DEVELOPMENT AND APPLICATIONS OF
THE 4D NCAT PHANTOM

Benjamin M.W. Tsui and W. Paul Segars

Division of Medical Imaging Physics
Department of Radiology
Johns Hopkins University

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TRADITIONAL RESEARCH & DEVELOPMENT TOOLS

- Hardware/system development
- Theoretical derivations
- Experimental methods
  - physical phantoms
- Simulation techniques
  - computer generated phantoms
  - simulated data
- Clinical studies
Simulation techniques

- ‘Truth’ can be known
- Allow separation of individual imaging effects
- Previous limitations
  - Overly simplistic computer generated phantoms
    - No patient motion, single phantom
  - Inaccurate simulated projection data
    - Inaccurate models of imaging process
  - Long simulation time
- Common criticisms
  - Computer games, unrealistic, useless, waste of time
  - Too much simulation may seem like the real thing
  - Simulation will remain … “Simulation”
RECENT ADVANCES IN SIMULATION TECHNIQUES & STUDIES

◆ Improved computer generated phantoms
  – Accurately models of human anatomy and physiological functions
  – Provides flexibility in modeling patient variations

◆ Improved data generation techniques
  – Monte Carlo simulation methods to generate data that closely resemble measured data

◆ Availability of high speed computing
COMPUTER GENERATED PHANTOMS

<table>
<thead>
<tr>
<th>simple</th>
<th>complex</th>
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</thead>
<tbody>
<tr>
<td>geometric</td>
<td>patient data</td>
</tr>
<tr>
<td>shapes based</td>
<td>based</td>
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<tr>
<td>4D MCAT</td>
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THE 3D MCAT PHANTOM

SNM Mathematical Phantoms

More realistic description of sizes & shapes of tissue organs

by mathematical formulations

MATHEMATICAL PHANTOM
Total-body of the ICRP Reference Man

MATHEMATICAL PHANTOM OF THE HEART

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Beating Heart

- Simulates changes in:
  - chamber volume
  - LV wall thickness
  - heart rotation

- Heart mass and volume is that of “average” male

Respiratory Model

- Simulates changes in:
  - diaphragm height
  - ribcage rotation
  - Lung and body expansion and contraction
3D ATTENUATION COEFFICIENT DISTRIBUTION

Transaxial Slices for 72 keV radionuclide (Tl-201)

Transmission projection (chest X-ray)

flat diaphragm raised liver & diaphragm

A B A B
C D C D

HUMAN

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3D RADIOACTIVITY UPTAKE DISTRIBUTION

Transaxial Slices with typical TI-201 Uptake Ratios

Projections of uptake phantom (with effect of attenuation)

left  anterior  right  posterior
**CHARACTERISTICS OF ITERATIVE RECONSTRUCTION ALGORITHMS**

<table>
<thead>
<tr>
<th>Mean Images</th>
<th>Variance Images</th>
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<tbody>
<tr>
<td>ML-EM</td>
<td>ML-EM</td>
</tr>
<tr>
<td>WLS-CG</td>
<td>WLS-CG</td>
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<tr>
<td>OS-EM</td>
<td>OS-EM</td>
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<tr>
<td>RBI-EM</td>
<td>RBI-EM</td>
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<tr>
<td>Chang</td>
<td>Chang</td>
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</tbody>
</table>

<table>
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<tr>
<th></th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
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<tr>
<td>ML-EM</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<td>WLS-CG</td>
<td><img src="image5.png" alt="Image" /></td>
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<td><img src="image7.png" alt="Image" /></td>
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<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
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<tr>
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<td>Chang</td>
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<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
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</tbody>
</table>

*Lalush et. al, UNC-CH*
Monte Carlo simulated projection data of 3D MCAT phantom modeling 99mTc SestaMIBI activity distribution including the effects of collimator-detector response, photon attenuation and scatter.

- w/ primary photons only
- w/ primary & scatter photons

**No Comp.**  
**w/ A**  
**w/ AD**  
**w/ ADS**

**A:** Attenuation compensation  
**AD:** Attenuation & detector response compensation  
**ADS:** Attenuation, detector response, and scatter compensation

Frey et al.
# ATTENUATION COMPENSATION

<table>
<thead>
<tr>
<th>Phantom</th>
<th>Male w/ flat diaphragm</th>
<th>Male w/ raised diaphragm</th>
<th>Female w/ large breasts</th>
<th>Phantom</th>
<th>Male w/ flat diaphragm</th>
<th>Male w/ raised diaphragm</th>
<th>Female w/ large breasts</th>
</tr>
</thead>
<tbody>
<tr>
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<td>No defect</td>
<td>No defect</td>
<td>No defect</td>
<td>No defect</td>
<td>No defect</td>
<td>No defect</td>
</tr>
<tr>
<td>Anterior defect</td>
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<td>Anterior defect</td>
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<tr>
<td>Inferior defect</td>
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<td>Inferior defect</td>
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<tr>
<td>Septal defect</td>
<td>Septal defect</td>
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<td>Septal defect</td>
<td>Septal defect</td>
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</table>

