Dual-Energy Dual Cone-Beam CT for Image Guided Radiotherapy (IGRT)

Purpose: Single polychromatic cone-beam CT reconstruction suffers in beam hardening effects and poor soft tissue contrast. Dual energy methods provide the potential to solve these inherent problems to provide more useful information for IGRT. This study aims to investigate dual-energy CT imaging using a recently developed dual cone-beam CT (CBCT) system.

Method and Materials:

1. **System Description**

A bench-top dual CBCT system with two orthogonally placed tube/detector sets is constructed in our lab. Two single CBCT imaging chains sharing one rotational stage are mounted on an optical bench with an angular separation of 90°, as shown in Figure 1. The X-ray tubes and detectors are located 100 cm and 50 cm away from the shared axis.

The geometric parameters were then measured using the methods provided in [1-2]. A summary of the parameters of the prototype dual CBCT system is illustrated in Table 1.

2. **Basis Material Decomposition**

Suppose two basis materials A and B are used for analysis. For CT measurement taken at two different energies E_L and E_H, we have two measurements I_L and I_H:

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

To solve two basis material components, an approximate conic surface solution for direct dual-energy decomposition proposed in [3] was used in the study.

$$\begin{aligned} F &= \frac{2A}{\sqrt{B^2 + 4AC} + B} \\ A &= a_0 + a_1x + a_2y + a_3x^2 + a_4xy + a_5y^2 + \ldots \\ &+ a_6x^3 + a_7x^2y + a_8xy^2 + a_9y^3 \\ B &= 1 + b_1x + b_2y + b_3x^2 + b_4xy + b_5y^2 \\ C &= c_0 + c_1x + c_2y \end{aligned} \quad (1)$$

where x is the measurement at low energy and y is the measurement at high energy, i.e. $x = -\ln(I_L / I_0)$ and $y = -\ln(I_H / I_0)$.

A basis material pair of aluminum and acrylic was used in our research, following the choices of early investigators in dual-energy CT study. To determine the decomposition coefficients in Equation (1), an aluminum step-wedge and an acrylic step-wedge were machined and stacked in an orthogonal pattern where high and low energy images were made at 150kV and 80kV, respectively. The stacked step-wedges are placed at approximately 65 cm away from the x-ray tube to reduce the scatter effect. The image pair data were then analyzed in MatLab to obtain the coefficients in Equation (1). Pictures of the acrylic and aluminum step-wedges as well as the image pair are shown in Fig. 2. Then the basis material decomposition is returned by applying these coefficients of the function over dual-energy data. The returned values are then submitted for FDK reconstruction to get volumetric data.

Synthesized monochromatic data can be obtained by multiplying the attenuation coefficients of the known basis material of arbitrary energy E_0 with decomposed material density map:

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

Linearly mixed images is another way to maneuver the information acquired in a dual-energy CT scan.

$$I_{Mix} = w_L I_L + w_H I_H.$$

Results:

The results shown here are dual-energy CT scans finished using one imaging chain in the dual CBCT system. The prereconstruction basis material decomposition is shown in Fig. 3. The bony structures can be easily viewed in the aluminum decomposition and as a negative image in the acrylic decomposition. Two reconstructed sample slices for aluminum and acrylic density map are shown in Fig. 4. Some artifacts due to inaccuracy of the basis material decomposition and scatter can be identified in the figure. The synthesized monochromatic image at 50kV is shown in Fig.5. The streak artifacts in the images are also partly due to the inaccuracy of basis material decomposition and scatter. Also shown in Fig. 5 is a linearly mixed image of corresponding slices with the weight $w_L = 0.3108$ and $w_H = 0.6892$. The weighting utilizes a ratio that aims at minimizing the standard deviation of the background of the linearly mixed image.

Conclusion

The dual-energy technique has been implemented in the cone-beam CT. Preliminary results have qualitatively demonstrated the validity of the technique. Dual energy CT imaging provides potential advantages for image guidance and functional imaging for radiotherapy.

