Title
Understanding differences in quantification of conventional versus experimental contrast materials with different clinical dual-energy computed tomography systems, and development of universal contrast quantification “handshake”

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Understanding differences in quantification of conventional versus experimental contrast materials with different clinical dual-energy computed tomography systems, and development of universal contrast quantification “handshake” by Samuel Shu

THESIS
Submitted in partial satisfaction of the requirements for degree of MASTER OF SCIENCE in
Biomedical Imaging in
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Understanding differences in quantification of conventional versus experimental contrast materials with different clinical dual-energy computed tomography systems, and development of universal contrast quantification “handshake”

Samuel Shu

Abstract

Dual energy computed tomography (DECT) has unique imaging capabilities with the potential to improve clinical diagnosis compared to conventional single energy CT. The impending development of novel contrast agents that can take advantage of the unique material differentiation capability of DECT could dramatically expand the diagnostic value of this technology. Unfortunately, clinical DECT systems show intersystem variations in contrast quantification. These inter-scanner differences have been recognized to a limited extent in the current literature. A polyurethane abdominal phantom containing various conventional and experimental contrast materials was constructed to quantify the variance in Hounsfield units (HU) across six clinically available DECT systems. The attenuation profiles of conventional and novel contrast materials presented in this study may serve as a means to correct for intersystem differences across the DECT systems examined.
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**Introduction:** Dual energy computed tomography (DECT) has unique imaging capabilities with the potential to improve clinical diagnosis compared to conventional single energy CT. These include basis material decomposition to create virtual non-contrast and virtual monoenergetic image reconstructions with reduced beam hardening artifact and increased contrast-to-noise ratio.\(^1,2,3\) The advantages of DECT have been hinted at over the past forty years, and most recently have become increasingly widespread in the past decade as every major CT manufacturer has now introduced scanners capable of rapid dual energy CT data acquisition.\(^4-9\)

Clinical DECT, whereby two CT datasets are simultaneously or near-simultaneously acquired with different x-ray energy spectra, has been achieved by a number of hardware implementations including dual source, rapid kVp switching with a single source and dual-layered detector, sequential acquisition, and quantum-counting detector designs – the former two of which are clinically most common.\(^8\) Each DECT hardware approach presents unique technical challenges to overcome in order to produce high-quality, clinically useful images. Dual source systems typically employ correction algorithms to address cross-scattering.\(^10\) Single source systems must similarly account for overlap between high and low energy spectra.\(^11\) One strategy to maximize spectral separation is the use of a tin filter to selectively attenuate low-energy photons from the intended high-energy spectrum.\(^9\)

Basis material decomposition can be performed on a voxel-by-voxel basis to generate single-material images based on material-specific attenuation characteristics. Compton scattering and the photoelectric effect are the major phenomena that account for x-ray attenuation and are dependent on photon energy and atomic number of the
attenuating material. Therefore, materials differentiable by DECT must be of sufficiently disparate effective atomic number, with iodine and water (soft tissue) commonly assumed as basis materials.\textsuperscript{8,12} From such basis material decomposition images, virtual monochromatic images (VMI) can be generated as a linear combination of the mass attenuation coefficients of the basis materials, with attenuation coefficients based on calibration measurements.\textsuperscript{1,8,9,11,13} The specific postprocessing methods used to generate VMI as well as virtual non-contrast (VNC) images vary between manufacturers and are proprietary.\textsuperscript{14} These operations can be performed in either the projection domain or image domain, with the former employed in the setting of DECT acquisition by single source fast kVp switching method and dual layer detector implementations.\textsuperscript{1}

DECT holds great promise for improving clinical diagnosis, particularly regarding contrast material detection, differentiation, and quantification.\textsuperscript{7} An exciting potential benefit of DECT is that multiple different contrast agents with different atomic composition may be delivered simultaneously and their signals digitally separated to provide multiple high-resolution, perfectly co-registered images with a single pass of the DECT scanner. The impending development of novel contrast agents that can take advantage of the unique material differentiation capability of DECT could dramatically expand the diagnostic value of this technology.\textsuperscript{15} Unfortunately, clinical DECT systems show intersystem variations in contrast quantification. These inter-scanner differences have been recognized to a limited extent in the current literature.\textsuperscript{13,16} My study aims to quantify the variance in Hounsfield units (HU) across six clinically available DECT systems and develop a universal contrast quantification by proposing a means to correct for intersystem differences. Currently, DECT data can only be processed using
vendor-specific software, presenting challenges to clinical workflow. My study will also address the possibility of generating virtual monoenergetic images using a vendor-agnostic DECT processing software.

