Potentials for Dual-energy kV/MV On-board Imaging and Therapeutic Applications

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Specific Objectives

- Development of a novel on-board imaging technique which allows generation of virtual monochromatic (VM) CBCT from combined polychromatic kV/MV beam projections
- Evaluation of the effectiveness of dual-energy CBCT for artifact reduction

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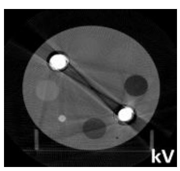
Introduction

- Onboard kV imaging
  - ➢ Good soft tissue contrast and clinically available
  - ➢ Less penetrating and more metal artifacts
- Onboard MV imaging
  - ➢ Less attenuation and less metal artifacts
  - ➢ Poor soft tissue contrast
- Can we take advantages of both kV and MV imaging?
  - – Monochromatic energy (replace polychromatic energies)
  - – Aggregated kV/MV projections

Introduction

- Conventional CBCT suffers artifacts: large object, metal,…
- Dual-energy technique can be used to reduce artifacts and photon starvation in kV ranges
- The research of applying dual-energy imaging technique into CBCT and kV/MV is still limited



Method: Dual Energy Imaging Principle

- In diagnostic x-ray energy range, the attenuation coefficient of a material can be decomposed into a photoelectric component and a Compton scatter component
- These two components are difficult to measure independently and are practically approximated with two basis materials, one with relatively high atomic number Z and the other with relatively low Z
- At a given energy, the high Z and low Z material have different composition of photoelectric effect and Compton scatter, which can be differentiated using dual-energy

Method: Dual Energy Imaging Principle

- **Two measurements I_L and I_H acquired with monochromatic beams at two different energies E_L and E_H can be therefore expressed as,**

$$\begin{cases} ln(I_L/I_0) = -x_A\mu_A(E_L) - x_B\mu_B(E_L) \\ ln(I_H/I_0) = -x_A\mu_A(E_H) - x_B\mu_B(E_H) \end{cases}$$

From these two equations

$$\begin{bmatrix} x_A \\ x_B \end{bmatrix} = \begin{bmatrix} -\mu_A(E_L) & -\mu_B(E_L) \\ -\mu_A(E_H) & -\mu_B(E_H) \end{bmatrix}^{-1} \begin{bmatrix} ln(I_L/I_0) \\ ln(I_H/I_0) \end{bmatrix}$$

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Method: Dual Energy Imaging Principle

- **Generalizations for polychromatic beams with low-energy spectrum $S_L(E)$ and high energy spectrum $S_H(E)$,**

$$\begin{cases} ln(I_L/I_0) = \int S_L(E)[-x_A\mu_A(E) - x_B\mu_B(E)]dE \\ ln(I_H/I_0) = \int S_H(E)[-x_A\mu_A(E) - x_B\mu_B(E)]dE \end{cases}$$

- **This involves integrals over the beam energy spectrum. In practice, it is difficult to have analytical solutions**

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Method: Dual Energy Imaging Principle

- **An approximate solution proposed by Cardinal et al:**

$$x_A = \frac{a_0 + a_1L + a_2H + a_3L^2 + a_4LH + a_5H^2}{1 + b_0L + b_1H}$$

$$x_B = \frac{c_0 + c_1L + c_2H + c_3L^2 + c_4LH + c_5H^2}{1 + d_0L + d_1H}$$

  - **where $L = -ln(I_L/I_0)$ and $H = -ln(I_H/I_0)$**
  - **The parameters a_i, b_j, c_i, d_j $(i = 0 \sim 5, j = 0, 1)$ can be experimentally determined and used for dual-energy imaging**

- Alvarez and Macovski, Energy-selective reconstructions in X-ray computerized tomography. Physics in Medicine and Biology, 1976. 21(5): p. 733-44
- Zou and Silver. Analysis of fast kV-switching in dual energy CT using a pre-reconstruction decomposition technique. Vol. 6913. 2008: SPIE. 691313

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Method: Dual Energy Imaging Principle

- For large object thickness with energy E lower than 17 MeV, the attenuation behaves asymptotically in a linear fashion and can be approximated as:

  $ln(I/I_0) \sim -\mu_{acrylic}(E_p)x_{acrylic} - \mu_{Al}(E_p)x_{Al}$

  E_p: the peak energy of polychromatic spectrum

- As a good approximation, extend the application of the diagnostic energy range to the MV range
  - Cardinal, H.N. and A. Fenster. An accurate method for direct dual-energy calibration and decomposition. Medical Physics, 1990 17(3):327-41

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Fundamentals of VM Technology

