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Monte Carlo simulation studies for the determination of microcalcification thickness and glandular ratio through dual-energy mammography

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HIGHLIGHTS

- An updated breast model was simulated for dual-energy applications.
- Several parameters were tested and evaluated for detection and estimation.
- Good correlation was found between estimated and nominal values.
- Microcalcifications as small as 200 μm were detected.
- Microcalcification thicknesses as small as 200 μm were well estimated.

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ABSTRACT

The majority of breast carcinomas can be associated to the presence of calcifications before the development of a mass. However, the overlapping tissues can obscure the visualization of microcalcification clusters due to the reduced contrast-noise ratio (CNR). In order to overcome this complication, one potential solution is the use of the dual-energy (DE) technique, in which two different images are acquired at low (LE) and high (HE) energies or kVp to highlight specific lesions or cancel out tissue background. In this work, the DE features were computationally studied considering simulated acquisitions from a modified PENELOPE Monte Carlo code. The employed irradiation geometry considered typical distances used in digital mammography, a CsI detection system and an updated breast model composed of skin, microcalcifications and glandular and adipose tissues. The breast thickness ranged from 2 to 6 cm with glandularities of 25%, 50% and 75%, where microcalcifications with dimensions from 100 up to 600 μm were positioned. In general, results pointed an efficiency index better than 87% for the microcalcification thicknesses and better than 95% for the glandular ratio. The simulations evaluated in this work can be used to optimize the elements from the DE imaging chain, in order to become a complementary tool for the conventional single-exposure images, especially for the visualization and estimation of calcification thicknesses and glandular ratios.

1. Introduction

The American Cancer Society points breast cancer as the third leading cause of cancer deaths among women, after respiratory and digestive systems carcinomas (Siegel et al., 2012). Further, according to histological examinations, almost 90% of all ductal carcinomas are related to the presence of microcalcifications in the breast (Gülsün et al., 2003) and about 50% of all non-palpable breast cancers are diagnosed exclusively through the visualization of those structures (Ferranti et al., 2000). Since the ability to diagnose an early malignancy provides higher chances of cure and lower risk of metastatic associated diseases, the identification of those structures as well as other soft-tissue masses is of significant interest.

Usually, the overlapping tissues is a limiting factor in general mammography because they can obscure the visualization of microcalcification clusters due to the reduced contrast-noise ratio (CNR) even for lesions much larger than the system resolution limit (Kappadath and Shaw, 2005). In order to overcome this complication, one potential solution is the use of the dual-energy (DE) imaging technique (Kappadath and Shaw, 2005; Johns and Yaffe, 1985; Brettle and Cowen, 1994; Jochelson et al., 2013). This

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technique uses the log-signals of two images, obtained at low (LE) and high (HE) energies or kVp, which are combined in a way to highlight specific lesions or cancel out tissue background, providing map estimations of calcification thicknesses, t_c, and glandular ratio, g_r.

In this work, the DE features were computationally studied considering an updated breast model and a modified PENELOPE Monte Carlo code (Salvat et al., 2008). The dual-energy technique was applied (i) to study the visualization and measurement of microcalcification thicknesses, (ii) to determine the glandular ratios and (iii) to evaluate the influence of the algorithm correction methods, using current mammography parameters and geometry. The breast thickness, t, the microcalcification thicknesses, the glandular ratio and the X-ray energies were assessed in order to characterize the application of the DE imaging technique for different simulated acquisitions.

2. Materials and methods

2.1. Breast model and geometry

The employed irradiation geometry reproduced the general system dimensions used in digital mammography. In this sense, divergent X-ray beams were generated by a 0.03 cm focal spot positioned at a source-to-image receptor distance (SID) of 65 cm. Monoenergetic energies ranging from 20 to 70 keV were simulated since the simulation of monoenergetic beams provides physical insights and assists in setting the upper limits from theoretical predictions (Ducote and Molloi, 2008). Further, an $18 \times 24\ cm^2$ acrylic compression plate was simulated with a 0.3 cm thickness (Cunha et al., 2010, 2013).

The adopted breast model considered an 8 cm radius, homogeneous, half cylinder composed of an adipose and glandular tissues mixture, surrounded by an uniform layer of skin. Since skin thickness is a significant structure to be considered when performing dosimetry in mammography, its value was carefully chosen. Thus, the adopted breast model considered a 1.45 mm skin, based on a recent computed tomography (CT) study (Huang et al., 2008). The breast thickness ranged from t=2 to 6 cm and the glandularities studied were 25%, 50% and 75%. The elemental compositions for each material considered the weight fractions and densities from Hammerstein et al. (1979). The microcalcifications were homogeneous spheres made of $CaCO_3$ and, as a conservative approach, were positioned at the upper skin layer, displaced in 3×3 clusters, with dimensions of (A) 100, (B) 150, (C) 180, (D) 200, (E) 250, (F) 300, (G) 400, (H) 500 and (I) 600 μm.