Work in Progress

Dual-energy scan using data from both imaging chains is being investigated. Improvement on basis material decomposition is underway and quantitative analysis will be carried out to validate the dual-energy technique, investigate scatter effect, cross-scatter effect and combinations of imaging parameters.

Reference:

1. Yang, K., et al., Med. Phys., 2006. **33**(6): p. 1695-706.
2. Johnston, S.M., G.A. Johnson, and C.T. Badea,. Med. Phys. 2008. **35**(5): p. 1820-9.
3. Cardinal, H.N., and Fenster, A., Med. Phys., 1990. **17**(3): p. 327-41.

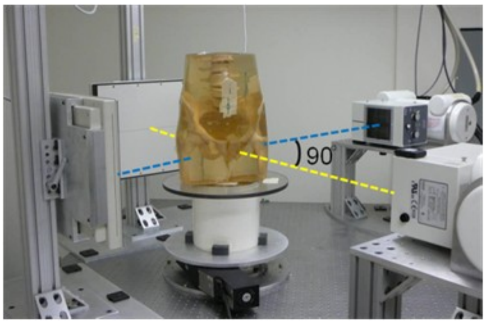

Figure 1. Picture of the dual cone-beam CT in the study.

TABLE I. Summary of characteristics of the prototype dual CBCT system

Dual CBCT Characteristics	Values
Acquisition Geometry	
Subsystem 1:	
Source-axis distance	99.9cm
Source-imager distance	150.0cm
Subsystem 2:	
Source-axis distance	100.0 cm
Source-imager distance	150.2cm
Cone Angle	~ 9.5°
Field of View	26.7 cm
Angular Separation (measured)	90.6°
X-ray Beam	
Beam Energy (Maximal)	150 kV
Exit Filtration	0.7 mm Al
Flat Panel Detectors	
Manufacture and Model	Varian Paxscan® 4030CB
Pixel Matrix	2048 x 1536
Pixel Pitch	194 µm
Effective Area	397 mm x 298mm
Limit Resolution	2.58 lp/mm @ 7.5 FPS (1x1) 1.29 lp/mm @ 30 FPS (2x2)
Conversion Screen	Integral columnar CsI:Tl
Receptor Type	Amorphous Silicon
Energy Range	40-150kVp
Acquisition Procedure	
Number of Projections	360
Angular Increment	1°
Rotational Speed	2°/s
Reconstruction Parameters	
Reconstruction matrix	512x512x160
Voxel Dimension	0.488 mm x 0.488 mm x1 mm

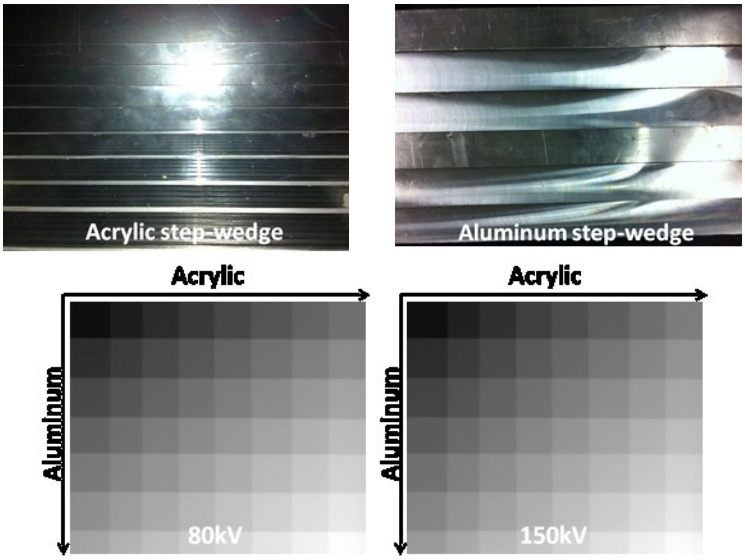

Figure 2. Pictures of the step-wedges and the image pair.

