**Multi-energy CT: Clinical Applications**

Cynthia H. McCollough, PhD, FAAPM, FACR  
Professor of Medical Physics and Biomedical Engineering  
Director, CT Clinical Innovation Center  
Mayo Clinic, Rochester, MN

---

**DISCLOSURES**

**Research Support:**

<table>
<thead>
<tr>
<th>NIH</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB 017095</td>
<td>Mayo Discovery Translation Award</td>
</tr>
<tr>
<td>EB 017185</td>
<td>Mayo Center for Individualized Medicine Award</td>
</tr>
<tr>
<td>EB 016966</td>
<td>Thrasher Foundation</td>
</tr>
<tr>
<td>DK 100227</td>
<td>Siemens Healthcare</td>
</tr>
<tr>
<td>HR 046158</td>
<td></td>
</tr>
<tr>
<td>RR 014908</td>
<td></td>
</tr>
</tbody>
</table>

**Off Label Usage**

None

---

**What Does CT Do Now Routinely**

**Anatomic Morphology!**

- CT of head, chest, abdomen and pelvis
- Musculoskeletal CT
- CT Angiography
- CT Colonography (large intestine)
- CT Enterography (small intestine)
- Cardiac CT
- CT-guided Intervention
Clinical Motivation

- Different materials can have the same CT number if atomic number differences are offset by appropriate density differences
- CT number depends on x-ray attenuation
  - Physical density (g/cm³) [electron-density]
  - Atomic number (Z)
- Dual-energy CT
  - Allows separate determination of density and Z
  - Can provide material composition information
**Dual Energy CT Images**

- Low / High energy source images
  - 80 kV and 140 kV images
- Mixed (blended) images
  - Combine low and high energy images together
  - Linear and non-linear blending
- Energy selective image
  - Virtual monochromatic (monoenergetic) images
- **Material selective images**
  - Iodine image, water image, bone image

---

**DECT Mixed Images**

- **Linear Blend**
  - 70% 140kV
  - 30% 80kV
- **Non-linear Blend**

---

**Dual-energy scans need not increase dose**

- **Single Energy (120 kV)**
  - March 2009
  - CTDIvol: 18.65 mGy
- **Indication: HCC**
  - 35 – 36 cm later width
- **Dual Energy Mixed**
  - April 2009
  - CTDIvol: 15.59 mGy
**Virtual Monoenergetic Imaging**

- Improve iodine contrast
- With energy domain noise reduction*, can be used to improve iodine CNR
  - Increase conspicuity of subtle lesions
  - Allow use of less iodinated contrast media
  - Compensate for poor venous access resulting in slow injection rates
- Reduce metal artifacts

*Leng et al. 2011*

---

**80 kV**

**140 kV**

**Mixed**

**50 keV**

---

**40 keV**

**85 keV**

**120 keV**

---

Virtual Monoenergetic – Metal Artifacts

- Use high keV to reduce strength of metal artifacts
- Use low keV to visualize iodine

Standard Image  Monoenergetic Image (105 keV)

Virtual Monoenergetic – Metal Artifacts

- Use high keV to reduce strength of metal artifacts
- Use low keV to visualize iodine
- Allows fast and flexible reduction of metal artifacts
**Transaortic Valve Replacement**

**Virtual Monoenergetic – Metal Artifacts**

- Use high keV to reduce strength of metal artifacts
- Use low keV to visualize iodine
- Allows fast and flexible reduction of metal artifacts
- Is not metal artifact correction
  - No metal detection or sinogram correction
- Especially helpful for complex metal objects

**Left Ventricular Assist Device CT (LVAD)**

- LVAD’s are mechanical pumps that function to reduce the load on the left ventricle
- Bridge to heart transplantation
- Destination therapy for patients ineligible to receive transplants
- Bridge to myocardial recovery

Anders Persson, Linköping University, Sweden
Inflow cannula

Outflow cannula

Drive line

LVAD pump

**LVAD** – Imaging Evaluation

- Echo used to evaluate LV function and cannula thrombus
- Extracardiac components, including the outflow cannula can be difficult to visualize
- CT increasingly used to evaluate LVAD function
Material Specific Applications

What significant clinical questions can material composition information help to answer?

