Dual Energy CT - Analysis of Kidney Stones for Individualized Patient Treatment

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Dual Energy – Everyday Usage
Dual Energy – How Does It Work?

• Attenuation values for each material is a function of the kVp
• CT enables material differentiation by the analysis of two X-ray spectra allowing the calculating of Compton and photoelectric effects
• The distinct attenuation values at chosen energy spectra are used for material differentiation in Dual-energy CT imaging provided that the atomic numbers and/or mass densities are different
• Materials can be distinguished more easily when large differences in atomic numbers are present
Principle of Dual-Energy CT

- Many materials show different attenuation at different mean energies
  
  ![Graph showing energy vs. attenuation for iodine and bone at 56 kV and 76 kV]

  - Reason: different attenuation mechanisms: Compton vs photo effect
Illustration of dual-energy technique shows hypothetical elements A and B, which have K edges of 90 keV and 190 keV, respectively.

A and B are 2 hypothetical elements with different k-edge values. The phantom is imaged with 2 different spectra and the images show different concentrations of the 2 materials in the phantom. Composition #1: neither A nor B is present; #2: mostly B; #3: mostly A; and #4 contains both.
Principle of Dual-Energy CT

- Bone at 400 HU
- Iodine at 250 HU
- Bone at 550 HU
- Iodine at 425 HU

80kV vs. 140kV
Attenuation Values of Various Tissues in Dual Energy (80 Vs. 140 kVp)
How to Implement Dual-Energy CT
Dual Source (Siemens)

- Two CT systems:
  - 2 tubes & detectors
- Can work in:
  - Dual-energy mode
  - Dual-source mode
  - Flash mode
Functional CT in addition to morphology
Simultaneous data acquisition with two tubes: 80 kV – 140 kV

\[ S_1: 80 \text{ kV} \quad S_2: 140 \text{ kV} \]

Mean Energy:
- Tube 1: 56 kV
- Tube 2: 76 kV

\[ \text{Photon energy (keV)} \]

Dual Source

• Better spectral separation via tin filter
• Dose optimized individually for each energy
• Dose in NOT 2X w/ DSCT
  • Asynchronous projections
  • Cross-scatter
  • Smaller FOV
Fast kV Switching (GE)

- Single source using fast switching between two energies
Fast kV Switching

- Projections are nearly synchronous
- Single source (only “one CT”)
- No cross scattering
- Dose cannot be individually optimized
- Less than perfect separation
Dual Spin: Helical Acquisition (Toshiba)

- Each voxel at high and low kV
- kV and mA automatically changed
- Orbital synchronization
- Switch off during anterior portion
Dual Spin: Pros and Cons

• Easy to Implement
  – Cost effective
  – Individually optimized
  – Filters
  – mA modulation
  – No cross-scatter

• Problems:
  – Delay for kV switching
  – Motion between scans
  – Only slice-level; no projection-level decomposition
Dual Layer (Philips)

- Detector sensitive to two different energies
- Each projection has a high and low energy component

(Not commercially available yet)
Photon Counting CT
The Future of Spectral CT

Incident x-ray

Photon to charge

Charge measured, counted, and stored digitally

Amplifier

Counting processing
Photon Counting - Advantages

Significant contrast improvement
• Noise reduction
• Dose reduction
• No electronic noise:
  – Ultra-low dose scans
• Multi-energy imaging
Nephrolithiasis

- Specifically refers to calculi in the kidneys, but renal calculi and ureteral calculi (ureterolithiasis) are often discussed in conjunction.
- A common disease that is estimated to produce medical costs of $2.1 billion per year in the United States.
- Renal colic affects approximately 1.2 million people each year and accounts for approximately 1% of all hospital admissions.
- Lifetime prevalence of nephrolithiasis is approximately 12% for men and 7% for women in the United States.
- Most urinary calculi develop in persons aged 20-49 years.
  - Peak incidence occurs in people aged 35-45 years, but the disease can affect anyone at any age.
  - Patients in whom multiple recurrent stones form usually develop their first stones while in their second or third decade of life.
Pathophysiology

