Deviceless respiratory motion correction in PET imaging – exploring the potential of novel data driven strategies

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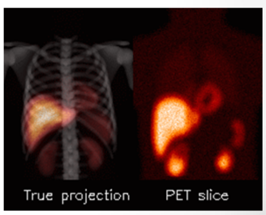
AAPM Spring clinical meeting, 2015

Introduction

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



Simulation

Slide prepared by Kate Petrova, MSc.

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"

*Daou D. Respiratory motion handling is mandatory to accomplish the high-resolution PET destiny. *European Journal of Nuclear Medicine and Molecular Imaging*. 2008;35(11)

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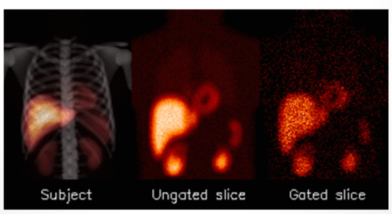
Introduction

- Gating is a potential solution



Simulation

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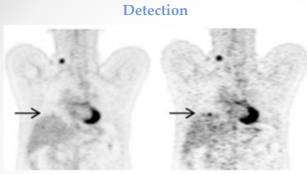
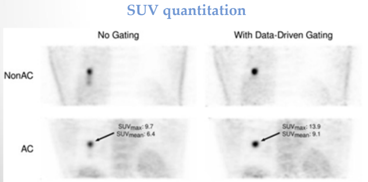
Detection



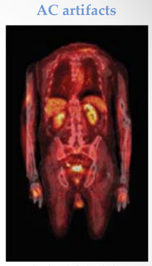
PET/CT Atlas on Quality Control and Image Artefacts, © IAEA, 2014, p59

SUV quantitation



Kesner et. al., EJNMMP Physics, 2014

AC artifacts



PET/CT Atlas on Quality Control and Image Artefacts, © IAEA, 2014, p59

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Introduction

- State of respiratory gating technology in nuclear medicine:
  - o 10+ years of research
  - o Major vendors sell integrated systems
  - o 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!

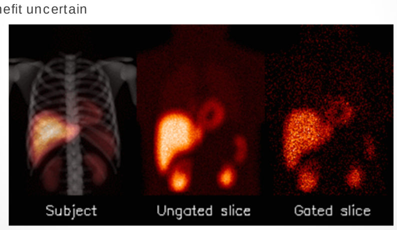
Introduction

- Cost / benefit of gating
  - o Most respiratory gating is implemented using hardware based respiratory tracking equipment

  - o Negatives of such equipment include
    - Patient discomfort
    - Prone to setup error
    - Slower throughput
    - Increased costs (hardware, training)
    - Increased radiation dose
  - o Overall gating represents a change towards complexity when considered for use in routine scanning

Introduction

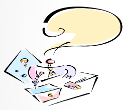
- Cost / benefit of gating
  - o There is a fundamental tradeoff when gating
    - Improved resolution comes with the loss of image statistics,
  - o Benefit uncertain



Simulation

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

Automated workflow

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
  - o Ease of use
  - o Operator independent
  - o None of the errors in the application of hardware
  - o If integrated properly, their implementation would be a software add-in, and require no change to current clinical protocols

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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?

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IVF method (2009)

- **I**mage **V**oxel **F**luctuation method for extracting respiratory signal from data
  - o Use the fluctuating signals per voxel over time
    - ~$2*10^{7}$ voxels in scan
  - o Signal extracted from each voxel evaluated

  - o Global respiratory signal is created as a combination of many individual voxel contributions
- Different than traditional image based methods of following structural movement
  - o fully automated

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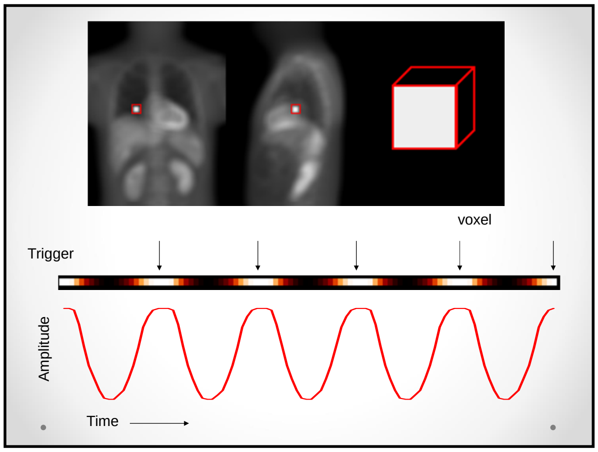
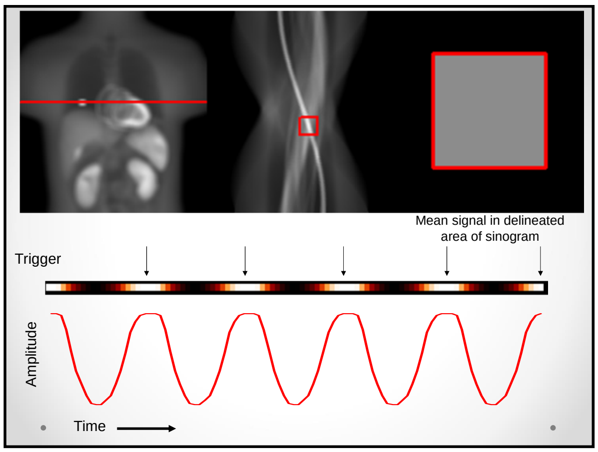
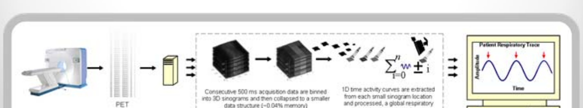




