Evolution: A Framework for Advanced SPECT Reconstruction with Compensation for Image Degrading Factors

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Clinical Bone SPECT Images and Evaluation
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Disclosure

Under a licensing agreement between the General Electric Company and the Johns Hopkins University, I (Eric Frey) am entitled to a share of royalty received by the University on sales of the Evolution product described in this presentation. The terms of this arrangement are being managed by the Johns Hopkins University in accordance with its conflict of interest policies.
Goals

- Describe Evolution and its constituents
  - Reconstruction
  - Optimization
  - Validation
- Describe Evolution reconstruction and its components
- Show some results from preclinical validation
- Discuss optimization of acquisition and reconstruction parameters
- Demonstrate application of Evolution reconstruction to clinical data
  - Bone SPECT
  - Myocardial perfusion SPECT
What is Evolution?

- Iterative Reconstruction Algorithm
- Models for Imaging System
- Attenuation Map

Evolution Reconstruction

Preclinical Validation

Integration

- Optimization
- Clinical Validation
- Evolution for ?Prostate?
- Evolution for ?Cardiac?
- Evolution for Bone

GE & JHU
Evolution Reconstruction

- Statistical Iterative Reconstruction
- Compensation for Physical Image Degrading Factors
Statistical Image Reconstruction

- Projection data are corrupted by Poisson noise
- Statistical reconstruction methods
  - Explicitly model Poisson noise
  - Operate by finding activity distribution that “best fits” measured projection data
  - “Best fit” is judged by value of objective function
Iterative Reconstruction-Based Compensation

- Initial Estimate
- Project at each View
- Computed Projections
- Compare Computed & Measured
  - Measured Projections
  - Objective Function
  - Iterative Algorithm
- New Estimate
- Update Estimate
- Computed Projections

Iterative Algorithm
Maximum Likelihood (ML) Objective Function

• “Likelihood” is a statistical concept
• Find activity distribution that is “closest” to projection data
• Problem: tends to fit noise in projections
Maximizing the Objective Function

– Requires iterative procedure
– A variety of iterative algorithms have been proposed
– Properties of iterative algorithms
  • Reconstruction time
  • Theoretical rigor
  • Complexity to implement
  • Properties of image
    – Noise magnitude and texture
    – Spatial resolution
    – Contrast resolution
Common Iterative Algorithms

• Expectation Maximization (EM)
  – Easily applicable to Poisson Likelihood Objective function (ML-EM)
  – Converges very slowly (many iterations required)

• Ordered subsets expectation maximization (OS-EM)
  – Much faster than EM (speedup $\approx$ # subsets)
  – Not theoretically rigorous
  – Problematic for very noisy data and large # subsets
Iterative Reconstruction-Based Compensation

- Initial Estimate
- Project at each View
- Computed Projections
- Compare Computed & Measured
- Measured Projections
- Objective Function
- Iterative Algorithm
- New Estimate
- Models of Degrading Effects
- Update Estimate
- Compare Computed & Measured
- Objective Function
- Iterative Algorithm
Image Degrading Factors

- SPECT Projection images are degraded by
  - Attenuation in patient
  - Scatter in patient
  - Collimator-detector response
  - Poisson noise
SPECT Image Formation

Point response function

Real Collimator

Absorbed

Scattered

Multiply Scattered

Source

Scattered

Attenuation

Scatter

CDR blurring
Characteristics of Attenuation

- Attenuation depends on depth, material, isotope

![Graphs showing attenuation for Tc-99m and TI-201 isotopes in muscle, lung, and bone across different depths.](slides_not_to_be_reproduced_without_permission_of_the_author)
Characteristics of Scatter

- Importance of scatter increases with depth
- More scatter for isotopes emitting lower energy photons
- Shape of scatter response varies spatially and is patient-dependent

![Graph showing scatter response vs. source depth for Tc-99m and TI-201](image)
Characteristics of the CDR

- Width of CDR increases with distance from face of collimator
- CDR is constant in planes parallel to face of collimator
Effect of Geometric CDR on SPECT Images

- Loss of resolution
- Spatially varying resolution

Point Source Phantom

FBP Reconstruction from Projections with LEHR Collimator
Poisson Noise

- Projection data corrupted by Poisson noise
- Noise level determined by:
  - injected activity
  - imaging time
  - sensitivity of collimator-detector system
- Noise is spatially varying
- Noise is irreversible, but effects can be "controlled"
Effect of Poisson Noise
OS-EM Reconstruction