The detection system consisted of an $8 \times 16\ cm^2$ pixelated CsI detector with an intrinsic spatial resolution of 100 μm and 150 μm thick.

The total mean glandular dose (MGD) to obtain the DE final image was fixed to 2.5 mGy, according to what was proposed by Kappadath and Shaw (2005) and it was calculated considering the method outlined by Boone (1999). The number of simulated showers was defined when 60% and 40% of the total MGD were respectively achieved by the LE and HE exposures, as assessed by Lemacks et al. (2002). These dose allocations were selected considering the higher contrast obtained by the LE images and the results provided by Ducote and Molloi (2008). Although applying a fixed MGD to all simulations may lead to inaccurate t_c and g_r values, as overestimations for thinner breasts and underestimations for thicker breasts, this study adopted this dose level in order to evaluate other irradiation parameters, as energy combination, and to study the DE imaging chain algorithm.

2.2. DE formalism and implementation

For monoenergetic X-rays, t_c and the glandular thickness, t_g, present linear combinations with D_l and D_h, which were calculated as the natural logarithm of a reference signal S_j^0 (usually a 100% adipose tissue) divided by the breast signal S_j, i.e., $D_j = \ln\left(\frac{S_j^0}{S_j}\right)$, for $j = l, h$, low and high energies, respectively. The signals were computed as the number of counted photons in the detector:

$$t_c = \frac{\Delta\mu_{gl} D_h - \Delta\mu_{gh} D_l}{\Delta\mu_{gl}\Delta\mu_{ch} - \Delta\mu_{cl}\Delta\mu_{gh}} \quad (1)$$

and

$$t_g = \frac{\Delta\mu_{ch} D_l - \Delta\mu_{cl} D_h}{\Delta\mu_{gl}\Delta\mu_{ch} - \Delta\mu_{cl}\Delta\mu_{gh}}, \quad (2)$$

where $\Delta\mu_{gj} = \mu_{gj} - \mu_{aj}$, $\Delta\mu_{cj} = \mu_{cj} - \mu_{aj}$ are the differences between the attenuation coefficients for glandular, g, adipose, a and microcalcifications, c (Lemacks et al., 2002). Once t_g is obtained, the glandular ratio can be evaluated as:

$$g_r = \frac{t_g \rho_g}{t\rho_a + t_g(\rho_g - \rho_a)}, \quad (3)$$

where ρ_a and ρ_g are the adipose and glandular tissue densities, respectively. From those equations, one can estimate t_c and g_r in a pixel-by-pixel basis.

This work also investigate the importance of scatter and noise correction algorithms during reconstruction in the imaging chain process. Thus, in order to increase image quality, scatter and noise reduction algorithms from a developed MATLAB® (MathWorks, USA) routine were applied to the obtained maps, according to the scheme shown in Fig. 1. The scatter correction algorithm considered image convolution and a spatially variant scatter point spread function, as outlined by Ducote and Molloi (2010). The noise correction algorithm was developed based on the Kalender noise reduction algorithm (KNR), which exploits the known correlation between the noise components in complementary DE material density images (Kalender et al., 1988). Other tested noise reduction filters applied on both images included the boxcar, HE median and Wiener.

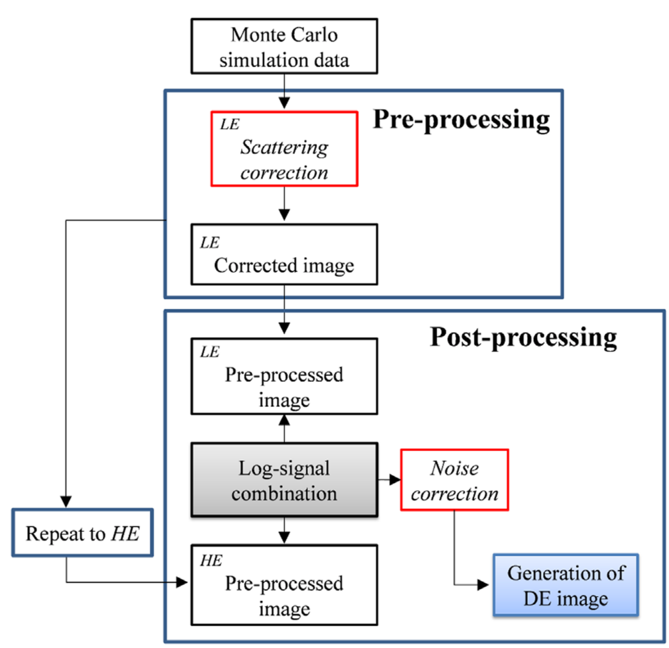

Fig. 1. Scheme showing the algorithm steps to obtain the low (LE) and high energy (HE) images, which are combined to generate the DE image.