Deviceless respiratory motion correction in PET imaging – exploring the potential of novel data driven strategies
Presented by Adam Kesner, Ph.D., DABR
Assistant Professor, Division of Radiologic Sciences, Department of Radiology, University of Colorado School of Medicine

Introduction

- Respiratory and cardiac motion are inherent problems in medical imaging
- Limits scan quality
  - Resolution
  - Quantification
  - Lesion detectability
  - AC artifacts

Thorax PET Spatial Resolution vs Time

Simulation

True projection, PET slice

2015 AAPM spring clinical meeting
Introduction

- Respiratory motion considered the resolution limiting factor in thorax imaging
- Future perspective

“Respiratory motion handling is mandatory to accomplish the high-resolution PET destiny”

Kesner et al., EJNMMP Physics, 2014

Detection AC artifacts

SUV quantitation
Introduction

- State of respiratory gating technology in nuclear medicine:
  - 10+ years of research
  - Major vendors sell integrated systems
  - Many clinics own necessary equipment

- Respiratory gating rarely used in routine imaging

- (my) question: why is respiratory motion correction failing its transition into the clinic?
- (my) answer: cost / benefit
- (my) solution: stick around for the talk!

- Cost / benefit of gating
  - Most respiratory gating is implemented using hardware based respiratory tracking equipment
  - Negatives of such equipment include
    - Patient discomfort
    - Prone to setup error
    - Slower throughput
    - Increased costs (hardware, training)
    - Increased radiation dose
  - Overall gating represents a change towards complexity when considered for use in routine scanning

- Cost / benefit of gating
  - There is a fundamental tradeoff when gating
    - Improved resolution comes with the loss of image statistics
    - Benefit uncertain
Introduction

• Gating comes with a cost and has uncertain benefit

If we can bring the cost of gating to nil, and the benefit to guaranteed – that could change the equation.

• We propose to do this with 2 independent / integratable steps
  o Both based on utilizing information currently unused

Presentation overview

Software driven motion control

1. Software driven gating analogous to hardware
2. "Gating+" method for signal optimization
3. Recovery of continuous motion method for decoupling data from gates it was created with
4. Summary/implications

Software driven gating

* * *

Section I
Respiratory gating in PET

- Hardware driven gating is the field standard
- In recent years several software-based methods have been presented to extract respiratory signal to be used for gating
- Software driven methods appeal
  - Ease of use
  - Operator independent
  - None of the errors in the application of hardware
  - If integrated properly, their implementation would be a software add-in, and require no change to current clinical protocols

Introduction

- The idea behind software based algorithms:
  - There is a lot of information in list mode data not being utilized
    - signal from respiratory motion
- The challenge:
  - How to sort out signal from the noise?

IVF method (2009)

- Image Voxel Fluctuation method for extracting respiratory signal from data
  - Use the fluctuating signals per voxel over time
    - ~2*10^7 voxels in scan
  - Signal extracted from each voxel evaluated
  - Global respiratory signal is created as a combination of many individual voxel contributions
- Different than traditional image based methods of following structural movement
  - Fully automated
Acquisition of respiratory signal (SRF method)

• Summary
Results – SRF method

- Comparison of hardware based and software based signals

NJH experiment

- We compared hardware vs software gating
  - 189 FDG PET scans were acquired around the thorax (116 patients)
  - Respiratory gated images reconstructed using software and hardware based methods.

Results

Triggers

- ~1 min of processing/scan for respiratory trigger extraction
- 92% percent of the cases exhibited periods of time where hardware failed to adequately acquire signal and software succeeded
Discussion

- Software gating appeared to work as well as (and in some cases better) than hardware gating
  - Limitations not yet seen
- Software gating has obvious advantages:
  - Uses existing information that is prematurely thrown out
  - Requires no changes to current clinical procedures
- Fits within “doing more with less” framework
  - All existing PET scanners are (theoretically) capable of software-based gating – require a software patch
- The “low cost” implementation of software gating can reasonably support a PET field where motion corrected images are ubiquitously available for review.
  - SUV max in images displayed increased an average of

Gated signal optimization: Gating+

Section II
Introduction

• Separating available statistics into phase-bins results in decreased image quality – less statistics per bin

Simulation

• A center with gating equipment has a choice

Gated images

Ungated image

Non-linear image morphing correction

Raw scan data

Dependable time tested

Improved resolution, inferior contrast

Improved resolution and contrast, uncertain accuracy

*Benefits condition specific

It appears utilization of extra motion information comes with uncertain risk

Methods

• Non-linear image morphing has been proposed for recombining gated data

• We present an alternative strategy for utilizing the additional information provided by motion characterization - "gating++"
  o Basic precept: Movement of signal in space is expressed in intensity fluctuations in individual voxels over the gated frames
  o Our methods are based on isolating the fluctuations in voxels, and modulating them according to their reliability
Methods

• A gated scan can provide two sets of information per voxel

Correctly gated

Randomly gated

Triggers

Methods

• By looking at the effective “signal” to “noise” ratio at every voxel, we can selectively accept fluctuation information in voxels that benefit from gating, and filter fluctuation information in voxels that do not, thus optimizing information at every voxel.