• One phenomenon is supersaturation of the urine by stone-forming constituents, including calcium, oxalate, and uric acid.
• Crystals or foreign bodies can act as nidi, upon which ions form the stones.
• Another phenomenon, which is most likely responsible for calcium oxalate stones, is deposition of stone material on a renal papillary calcium phosphate nidus, typically a Randall plaque (which are always composed of calcium phosphate).
Etiology

- Calcium stones account for 75% of renal calculi.
  - Low-protein, low-salt diet may be preferable to a low-calcium diet in hypercalciuric stone formers for preventing stone recurrences.
- Struvite stones account for 15% of renal calculi.
  - Associated with chronic urinary tract infection (UTI) with gram-negative rods capable of splitting urea into ammonium, which combines with phosphate and magnesium.
- Uric acid stones account for 6% of renal calculi.
  - Associated with urine pH less than 5.5, high purine intake (e.g., organ meats, legumes, fish, meat extracts, gravies), or malignancy (i.e., rapid cell turnover).
  - Approximately 25% of patients with uric acid stone have gout.
- Cystine stones account for 2% of renal calculi.
  - Arise because of an intrinsic metabolic defect resulting in failure of renal tubular reabsorption of cystine, ornithine, lysine, and arginine.
  - Urine becomes supersaturated with cystine, with resultant crystal deposition.
Renal Stone Composition:

11 studies (dsDECT=8 & ssDECT=3)

• Uric Acid vs. Non Uric Acid stone differentiation possible
  – Phantom and humans 100%
  – Reliable for stones 3 mm and above

• Non-Uric Acid subtype of pure composition possible in phantom and in humans
  – Mixed composition stones difficult to characterize
Complications

Serious complications of urinary tract stone disease include the following:

- Abscess formation
- Serious infection of the kidney that diminishes renal function
- Urinary fistula formation
- Ureteral scarring and stenosis
- Ureteral perforation
- Extravasation
- Urosepsis
- Renal loss due to long-standing obstruction
Workup

- 24-Hour Urine Profile
- Plain (Flat Plate or KUB) Radiography
- Ultrasonography
- Intravenous Pyelography (Urography)
- Computed Tomography Scanning
Treatment

- short- and long-term therapies for stone disease:
  - Short term: Measures to dissolve the stone (possible only with noncalcium stones) or to facilitate stone passage
  - Long term: Treatment to prevent further stone formation
- Emergency management of renal (ureteral) colic, including:
  - Surgical interventions where indicated
  - Medical therapy for stone disease
Treatment (cont.)

• A stone chemical composition analysis should be performed whenever possible, and information should be provided to motivated patients about possible 24-hour urine testing for long-term nephrolithiasis.

• Uric acid and cystine calculi can be dissolved with medical therapy.
  – Patients with uric acid stones who do not require urgent surgical intervention for reasons of pain, obstruction, or infection can often have their stones dissolved with alkalization of the urine.
Treatment (cont.)

- Urinary calculi composed predominantly of calcium cannot be dissolved with current medical therapy; however, medical therapy is important in the long-term chemoprophylaxis of further calculus growth or formation.
Stone Fragility in Guiding Treatment

- CT helps predict stone fragility and susceptibility to lithotripsy
- Stones which are heterogeneous are more fragile than homogenous stones that are more resistant to ESWL
## Stone Size & Treatment Decisions

<table>
<thead>
<tr>
<th>Stone &lt; 5mm</th>
<th>Stones &gt; 6mm &amp; &lt;15mm</th>
<th>Stone &gt;15mm or Staghorn Calculi</th>
</tr>
</thead>
<tbody>
<tr>
<td>(98% for stones &lt; or = 4mm pass spontaneously)</td>
<td>(6-9 mm ureteral stone 60-25% pass) Stone location predicts outcome Upper=48%, mid=60%, lower 75-79% likely to pass spontaneously</td>
<td></td>
</tr>
</tbody>
</table>