- For the polychromatic kV and MV projections:

$$\begin{cases} \ln(I_{kV}/I_0) = \int S_{kV}(E)[-x_A\mu_A(E) - x_B\mu_B(E)]dE \\ \ln(I_{MV}/I_0) = \int S_{MV}(E)[-x_A\mu_A(E) - x_B\mu_B(E)]dE \end{cases}$$

I_{kV}: kV intensity
I_{MV}: MV intensity
S_{kV}: kV spectrum
S_{MV}: MV spectrum

- If we know x_A and x_B, we can create the virtual monochromatic energy projections:

$$\int \mu(E_0)ds = x_A\mu_A(E_0) + x_B\mu_B(E_0)$$

- $\mu_A(E_0)$ and $\mu_B(E_0)$ are attenuation coefficients which may be obtained from NIST at a arbitrarily selected VM energy E_0

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Fundamentals of VM Technique

- Acquires two sets of projections with low- and high-energy beams of the same object
- Pre- or post-reconstruction processing to extract the spectral information for different applications
- Synthesize a single set of monochromatic (VM) CBCTs using dual-energy projection data (Alvarez et al)
  - A basis material decomposition before reconstruction
  - Linear combination of density maps for the decomposed images
  - Remove beam hardening artifacts and photon starvation as the major benefits of VM application in diagnostic CT

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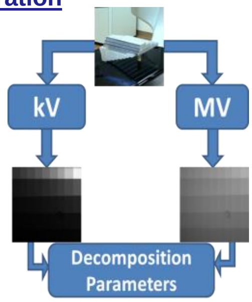
Methods: Beam Calibration



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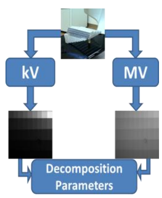
Methods: Beam Calibration

To get x_A and x_B, we use the approximate solutions:

$$x_A = \frac{a_0 + a_1 L + a_2 H + a_3 L^2 + a_4 LH + a_5 H^2}{1 + b_0 L + b_1 H}$$

$$x_B = \frac{c_0 + c_1 L + c_2 H + c_3 L^2 + c_4 LH + c_5 H^2}{1 + d_0 L + d_1 H}$$

where
$L = -\ln(I_{kV}/I_0)$
$H = -\ln(I_{MV}/I_0)$



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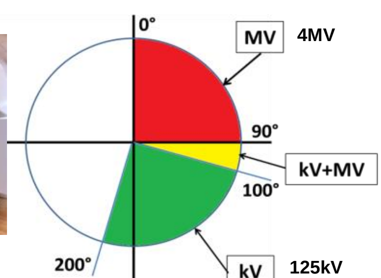
Methods: Acquisition Scheme



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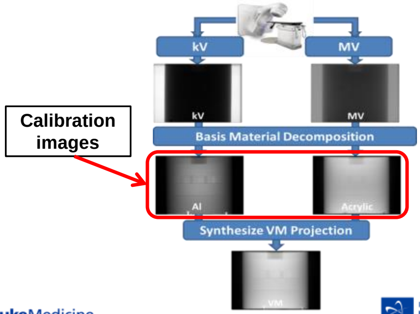
Methods: VM Projeciton Generation



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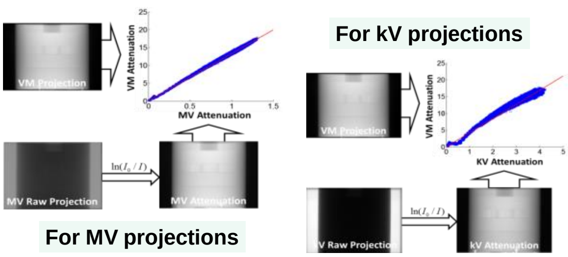
Methods: Attenuation Conversion



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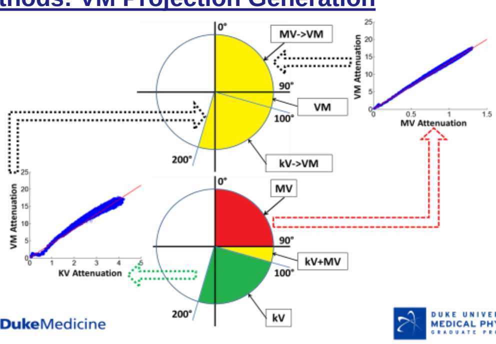
Methods: VM Projection Generation