**Methods:** **Phantom Construction:** An ovoid cylinder of polyurethane rubber was cast to construct a phantom mimicking the adult human abdominal environment with approximate water attenuation. The phantom consisted of three identical parts, designated Part 1, Part 2, and Part 3, with cross-section 30 cm by 22 cm and depth 18 cm. Twelve cylindrical slots were made in the cross-sectional face of each phantom part accommodating twelve polypropylene 50mL self-standing centrifuge tubes (Corning Science Mexico S.A. de C.V., ref. 430897). Each slot was loaded with one of 80 tubes containing 50mL of deionized water, lard, canola oil, a single contrast material, or a mixture of two contrast materials (Table 1). Tubes slots were arranged as far apart as possible within the phantom to minimize the effects of scatter during scanning (Figure 1). Tubes were placed in the phantom parts in 3 batches, scanned as Setup 1, Setup 2, and Setup 3. The first 36 tubes were loaded into Parts 1-3 of the phantom in numerical order. This phantom setup was designated and scanned as Setup 1. The tubes in Parts 2 and 3 were removed and tubes 37 through 56 were loaded in numerical order. This revised setup of Part 2 and Part 3 was scanned separately as Setup 2. Setup 3 consisted of phantom Parts 2 and 3 containing tubes 57 through 80.
Table 1. Summary of tube contents, position in phantom, and expected HU at 120 kVp

<table>
<thead>
<tr>
<th>Tube Number</th>
<th>Contents</th>
<th>Expected HU at 120 kVp</th>
<th>Phantom Position (part-slot)</th>
<th>Tube Number</th>
<th>Contents</th>
<th>Expected HU at 120 kVp</th>
<th>Phantom Position (part-slot)</th>
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<tbody>
<tr>
<td>1</td>
<td>80%I</td>
<td>240</td>
<td>1-01</td>
<td>41</td>
<td>60%I</td>
<td>180</td>
<td>2-05</td>
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<tr>
<td>2</td>
<td>20%I</td>
<td>60</td>
<td>1-02</td>
<td>42</td>
<td>40%W, 20%Ca</td>
<td>180</td>
<td>2-06</td>
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<tr>
<td>3</td>
<td>40%I</td>
<td>120</td>
<td>1-03</td>
<td>43</td>
<td>10%W, 10%Ca</td>
<td>60</td>
<td>2-07</td>
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<tr>
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<td>Vial Number</td>
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<td>Phantom Position (part-slot)</td>
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<td>72</td>
<td>9% NX9</td>
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<tr>
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<td>3-09</td>
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<td>2-02</td>
<td>78</td>
<td>3% NX9</td>
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<td>300</td>
<td>2-04</td>
<td>80</td>
<td>20 mg/mL Tantalum</td>
<td>3-12</td>
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</tbody>
</table>

**Contrast Solutions Preparation:** Contrast materials were prepared as aqueous solutions of iodine (Omnipaque iohexol injection, GE Healthcare, NDC 0407-1414-91), calcium (calcium chloride dihydrate, Research Products International, Mt. Prospect, IL 60056 USA), tungsten (sodium tungstate dihydrate, Sigma Aldrich, ACS reagent, \( \geq 99\% \)), and an experimental CT contrast agent NX9. Stock solutions of iodine, calcium,
and tungsten were prepared such that each appeared as 300 HU at 120 kVp. Stock solutions consisted of 12.6 mg/mL iodine, 56.17 mg/mL calcium, and 11.17 mg/mL tungsten. The attenuation of each of these stock solutions was confirmed to be 300 HU at 120 kVp as scanned using the General Electric Discovery CT 750HD. Xanthan gum was added to stock solutions of calcium and tungsten in order to hold the particulate materials in suspension. Three hundred HU was arbitrarily chosen as a target value that allows easy observation of positive or negative fluctuations in HU with different scan/reconstruction parameters without causing excessive streak artifact. Stock solutions were designated as “100%” material solutions and dilutions were performed to produce 20%, 40%, 60%, and 80% solutions of each contrast material. Tubes containing water were used to represent the 0% solution of any contrast material in analyses. Additionally, solutions of 10, 15, and 20 mg/mL iodine were included in Setup 3. Aqueous solutions of tantalum and neodymium were provided by General Electric Medical Systems. Solutions of 5, 10, 15, and 20 mg/mL tantalum were made. Solutions of 10, 15, and 20 mg/mL neodymium were made. The experimental contrast agent, NX9, contains a negatively attenuating, low-density microparticle of composition that is proprietary to the developer Nextrast, Inc. at the time of this study. The NX9 particles used in Setup 2 had a density 30% greater than that of those used in Setup 3. The lower density NX9 particles in Setup 3 were formulated in concentrations of 3, 6, 9, 12, and 15 percent of solution by weight.