**Medical Expulsive therapy (Alpha blockers)**

**Extracorporeal Shockwave lithotripsy (ESWL)**
- Ureteroscopic lithotripsy (upper ureter or larger stone)

**Percutaneous Nephrolithotomy (PCNL)**
## Stone Composition & Treatment Decisions

<table>
<thead>
<tr>
<th>Uric Acid Stone</th>
<th>Non Uric Acid Stone</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;400 HU</td>
<td>&lt;1000 HU (Struvite)</td>
</tr>
<tr>
<td>Medical Management</td>
<td>ESWL</td>
</tr>
<tr>
<td></td>
<td>&gt;1000 HU (Brushite, Cystine, COM)</td>
</tr>
<tr>
<td></td>
<td>Ureteroscopic PCNL</td>
</tr>
</tbody>
</table>
CT and Stone Composition

- Stone composition can be determined using HU
- CT Attenuation values – 64-77% accuracy in determination of stone composition is not robust and reliable
- Stone composition also effects the efficacy of ESWL (Brushite, cystine and COM stones are hard and resistant, while struvite stones usually fragment easily)

<table>
<thead>
<tr>
<th>Stone Composition</th>
<th>Attenuation value at 120kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uric Acid</td>
<td>200-450 HU</td>
</tr>
<tr>
<td>Struvite</td>
<td>600-900 HU</td>
</tr>
<tr>
<td>Cystine</td>
<td>600-1100 HU</td>
</tr>
<tr>
<td>Calcium Phosphate</td>
<td>1200-1600 HU</td>
</tr>
<tr>
<td>COM and Brushite</td>
<td>1700-2800 HU</td>
</tr>
</tbody>
</table>
Image Based Methods

- Modified 2-material decomposition: Characterization of kidney stones
  → Urine + calcified stones / uric acid stones
Characterization of a Renal Calculus with Dual-Energy Techniques

825 HU
Characterization of a Renal Calculus with Dual-energy Techniques
Characterization of a Renal Calculus with Dual-energy Techniques

Ca Oxalate Monohydrate
Modified 2-material decomposition: Characterization of kidney stones

- Urine + calcified stones / uric acid stones

- Accuracy > 93%, sensitivity > 88% depending on scan conditions

Courtesy of CIC Mayo Clinic Rochester, MN, USA
### Renal Stone Types, Attenuation Values, and Correlation between Dual-Energy CT and X-ray Diffraction Findings