- Noise increases with # updates
- Post-filter needed to control noise

Updates

No Post-filter

3D Butterworth Post-filter
goed=8
cutoff=0.24 pixel^{-1}

Updates= # iterations x # subsets
Modeling Attenuation in Evolution

- Requires patient-specific attenuation map
- Can be obtained by
  - transmission imaging
  - x-ray CT image
- Good registration is critical (better than 1 pixel)
Scatter Modeling in Evolution

- Estimated using effective scatter source estimation (ESSE)
  - Physics-based method
  - Accurately models spatial variance of scatter response

- Better than alternative approaches such as triple-energy window (TEW) method which can
  - Provide less accurate scatter compensation
  - Result in increase image noise
CDR Modeling in Evolution

- Models spatially varying geometric CDR based on analytical formulas
- Supports modeling of full CDR

MEGP Collimator

HEGP Collimator

Distance from Collimator Face

5 cm  10 cm  15 cm  20 cm

I-131 Point Source

30 cm
Efficacy of Attenuation and Scatter Compensation

From Unscattered Photons
From Unscattered+ Scattered Photons

No Comp
Atten Comp
Atten & Scatter Comp

Reconstructed Pixel Value
Pixel Number

Unscattered-NC
Scattered+Unscattered-NC
Unscattered-AC
Scattered+Unscattered-AC
Scattered+Unscattered-ASC
Efficacy of CDR Compensation

- Resolution improves with iteration but remains limited: cannot totally recover resolution
- Resolution remains spatially varying
- Resolution for LEHR better than for LEGP
Effect of Compensation on Image Noise

- Noise increases with iteration
- Attenuation Comp has larger noise where attenuation is greatest
- CDR comp results in "lumpy" noise
- Texture of noise w/CDR comp
  - varies spatially
  - depends on collimator

<table>
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<th>Updates</th>
<th>128</th>
<th>320</th>
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<th>1280</th>
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<tr>
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<td>Atten</td>
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<tr>
<td>CDR LEGP</td>
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<tr>
<td>CDR LEHR</td>
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</table>
Tools for Validation and Optimization

- Phantoms
- MC Simulation
- Observer studies
- ROC Analysis
Tools for Validation: Phantoms

- **Physical Phantoms**
  - Cylindrical Phantoms
    - 270°
    - 180°
    - 90°
    - 0°
  - RSD Phantom
  - Torso Phantom

- **Mathematical Phantoms**
  - MCAT Phantom
  - NCAT Phantom

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Tools for Validation: Phantoms

- Phantom population
MC Simulation

Comparison of MC Simulation and Experiment
3.39 cm diameter Sphere w/In-111 in Elliptical

Example of Simulation of In-111 Zevalin Distribution

Computer Cluster

Activity Attenuation Low-Noise SPECT
Map Projections Projection
Preclinical Validation

• Validate accuracy of models of degrading effects compared to simulation and experiment
  – Simple activity distributions
  – Realistic activity distributions

• Validate effect on reconstructed images
  – Contrast, noise, SNR
  – Observer studies
Observer Studies

• Evaluate image quality with respect to detection of
  – Bone lesions
  – Perfusion defects

• Use
  – Human observer studies
  – Mathematical observer studies
    • Similar to computer aided diagnosis tools
    • Designed to predict human observer performance
      – > 90% correlation in predicting performance
      – > 96% correlation in predicting rankings
Observer Studies

- Use ROC Analysis
- Area under ROC curve is measure of performance
  - AUC=1 for perfect performance
  - AUC=0.5 for guessing

![ROC Curve Diagram]

False Positive Fraction (1-specificity)
True Positive Fraction (sensitivity)

- FBP
- OSADS
- OSADS-NCC
- OSADS-MBCC
- OSADS-True CC
Validation Using Simple Phantoms

Tc-99m

9.7 cm diameter circular cylinder filled with styrofoam beads and water (dens=32% of water)

31.2 x 22.8 cm water-filled elliptical cylinder

1 cm diameter sphere w/ Tc-99m

Non-Uniform Attenuator
Validation Using Simple Phantoms: Tc-99m
Validation using MCAT Phantom

Error in SPR over all views: <5%

-45°  0°  45°  90°  135°

MC simulation

Difference

projector
Validation: Bone SPECT

- Hot sphere on warm background
  - background:sphere = 1:20
  - 120 views, 360 degrees, 2.21 mm pixels
  - Collimator

Phantom:
- 1.3 cm
- 1.0 cm
- 0.9 cm
- 3.5 cm

Study performed by GE Haifa

OS-EM
2 it, 10 subsets
Chang AC

OS-EM w/CDR
4 it, 10 subsets
Chang AC
Validation: Torso Phantom Reconstruction

Activity ratios: heart : liver: torso = 10 : 10 : 1

A=Attenuation Compensation
AD=Attenuation and CDR Compensation
AS=Attenuation and Scatter Compensation
ADS=Attenuation, CDR and Scatter Compensation
Preclinical Validation
In-111 Imaging

