Quantitative Multi-Energy Computed Tomography:
Imaging and Therapy Advancements

# MECT Systems Overview and Quantitative Opportunities

Taly Gilat Schmidt, PhD
Associate Professor
Department of Biomedical Engineering
Marquette University & Medical College of Wisconsin

## Disclosures

The speaker receives research funding from GE Healthcare

## Overview

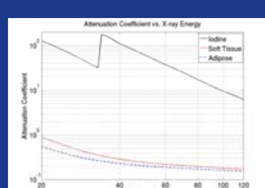
- Why multi-energy?
- Important considerations in multi-energy acquisition
- Overview of clinical multi-energy acquisition approaches
- Introduction to multi-energy processing approaches

## Computed Tomography (CT)

What does each gray level represent?

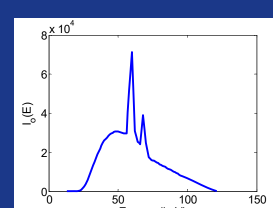
## CT Numbers

- Pixel values (CT numbers) are in Hounsfield Units (HU)
- Hounsfield Units represents x-ray attenuation of the material
- X-ray attenuation depends on material properties
  - Density
  - Atomic #
- X-ray attenuation depends on energy




## Polyenergetic Acquisition

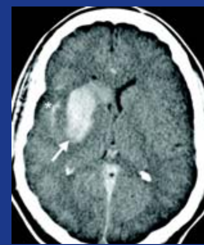
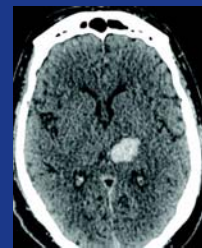
- CT data is acquired with a polyenergetic x-ray spectrum
- Conventional detectors integrate the detected signal over energy
- Energy-dependent information is lost
- HU represents the *effective* X-ray attenuation coefficient



## Lost Spectral Information

- Different materials may have same HU value in the reconstructed image
  - ex. Calcium and Iodine
- Can't distinguish between changes in material density and changes in material composition
- The reconstructed HU value depends on the thickness of the material
  - Beam hardening artifacts

## Hemorrhage or Retained Iodine?

C.M. Phan et al. AJNR Am J Neuroradiol 2012;33:1088-1094



## Gout or Pseudo-Gout?

Madhura A. Desai; Jeffrey J. Peterson; Hillary Warren Garner; Mark J. Kransdorf; *RadioGraphics* **2011,** 31, 1365-1375.
DOI: 10.1148/rg.315115510

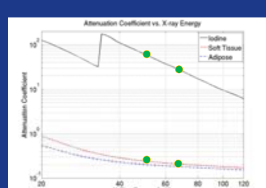

## X-ray Attenuation & Material Decomposition

- X-ray attenuation occurs through primarily two processes in the CT energy range
  - Compton Scatter
  - Photoelectric Absorption

  (Different Energy / Material Dependency)
- $\mu(E) \approx a\,\mu_{compton}(E) + b\,\mu_{photoelectric}(E)$
- Separate the effects of material composition and density
- 2 unknowns
- We can solve for (a,b) if we have x-ray measurements at two energies

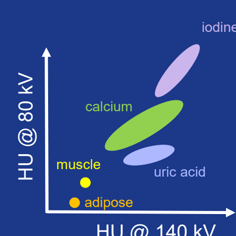
## Another Way to Understand Material Decomposition

- Materials with higher atomic number have a greater change of x-ray attenuation with energy




## Another Way to Understand Material Decomposition

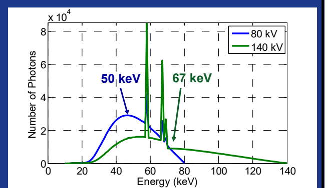
- Materials with higher atomic number have a greater change of x-ray attenuation with energy
- By acquiring CT at two energies, we can measure the change in attenuation with energy
- Can discern changes in attenuation due to atomic number versus density




Slope represents material composition
Distance from origin represents density

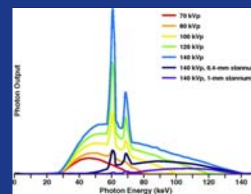
## Multi-Energy Acquisition

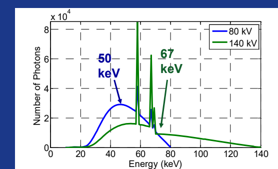
- CT systems can acquire CT data using two spectra
- High energy, low energy
- Methods differ across manufacturers




## Dual-Energy Acquisition Considerations

- Spectral separation improves dose efficiency



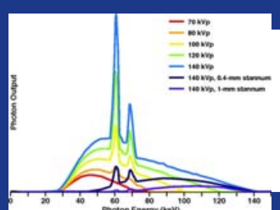




Beam filtration reduces overlap between the two spectra

Johnson, AJR S3-S8, 2012

## Dual-Energy Acquisition Considerations

- Spectral separation improves dose efficiency
- Optimized dose allocation reduces noise