Material-specific applications

- Material characterization
  - Kidney stone characterization
  - Gout detection and quantification
  - Silicone breast implant leakage
- Iodine imaging
  - Automated bone removal in CT angiography
  - Plaque removal
  - Blood pool imaging (Perfused blood volume)
- Soft tissue imaging
  - Virtual non-contrast (Iodine removal/highlighting)
  - Virtual non-calcium (Bone removal/highlighting)
**Material-specific applications**

- Material characterization
  - Kidney stone characterization
  - Gout detection and quantification
  - Silicone breast implant leakage
- Iodine imaging
  - Automated bone removal in CT angiography
  - Plaque removal
  - Blood pool imaging (Perfused blood volume)
- Soft tissue imaging
  - Virtual non-contrast (Iodine removal/highlighting)
  - Virtual non-calcium (Bone removal/highlighting)

**Urinary Stone Characterization**

- Kidney stone are common
  - 5.2% US population (ages 20–70)
  - Recurrence rate 50% in 5–10 years
- Stone composition information is important in stone management
  - Directly related to treatment strategy
  - Better understanding of pathogenic factors

From MayoClinic.org

Stamatelou, 2003
Moe, 2006

**Three Material Decomposition**

![Diagram showing three material decomposition with Hounsfield Units (HU) at 80 kV and 140 kV]

"pure" stone
real stone
"urine"
Three Material Decomposition

80 kV (HU)  

“pure” non-UA stone  

“pure” UA stone  

“urine”  

140 kV (HU)
**Dual-energy CT Stone Classification**

Stones are color coded according to composition.

**Dual Source DECT – UA vs Non-UA**

- >15 publications on stone composition differentiation using dual energy CT
- Both *in vitro* and *in vivo* studies
- High accuracy, sensitivity and specificity reported
- Used in routine clinical practice

**Non-uric acid stones**

- Apatite, calcium oxalate monohydrate
  - Most suitable for extracorporeal shockwave lithotripsy.
- Cystine, brushite, calcium oxalate dihydrate
  - Surgical removal (ureteroscopic lithotripsy, percutaneous, nephrolithotomy, and laparoscopic) more appropriate
Can we differentiate non-UA stones?

80 kV (HU) → "pure" non-UA stone

140 kV (HU) → "pure" UA stone

Can we differentiate non-UA stones?

80-140 kV
Small phantom

Original

More filtration

100-140 kV
Large phantom

Non-UA stone type characterization

Commercial UA vs. non-UA differentiation available in clinic practice

5-group differentiation available using extra filtration and custom SW
Crystalline Arthropathies

- Prevalence of crystal-induced arthropathies increasing
- Monosodium urate (*uric acid*) crystals → gout
  - painful and disabling chronic disorder, joint destruction
  - decreased renal function, kidney stones, increased CV risk
- Calcium pyrophosphate dihydrate (*calcium*) → pseudogout
  - similarly painful, chronic, disabling
- Basic calcium phosphate (BCP) → calcific periarthritis/tendinitis or destructive arthropathy
  - growing evidence suggest role in pathogenesis of osteoarthritis

Diagnostic dilemma

- Patient presents with hot, painful, inflamed joint
  - Causes: Gout, pseudogout, BCP or infection?
- Treatments vary considerably
- Diagnosis made clinically
  - Speed of onset, severity of pain, inflammation, location
  - Hyperuricemia
- Definitive diagnosis
  - aspiration of joint fluid or tophi, polarized light microscopy
  - 50% of aspirations non-diagnostic
- Great need for non-invasive diagnostic methods
Plain lateral radiograph

High density material in soft tissues within and surrounding joints consistent with tophaceous deposits
Disease Quantitation