**Phantom Scans:** Phantom scans were performed at University of California, San Francisco, Zuckerberg San Francisco General Hospital, and San Francisco Veterans Affairs Medical Center with 6 DECT systems in clinical use: Siemens Somatom
Definition Edge (Edge), Siemens Somatom Definition Flash (Flash), Siemens Somatom Definition Force (Force), Philips IQon Spectral CT (IQon), General Electric Discovery CT 750HD (Discovery), General Electric Revolution CT (Revolution), and Canon Aquilion ONE GENESIS 640 (Canon). Acquisition parameters were kept as similar as possible given the variation of design and technical specifications between systems (Table 1), and CTDIvol was set to 30 ± 4 mGy. Images were acquired from the minimum to maximum kVp in intervals of 20 kVp on each system, and axial VMI were reconstructed from the minimum to maximum keV in intervals of 5 keV. Phantom Setups 1 and 2 were scanned separately on each system in the same orientation. Phantom parts were placed in numerical order as close together as possible on the table, with tube caps oriented outward of the scanner, and the scan beginning with Part 3. For logistic reasons, Setup 3 was scanned only on the IQon, Revolution, and Discovery systems. To assess the effects of position within the phantom on tube attenuation, Setup 3 was scanned on the Discovery scanner with the original tube arrangement as in Table 1 as well as in a scrambled setup, where the positions of 3 tube pairs were switched: 57 and 63, 61 and 68, and 69 and 75. These alternate tube positions were used to assess the effect of deep vs superficial positioning within the phantom of 100% tungsten, 15 mg/mL iodine, and 15% NX9 tubes. To assess the effect of possible phantom inhomogeneity, phantom Parts 1, 2, and 3 were also scanned on the Discovery system with only a single tube in each phantom part (15% NX9, 20 mg/mL iodine, 20 mg/mL tantalum). Each tube was positioned in slot 8 of a phantom part.
### Table 2. Summary of scanner specifications and phantom scan parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Edge</th>
<th>Flash</th>
<th>Force</th>
<th>Iqon</th>
<th>Revolution</th>
<th>Discovery</th>
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<tbody>
<tr>
<td>Tube voltage gap (kV, low/high)</td>
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<td>80/140, 100/140</td>
<td>80/150, 100/150</td>
<td>80/140</td>
<td>70/140</td>
<td>80/140</td>
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<tr>
<td>Tube current (mA)</td>
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<td>126/78, 147/75</td>
<td>406</td>
<td>200</td>
<td>200</td>
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<td>Field of view (cm)</td>
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<td>50</td>
<td>50</td>
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<td>Gantry revolution time (sec)</td>
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<td>1.25</td>
<td>1.25</td>
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<tr>
<td>Slice gap (mm)</td>
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<td>Br40d/3</td>
<td>B</td>
<td>Standard</td>
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<td>Filter</td>
<td>Sn, Au</td>
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<td>SN_D3</td>
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</tr>
<tr>
<td>Source to Detector Distance (cm)</td>
<td>108.56</td>
<td>108.56</td>
<td>108.56</td>
<td>104</td>
<td>109.76</td>
<td>94.67</td>
</tr>
<tr>
<td>Source to Patient Distance (cm)</td>
<td>59.5</td>
<td>59.5</td>
<td>59.5</td>
<td>57</td>
<td>62.56</td>
<td>53.85</td>
</tr>
</tbody>
</table>
**Image Analysis:** The average HU of each vial in each image reconstruction was semi-automatically measured using the image processing software ImageJ. Ten circular regions of interest (ROI) were manually placed within each vial of one reconstruction of Setup 1 and 2 from each scanner system, taking care to avoid air bubbles and obvious regions of signal inhomogeneity as well as to distribute the ROI’s along the length of the tube as much as possible. A macro was employed to record the average HU of each ROI in all image reconstructions from a given scanner. The 10 ROI measurements of each vial were then averaged to represent the average HU in each vial. Data visualization and curve fitting was performed using the statistical software R Studio.