Johnson, AJR S3-S8, 2012

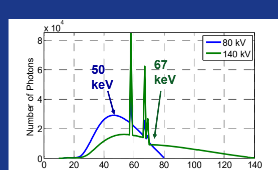
## Dual-Energy Acquisition Considerations

- Spectral separation improves dose efficiency
- Optimized dose allocation reduces noise
- Reduced time between two spectral measurements reduces artifacts
  - Motion artifacts
  - Contrast enhancement
  - Beam hardening artifacts (raw data processing)

## Dual-Energy Acquisition Considerations

- Spectral separation improves dose efficiency
- Optimized dose allocation reduces noise
- Reduced time between two spectral measurements reduces artifacts

  Motion artifacts, Beam hardening artifacts (raw data processing)
- Workflow considerations




## Multi-Energy Approaches

Sequential Acquisition (Siemens)

## Sequential Dual-kV Acquisition

- Complete helical scan is first performed at low kV, followed by high kV
- kV, mA, pitch can be modified between the two scans
- Images are registered after reconstruction

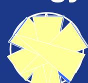
https://health.siemens.com/ct_applications/somatomsessions/index.php/dual-energy-spectral-ct-more-precisely-defined/

## Sequential Dual-kV Acquisition

| | |
|---|---|
| Spectral Separation | kV selection<br>Additional filtration possible, but not implemented |
| Dose Allocation | Can be optimized by mA selection, pitch |
| Time Between Spectral Measurements | ~ Seconds |
| Workflow / Other | Adds dual energy acquisition to existing scanners |

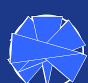
## Multi-Energy Approaches

Sequential Acquisition (Siemens)



Rapid kV Switching (GE)

Slow kV Switching (Toshiba)

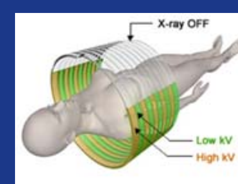


Layered Detector (Philips)

Dual Source (Siemens)

## Slow kV Switching Acquisition

- kV alternates for over each gantry rotation
- Tube turned off during anterior views
- mA can be adjusted between views




http://www.toshiba-medical.eu/eu/product-solutions/computed-tomography/aquilion-one/aquilion-one-advanced-applications/

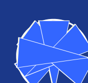
## Slow kV Switching Acquisition

| | |
|---|---|
| Spectral Separation | kV selection<br>Additional spectral filtration possible, but not implemented |
| Dose Allocation | Optimized by mA selection |
| Time Between Spectral Measurements | Gantry rotation time (~0.5 seconds) |
| Workflow / Other | |

## Multi-Energy Approaches

Sequential Acquisition (Siemens)

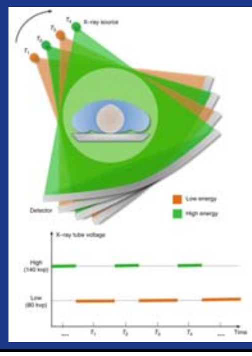
Slow kV Switching (Toshiba)



Rapid kV Switching (GE)

## Fast kV Switching

- Alternates between low and high kV between projections
- Tube current cannot rapidly modified
- Instead, dwell time increased for low kV



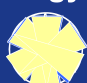

https://radiologykey.com/technical-advancements-in-dual-energy/

## Fast kV Switching Acquisition

| | |
|---|---|
| Spectral Separation | kV selection |
| Dose Allocation | Integration time |
| Time Between Spectral Measurements | < 1 ms<br>Raw data processing possible |
| Workflow / Other | |

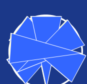
## Multi-Energy Approaches

Sequential Acquisition (Siemens)



Dual Source (Siemens)

Slow kV Switching (Toshiba)



Rapid kV Switching (GE)

## Dual-Source Acquisition

- Dual-source system operates with the two sources at different kV, and mA settings
- Filter can be added to high-kV gantry


https://health.siemens.com/ct_applications/somatomsessions/index.php/dual-energy-spectral-ct-more-precisely-defined/

## Dual Source Acquisition

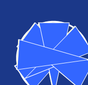
| | |
|---|---|
| Spectral Separation | kV selection<br>Additional spectral filtration |
| Dose Allocation | mA selection |
| Time Between Spectral Measurements | ¼ gantry rotation (~100 ms) |
| Workflow / Other | Increased scatter due to dual x-ray beam |

## Multi-Energy Approaches

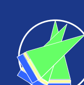
Sequential Acquisition (Siemens)

Dual Source (Siemens)

Slow kV Switching (Toshiba)



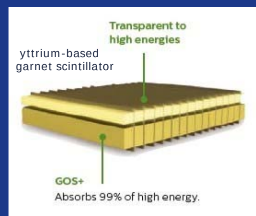
Layered Detector (Philips)



Rapid kV Switching (GE)

## Dual-Layer Detector Acquisition

- Detector is composed of two layers
- Top layer is low-density scintillator, sensitive to low-energy photons
- Bottom layer is high-density scintillator sensitive to high-energy photons