Acquisition of respiratory signal (SRF method)

- Summary



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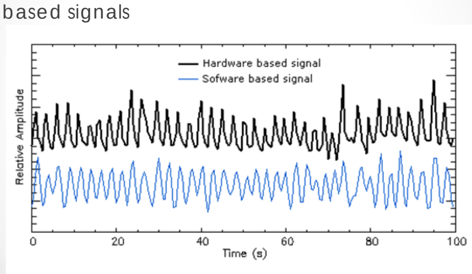
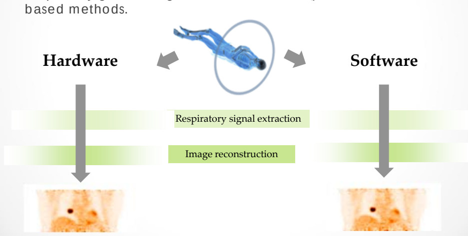
Results – SRF method

- Comparison of hardware based and software based signals



NJH experiment

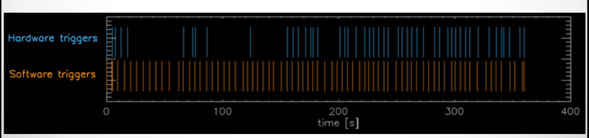
- We compared **hardware** vs **software** gating
  - 189 FDG PET scans were acquired around the thorax (116 patients)
  - Respiratory gated images reconstructed using software and hardware based methods.



Results

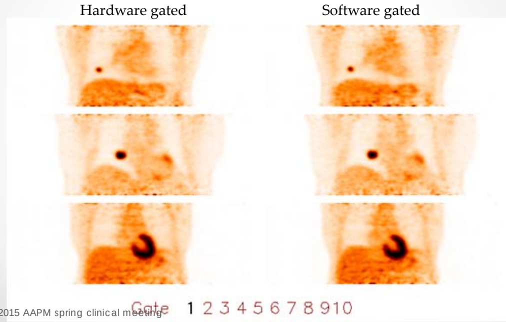
Triggers

- ~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



Example hardware fail

NJH scan results



Discussion

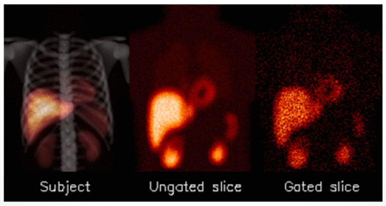
- Software gating appeared to work as well as (and in some cases better) than hardware gating
  - Limitations not yet seen
- Software gating has obvious advantages:
  - Uses existing information that is prematurely thrown out
  - Requires no changes to current clinical procedures
- Fits within "doing 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

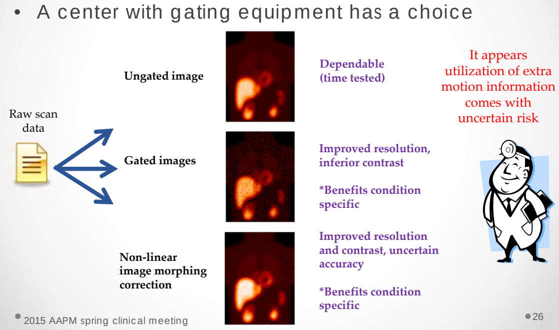
- Separating available statistics into phase-bins results in decreased image quality – less statistics per bin



Simulation

Introduction

- A center with gating equipment has a choice

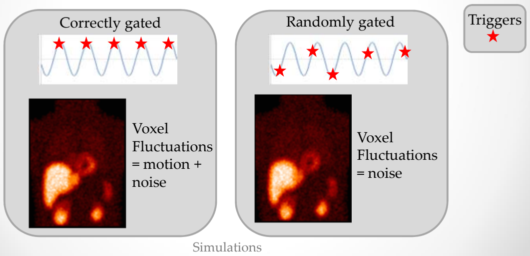


Methods

- 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

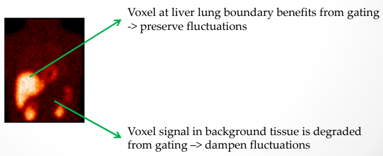
Methods

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



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.