Additional virtual monoenergetic images were reconstructed using a prototype vendor-agnostic dual energy processing software called Vitrea in development by Vital Images, Inc. (Minnetonka, MN 55343). With the unavailability of raw sinogram scan data, the 55 and 70 keV monoenergetic images were used as source images to generate third-party virtual monoenergetic images in Vitrea. Images of 55 and 70 keV were chosen as source images for Vitrea as they best approximate the 80 and 140 kVp dual energy source data commonly used in DECT systems. Iodine maps quantification maps were also generated using the Vitrea software in addition to the vendor-specific iodine maps. The attenuation profiles generated by this third-party software were compared to those generated by the vendor-specific, “native,” software.

**Results: Polychromatic Images:** A summary of expected and measured HU for select concentrations of iodine, calcium, and tungsten at 120 kVp is presented in *Table 3*. These results reflect the spectral imaging performance of DECT systems for which 120 kVp data was collected: Philips IQon, GE Revolution, GE Discovery. In polychromatic
images of iodine, calcium, and tungsten solutions, HU appears linearly related to material concentration on all scanners with strong linear correlation, $R^2$ greater than 0.97 (Figure 2). In general, intersystem variation in HU also appears to increase with material concentration.

<table>
<thead>
<tr>
<th>Tube Contents</th>
<th>Attenuation at 120 kVp (HU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td>10 mg/mL Iodine</td>
<td>250</td>
</tr>
<tr>
<td>15 mg/mL Iodine</td>
<td>375</td>
</tr>
<tr>
<td>20 mg/mL Iodine</td>
<td>500</td>
</tr>
<tr>
<td>20% Calcium</td>
<td>60</td>
</tr>
<tr>
<td>60% Calcium</td>
<td>180</td>
</tr>
<tr>
<td>100% Calcium</td>
<td>300</td>
</tr>
<tr>
<td>20% Tungsten</td>
<td>60</td>
</tr>
<tr>
<td>60% Tungsten</td>
<td>180</td>
</tr>
<tr>
<td>100% Tungsten</td>
<td>300</td>
</tr>
</tbody>
</table>

2.1
Figure 2. HU vs Concentration of iodine polychromatic reconstructions by scanner
Similar behavior is seen in the HU vs Concentration plots of polychromatic images of calcium and tungsten, with tungsten exhibiting notably less variation in HU between scanners (Figure 3).

Figure 3. HU vs Concentration of calcium and tungsten polychromatic reconstructions by scanner

**Monoenergetic Images:** For all materials except tungsten, monoenergetic image reconstructions from all scanners show that conspicuity of all concentrations of contrast material increases with decreasing energy of reconstruction, with HU following a
second-degree exponential decay with increasing monoenergetic kilovoltage (Figure 4). All scanners produced similar exponential curves for all material concentrations except tungsten, which showed positive exponential behavior on the Philips IQon and Siemens Edge scanners (Figure 4).

### Figure 4

**100% Iodine: HU vs. Monoenergetic Reconstruction**

- $y = -1570674 + 1570657 \times e^{(1/k^2)}$, $r^2 = 0.998$
- $y = -1534804 + 1534787 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -1510333 + 1510335 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -1533580 + 1533580 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -1553492 + 1553473 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -1572231 + 1572213 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -1625839 + 1625805 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -1526230 + 1526184 \times e^{(1/k^2)}$, $r^2 = 0.999$

**100% Calcium: HU vs. Monoenergetic Reconstruction**

- $y = -1038483 + 1038549 \times e^{(1/k^2)}$, $r^2 = 0.998$
- $y = -945850 + 945924 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -964504 + 964594 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -969225 + 969315 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -971283 + 971357 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -972814 + 972890 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -1123425 + 1123474 \times e^{(1/k^2)}$, $r^2 = 0.999$
- $y = -982786 + 982834 \times e^{(1/k^2)}$, $r^2 = 0.999$
4.3 Figure 4. HU vs monoenergetic reconstruction of 100% iodine, calcium, and tungsten