Voxel fluctuations = motion + noise

Voxel at liver/lung boundary benefits from gating – preserves fluctuations

Voxel signal in background tissue is degraded from gating – damps fluctuations

Methods

• Gating protocol:
  1. Look at activity over gates in every voxel, for volume
  2. Characterize real fluctuations (correctly gated scan) and noise (randomly gated scan) through frequency amplitude analysis
  3. Accept only those frequencies which are supported by statistics

• Method verification
  ○ Simulations
  • 189 NJ HFDG PET scans
  • Previous work in small animal PET
Results

Simulation

<table>
<thead>
<tr>
<th>Ungated</th>
<th>Gated</th>
<th>Gating+</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>55</td>
<td>2000</td>
<td>1</td>
</tr>
</tbody>
</table>

Relative count statistics

<table>
<thead>
<tr>
<th>Ungated</th>
<th>Gated</th>
<th>Gating+</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td>50%</td>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td>50%</td>
<td>100%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Max

<table>
<thead>
<tr>
<th>ungated</th>
<th>gated</th>
<th>gating+</th>
</tr>
</thead>
<tbody>
<tr>
<td>76%</td>
<td>174%</td>
<td>76%</td>
</tr>
<tr>
<td>58%</td>
<td>112%</td>
<td>58%</td>
</tr>
<tr>
<td>94%</td>
<td>90%</td>
<td>55%</td>
</tr>
</tbody>
</table>

Volume (70% max)

<table>
<thead>
<tr>
<th>ungated</th>
<th>gated</th>
<th>gating+</th>
</tr>
</thead>
<tbody>
<tr>
<td>29%</td>
<td>4%</td>
<td>29%</td>
</tr>
<tr>
<td>154%</td>
<td>4%</td>
<td>171%</td>
</tr>
<tr>
<td>102%</td>
<td>46%</td>
<td>71%</td>
</tr>
</tbody>
</table>

SUV (mean/background)

<table>
<thead>
<tr>
<th>ungated</th>
<th>gated</th>
<th>gating+</th>
</tr>
</thead>
<tbody>
<tr>
<td>63%</td>
<td>187%</td>
<td>63%</td>
</tr>
<tr>
<td>49%</td>
<td>112%</td>
<td>49%</td>
</tr>
<tr>
<td>73%</td>
<td>72%</td>
<td>73%</td>
</tr>
</tbody>
</table>

FWHM

<table>
<thead>
<tr>
<th>ungated</th>
<th>gated</th>
<th>gating+</th>
</tr>
</thead>
<tbody>
<tr>
<td>130%</td>
<td>27%</td>
<td>130%</td>
</tr>
<tr>
<td>177%</td>
<td>50%</td>
<td>169%</td>
</tr>
<tr>
<td>104%</td>
<td>104%</td>
<td>104%</td>
</tr>
</tbody>
</table>

Lesion/background ratio = 3

Upper diaphragm/background = 1.5

Lower diaphragm/background = 3.0

Example PET slice (18F-FDG)

Results — gating and gating+ side by side
Discussion

• Our gating + gate combination algorithm offers an alternative approach to optimizing information acquired in a gated scan.

• All correction comes down to (simple) 1-dimensional equation.

• Characterizable/reproducible.

• Fast: ~20 sec processing for gating + (µPET volume * 16 gates).

• Accuracy:
  o All corrected voxels in simulation have a higher probability of being closer to truth than uncorrected voxels.
  o Corrected image is derived from a selective use of raw information.

• 100% Fully automated.

Algorithm works with effective signal:
  o Irrespective of reconstruction algorithm, smoothing, etc.
  o Irrespective of quality of signal.
  o Areas not benefiting from gating, or entire scans not benefiting from gating, will be returned to their ungated embodiment.

Algorithm utilizes available information and optimizes its transformation into Cartesian space.
  o Does not preclude the use of non-linear morphing algorithms.

Potential applications:
  o Support use of routine gating thorax imaging.
  o Cardiopulmonary, Cardiac imaging.
  o Human, small animal.
  o PET, SPECT, CT (low dose 4D CT), MRI...

Motion-gate information decoupling
  Section III
Introduction

- When information is optimized in frequency space, during the gating+ processing, there is an opportunity to shift the phase of the signal by rotating the frequency components in real and imaginary space. This allows a user to extract a voxel value at any and all phases of the cycle.
  - Values adhere to the optimized frequency information
- By repeating process for all voxels, can reconstruct phase shifted images
  - ~0.02 seconds processing per slice
- With this process, we can reconstruct continuous motion image (CMI) sequences

Phase shifted curve validation

- We generated 10^6 simulations of true gate-activity
  - Signal < Nyquist frequency
- Gated (step function) values were derived from the true curves, CMI values were derived from gated curves
- In 100% of the simulations the CMI curves correlated better with truth than the respective gated curves.

Combined data driven workflow results

- Data driven gating
- Gating+
- Phase shifted CMI frame images
Workflow results

• All images created using standard FDG PET acquisitions
• Animations created with 90 frames/cycle, displayed with 30 frames/second
Movie 3
Useful information

NO useful information

Results quantified
In progress

Human work
**Presentation summary**

- There is information in PET data that is not being utilized.
- We present data driven gating, signal optimization, and information decoupling strategies:
  - Can be used separately or combined in an automated workflow.
  - Can be implemented in clinical setting with minimal impact.
  - Can be used with minimal risk of degradation of care.
- Our strategies can reframe the boundaries of motion control:
  - Number of gates vs noise paradigm.
  - Characterization of motion control strategies.
  - Risks of using motion correction.
  - Visualization of motion.
- Further validation needed – we provided proof of principles and small population measurements.
- Still room for improvement:
  - Not seen limits in accuracy or speed.
  - As technology advances (sensitivity and resolution), so will potential of such algorithms.
- Still areas of application to explore.
• Thank you

Acknowledgements

Current collaborators
Phillip Koo (UC Denver)
Kate Petrova (UC Denver)
Jonathan Chung (NJH)
Vicki LaRue (NJH)

Siemens support
Jim Hamill
Judson Jones

Mentors
Daniel Silverman (UCLA)
Stig Palm (IAEA)
Nanette Freedman (Hebrew University)

Co-data driven pioneers
Paul Schleyer (Kings College)
Florian Büthe (University of Münster)