Principles of medical imaging data acquisition, registration, visualization and segmentation

Randy L. Gollub, MD, PhD
MGH Departments of Psychiatry & Radiology

September 30, 2009

Fundamentals of Image Processing for Extraction of Quantitative Metrics

• Anatomic (volume, label)
• Functional (DCE-MRI, fMRI or PET activation)

Available, reliable, reproducible, automatic or semi-automatic methods for each step.
Visualization

X-Ray Fluoroscopy

Computed Tomography

Magnetic Resonance Imaging

Ultrasound Imaging

Matching Image Acquisition Parameters to Target Biomarker

Primary outcome measures determine details of acquisition and analysis
Example: Advances in Structural MRI

Image acquisition
- Traditional pulse sequences
- Novel pulse sequence improves subcortical region

Acquisition Standardization Issues

- Within site
  -- Across hardware/software upgrade

- Across sites
  -- Across vendor, platform, (field strength)

- Longitudinal
Challenges of Advances in Image Acquisition

- Subtle (and not so subtle) differences in scanner platform
- Compliance with acquisition protocol
- Need for multi-modal registration
- Increased resolution results in increased sensitivity to error contributed by image acquisition and analysis methods

Interact in 3D to enhance data interpretation
What is an image?

2D array of pixels
**Pixel Dimensions**

The pixel size is the dimension in millimeters of the pixels.

**Data Representation**

The result of the acquisition is a 3D Volume of data related to the patient.

The 3D volume is sampled on a 3D grid in the acquisition coordinate system (I,J,K).
Anatomical Planes

A 3D Viewer displays a model of the head.

The 2D Viewers display the three anatomical planes (axial, sagittal, coronal).

Space Directions

Superior

Posterior

Right

Left

Inferior

Anterior
Space Orientation

Axes for Spatial Coordinates

RAS: Right-Anterior-Superior

The index \(i\) in the file increases from the Left to the Right side of the Patient.

The index \(j\) in the file increases from Posterior to Anterior.

The index \(k\) in the file increases from Inferior to Superior.
Axes for Spatial Coordinates

LPS: Left-Posterior-Superior

The index $i$ in the file increases from the Right to the Left side of the Patient.

The index $j$ in the file increases from Anterior to Posterior.

The index $k$ in the file increases from Inferior to Superior.

DICOM 3.0 Standard

Example of DICOM header content
Registration

Registration is the process of transforming these three different spaces into a common reference frame.

Patient → Image Transform

Patient Space

Image Space
Uses for Image Registration

Within or Intra-subject: images acquired at near or same time
Purpose: to combine functional and anatomical information of different imaging modalities
Examples: CT and MR for surgical planning
MR and PET/SPECT images of tracer uptake for localization of functional activity

Across or Inter-subject:
Purpose: To assess individual or group variability in some anatomical or functional measure
Examples: Responders vs. non-responders to treatment

Serial or Longitudinal: a sequence of images collected over time of the same subject(s)
Purpose: To assess change within a subject or group over time due to development, aging, disease progression and/or to monitor response to treatment.
Examples: Deformation based morphometry (months), fMRI (minutes)

Subject to atlas:
Purpose: To use population based information as priors to inform labeling or registration
Examples: Brain segmentation and parcellation, Boundary based registration

Why use registration?
(two time points, same subject)
How a Registration Algorithm Works

What Characterizes a Registration Algorithm?

1) Similarity metric (objective function): Sum of Square Differences (SSD), MSD, Normalized Correlation Ratio (n)CR, Normalized Correlation Coefficient (n)CC, Mutual Information (MI), …

2) Transformation: affine, piecewise linear, nonlinear …

3) Regularization: multi-resolution/scale, Gaussian blur, …

4) Optimization algorithm: simplex, gradient descent, …. 

5) Interpolation: nearest-neighbor (for label maps), trilinear, cubic, sinc, …
Transformation Models

Transformations are described by the number of parameters (often referred to as Degrees of Freedom or DOF)

<table>
<thead>
<tr>
<th>Transformation</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>identity</td>
<td>0</td>
</tr>
<tr>
<td>rigid</td>
<td>6</td>
</tr>
<tr>
<td>rigid+scaling</td>
<td>7, 9</td>
</tr>
<tr>
<td>affine</td>
<td>12, 15</td>
</tr>
<tr>
<td>non-rigid</td>
<td>10's - 100,000's</td>
</tr>
</tbody>
</table>

Number of Parameters

Rigid-body Transformation

- Compensates for global patient repositioning
- Preserves distances, planes and angles.

- Appropriate for:
  - brain, bone, optically tracked surgical instruments
  - often used to initialise non-rigid registration
**Affine Transformation**

- Compensates for additional global size changes and shears

  ![Smiley faces](image)
  
  Scaling (3)  Shear (3+3)

---

**Non-rigid Transformation**

- Pre-contrast
- Post-contrast
- Subtraction of pre- and post-contrast
- Subtraction of pre- and post-contrast after non-rigid registration
Challenges for Image Registration

• Matching the spatial scale of the tissue of interest (e.g. cortical thickness 1-5 mm)
• Image intensity inconsistencies
  - Contrast difference (e.g. T1 vs T2 MRI)
  - Distortion differences (e.g. EPI MRI vs MRI or PET)
• Image intensity inhomogeneities (e.g. due to receiver coil characteristics)

Segmentation Goals

Identify or label structures present in the image for:
- Quantitative measurement of volume, shape or location
- Provide boundary for visualization by surface rendering
Segmentation Methods

- Interactive or manual delineation
- Supervised approaches with user initialization
  - Thresholding
  - Clustering
  - Region growing
  - Edge detection
- Atlas based alignment with a template
- Statistical pattern recognition

Structural localization of function

Brodmann 1909
Desikan 2009
Automatically segmented structures

Freesurfer subcortical segmentation of the putamen, thalamus, hippocampus, amygdala, and caudate. Image constructed using Slicer 2.7 (www.slicer.org).

Automated Freesurfer segmentation output predicts MCI

- Entorhinal cortical thickness
- Hippocampal volume
- Supermarginal gyrus thickness

Desikan, et al in press, Brain
Technical Validation of Registration

Robustness:
  Measurement precision
Consistency:
  Circular (invertible) transformations
Visual assessment:
  Subtraction images, overlays, landmarks
Gold Standard:
  Implanted/attached markers, landmarks
Simulation of ground truth:
  Misregistration followed by motion recovery

Validation of Registration, Segmentation or any Image Processing Method

Prior to entering clinical practice:

Technical validation
  Speed, robustness, accuracy, reliability

Clinical validation
  Utility, improved diagnosis and patient management

FDA approval, incorporation into commercial system (?)
  Liability
Acknowledgements

Content sources include:
Arno Klein, PhD (Columbia)
Lilla Zolli, PhD (MGH)
Sonia Pujol, PhD (BWH)
Julia Schnabel, PhD (University of Oxford)
Daniel Rueckert, PhD (Imperial College London)
Simon Warefield, PhD (CHB)

National Alliance for Medical Image Computing
NIH U54EB005149