FBP reconstructed images
With no compensation

ML-EM reconstructed images
w/ attenuation compensation
POPULATIONS OF 3D MCAT PHANTOM

**Human PET Images**

- Male Population
- Female Population

**3D MCAT**
- w/ flat diaphragm
- w/ raised diaphragm

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ROC RESULTS
Human observers viewing simulated images*

Average of 6 Observers

MALE
FLAT diaphragm

MALE
RAISED diaphragm

FEMALE
FLAT diaphragm

FPF

TPF

FB: FBP reconstruction without any compensation
ML: ML-EM reconstruction with attenuation compensation

* Data from a population of 24 3D MCAT phantoms

LaCroix et al.
Limitations of 3D MCAT phantom
- Difficulty in modeling exact shapes of organs by equations
- Limited ability in modeling physiological functions

Solutions
- Visible Human dataset for modeling organ shapes
- Non-uniform rational b-splines (NURBS) to describe organ shapes
- 4D tagged MRI data for modeling heart motion
  (courtesy of Elliott McVeigh, Ph.D., NIH)
- 4D respiration gated CT data for modeling respiratory motion
  (courtesy of Eric Hoffman, Ph.D., University of Iowa)
NURBS-based Cardiac-Torso (NCAT) Phantom

Previous 3D MCAT Phantom

Sample Slices from the Visible Human CT Data Set

4D NCAT Phantom (anterior view)

3D NURBS Organ Models

With realistic beating heart & respiratory motions

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NCAT Heart Model
Coronary Artery Disease (CAD)

Plaques and Perfusion Defects

- Plaques modeled as NURBS surfaces on the interior of the arteries
- Perfusion defects modeled as wedges in the LV myocardium as in the MCAT
SAMPLE 3D NCAT PHANTOM POPULATION

- Anatomical and organ uptake variations
  - Geometric parameters of torso
  - Size, shape and orientation of heart
  - Radioactivity uptakes of different organs

Heart Variations

24 phantoms (half male, half female)

Anatomical Variations

He, Frey, Segars, Tsui et. al, JHU

Uptake Variations
EVAULATION OF QUANTITATIVE MYOCARDIAL SPECT

- A population of 3D NCAT phantoms
- Monte Carlo simulated data
- Hotelling Observer

![Graph showing AUC vs Cutoff Frequency](image)
Experimental Results (TI Short-axis images)

From Separate Acquisition

From Simultaneous Acquisition

Reconstructed using OS-EM with compensation for attenuation, collimator-detector response and scatter. 4 images per subset, 5 iterations

He, Frey et al.
AUC for Optimal Parameters (TI-201 Images)

Frey et al.
NCAT Heart Model Based on Tagged MRI Data

Diastole | Systole
---|---
short axis slice (x)

orthogonal short axis slice (y)

long axis slice (z)

Animated Motion Derived From Tagged Data

Data courtesy of McVeigh et al., NIH and Johns Hopkins University

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NCAT Heart Model Based on Tagged MRI

Long Axis View

Contracting motion (ED to ES)

Twisting motion (ED to ES)

Short Axis View
### Conventional Filtered Backprojection Method

**Number of Time Frames per Cardiac Cycle**

| 8 | 12 | 16 | 24 |

**Ramp Filter**

- **Cutoff Frequency (cycle/pixel)**
  - 0.5
  - 0.25

*Images showing different time frames and cutoff frequencies.*

---

*Lee, Tsui, Segars*
## GATED MYOCARDIAL SPECT

### Comparison of FBP, OS-EM and 4D RBI-MAP Methods

<table>
<thead>
<tr>
<th># of Cardiac Gates</th>
<th>FBP (ramp filter)</th>
<th>OS-EM (16, NoCorr.)</th>
<th>OS-EM w/Corr. (16 update)</th>
<th>4D MAP w/Corr. (16 update)</th>
</tr>
</thead>
</table>

# of Updates = # of iterations x # of subsets

Corrections of attenuation, detector response and scatter

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Lee, Tsui, Segars

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NCAT Respiratory Model

- Based on respiratory-gated CT data (U. of Iowa)
- Used IDL program to mark and track points on the respiratory structures (U. Mass.)

