Respiration-Correlated CT/PET: Principles, Advancements and Clinical Applications Daniel Low, Ph.D.

UCLA

#### Disclosures

• Grant – Varian

• Grant – Accuray

Stock - ViewRay



Bradley, J. et al., Int J Radiat Oncol Biol Phys, 82, 435-441, e1, 2012

## Thoracic PET imaging: Breathing motion

- Deformed Lesion volume
- Reduced signal
- Reduced contrast
- Reduced SUV
   Increased
- Increased Registration Errors



• Attenuationcorrection errors

Beyer et al., Germany, 2005

Nehmeh and Erdi: Sem Nuc Med 38, 167 (2008)



## Early experiments (~2005)





Target Background Ratio 6.6 1.7

## Methods for recovering static image

- Retrospective Gating
- Breathing model based
- Motion-compensated reconstruction
  Internal-external correlations
- Data-driven

#### **Retrospective Binning**

- Breathing cycle measured using surrogate
- PET data acquired (list mode)
- Correlate list mode data and breathing phases
- Select list mode data
- for each desired phase
- Reconstruct image



#### **Retrospective Binning**

- Each image has fraction of total counts
  - Increased imaging time
  - Decreased signal to noise
- Attenuation image not necessarily aligned to PET breathing phases
  - Causes artifacts in PET activity near diaphragm

## Nehmeh MP 31 1333 (2004)

- 4DCT and 4DPET
- External markers on abdomen
- CT sorted by respiratory phase
- Breathing cycles for PET divided into ten 500 ms bins
- Audio prompting to maintain breathing period
- Average 4DCT period was within 18% of PET
- Amplitude variations bin to bin were max 15%
- Two out of five patients experienced differences between CT and PET breathing patterns



#### Results

Coaching: End Inspiration inconsistency



# Jani Int J Radiat Oncol Biol Phys 87, 563 (2013)

Amplitude vs Phase Gating

#### • Influence on PET image quality?

• Patients and phantoms









#### Li, MP 33, 1288 (2006)

- Build PET with full statistics?
- Develop motion model using 4DCT
- Reconstruct PET images with model
   Maximum-likelihood expectation-maximization (ML-EM) algorithm
  - Includes motion model from 4DCT in PET reconstruction
  - Forward and backward projections Use all projection data at different phases
- · Improves statistics over gating-only methods
- Simulation, phantom, patient case

## Li Results, Simulations





## Li, Results: Experimental













### Thorndyke et al (2006)

- Retrospective stacking PET images using breathing amplitude (range of 4-7 bins)
- Subdivide list mode into short time increments (0.2 s)
- B-spline image registration of phase-specific PET images Register the PET images and average
- · Correlate with breathing amplitude

Thorndyke et al Med. Phys. 33 (7), July 2006, 2632





#### Lamare PMB 52, 5187 (2007)

- Phantom only (NCAT)
- Elastic transformation within list-mode based reconstruction
- Transformed lines of response
- Used all event data
- CT provided deformation information
- Incorporate motion during reconstruction One-pass list mode expectation maximization (OPL-EM]
   1) Interpolation based

  - 2) Elastic direct
- Compare against affine transformation of list mode data prior to reconstruction

## Lamare, Interpolation methods



## Lamare, Results

% Position improvement	Lesion diameter (mm)	Elastic Method 1		Elastic Method 2		# EWIM	Lesion	Elastic Method 1		Elastic Method 2	
		Y	Ζ	Y	Ζ	improvement	(mm)	Y	Ζ	Y	Ζ
Upper lobes	15	91.15	90.16	96.48	96.48	Upper lobes	15	73.37	60.62	93.96	84.5
of the lungs	21	76.90	79.54	98.64	95.17	of the lungs	21	81.00	75.85	81.89	87.0
Middle lobes	15	84.34	78.83	92.65	94.60	Middle lobes	15	47.95	90.06	92.39	99.1
of the lungs	21	84.79	93.65	78.84	96.07	of the lungs	21	77.20	96.81	94.26	97.4
Lower lobes	15	91.04	94.88	94.66	97.50	Lower lobes	15	73.84	86.58	90.13	92.2
of the lungs	21	62.55	88.87	86.64	97.41	of the lungs	21	94.45	68.20	92.74	92.6

### Lamare, Results



# Data Driven Strategies (From Ren PMB 62, 4741 (2017))

- Measure center-of-mass of manually defined region-of-interest (Bundschuh et al 2007)
- Total counts in ROI (Visvikis et al 2003)
- Raw count data, variations of activity or axial component of center-ofmass (Buther 2009, 2010, Schleyer 2009, 2011, 2014, Kener and Kuntner 2010, Thielems 2011). Promising but create noisy estimated motion traces.
  - All of these gated events
  - Increased noise
- Event-by-event (EBE) correction (e.g. Victor 2009)

#### Ren et al, PMB 62, 4741 (2017)

- Data-driven respiratory gating
- Event by event
- Time of flight data with Centroid-of-distribution (COD) to determine motion
- Use motion to drive event by event corrected reconstruction
- MOLAR reconstruction (Motion-compensation OSEM (ordered subset expectation maximization) list-mode algorithm for resolution-recovery reconstruction)
- Pancreas beta-cell tracer, 10 subjects
- Compare results to external system (surrogate)

### Ren: Results, Pancreas Patient





#### Ren: Results for Pancreas Patients



### Conclusions

- Breathing motion management increases quantitation of PET images for thorax and upper abdomen
  - Activity
     Localization
- With and without surrogate
- Challenging to correlate improvements with outcomes
- <u>What has been commercially implemented?</u>
   <u>4DCT and retrospectively gated PET</u>
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