The R-squared values of all curves fitted to HU vs. monoenergetic reconstruction energy plots were greater than 0.97. As a result, 95% confidence intervals are not visible on the plotted data. The equations describing HU vs. monoenergetic reconstruction energy are of the form \( y = A + B/\sqrt{x}, r^2 = 0.998 \) where A and B are constants unique to each curve. Constants corresponding to the native and Vitrea-generated monoenergetic curves in Figure 5 are reported in Table 4 (see Appendix, Figure 10, for monoenergetic plots of other material concentrations). Linear plots of tungsten and tantalum attenuation have only a single constant A.
Figure 5. Native vs Vitrea monoenergetic attenuation curves by scanner
Table 4. Native vs Vitrea monoenergetic attenuation curves constants

<table>
<thead>
<tr>
<th>Constant</th>
<th>IQon Native</th>
<th>IQon Vitrea</th>
<th>Revolution Native</th>
<th>Revolution Vitrea</th>
<th>Discovery Native</th>
<th>Discovery Vitrea</th>
</tr>
</thead>
<tbody>
<tr>
<td>NX9.1 A</td>
<td>-104698</td>
<td>-580504</td>
<td>-87932</td>
<td>-554381</td>
<td>-125193</td>
<td>-597020</td>
</tr>
<tr>
<td>NX9.1 B</td>
<td>104415</td>
<td>580143</td>
<td>87651</td>
<td>554028</td>
<td>124911</td>
<td>-597020</td>
</tr>
<tr>
<td>100% Iodine A</td>
<td>-1647809</td>
<td>-2032821</td>
<td>-1572435</td>
<td>-1926130</td>
<td>-1512342</td>
<td>-1895779</td>
</tr>
<tr>
<td>100% Iodine B</td>
<td>1647776</td>
<td>2032777</td>
<td>1572407</td>
<td>1926104</td>
<td>1512289</td>
<td>1895719</td>
</tr>
<tr>
<td>100% Calcium A</td>
<td>-1090702</td>
<td>-1232638</td>
<td>-1524832</td>
<td>-1815207</td>
<td>-1029952</td>
<td>-1223980</td>
</tr>
<tr>
<td>100% Calcium B</td>
<td>1090757</td>
<td>1232701</td>
<td>1524849</td>
<td>1815236</td>
<td>1029985</td>
<td>1224020</td>
</tr>
<tr>
<td>100% Tungsten A</td>
<td>199330</td>
<td>322.4826</td>
<td>-137695</td>
<td>295.5768</td>
<td>-42891</td>
<td>282.861</td>
</tr>
<tr>
<td>100% Tungsten B</td>
<td>-198965</td>
<td>NA</td>
<td>43166</td>
<td>NA</td>
<td>43166</td>
<td>NA</td>
</tr>
<tr>
<td>20 mg/mL Tantalum A</td>
<td>204834</td>
<td>458.2761</td>
<td>-300581</td>
<td>422.1256</td>
<td>-213758</td>
<td>495.993</td>
</tr>
<tr>
<td>20 mg/mL Tantalum B</td>
<td>-204325</td>
<td>NA</td>
<td>300940</td>
<td>NA</td>
<td>214211</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Discussion:** Polychromatic Images: Comparison of expected vs. measured HU of iodine, calcium, and tungsten at 120 kVp across the Philips and GE DECT systems demonstrates inconsistency between systems. Both GE systems produced near-expected HU values for iodine with greater accuracy than Philips, but performed no better or worse than Philips in achieving expected HU values for calcium and tungsten. HU vs Concentration plots of materials by scanner further demonstrate differences in performance of the various scanner systems.

**Limitations:** Analysis was based on a single size phantom. Different sized mass-attenuators could result in deviations of the observed HU values. Furthermore, this particular phantom series is limited by a small number of missing data points. These
consisted of a few clear outliers which were intentionally omitted and certain 
monoenergetic reconstructions which, for logistic reasons, could not be recovered. 
Image series are missing for the Siemens Force 150 keV (energy gap 80/150 kVp) and 
70 keV (energy gap 100/150 kVp) reconstructions of Setup 1, as well as the 155 keV 
(100/150 kVp) and Part 3 of the 150 keV (100/150 kVp) monoenergetic reconstructions 
of Setup 2. Likewise, Setup 3 could only be scanned using the Philips IQon and GE 
Revolution and Discovery systems for logistic reasons, only phantom Setup 1 was 
scanned on the Canon system. Inhomogeneity and small air bubbles suspended in the 
phantom tubes may also contribute to the inherent variability in the data as well as the 
presence of outliers.