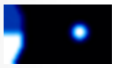


Methods

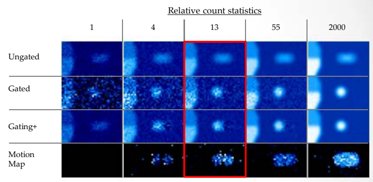
- Gating+ protocol:
  1. Look at activity over gates in every voxel$_{x,y,z}$ for volume
  2. Characterize real fluctuations (correctly gated scan) and noise (randomly gated scan) through frequency amplitude analysis
  3. Accept only those frequencies which are supported by statistics
- Method verification
  - o Simulations
  - 189 NJH FDG PET scans
  - Previous work in small animal PET

Results

- Simulation



Lesion/background ratio = 3
Upper diaphragm/background = 1.5
Lower diaphragm/background = 3.0



Relative Counts	1			4			13			55			2000		
	ungated	gated	gating+	ungated	gated	gating+	ungated	gated	gating+	ungated	gated	gating+	ungated	gated	gating+
Max	76%	174%	76%	58%	112%	87%	58%	94%	90%	55%	79%	79%	55%	76%	75%
Volume (70% max)	29%	4%	29%	154%	4%	29%	171%	46%	71%	188%	96%	92%	183%	100%	96%
SUV (mean/bckgrnd)	63%	187%	63%	49%	112%	77%	49%	73%	72%	47%	66%	67%	47%	65%	65%
FWHM	130%	27%	130%	177%	50%	85%	169%	102%	104%	216%	105%	95%	189%	100%	101%

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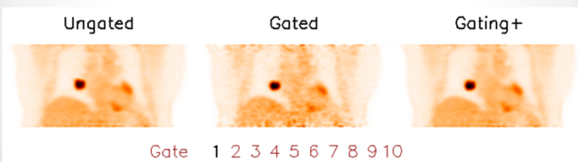
Results

Example PET slice (^{18}F-FDG)



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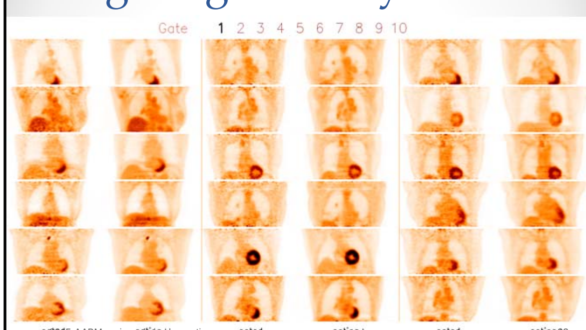
Results – gating and gating+ side by side



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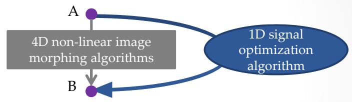
Discussion

- Our gating+ gate combination algorithm offers an alternative approach to optimizing information acquired in a gated scans



- All correction comes down to (simple) 1dimensional equation
- Characterizable/reproducible
- Fast
  - ~20 sec processing for gating+ (µPET volume * 16 gates)
- Accuracy:
  - All corrected voxels in simulation have a higher probability of being closer to truth than uncorrected voxels
  - Corrected image is derived from a selective use of raw information
    - No offset vectors created from assumptions
- 100% Fully automated

Discussion

- Algorithm works with effective signal
  - Irrespective of reconstruction algorithm, smoothing, etc
  - Irrespective of quality of signal
    - 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.
  - Does not preclude the use of non-linear morphing algorithms
- Potential applications:
  - Support use of routine gating thorax imaging
  - Respiratory, Cardiac imaging
  - Human, small animal
  - 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

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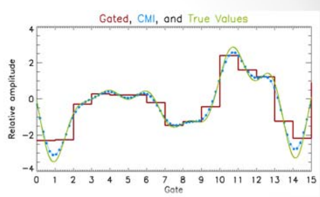
Phase shifted curve validation

- We generated 10^6 simulations of true gate-activity
  - Signals < 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.



Example randomly generated voxel activity vs gate curve simulation.

