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Dual-Source Multi-Energy CT with Triple or Quadruple X-ray Beams

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Abstract

Energy-resolved photon-counting CT (PCCT) is promising for material decomposition with multi-contrast agents. However, corrections for non-idealities of PCCT detectors are required, which are still active research areas. In addition, PCCT is associated with very high cost due to lack of mass production. In this work, we proposed an alternative approach to performing multi-energy CT, which was achieved by acquiring triple or quadruple x-ray beam measurements on a dual-source CT scanner. This strategy was based on a “Twin Beam” design on a single-source scanner for dual-energy CT. Examples of beam filters and spectra for triple and quadruple x-ray beam were provided. Computer simulation studies were performed to evaluate the accuracy of material decomposition for multi-contrast mixtures using a tri-beam configuration. The proposed strategy can be readily implemented on a dual-source scanner, which may allow material decomposition of multi-contrast agents to be performed on clinical CT scanners with energy-integrating detector.

Keywords

Multi-energy CT; basis material decomposition; dual-energy CT; dual-source CT

1. Introduction

Dual-energy CT has gained wide clinical applications through a variety of scanner configurations, including dual-source, dual-detector layer, fast-kV switching, and slow-kV switching [1-3]. Using dual-energy CT with energy integrating detectors, at most 3 materials in a mixture can be quantified if an additional physical constraint (e.g., volume conservation) is applied in addition to the dual-energy measurements [4, 5]. Without invoking the additional constraint, dual-energy CT can only allow a 2-material mixture to be stably resolved. When the number of materials in a mixture is more than 2, and one or more of the components has distinctive K-edges such as those in multi-contrast agents, it is challenging for dual-energy CT to perform accurate and stable material decomposition.

Energy-resolved photon-counting CT (PCCT) is promising for material decomposition with multiple contrast agents [6-8]. However, due to many non-idealities of the PCCT detector such as charge sharing, K-escape, and pulse pileup, the spectrum information in each energy bin may become distorted [9]. Compensation or correction for those non-idealities remains active research areas [9]. In addition, PCCT is associated with very high cost due to lack of mass production. As an alternative approach to PCCT for material decomposition involving multiple contrast agents, traditional methods involving multiple x-ray beam measurements

may still be used. The main challenge is to make multiple x-ray beam measurements near simultaneously in order to reduce the influence of potential patient motion between scans.

The purpose of this study was to propose an alternative scanner design for multi-energy CT, which was achieved by making three or four x-ray beam measurements on a dual-source CT scanner. Computer simulations were performed to evaluate the accuracy of material decomposition of multi-contrast agents for a tri-beam configuration.

2. Methods

2.1 Dual-source CT geometry with tri-beam or quadruple-beam acquisition

Figure 1a shows a “Twin Beam” design proposed by Siemens on a single source CT scanner. In this design, the same x-ray beam is pre-filtered before patients by two different materials, gold (Au) and tin (Sn), each of which covers half of the detector rows along the longitudinal direction. The x-ray beam filtered by Sn is hardened to form the “high-kV” and the x-ray beam filtered by Au is softened because of the K-edge (80.7 keV) to form the “low-kV”. In a helical scan with a slow helical pitch, dual-energy data for the same image slice can be acquired at a time interval approximately half of the rotation time, which can be as quick as 125 ms.

Similar idea can be readily extended to a dual-source CT scanner. Figure 1b shows a tri-beam configuration in which one of the sources is operated at the “Twin beam” mode, while the other source is operated in a single-energy mode. Together, three distinct x-ray beam measurements can be obtained. Figure 1c shows a quadruple-beam configuration in which both sources are operated at the “Twin beam” mode.

2.2. Beam filter selection and X-ray beam spectrum

Figure 2 provides two possible selections of the pre-filters and the corresponding x-ray beam spectrum. For the tri-beam configuration, one of the sources was chosen to be 70 kV, the other one was at 150 kV but filtered by 0.6 mm of Sn and 0.08 mm of Au plus 0.1 mm of Bi. The bismuth was added to further reduce the overlap with the Sn filtered beam at high energy ranges. Other choices of filter materials and thickness may also be explored.

2.3. Simulation of tri-beam acquisition and material decomposition

A cylindrical water phantom in a diameter of 20 cm containing 9 inserts, including 3 iodine solutions (4, 6, 8 mg/cc of iodine); 3 gold nanoparticle solutions (2, 3, 4 mg/cc of Au); and iodine/gold mixtures (8/4, 6/3, 4/2 mg/cc of I/Au), was used in the simulation. The tri-beam spectra shown in Figure 2a were used to generate the three beam measurements (DRASIM, Siemens Healthcare), which were subsequently corrected for beam hardening using a calibration water phantom at each corresponding spectrum. The mAs was 460 for the two 150 kV beams and 1110 for the 70 kV such that the total energy was approximately matched. Images were reconstructed using a filtered-backprojection method. Material decomposition was performed on images after reconstruction. For each pixel, in addition to the three energy measurements, volume conservation was still used as a physical constraint, which yields four linear equations for each pixel. The coefficient matrix was determined by

using a calibration procedure. A least square optimization method was used to solve the mass density of iodine, gold, and water at each pixel.

3. Results

Figure 3(a-c) shows the images reconstructed from the tri-beam acquisitions: 70 kV, 150 kV + Au filter (150Au), and 150 kV + Sn filter (150Sn), respectively. As expected, the CT number of the iodine decreased as the x-ray beam became harder. However, the CT number of gold was higher at a harder beam at 150Sn than at 150Au because of the K edge.

Figure 3(d-f) shows the mass density map of the three materials: iodine, gold, and water, respectively. The mean percent error compared to the true mass density of the three 3-material mixtures in the middle column of the image was: -3.8%, 2.8%, 0.0% for iodine, gold, and water, respectively.

4. Conclusions/New and Breakthrough Work

We proposed an alternative scanner design to perform multi-energy CT, which was achieved by acquiring triple or quadruple x-ray beam measurements on a dual-source CT scanner. This design can be readily implemented on a dual-source scanner, which may allow material decomposition of multi-contrast agents to be performed on CT scanners with energy-integrating detector. Optimization of spectrum shape and pre-filter materials and thickness is still ongoing.

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Figure 1.

(a) Twin-beam acquisition on a single source CT (Siemens); (b) Tri-beam acquisition on a dual-source CT; (c) Quadruple-beam acquisition on a dual-source CT.

Figure 2.

Example of x-ray beam spectra generated by a tri-beam configuration (a) and a quadruple-beam configuration (b).

Figure 3.
Mass density map of the three materials: (a) iodine, (b) gold, and (c) water.