Streak artifacts from relatively high-density tubes may affect the measured 
attenuation of other nearby tubes. The neighborhood and position within the phantom of 
a given tube may be factors contributing to its measured attenuation in addition to its 
contents. In the alternate tube arrangement of Setup 3, scanned on the GE Discovery 
system, the effect on measured attenuation of deep vs superficial tube placement within 
the phantom was assessed for 3 tubes: 100% tungsten, 15 mg/mL iodine, and 15% 
NX9. The differences in HU values at 120 kVp were found to be within the standard 
deviation of a given tube in either position (Table 5). One exception is noted in the case 
of 15 mg/mL iodine, where the difference in HU was slightly greater than the standard 
deviation of HU in the superficial position. Likewise, the tubes (15% NX9, 20 mg/mL 
iodine, and 20 mg/mL tantalum) scanned individually in separate phantom parts showed 
monoenergetic attenuation profiles (Figure 6) with near perfect match to the same 
tubes scanned in phantom Setup 3.
Table 5. Difference in HU with alternate tube position

<table>
<thead>
<tr>
<th>Material</th>
<th>Difference in Average HU between Deep and Superficial Position at 120 kVp</th>
<th>Standard Deviation, Deep</th>
<th>Standard Deviation, Superficial</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Tungsten</td>
<td>6.76</td>
<td>19.26</td>
<td>16.42</td>
</tr>
<tr>
<td>15mg/mL Iodine</td>
<td>19.29</td>
<td>21.01</td>
<td>16.64</td>
</tr>
<tr>
<td>15% NX9</td>
<td>0.87</td>
<td>17.89</td>
<td>13.45</td>
</tr>
</tbody>
</table>

Figure 6. HU vs monoenergetic reconstruction in Single vs Full Phantom

Monoenergetic Images: All curves fitted to HU vs. monoenergetic reconstruction energy plots had near perfect fit to the plotted data, with r-squared values greater than 0.97 in all cases. Variability in local tube environment within the phantom, as a result of depth within the polyurethane phantom or possible streaking artifacts from neighboring tubes of relatively high density, was shown to have negligible effect on the HU of the
materials tested under these variable conditions. The fitted curves of HU vs. monoenergetic reconstruction can therefore be considered as good representations of the monoenergetic attenuation profiles of the materials as imaged with the specific DECT systems in question.

The 15 mg/mL tantalum tube in Setup 3 of the phantom was obtained from a stock solution which had been in storage for an extended period of time. The original concentration of tantalum may not have been preserved due to evaporation, resulting in inaccurate dilution. For this reason, the 15 mg/mL tantalum tube was excluded from analysis. A limited supply of tantalum precluded the replacement of the 15 mg/mL tantalum solution. All other dilutions of tantalum were obtained from a different stock solution and appeared to be of the correct concentration.

The GE Revolution and Siemens Force (100, 150 kVp) monoenergetic HU values of tungsten appear more closely related to one another than to those of the other scanners, especially at low extreme of monoenergetic reconstruction. Similarly, the Philips IQon and Siemens Edge monoenergetic HU values of tungsten appear to share a horizontal asymptote, with the two curves nearly coincidental from 130 keV and above. As opposed to the relative uniformity of polychromatic attenuation plots of tungsten, monoenergetic reconstructions of tungsten appeared to produce the greatest intersystem variation.

Comparison of native vs Vitrea monoenergetic reconstructions of various materials scanned on the same DECT system (Figure 5) show that the Vitrea reconstructions approximate the native attenuation profiles. The Vitrea NX9 curves have a steeper vertical asymptote than their native counterparts. Of note, the Vitrea-
generated monoenergetic attenuation profiles of high-z materials tungsten and tantalum are transformed from a native exponential curve to be perfectly linear on all scanners except the Siemens Edge and Force. Comparison of the native vs Vitrea monoenergetic reconstructions of the same material across different DECT systems (Figure 7) shows that Vitrea is able to resolve some degree of disparity in the attenuation profiles generated by different systems for tungsten and NX9, though not so for iodine and calcium.
7.3

NX9 Native Monoenergetic Reconstructions

\[ y = -98874 + 98671 \ exp(1/x^2), \ R^2 = 0.994 \]
\[ y = -183463 + 163218 \ exp(1/x^2), \ R^2 = 0.999 \]
\[ y = -135786 + 135544 \ exp(1/x^2), \ R^2 = 0.999 \]