- Allow accurate assessment of disease burden (in terms of crystal volume)
- Allows pre and post treatment comparisons to identify non-responders early and alter their treatment course
- Provides definitive outcome measures for therapeutic regimens

**Detection of Silicone Breast Implant Leaks**

- Silicone can be taken up into surrounding tissues and lymph nodes and cause autoimmune illness
- FDA allowed silicone breast implants to return to the market, but recommended ANNUAL cross-sectional imaging to evaluate for leakage
- MRI is the only FDA-cleared cross-sectional technique for this application
- It is cost-prohibitive for most patients and few undergo surveillance imaging
Material-specific applications

- Material characterization
  - Kidney stone characterization
  - Gout detection and quantification
  - Silicone breast implant leakage
- Iodine imaging
  - Automated bone removal in CT angiography
  - Plaque removal
  - Blood pool imaging (Perfused blood volume)
- Soft tissue imaging
  - Virtual non-contrast (Iodine removal/highlighting)
  - Virtual non-calcium (Bone removal/highlighting)
Automated Bone Removal in CT Angiography

- CT angiography is a minimally invasive technique to determine location, size, and patency of arteries and veins
- It has all but replaced invasive (catheter-based) angiography for diagnostic purposes
- A single exam can produce 100’s to 1000’s of images for interpretation
- Overlying bony anatomy interferes with useful visualization techniques (e.g., MIP and VRT)
- Manual or semi-automated bone removal can be labor intensive and/or operator dependent
**Perfused Blood Volume (Blood Pool Imaging)**

- Assessment of blood distribution with a measurement made at a single time point
  - Perfusion measurements require temporal measurements
- Quantitative assessment of perfused blood volume shown to serve as a surrogate marker for ischemia/infarct and to correlate with direct measures of perfusion and flow

**Plaque Removal**

- Bright calcified plaques mask less-bright iodine-filled lumens, especially in MIP and VRT images
- Presence of significant calcifications can make CT angiogram uninterruptable, leading to the need for invasive diagnostic procedures
- Identification and digital suppression of calcium signal can preserve diagnostic value of CT angiography
Heavily calcified atheromatous plaque with high grade stenosis of the aorta is difficult to see on routine windows (left). Need to use wide window settings (right).
Material-specific applications

- Material characterization
  - Kidney stone characterization
  - Gout detection and quantification
  - Silicone breast implant leakage
- Iodine imaging
  - Automated bone removal in CT angiography
  - Plaque removal
  - Blood pool imaging (Perfused blood volume)
- Soft tissue imaging
  - Virtual non-contrast (Iodine removal/highlighting)
  - Virtual non-calcium (Bone removal/highlighting)
Virtual Noncontrast Images:

- Many diagnostic tasks require injection or ingestion of iodinated contrast media or barium
- Scans performed without contrast media not routinely included in most contrast-enhanced exams
- Sometimes, unexpected findings (e.g., modestly enhancing renal masses) are un-interpretable without having a non-contrast scan for comparison
- Identification and digital suppression of iodine signal can create a perfectly registered “virtual” non-contrast scan
Virtual Non-Calcium Images:

- Traumatic or oncologic bone lesions (bruising, edema, bone marrow lesions) cannot be appreciated on CT in the presence of bright calcium signal
- These lesions can point to severity of joint injury, occult fractures, or oncogenic bone lesions
- Identification and digital suppression of calcium signal can allow appreciation of these findings, previously observed only with MRI
Summary

- Multi-energy CT is a relatively recent clinical tool
  - Brief availability in 1980s
  - Reappearance in 2006
- Now commercially available using 4 different technical implementations from 4 different CT manufacturers
- Clinical applications were originally thought to be primarily related to bone or iodine removal
- Greatest impact to date has been with material characterization (kidney stones, gout, silicone)
- As technology continues to improve, more (and more quantitative) applications can be expected

Mayo Clinic CT Clinical Innovation Center
http://mayoresearch.mayo.edu/mayo/research/ctcic

Thank you