Radiation Physics and Chemistry 132 (2017) 46–51

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Dose optimization for dual-energy contrast-enhanced digital mammography based on an energy-resolved photon-counting detector: A Monte Carlo simulation study

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ARTICLE INFO

Keywords:
Dual-energy imaging
Photon-counting detector
Contrast-enhanced digital mammography
Radiation dose
Monte Carlo simulation

ABSTRACT

Dual-energy contrast-enhanced digital mammography (CEDM) has been used to decompose breast images and improve diagnostic accuracy for tumor detection. However, this technique causes an increase of radiation dose and an inaccuracy in material decomposition due to the limitations of conventional X-ray detectors. In this study, we simulated the dual-energy CEDM with an energy-resolved photon-counting detector (ERPCD) for reducing radiation dose and improving the quantitative accuracy of material decomposition images. The ERPCD-based dual-energy CEDM was compared to the conventional dual-energy CEDM in terms of radiation dose and quantitative accuracy. The correlation between radiation dose and image quality was also evaluated for optimizing the ERPCD-based dual-energy CEDM technique. The results showed that the material decomposition errors of the ERPCD-based dual-energy CEDM were 0.56–0.67 times lower than those of the conventional dual-energy CEDM. The imaging performance of the proposed technique was optimized at the radiation dose of 1.09 mGy, which is a half of the MGD for a single view mammogram. It can be concluded that the ERPCD-based dual-energy CEDM with an optimal exposure level is able to improve the quality of material decomposition images as well as reduce radiation dose.

1. Introduction

Dual-energy imaging techniques have been used to decompose materials from a mixture and improve image quality (Boone et al., 1990; Johnson et al., 2007). However, the dual-energy imaging techniques cause an increase of radiation dose due to an additional exposure. Although the X-ray sources used in clinical fields produce polychromatic radiation, the conventional X-ray detectors, which are operated in the energy-integrating mode, are insensitive to spectral information (Roessl and Proksa, 2007). The spectral filtration is used to separate polychromatic X-ray spectra for the dual-energy imaging, but the non-optimized filtration decreases the signal-to-noise ratio (SNR) in high-energy images or is limited to exactly separate X-ray spectra without overlap (Primak et al., 2009; Thomas et al., 2010). Energy-resolved photon-counting detectors (ERPCDs) have been considered as an alternative device for overcoming these limitations. The ERPCDs are able to measure the photon energy deposited by each event and provide spectral information by using energy thresholds (Shikhaliev, 2008; Wang et al., 2011a, 2011b). This capability allows multi-energy X-ray imaging without additional exposures and an increase of radiation dose. A polychromatic X-ray spectrum can be separated into different energy ranges without overlap using the ERPCDs, and it results in more efficient material decomposition for the dual-energy imaging.

One potential application of the ERPCDs is the contrast-enhanced digital mammography (CEDM), which aims to demonstrate functional information about a breast tumor by injecting contrast agents into blood (Diekmann and Bick, 2007). The CEDM using a single exposure degrades the efficiency of tumor detection due to overlapping induced by the structures of glandular tissues, adipose, ducts, and vessels (Lewin et al., 2003). Although a number of groups reported dual-energy CEDM techniques with the energy-integrating X-ray detectors for decomposing tumors from breast tissues, these techniques increase radiation dose and lead to the inaccuracy of material decomposition images caused by the overlap between low- and high-energy X-ray spectra (Primak et al., 2009; Leschka et al., 2008; Qu et al., 2011). On the other hands, the dual-energy CEDM with the ERPCD is able to resolve the issues of radiation dose and spectral overlap using their energy-discrimination capabilities. In a previous study, we reported

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http://dx.doi.org/10.1016/j.radphyschem.2016.11.016
Received 1 July 2016; Received in revised form 24 November 2016; Accepted 27 November 2016
Available online 28 November 2016
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that the material decomposition was feasible with a single exposure using the ERPCD (Lee et al., 2014). The study also showed that the quantitative accuracy depended on calibration techniques and basis materials. In this study, the ERPCD-based dual-energy CEDM was compared with the conventional dual-energy CEDM in terms of radiation dose and image quality using Monte Carlo simulations. The optimization of radiation dose in the proposed technique was performed for obtaining acceptable image quality and enhancing the degree of quantitative accuracy.

2. Materials and Methods

2.1. Dual-energy contrast-enhanced mammography

In the CEDM, the incident X-ray intensity per photon energy E, $I_0(E)$, is attenuated by breast tissue with a thickness of t_{breast} and contrast agent with a thickness of t_{agent}. The log signal functions for low energy, L, and high energy, H, can be written as the natural logarithms of the ratios of the incident X-ray intensity to the attenuated X-ray intensity, $I(E)$:

$$\ln(I_0(L)/I(L)) = \mu_{breast}(L)t_{breast} + \mu_{agent}(L)t_{agent} \text{ and}$$
$$\ln(I_0(H)/I(H)) = \mu_{breast}(H)t_{breast} + \mu_{agent}(H)t_{agent}, \quad (1)$$

where $\mu_{breast}(E)$ and $\mu_{agent}(E)$ are the linear attenuation coefficients (LACs) for breast tissue and contrast agent, respectively. Eq. (1) can be expressed in matrix form as shown below:

$$\begin{bmatrix} \mu_{breast}(L) & \mu_{agent}(L) \\ \mu_{breast}(H) & \mu_{agent}(H) \end{bmatrix} \begin{bmatrix} t_{breast} \\ t_{agent} \end{bmatrix} = \begin{bmatrix} \ln(I_0(L)/I(L)) \\ \ln(I_0(H)/I(H)) \end{bmatrix}. \quad (2)$$