7.4

NX9 Vitrea Monoenergetic Reconstructions

\[ y = -480303 + 479745 \ exp(1/x^2), \ R^2 = 0.999 \]
\[ y = -508168 + 507870 \ exp(1/x^2), \ R^2 = 0.999 \]
\[ y = -487103 + 486804 \ exp(1/x^2), \ R^2 = 0.999 \]

7.5

100% Calcium Native Monoenergetic Reconstructions

\[ y = -340321 + 340396 \ exp(1/x^2), \ R^2 = 0.999 \]
\[ y = -958553 + 958434 \ exp(1/x^2), \ R^2 = 0.999 \]
\[ y = -965434 + 965509 \ exp(1/x^2), \ R^2 = 0.999 \]
\[ y = -924732 + 924819 \ exp(1/x^2), \ R^2 = 0.999 \]
Figure 7. Native vs Vitrea monoenergetic attenuation curves by material

The plotted Vitrea-generated iodine quantification maps for the Discovery and Revolution scanners across iodine concentrations had a y-intercept and slope greater than that of the natively generated plot (Figure 8). The strong correlation between the iodine concentration vs attenuation profile of the two scanners is maintained, and the greater slope of the Vitrea-generated plots suggests that greater contrast and thereby easier quantification of iodine concentration may be achieved with this third-party software.
The method by which Vitrea generates virtual monoenergetic images and iodine maps is proprietary knowledge of Vital Images, Inc. It is unknown whether better results can be achieved when the software is used to process spectral vs monoenergetic images. At the time of this study, Vitrea software remains in development and further validation with contrast agents approved by the Food and Drug Administration is needed.

**Conclusion:** The results of this study affirm that there exists a general correlation of HU values between DECT scanners for most of the materials examined, but that a degree of intersystem variation in HU is present among the DECT systems examined. Despite differences between scanner systems, the attenuation profiles of the materials examined are readily differentiable. Certain materials examined in this study, such as NX9 and tantalum, may one day enter clinical use as contrast agents. A catalog of the attenuation profiles of various contrast materials scanned on the full range of clinical DECT systems can serve as a “Rosetta stone” and provide a means of translating the...
HU outputs between scanners. Presently, the main focus of this project has been to describe intersystem HU variance in a variety of contrast materials. To further validate the results of this study, intersystem HU correction may be applied to in vivo multi-contrast animal DECT images.
References


Appendix

9.1

Calcium 80 kVp

\[ y = -9.71 + 4.15 x, \quad r^2 = 0.996 \]
\[ y = -4.73 + 3.75 x, \quad r^2 = 0.997 \]
\[ y = -3.63 + 3.78 x, \quad r^2 = 0.994 \]
\[ y = 4.67 + 3.5 x, \quad r^2 = 0.998 \]
\[ y = 1.23 + 3.74 x, \quad r^2 = 1.0 \]

9.2

Calcium 100 kVp

\[ y = -5.54 + 3.36 x, \quad r^2 = 0.996 \]
\[ y = -1.27 + 2.99 x, \quad r^2 = 0.997 \]
\[ y = -3.36 + 3.05 x, \quad r^2 = 0.996 \]
\[ y = 1.59 + 2.83 x, \quad r^2 = 0.999 \]
\[ y = 3.02 + 3.02 x, \quad r^2 = 1.0 \]

9.3

Calcium 140 kVp

\[ y = -4.25 + 2.57 x, \quad r^2 = 0.995 \]
\[ y = 1.01 + 1.86 x, \quad r^2 = 0.996 \]
\[ y = 4.02 + 2.2 x, \quad r^2 = 0.999 \]
\[ y = 4.12 + 2.27 x, \quad r^2 = 1.0 \]
9.4 Calcium 120 kVp