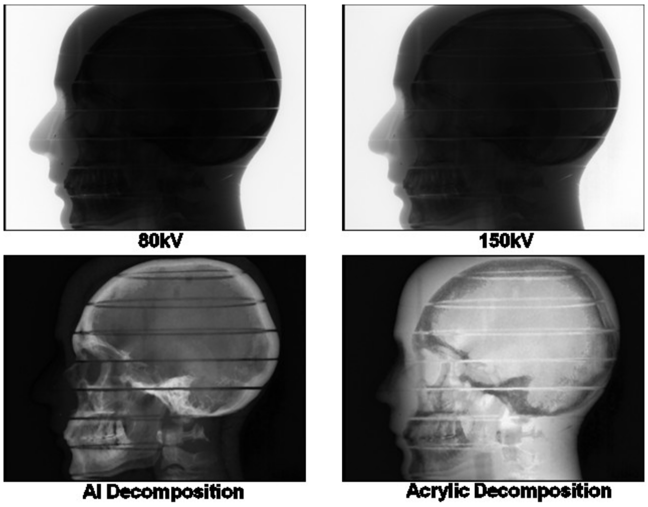

Figure 3. Prereconstruction basis material decomposition.

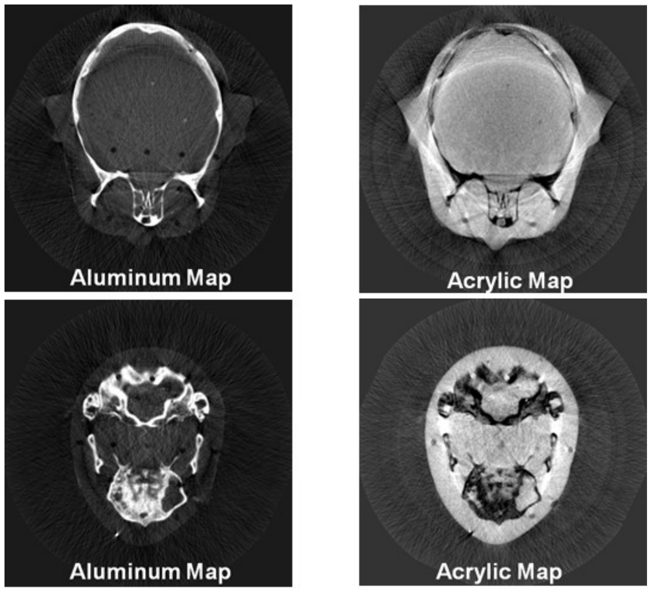

Figure 4. Reconstructed slices of basis material decomposition

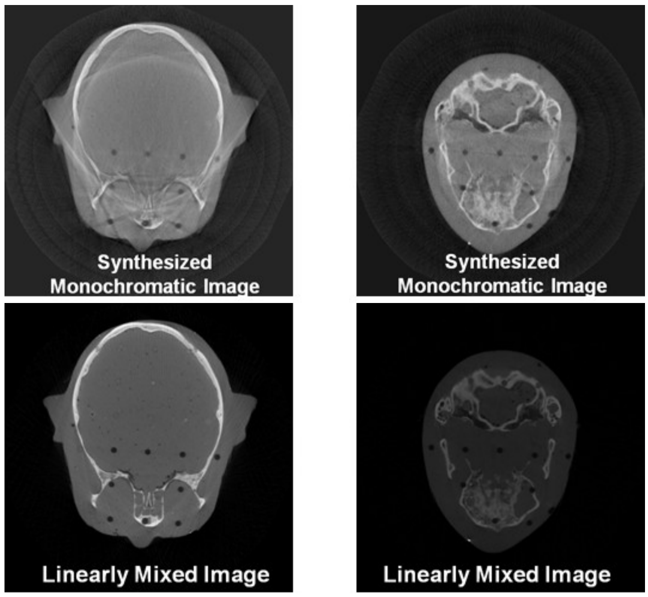

Figure 5. Synthesized monochromatic images and linearly mixed images.