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Attenuation Ratio</th>
<th>Low-Energy Attenuation (HU)*</th>
<th>High-Energy Attenuation (HU)*</th>
<th>CT-predicted Stone Type</th>
<th>X-ray Diffraction-confirmed Stone Type</th>
<th>Correlation with X-ray Diffraction?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.26</td>
<td>1484.6 ± 23</td>
<td>1185.7 ± 15</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
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<tr>
<td>2</td>
<td>1.27</td>
<td>1241 ± 24</td>
<td>980 ± 22</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
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<tr>
<td>3</td>
<td>0.99</td>
<td>462.9 ± 13.2</td>
<td>486.5 ± 9</td>
<td>Uric acid</td>
<td>Uric acid</td>
<td>Yes</td>
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<tr>
<td>4</td>
<td>1.26</td>
<td>1297 ± 22.3</td>
<td>991 ± 15.1</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
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<tr>
<td>5</td>
<td>0.97</td>
<td>340 ± 10.1</td>
<td>350 ± 6.8</td>
<td>Uric acid</td>
<td>Uric acid</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>1.23</td>
<td>1333 ± 33.3</td>
<td>1078 ± 23.4</td>
<td>Cystine</td>
<td>Calcium</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>1.23</td>
<td>928 ± 24</td>
<td>754.3 ± 14.2</td>
<td>Cystine</td>
<td>Calcium</td>
<td>No</td>
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<tr>
<td>8</td>
<td>0.98</td>
<td>563.3 ± 18.4</td>
<td>569.6 ± 12.4</td>
<td>Uric acid</td>
<td>Uric acid</td>
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<tr>
<td>9</td>
<td>1.30</td>
<td>830 ± 26.7</td>
<td>631 ± 20.1</td>
<td>Calcium</td>
<td>Calcium</td>
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<tr>
<td>10</td>
<td>1.23</td>
<td>1353 ± 37.5</td>
<td>1094 ± 26.9</td>
<td>Cystine</td>
<td>Calcium</td>
<td>No</td>
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<tr>
<td>11</td>
<td>1.26</td>
<td>415 ± 9</td>
<td>329 ± 5.4</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
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<tr>
<td>12</td>
<td>0.96</td>
<td>515.8 ± 17</td>
<td>532.8 ± 12.4</td>
<td>Uric acid</td>
<td>Uric acid</td>
<td>Yes</td>
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<tr>
<td>13</td>
<td>1.17</td>
<td>743 ± 25.9</td>
<td>633 ± 18.6</td>
<td>Cystine</td>
<td>Cystine</td>
<td>Yes</td>
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<tr>
<td>14</td>
<td>1.25</td>
<td>1400 ± 38</td>
<td>1113 ± 30.5</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
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<tr>
<td>15</td>
<td>0.95</td>
<td>514.5 ± 14</td>
<td>536.9 ± 9.4</td>
<td>Uric acid</td>
<td>Uric acid</td>
<td>Yes</td>
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<tr>
<td>16</td>
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<td>1265.7 ± 24</td>
<td>935.8 ± 15.4</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
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<tr>
<td>17</td>
<td>1.27</td>
<td>1217.3 ± 32</td>
<td>960.3 ± 24</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
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<tr>
<td>18</td>
<td>1.26</td>
<td>1335.9 ± 37.1</td>
<td>1052.3 ± 31.1</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
</tr>
<tr>
<td>19</td>
<td>1.31</td>
<td>798 ± 20.2</td>
<td>808 ± 14.1</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
</tr>
<tr>
<td>20</td>
<td>1.26</td>
<td>1332 ± 38.5</td>
<td>1053 ± 28.2</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
</tr>
<tr>
<td>21</td>
<td>1.26</td>
<td>1031.7 ± 28</td>
<td>806.1 ± 21</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
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<tr>
<td>22</td>
<td>0.99</td>
<td>378.9 ± 16</td>
<td>384 ± 12.4</td>
<td>Uric acid</td>
<td>Uric acid</td>
<td>Yes</td>
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<tr>
<td>23</td>
<td>1.23</td>
<td>1267.1 ± 35.4</td>
<td>1050.6 ± 27.5</td>
<td>Cystine</td>
<td>Cystine</td>
<td>No</td>
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<tr>
<td>24</td>
<td>1.25</td>
<td>1243 ± 40</td>
<td>990.5 ± 32.5</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
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<tr>
<td>25</td>
<td>1.26</td>
<td>1619 ± 26</td>
<td>1259 ± 18.5</td>
<td>Calcium</td>
<td>Calcium</td>
<td>Yes</td>
</tr>
<tr>
<td>26</td>
<td>1.26</td>
<td>1040 ± 27</td>
<td>819 ± 19.8</td>
<td>Cystine</td>
<td>Cystine</td>
<td>Yes</td>
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<tr>
<td>27</td>
<td>1.18</td>
<td>657 ± 22.2</td>
<td>554 ± 14.4</td>
<td>Cystine</td>
<td>Struvite</td>
<td>No</td>
</tr>
</tbody>
</table>

* Mean attenuation values ± standard deviations.
• All patients who were sent for CT for Kidney Stones were scanned in a dual-source CT (Siemens Flash CT) from November 2012 until July 2013
• Post processing using SingoVia workstation (Siemens) was done for all patient successfully
• 1376 patients (total of 1516 examinations) were scanned
• Patent age range: 15 Months to 96 years
• 489 females and 887 males
• Stones were differentiated to Oxalate, Hydroxylapatite, Cystine and Uric acid.
Uric Acid Stone
Uric Acid Stone
Non Uric Acid Stone
Non Uric Acid Stone
Non Uric Acid Stone
Non Uric Acid Stone
Another Possible Application?
Conclusions

Dual-energy CT improve material differentiation.
Dual-energy CT emerge as promising techniques providing functional information above and beyond CT imaging of morphology alone.
Identifying the exact composition of Kidney stones can provide important clinical information for the accurate treatment.
Using the Dual energy CT allows better assessment of Kidney stones for the individual patient.
Uric acid stones and Non uric acid stones can be recognized for better individualize treatment of the patient.
Further studies are need to evaluate the accuracy of our reports however such studies were done already.
Thank you!