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Combined data driven workflow results

Data driven gating
+
Gating+
+
Phase shifted CMI frame images

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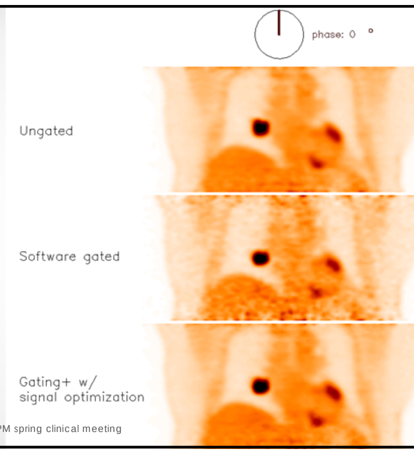
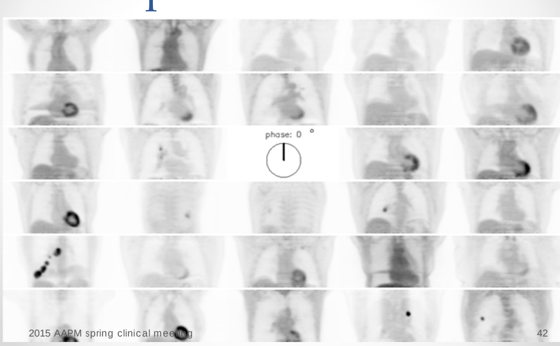
Workflow results

- All images created using standard FDG PET acquisitions
- Animations created with 90 frames/cycle, displayed with 30 frames/second

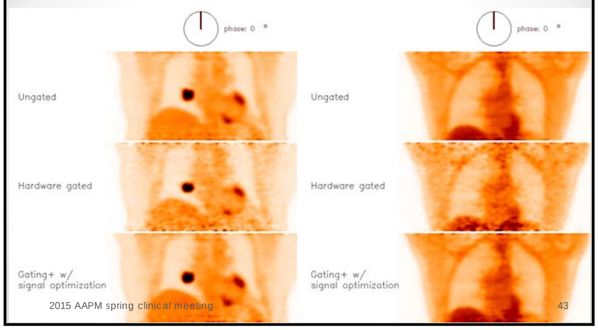


Population motion



Movie 3

Useful information | NO useful information



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Results quantified

In progress

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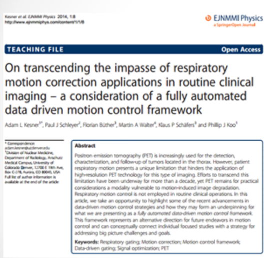
Human work



Kesner et al. EJNMMI Physics 2014, 1:8
http://www.ejnmmiphys.com/content/1/1/8

EJNMMI Physics
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On transcending the impasse of respiratory motion correction applications in routine clinical imaging – a consideration of a fully automated data driven motion control framework

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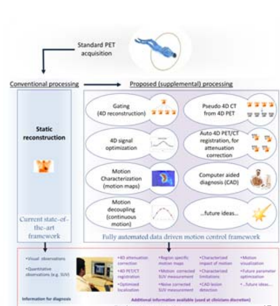
Abstract

Positron emission tomography (PET) is increasingly used for the detection, characterization, and follow-up of tumors located in the thorax. However, patient respiratory motion presents a unique limitation that hinders the application of high-resolution PET technology for this type of imaging. Efforts to transcend this limitation have been underway for more than a decade, yet PET remains for practical considerations a modality vulnerable to motion-induced image degradation. Respiratory motion control is not employed in routine clinical operations. In this article, we take an opportunity to highlight some of the recent advancements in data-driven motion control strategies and how they may form an underpinning for what we are presenting as a *fully automated data-driven motion control framework*. This framework represents an alternative direction for future endeavors in motion control and can conceptually connect individual focused studies with a strategy for addressing big picture challenges and goals.

Keywords: Respiratory gating; Motion correction; Motion control framework; Data-driven gating; Signal optimization; PET



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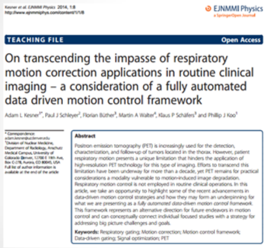
Human work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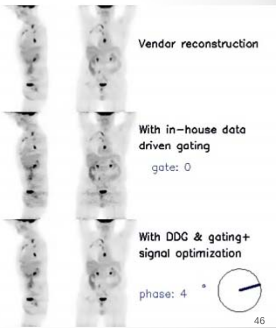
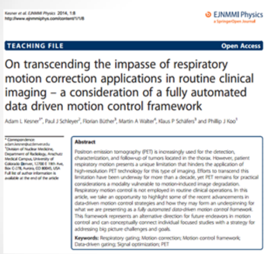
Abstract



Human work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On transcending the impasse of respiratory motion correction applications in routine clinical imaging – a consideration of a fully automated data driven motion control framework

Abstract

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
  - # 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
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Vicki LaRue (NJH)

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