When monochromatic X-ray sources are used to measure dual-energy signals, Eq. (2) allows for inversion of the matrices to solve for the thicknesses of materials. However, in practice, attenuation models for the polychromatic X-ray sources, which are used in clinical fields, cannot provide an analytic solution because the log signal functions are non-linear with the LACs and thicknesses of materials as follows (Lemacks et al., 2002):

$$U_E = \ln(S_0(E)/S(E)) = \ln\left(\int I_0(E)dE / \int I_0(E) \exp(-(\mu_{breast}(E)t_{breast} + \mu_{agent}(E)t_{agent}))dE\right), \quad (3)$$

where U_E is the log signal function for a polychromatic X-ray source described by the non-attenuated detector signal, $S_0(E)$, and the attenuated detector signal, $S(E)$. In this study, the inverse fitting function was modeled for calculating the thickness of contrast agent in Eq. (3). This technique recovers material thicknesses from two spectral measurements for dual-energy imaging (Brody et al., 1981; Kappadath and Shaw, 2003). A non-linear rational fitting function was used to solve Eq. (3) for the thickness of contrast agent due to its high accuracy as shown below (Lee et al., 2014):

$$t_{agent} = \frac{a_0 + a_1U_L + a_2U_H + a_3U_L^2 + a_4U_H^2 + a_5U_LU_H + a_6U_L^3 + a_7U_H^3}{1 + b_0U_L + b_1U_H + b_2U_L^2 + b_3U_H^2}, \quad (4)$$

where a_k and b_k are the coefficients of the fitting function. In the calibration process, the known material thicknesses and the log signal functions of dual-energy measurements were substituted into Eq. (4). Subsequently, the fitting coefficients were determined by using the least-squares minimization algorithm with Gauss-Newton method (Levenberg, 1944). The values were also optimized through the convergence of the algorithm in the iterative process. We input the obtained coefficients and the log signal functions of dual-energy signals measured from a mixture composed with unknown material thicknesses into Eq. (4) for the material decomposition process.

2.2. Monte Carlo simulations

Geant4 Application for Tomographic Emission (GATE) version 6.1 was used to simulate a dual-energy CEDM system based on the ERPCD. GATE is a generic simulation platform based on general-purpose Geant4 codes and an advanced open-source software developed by the international OpenGATE collaboration (Jan et al., 2011). Electromagnetic processes, such as the photoelectric effect, Compton scattering, Rayleigh scattering, and Bremsstrahlung, were taken into account to simulate the electromagnetic interactions of X-ray photons with matter.

A cadmium zinc telluride (CZT)-based ERPCD (eValuator-3500, eV Products, USA) was modeled in this study. The detector consists of a linear low of CZT crystals, and it has a size of 128×0.5 mm^2, a pixel pitch of 0.5×0.5 mm^2, a thickness of 3 mm, and the peaking time of 16×10^{-10} s. The maximum count rate and energy resolution of the detector were assumed as 1×10^6 counts per second (CPS) per pixel and 1 keV, respectively, and the measureable energy range of 20–160 keV was determined by the manufacturer. The detector allows multi-energy X-ray imaging with a single exposure because the spectral information can be achieved by five user-definable energy thresholds. In general, the ERPCDs suffer from the pulse pile-up effect, which is mainly caused by the high flux of photons and potentially distorts the measured X-ray energy spectrum (Wang et al., 2011a, 2011b). We simulated a micro-focus X-ray tube (L8601-01, Hamamatsu, Japan), which has a focal spot of 5 μm and a tungsten (W) anode with a target angle of 39 degree, for reducing the flux of photons and the spectral distortion. The simulated X-ray tube and detector were synchronized and translated in 0.5 mm steps toward one direction for obtaining two-dimensional images.

A calibration phantom consisted of the homogeneous breast tissue, which had the chemical composition of 50% adipose and 50% glandular tissues. This phantom had a thickness of 45 mm and an effective density of 0.98 g/cm^3, and included 30 mg/ml iodine solutions with known thicknesses. In the calibration process, the log signal functions for low- and high-energy images measured from the calibration phantom were substituted into Eq. (4) for obtaining the fitting coefficients. The fitting accuracy was estimated by comparing the calibrated iodine thicknesses with the known thicknesses. We simulated a half-cylindrical phantom with a diameter of 100 mm and a thickness of 45 mm for validating the material decomposition process, as shown in Fig. 1. The phantom was composed of 50% adipose and 50% glandular tissues, and iodine solutions with a mass density of 30 mg/ml and various thicknesses (0.3, 0.6, 0.9, 1.5, and 2.5 mm) were inserted into the validation phantom. During simulations, we measured the absorbed radiation dose for the phantoms using the Actor module, which provides information of the deposited energy and the number of particles created in a given volume (Jan et al., 2011; Grevillot et al., 2011).

2.3. Imaging conditions and data analysis

The incident X-ray spectra were simulated by using the SpekCalc program (REAL Software, Inc., USA) (Poludniowski et al., 2009). The simulated spectra were binned to mono-energetic sub-regions in 1 keV steps and were utilized to obtain low- and high-energy images. For the conventional dual-energy CEDM, the low- and high-energy X-ray spectra were simulated at 30 and 50 kVps, respectively, for differentiating the attenuation properties of contrast agent as a function of incident X-ray energies. Both the X-ray energy spectra were filtered by 0.03 mm rhodium (Rh), which has the K-edge absorption energy of 23.2 keV and is commonly used for rejecting low-energy photons in CEDM (Jong et al., 2003; Dromain et al., 2012). The additional aluminum (Al) filters for the high-energy X-ray spectra were used to reduce spectral overlap and improve the quantitative accuracy of material decomposition images in the conventional dual-energy

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