RSD Phantom Projection Coronal CT Image

NC A AS AGS ADS Atn Map

NC=No Compensation
A=Attenuation Compensation
AD=Attenuation and CDR Comp
AS=Attenuation and Scatter Compensation
ADS=Attenuation, CDR and Scatter Comp
Accuracy of Activity Quantitation: RSD Phantom and In-111

% Error in total activity estimation: (true-estimate)/true x 100%

With appropriate reconstruction, quantitative SPECT is possible!
Preclinical Validation: In-111 Prostascint

Clinical Images w/Simulated high-contrast lesion

OS-EM
No effects modeled,
20 updates, (clinical default)
Post-filtered

OS-EM ,
Attenuation Modeling,
12 updates, ("optimized")
Post-filtered

OS-EM
Atten, CDR and Scatter Modeling,
16 updates, ("optimized")
Post-filtered
Clinical Applications

• Bone SPECT
  – Optimization
  – Clinical Validation

• Myocardial Perfusion SPECT
  – Optimization
  – Clinical Application
Bone SPECT Optimization

• Is OS-EM w/ CDR compensation better than OS-EM w/ no compensation for
  – Same acquisition time
  – Half acquisition time
  – Same collimator
  – LEGP vs. LEHR collimator
Bone SPECT Optimization: Phantom Study

• Methods
  – Hot spheres on warm background
  – Computed sphere SNR and Contrast Recovery

• Results
  – LEHR better than LEGP
  – OSEM w/ CDR better than OSEM w/o CDR
  – OSEM w/ CDR at ½ acquisition time better than OSEM w/o CDR

Study performed by GE Haifa
Bone SPECT Optimization: Simulation Study

- NCAT Phantom Population
- LEHR Collimator
- Clinical count level
- Simulated Poisson noise
- Mathematical Observer (MO)
- ROC Analysis

Bone SPECT Optimization: Simulation Study

- Multiple lesion locations
- Lesion contrasts
  - 2:1, 3:1, 5:1
- Lesion Sizes
  - 0.5, 1.0, 2.0 cm

MIP image for 10 min SPECT acquisition reconstructed with CDR compensation
Bone SPECT Optimization: Simulation Study Results

NC=no comp
CDR= w/CDR comp
Full Time=Normal clinical acq. time
Half Time=half clinical acq. time

Half time reduces AUC

Half time w/CDR as good or better than full time w/o CDR

Area under ROC Curve

pelvis
spinous process
transverse process
rib
vertebral body
Clinical Application of Evolution for Bone

Today

Whole Body Planar  20 min
SPECT 1  15 min

Today’s procedure

Evolution - ½ time

Whole Body Planar  20 min
SPECT 1  7.5 min

Reduce overall acquisition time by 30% w/same quality

Evolution - WB SPECT

SPECT 1  7.5 min
SPECT 2  7.5 min
SPECT 3  7.5 min

3D Imaging in same time as planar imaging
Clinical Validation
Bone SPECT

- 46 patients, 102 lesions, Consensus read by 4 physicians
- OS-EM full-time vs. half-time OS-EM
  - 14 studies had similar quality
  - 32 studies half-time had poorer quality
  - 5 lesions detected missed on half-time acquisition
- OS-EM full-time vs. half-time OS-EM w/CDR
  - 74% of studies had similar quality
  - 5 studies: OS-EM had better quality
  - 7 studies: Half-count OS-EM w/CDR had better quality
  - 1 lesion seen only on OS-EM w/CDR
  - 1 lesion changed from 1 to 2 (5 point scale) on OS-EM w/CDR

Clinical Validation
Bone SPECT

In 34 of 120 patients (28%), Multi-FOV SPECT detected lesions that would have been missed had planar and a single SPECT been performed.

Courtesy of Dr. E. Even-Sapir, Tel Aviv Medical Center
Clinical Validation

Bone SPECT

Lesion missed on wholebody planar images

Images from Dr. E. Even-Sapir,
Tel Aviv Medical Center
Clinical Validation
Bone SPECT

Prostate Cancer: high risk for bone metastases.

What FOV for spot SPECT?

Images from Dr. E. Even-Sapir, Tel Aviv Medical Center

Planar Wholebody

Tc-MDP SPECT

MIP
Clinical Validation
Bone SPECT

Prostate cancer w/ high risk for bone metastases

Images from
Dr. E. Even-Sapir,
Tel Aviv Medical Center

Spot Planar

SPECT

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Clinical Validation
Bone SPECT

Was SPECT correct?