Interactive IDL Program

Motion vectors for the lung
NCAT Respiratory Model

Inspiratory Motion in the NCAT

Animated Motion

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EFFECT OF RESPIRATORY MOTION on PET lung nodule detection

PET Simulation

4D NCAT Phantom with Lung Lesion

Reconstructed Images
NCAT Respiratory Model

Effects of Respiratory Motion on Myocardial SPECT

- NCAT phantom was set to simulate Tc-99m Sestamibi uptake
- Imaging process simulated with and without an average respiratory motion
- Resulting images compared to see the effects of respiratory motion

Without respiratory motion

With respiratory motion (2 cm)

With respiratory motion (4 cm)

Reconstructed SA slice (OSEM) Bull’s eye

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Effects of Respiratory Motion on Myocardial SPECT

No Respiratory Motion

<table>
<thead>
<tr>
<th>Location</th>
<th>Image</th>
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<tbody>
<tr>
<td>Normal</td>
<td>No defects</td>
</tr>
<tr>
<td>Inferior</td>
<td>Defect</td>
</tr>
<tr>
<td>Lateral</td>
<td>Defect</td>
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<td>Defect</td>
</tr>
<tr>
<td>Septal</td>
<td>Defect</td>
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Respiratory Motion

No respiratory gating, attenuation correction using average attenuation map

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<td>Defect</td>
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</table>
RESPIRATORY GATING SCHEMES
in Respiratory Gated Myocardial SPECT
3 Respiratory Gates with Gated Attenuation Map

No defect
Normal: No defects
Inferior: defect
Lateral: defect
Anterior: defect
Septal: defect

3 Respiratory Gates with Averaged Attenuation Map

No defect
Normal: No defects
Inferior: defect
Lateral: defect
Anterior: defect
Septal: defect

Intensity Ratio vs. Gate Number for different schemes:

- Scheme 3A
- Scheme 3B
- Scheme 3C
- Scheme 3D

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6 Respiratory Gates with Gated Attenuation Map

Normal                       Inferior                      Lateral                     Anterior                      Septal
No defects                     defect                        defect                       defect                         defect

6 Respiratory Gates with Averaged Attenuation Map

Normal                       Inferior                      Lateral                     Anterior                      Septal
No defects                     defect                        defect                       defect                         defect
RECENT ADVANCES IN THE 4D NCAT PHANTOM

Beating Heart with Coronary Arteries

Extended Anatomy

Detailed Vasculature

LV with Coronary Arteries, a defect and a plaque

Brain Model

Complete Airway Tree

WP Segars & BMW Tsui, Johns Hopkins
Future Developments

More detailed heart structures and vessels based on high-resolution Multislice CT

Modeling of heart fiber angles based on diffusion tensor MRI

Segars, Tsui, Gullberg
Future Developments

Segmented Airway Tree

Complete 4D Airway Tree Model
(extended using mathematical algorithm based on physiology)

Garritty, Segars, Tsui
Molecular Imaging Simulation

- Development of a 4D digital mouse whole body (MOBY) phantom for molecular imaging research

Digital Mouse Phantom

MicroCT images simulated from the mouse phantom

MicroSPECT (bonescan) images simulated from the mouse phantom

MicroSPECT (bonescan) images simulated from an actual mouse

MicroCT images from an actual mouse

Segars, Tsui
4D Beating Heart and Respiration Models

Beating Heart Animation

Heart Volume Curves

Segars, Tsui

RV LV RA LA

Time Frames

Volume (microliters)

0 2 4 6 8 10 12

0 10 20 30 40 50 60

Segments

Resp. parameter (mm)

0 1 2 3 4 5 6

0 -0.2 -0.4 -0.6 -0.8 -1.0

ΔAP

Vol. (mL)

0 0.04 0.08 0.12 0.16

0 1 2 3 4 5 6

Δdiaphr.
SUMMARY

- The 4D NCAT phantom is based on anatomical and dynamic image data from normal human subjects.
- It realistically models human anatomy and beating heart and respiratory motions.
- The use of computer graphics tools allows flexibility to model patient populations.
- It has been extended to include the entire human body.
- It has been found useful in a wide range of applications in nuclear medicine imaging research.
- Continuing development is underway to extend the 4D NCAT phantom to higher resolution for applications in CT and MRI.
ACKNOWLEDGEMENTS

Research Grant Support

◆ NIH grant, “Corrective Image Reconstruction Methods for ECT”
◆ NIH grant, “Simultaneous Dual Isotope SPECT w/Cross-talk Correction”
◆ NIH grant, “Task-Based Optimization for Gated Myocardial SPECT”
◆ U.S. Army CDMRP Idea Development Award, “Corrective In-111 Capromab Pendetide SPECT Image Reconstruction Methods for Improved Detection of Recurrent Prostate Cancer”
◆ NIH grant, “SPECT Mammography using rotating slant hole collimator”
◆ NIH grant (subcontract), “Improved Heart SPECT Imaging with Convergent Collimators”