$y = -4.63 + 2.89 \times x$, $r^2 = 0.996$

$y = -5.52 + 1.97 \times x$, $r^2 = 0.996$

$y = -6.41 + 2.38 \times x$, $r^2 = 0.995$

$y = 5.59 + 2.46 \times x$, $r^2 = 0.985$

$y = 2.55 + 2.56 \times x$, $r^2 = 1$

9.5 Tungsten 80 kVp

$y = -3.71 + 3.05 \times x$, $r^2 = 0.999$

$y = 4.14 + 2.95 \times x$, $r^2 = 0.988$

$y = -3.03 + 2.94 \times x$, $r^2 = 0.999$

$y = 2.81 + 2.66 \times x$, $r^2 = 0.997$

$y = -3.78 + 2.78 \times x$, $r^2 = 0.992$

9.6 Tungsten 100 kVp

$y = -0.132 + 3.36 \times x$, $r^2 = 0.999$

$y = 6.48 + 3.42 \times x$, $r^2 = 0.999$

$y = 2.9 + 3.33 \times x$, $r^2 = 0.99$

$y = 2.5 + 3.03 \times x$, $r^2 = 0.99$

$y = 0.00357 + 3.18 \times x$, $r^2 = 0.955$
Figure 9. HU vs Concentration of calcium and tungsten by scanner

9.7 Tungsten 120 kVp

9.8 Tungsten 140 kVp

20% Iodine: HU vs. Monoenergetic Reconstruction

10.1
10.10

80% Calcium: HU vs. Monoenergetic Reconstruction

\[ y = 836206 + 832658 \cdot x^{1/0.8}, \quad r^2 = 0.998 \]
\[ y = -772478 + 772541 \cdot x^{1/0.8}, \quad r^2 = 0.999 \]
\[ y = -793509 + 793575 \cdot x^{1/0.8}, \quad r^2 = 0.999 \]
\[ y = -613047 + 613111 \cdot x^{1/0.8}, \quad r^2 = 0.999 \]
\[ y = -556677 + 556732 \cdot x^{1/0.8}, \quad r^2 = 0.999 \]
\[ y = -885884 + 885925 \cdot x^{1/0.8}, \quad r^2 = 0.999 \]
\[ y = -784499 + 784535 \cdot x^{1/0.8}, \quad r^2 = 0.999 \]

Scanners
- IQon
- Edge
- Flash_80
- Flash_100
- Force_80
- Force_100
- Revolution
- Discovery

10.8

20% Tungsten: HU vs. Monoenergetic Reconstruction

\[ y = 52650 + 52572 \cdot x^{1/0.6}, \quad r^2 = 0.998 \]
\[ y = 45501 + 45431 \cdot x^{1/0.6}, \quad r^2 = 0.997 \]
\[ y = 3941 + 3877 \cdot x^{1/0.6}, \quad r^2 = 0.995 \]
\[ y = 108710 + 108762 \cdot x^{1/0.6}, \quad r^2 = 0.999 \]
\[ y = -57088 + 57136 \cdot x^{1/0.6}, \quad r^2 = 0.999 \]
\[ y = -135090 + 135130 \cdot x^{1/0.6}, \quad r^2 = 0.999 \]
\[ y = -102962 + 103003 \cdot x^{1/0.6}, \quad r^2 = 0.999 \]
\[ y = -7629 + 7684 \cdot x^{1/0.6}, \quad r^2 = 0.684 \]

Scanners
- IQon
- Edge
- Flash_80
- Flash_100
- Force_80
- Force_100
- Revolution
- Discovery

10.9

40% Tungsten: HU vs. Monoenergetic Reconstruction

\[ y = 90133 - 89984 \cdot x^{1/0.6}, \quad r^2 = 0.998 \]
\[ y = 31943 - 31806 \cdot x^{1/0.6}, \quad r^2 = 0.988 \]
\[ y = -25552 - 25270 \cdot x^{1/0.6}, \quad r^2 = 0.969 \]
\[ y = -237794 + 238043 \cdot x^{1/0.6}, \quad r^2 = 0.999 \]
\[ y = -63876 + 63978 \cdot x^{1/0.6}, \quad r^2 = 0.997 \]
\[ y = -222836 + 222984 \cdot x^{1/0.6}, \quad r^2 = 0.999 \]
\[ y = -80866 + 81712 \cdot x^{1/0.6}, \quad r^2 = 0.999 \]
\[ y = -25483 + 25589 \cdot x^{1/0.6}, \quad r^2 = 0.971 \]

Scanners
- IQon
- Edge
- Flash_80
- Flash_100
- Force_80
- Force_100
- Revolution
- Discovery

10.10
Figure 10. HU vs Monoenergetic reconstruction plots of iodine, calcium, and tungsten at concentrations 20% 40%, 60%, and 80%
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Author Signature                          Date

9 September 2019