SPECT

CT

F-18 PET

Image quality approaching PET

24 min

F-18 PET MIP

SPECT MIP

Images from Dr. E. Even-Sapir, Tel Aviv Medical Center
Cardiac SPECT Optimization

• Questions
  – Which combination of compensations?
    • A, AS, AD, ADS?
  – What is optimal number of iterations/subsets?
  – What is optimal post-reconstruction filter?
  – 180 or 360° acquisition arc?
  – Can we reduce acquisition time?
Perfusion Defects

– Six different locations with 36 different sizes
  • Size: randomly varied ±25% around the mean
  • Contrast: randomly varied in the range 10-35%
Optimization of Iterative Reconstruction

- Area under ROC Curve vs. Iterations
- Area under ROC Curve vs. Cutoff Frequency (pixels\(^{-1}\))

- Iterations: 2, 4, 6, 8, 10, 12
- Cutoff Frequency: 0.12, 0.16, 0.2, 0.24, 0.28, 0.32

Lines and markers indicate different cutoff frequencies:
- 0.12 pixel\(^{-1}\)
- 0.16 pixel\(^{-1}\)
- 0.28 pixel\(^{-1}\)
Cardiac SPECT Optimization

AUC for defects in 6 different locations when using ADS, A and N method.

- AUC values varied with defect location
- Sometimes A is worse than N
- ADS as good as or better than any method for all defect locations

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Cardiac SPECT Optimization: 180° or 360° Arc

<table>
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<th>Method</th>
<th>180°</th>
<th>360°</th>
<th>p-value</th>
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<tr>
<td>ADS</td>
<td>0.782</td>
<td>0.780</td>
<td>0.32</td>
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<tr>
<td>AD</td>
<td>0.777</td>
<td>0.770</td>
<td>0.26</td>
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<tr>
<td>AS</td>
<td>0.770</td>
<td>0.762</td>
<td>0.1</td>
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<tr>
<td>A</td>
<td>0.764</td>
<td>0.756</td>
<td>0.2</td>
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<tr>
<td>N</td>
<td>0.741</td>
<td>0.735</td>
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<td>FBP</td>
<td>0.740</td>
<td>0.718</td>
<td>0.0066*</td>
</tr>
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* Statistically significant difference at p<0.05
Cardiac SPECT Optimization
Acquisition Time

MO Study

Clinical count level = 1.0

- OSEM w/ ADS better than OSEM w/ No Compensation (NC)
- Can reduce acquisition time by ½ w/o degrading lesion detectability

Compare MO and Human Observers
Cardiac Imaging
Clinical Validation

- Clinical validation by GE and JHU in progress

<table>
<thead>
<tr>
<th>FB</th>
<th>A</th>
<th>AD</th>
<th>ADS</th>
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<td>VLA</td>
<td></td>
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<tr>
<td>SA</td>
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FB: Filtered Backprojection
A: OS-EM w/ Atten. Comp.
AD: OS-EM w/Atten. and DRF Comp.
ADS: OS-EM w/Atten., DRF & SRF Comp.
Butterworth Post filter (order=5, cutoff=0.28 pixel⁻¹)
Summary
Statistical Image Reconstruction

• Statistical reconstruction
  – Allows compensation for image degrading factors
  – Requires application-specific optimization
  – Can provide improved image quality
  – Can provide quantitative SPECT images
Summary
Compensation for Degrading Effects

- **Attenuation**
  - works well with high-quality attenuation map

- **Scatter**
  - works well when appropriately implemented
  - Model-based can provide reduced noise compared to energy-window based (E.g., TEW)

- **CDR**
  - Improves resolution
  - Reduced high frequency noise
  - Does not completely restore resolution
  - Resolution remains spatially varying
  - Introduces spatially-varying noise texture

- **Noise**
  - Appropriate # of subsets, iterations and post-reconstruction filter help control noise
Summary
Evolution Framework

• Evolution Framework
  – Evolution Reconstruction
    • OS-EM
    • Models for Attenuation, CDR, Scatter
  – Preclinical Validation
  – Application-specific optimization
  – Clinical Validation
Summary

Current Status of Evolution

- Evolution for Bone now available
- Evolution for Cardiac, Prostate
  - Clinical validation in progress
Summary
Evolution for Bone

• OSEM w/CDR allows SPECT in ½ time (7.5 min) of clinical standard with equivalent or better image quality compared to OSEM w/o CDR

• Can perform whole body SPECT (4 FOV) in same time as wholebody + 1 FOV SPECT
  – Equal or better contrast compared to planar
  – 3D information provides better localization information
  – No need to interrupt clinical flow or guess at appropriate FOV for SPECT
  – Image quality approaching PET w/o equipment upgrade