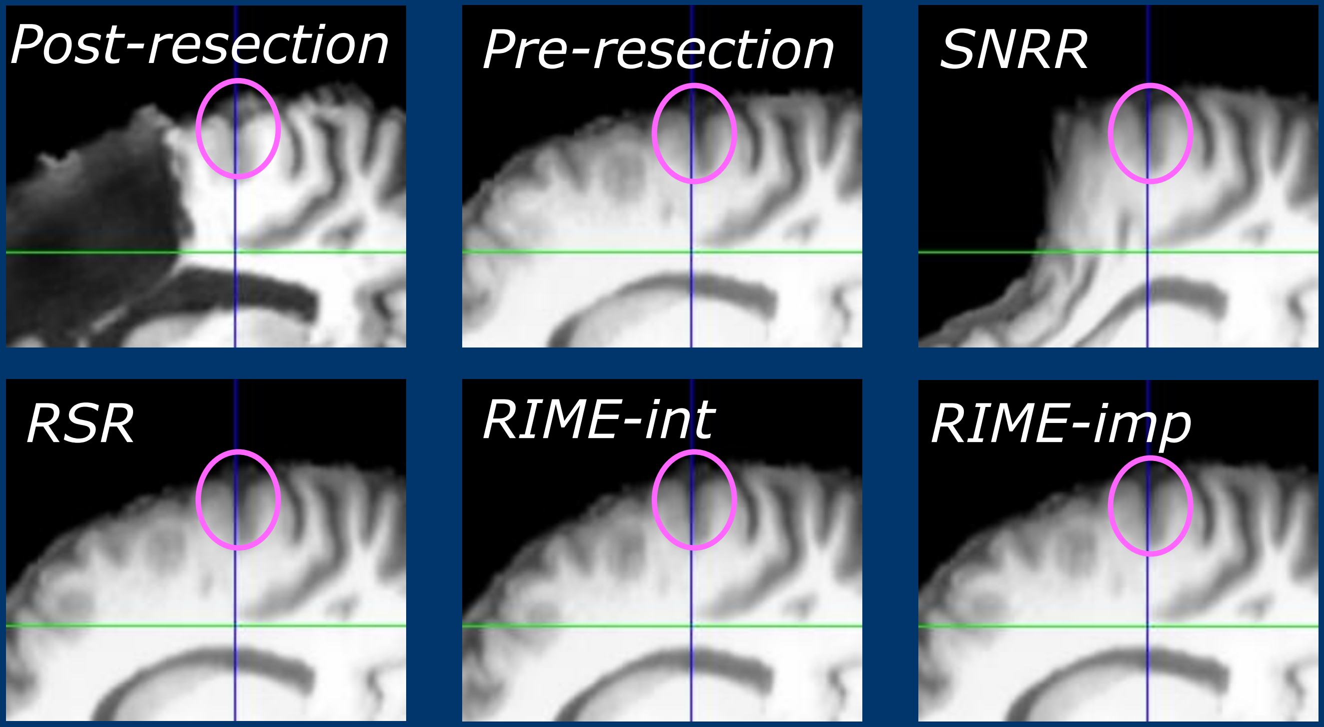


Dice: 0.99

($p = 0.0001$)

Patient Data: Registration Results

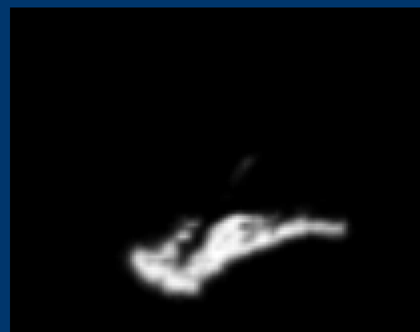
- 6 pairs, affine-aligned to standard MNI brain
- Custom atlas based on MNI atlas: 19 labels



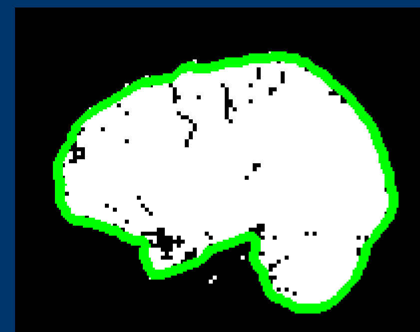
RIME-imp produced lowest RMSE ($p < 0.05$)

Real Data: Indicator Map Estimation

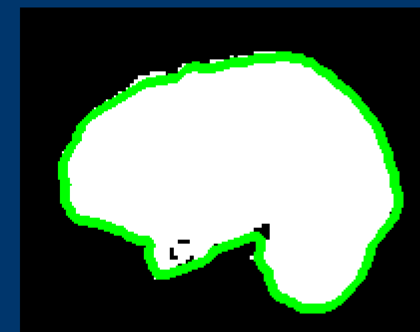
Left temporal lobe resection



Atlas for missing region location prior



Valid correspondence region using *RIME-int*



Valid correspondence region using *RIME-imp*

Average dice overlap between true and valid tissue regions:	*RIME-int*	*RIME-imp*
	0.92	0.96

* *RIME-imp* significantly increased overlap ($p < 0.05$)

Conclusions and Future Work

- Contributions
  - Registration handles missing correspondences by simultaneously estimating indicator map
  - Included MRF-based indicator map prior to incorporate location information and map smoothness

    → Improved label segmentation and registration accuracy
- Future Work
  - Increase number of labels, e.g. for CSF
  - Adapt general framework to other registration problems with missing correspondences

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