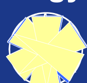

http://clinical.netforum.healthcare.philips.com/global/Explore/White-Papers/CT/Detector-technology-in-simultaneous-spectral-imaging

## Dual-Layer Detector Acquisition

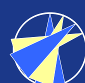
| | |
|---|---|
| Spectral Separation | Detector layer material, thickness |
| Dose Allocation | Can't be optimized |
| Time Between Spectral Measurements | Simultaneous acquisition |
| Workflow / Other | Dual-energy acquired as part of routine scan |

## Multi-Energy Approaches

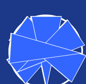
Sequential Acquisition (Siemens)



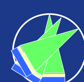
Rapid kV Switching (GE)



Slow kV Switching (Toshiba)

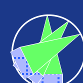


Layered Detector (Philips)



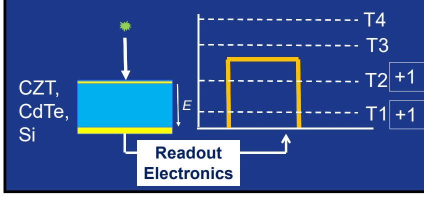
Dual Source (Siemens)

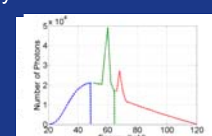
Photon-counting Detector (under development)



## Photon-Counting Detector Acquisition

- Direct-conversion semiconductor detectors perform pulse-height analysis to acquire spectral information
- Pulse proportional to deposited energy

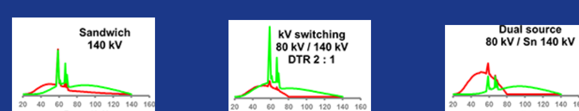



## Photon-Counting Detector Acquisition

| | |
|---|---|
| Spectral Separation | Detector spectral response |
| Dose Allocation | Threshold settings |
| Time Between Spectral Measurements | Simultaneous acquisition<br>Raw data processing possible |
| Workflow / Other | 2+ spectral measurements<br>Acquired as part of routine scan |

## Comparison: Spectral Separation




Dual-Layer Detector

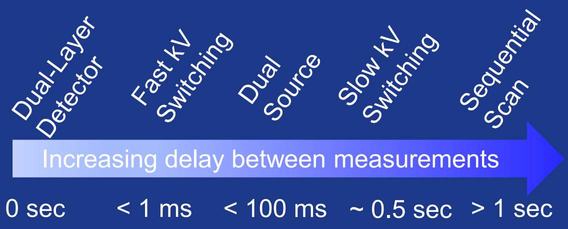
Dual-kV, no filtration

Dual-kV with filtration

Increasing Spectral Separation

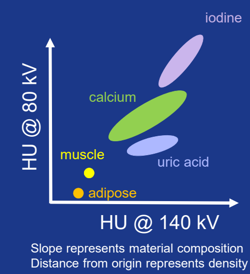
Faby et al. Med. Phys. 2015;42: 4349–4366

## Comparison: Time Between Spectral Measurements

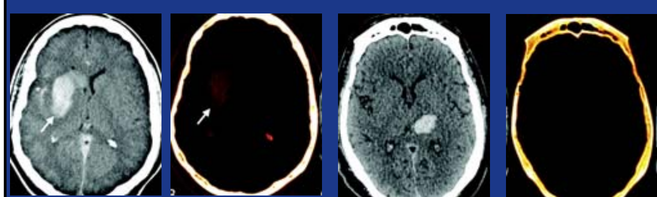



## Multi-Energy Data Processing

- Blend high and low energy images to create CT image with improved contrast/noise
- Material Separation
- Material Decomposition:
  $\mu(E) \approx a\,\mu_{compton}(E) + b\,\mu_{PE}(E)$
  Effective Z, density images
- Effective monoenergetic images



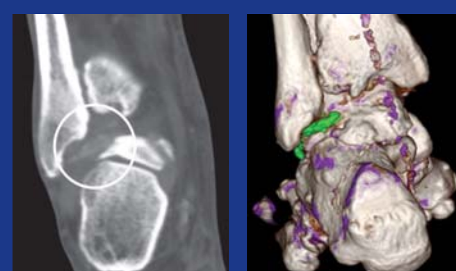

## Hemorrhage or Retained Iodine?



C.M. Phan et al. AJNR Am J Neuroradiol 2012;33:1088-1094



## Gout or Pseudo-Gout?



Madhura A. Desai; Jeffrey J. Peterson; Hillary Warren Garner; Mark J. Kransdorf; *RadioGraphics* **2011,** 31, 1365-1375.
DOI: 10.1148/rg.315115510


## What about dose?

- Depends on the application
- Must compare multi-energy and conventional CT protocols at equivalent image quality, optimized for the application
- Studies have demonstrated dual-energy dose neutrality for some applications [Henzler et. al, AJR, 2012]

## Conclusions

- Multi-energy CT separates the effects of material composition and material density
- Enables separating materials that are indistinguishable on conventional CT images
- Vendors have different approaches for multi energy imaging with different advantages and disadvantages