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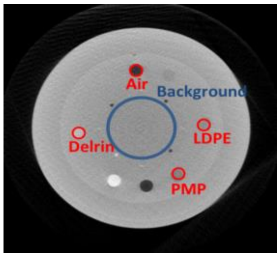
Evaluation: Effect of VM Energy

$$CNR = \frac{|s_{ROI} - s_B|}{\sigma_B}$$

s_{ROI} - Average background
s_B - Each ROI
σ_B - Standard Deviation



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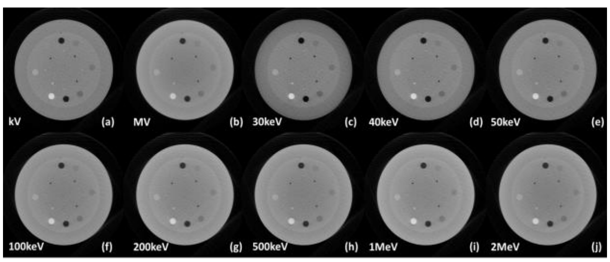
Results: Effect of VM Energy



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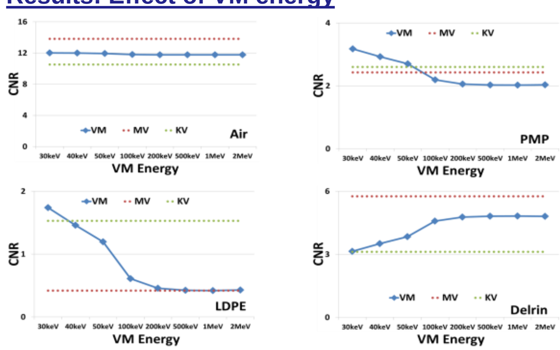
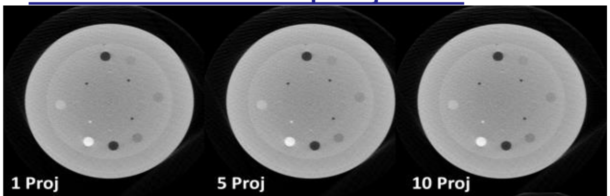
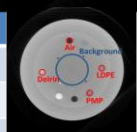
Results: Effect of VM energy



Results: Effect of Overlap Projections

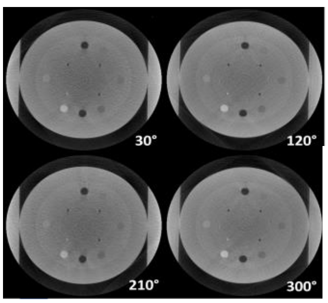


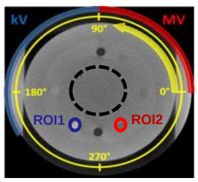
	Air	PMP	LDPE	Delrin
1 proj	12.30	2.03	0.42	4.82
5 proj	12.39	2.03	0.39	4.88
10 proj	12.50	2.04	0.36	4.87

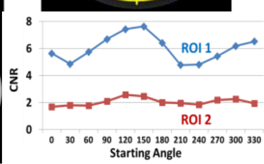


Results: Effect of Beam Orientaiton

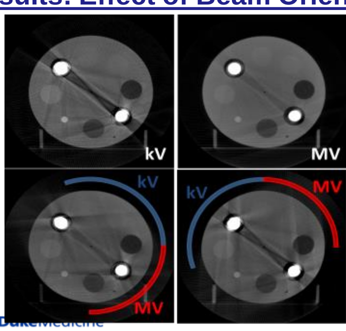
CNR as a function of beam angle







Results: Effect of Beam Orientation



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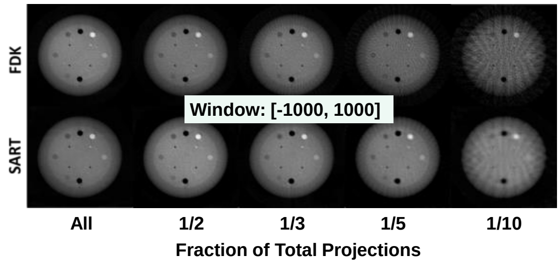
[-500 2000]

Results: Effect of Iteration Reconstruction



SART: Simultaneous algebraic reconstruction techniques

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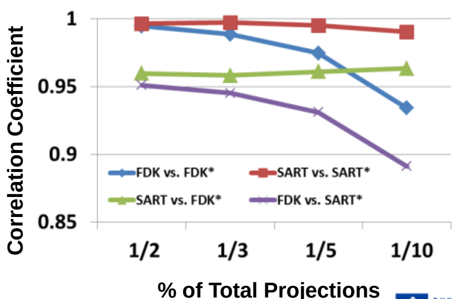
Results: Effect of Iteration Reconstruction



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Conclusion

- A novel aggregate technique was proposed to generate VM CBCTs from kV/MV projections.
- CNR improvement depend on the selection of VM energies and the material.
- For the CatPhan study, one overlap projection can suffice to generate CBCT images.
- The favored orientations for kV/MV beams are
  - MV beam through heavy attenuation direction
  - kV beam through light attenuation direction

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