Volumetric Analysis of the Heart from Tagged-MRI

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Introduction & Background

- Heart
- Heart disease
- Heart motion
- Heart dynamics
- Deformable model
Motivation

The right ventricle (RV)

- Plays a role in normal hemodynamics
- Pathological states
  - May adversely affect the left ventricle (LV)
  - Can lead to heart failure
  - May be a result of pulmonary disease

Anatomy

From "Atlas of Human Anatomy", Netter, 93
Kinematic Approach

- Proper RV function depends on many factors (e.g. activation, perfusion)
- Several pathological states can affect motion
  - Infarction/Ischemia
  - Hypertrophy
- Abnormal RV motion can serve as an indicator of heart and lung disease
- Normal motion must first be characterized

Previous Methods: Kinematics

1. Radiopaque markers (i.e. lead beads)
   - Invasive
   - Provide discrete information
2. Echocardiography, CT, Conventional MRI
   - Provide information about wall borders
   - Motion is difficult to study due to:
     - Complex geometry and contraction patterns
     - Relative thinness
     - Lack of landmarks
3. Tagged MR images
MRI Image Plane Orientation

Short-axis

Long-Axis

MRI-SPAMM Tissue Tagging

Parallel Tagging Planes

Image Plane

Short-Axis

Long-Axis
Stacked set of images

Stripes provide a sampling of tag surface

Previous Planar Tagged MRI

- Non-invasive
- Cannot capture 3D motion
- Measurements are limited to image plane locations
- However, image sets from multiple views provide 3D motion information.
Image Acquisition for 3D Motion Information

Tag plane (dark) and image plane orientation

Possible tag motion in image plane

Representative images

3D Motion Reconstruction

Most techniques have been applied to the LV

1. Model based
   - Finite element mesh / Non-linear optimization [Young et al, 92]
   - This technique was applied to an RV surface model [Young et al, 96]
   - Superquadrics/ Deformable modeling [Park et al, 96]

2. Non-model based
   - Reconstruct tag surface data from multiple images
   - Intersect tag surfaces to obtain 3D motion of discrete points.
Right Ventricular Hypertrophy

- Increase in wall mass due to
  - Volume overload - congenital heart disease
  - Pressure overload - pulmonary hypertension
  - Both states can occur simultaneously
- Has been known to alter wall motion [Fayad et al, 96]
- Kinematics studies can be used to discriminate between normal hearts and those with RVH

Right Ventricular Hypertrophy

- Short-Axis
- Long-Axis
METHODS

Overview

- Image acquisition
- Contour segmentation
- Tag tracking
- RV-LV finite element mesh generation
- 3D motion reconstruction
- Validation
- Motion analysis
Geometry

Short-axis contours

Finite Element Mesh
Shaded Endocardial Walls

3D Motion Reconstruction
Deformable Modeling Approach

• Geometric model is fit to image-derived data
• Allows for inclusion of a priori geometric information
3D Motion Reconstruction

- Deformable Model Dynamics:
  \[ \frac{dq}{dt} = F_e + F_i \]
  where \( q \) = displacement at nodes

- \( F_e \): External, spring-like forces
  - Tags (SPAMM forces)
  - Contours
- \( F_i \): Internal, smoothing forces
  - Forces from all 3 directions were applied simultaneously

SPAMM forces

- Register initial position of tag planes to model
SPAMM forces

- Register initial position of tag planes to model
- Reconstruct tag surfaces from tag stripes

SPAMM forces

- Register initial position of tag planes to model
- Reconstruct tag surfaces from tag stripes
- Forces pull material points to tag surface
Validation

1. Motion simulator
   • Define a geometry and deformation
   • Generate synthetic tag and contour data
   • Apply 3D motion reconstruction
   • Compare known deformation to recovered deformation

2. *In-vivo* data
   • Intersect material planes with planes of the original images
   • Display intersection points with original images

Data Analysis

Applied fitting technique to 5 normals and 4 RVH patients

Finite deformation quantities:
• Minimum principal strain: $E_3$
• Minimum principal strain direction: $v$
• $\alpha_3$, angle between $v$ and local circumferential direction, $c$. 

\[ \alpha_3 \]
Regional Comparisons

Separated free wall and septum into regions using anatomical landmarks

RESULTS
Validation: Short-axis

End-diastole

End-systole

Validation: Long-axis

End-diastole

End-systole
• Contraction was significantly less in the basal region of the free wall and septum.
• No significant differences were found between corresponding regions in the free wall and septum.
Normals: Regional $\alpha_3$

- $\alpha_3$ was significantly smaller (more circumferential) at the base
- Free wall vs. septum: $\alpha_3$ was significantly smaller at the septal base and mid-ventricle

RVH: Displacement

0.0 28.8 mm

Paths of mid-wall points
RVH: E3

Free wall

- Significant decreases in base, mid, and outflow tract
Normal vs. RVH

$\alpha_3$

![Bar chart showing comparison between Normal and RVH at different angles (Base, Mid, Apex, Outflow).]

Free wall

DISCUSSION
Methodology

Combined:
- Deformable modeling [Park et al., 96]
- Registering material planes to model [Young, 98]
- Reconstruction tag surfaces [Moulton et al, 96]

Added:
- Detailed geometric RV-LV model
- Boundary forces to compensate for thin free wall
- Local, FEM-based, piecewise smoothing
- Automation of fitting technique
- First to successfully apply methods to RV

Time Requirements

<table>
<thead>
<tr>
<th>Time Required to Analyze Each Data Set</th>
<th>Method</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Contour segmentation (RV &amp; LV)</td>
<td>10 hours</td>
</tr>
<tr>
<td></td>
<td>Tag Tracking</td>
<td>1 ½ hours</td>
</tr>
<tr>
<td></td>
<td>3D Model Fitting (automatic)</td>
<td>40 min. (SGI  O²)</td>
</tr>
</tbody>
</table>
Limitations

- Spatial resolution
  - ~ 1mm/pixel in image
  - 6mm slice thickness
- Low temporal resolution (~40ms)
- Tag spacing: 5 to 6 mm
- Geometric model slightly misregistered
- Some parts of the mesh were too stiff to adequately fit the data

Normal Motion

- Angular displacement of RV similar to LV
- Greatest displacement at base
- Increasing base-apex gradient in free wall contraction similar to [Waldman, et al., 96].
- Planar (2D) deformation values similar to short-axis MRI measurements [Fayad 96, Klein 98, Stuber 95]
- Septal E3 values similar to 3D LV studies [Young, et al, 94].
Normal Motion

- Angle of E3 more circumferential in septum compared to free wall
- Previous 2D measurements found greater contraction in septum [Fayad, et al., 96]
- 2D measurements do not distinguish between magnitude and angle of contraction

Right Ventricular Hypertrophy

- Rotation of biventricular unit dissappeared
- Previous studies found decrease in 1D shortening for all regions [Fayad, et al., 96]
- We found significant decreases in E3 and an average decrease in E3 direction in the free wall
- Hypertrophied muscle:
  - Cells exhibit greater stiffness
  - Increased fibronectin in extracellular space
  - Orientation of fibers more circumferential [Tezuka, et al., 90]
Conclusions

- Developed the first volumetric 3D motion reconstruction technique for the RV
- Validation: good agreement between model and original images
- Obtained consistent results for 5 normal volunteers
- Found notable differences in deformation for RVH patients

Future Work

- The dense set of 3D motion data can be used to characterize RV motion, including timing differences
- Contraction can be compared with fiber angles
- Changes in deformation quantities during RVH can be correlated with presence and severity of disease