Error Analysis of Calibration Materials on Dual-Energy Mammography

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Abstract. Dual-energy mammography can suppress the contrast between adipose and glandular tissues and improve the detectability of microcalcifications (MCs). In clinical dual-energy mammography, imaging object is human breast, while in calibration measurements, only phantoms of breast-tissue-equivalent material can be used. The composition and density differences between calibration materials and human breast bring the differences of linear attenuation coefficient which lead to the calculation errors in dual-energy imaging. In this paper, the magnitude of MC thickness error from calibration materials has been analyzed using a first-order propagation of error analysis. This analysis shows that the thickness error from calibration materials ranges from dozens to thousands of microns which can not be ignored when carrying out dual-energy calculations. The evaluation of several popular phantoms shows that it is of great importance to adopt the phantom materials approaching human breast most.

Keywords: dual-energy, mammography, calibration materials, error analysis.

1 Introduction

Microcalcifications (MCs) are the principal indicator of breast cancer. Thus the visualization and detection of MCs in mammography play a crucial role in reducing the rate of mortality of breast cancer. MCs are composed mainly of calcium compounds. Although MCs are small in size, almost below 1 mm, they have greater x-ray attenuation than the surrounding breast tissue. This makes MCs relatively apparent on homogeneous soft-tissue backgrounds. However, visualization of MCs may be obscured in mammograms by overlapping tissue structures.

In dual-energy digital mammography, high- and low-energy images are acquired and synthesized to suppress the contrast between adipose and glandular tissues, improve the detectability of MCs and calculate the thickness of the MC. However, quantitative dual-energy imaging can be influenced by many factors in practical application, such as the selection of high- and low-energy spectra, scatter, quantum noise, DQE (detection quantum efficiency) of detectors and the choice of calibration polynomials, all of which decrease the calculation precise

and cause quantitative information inaccurate. Research work in dual-energy imaging has mainly focused on the selection and optimization of high- and low-energy spectra [1], scatter corrections [2], analysis of detectors [3] and selection of inverse-map functions [4].

In clinical dual-energy mammography, the imaging object is human breast, while in calibration measurements, only phantoms of breast-tissue-equivalent material can be used. Also, the elemental composition ratio of human breast presents a wide range [5]. The composition and density differences between the phantom materials and human breast bring the differences of linear attenuation coefficients which lead to the calculation error in dual-energy imaging. However, such error hasn't been accounted for in the published literatures on dual-energy imaging till now. In this paper, we assess the magnitude of the calculation error introduced by calibration materials using an error propagation analysis. Simulated experiments verify the magnitude of such error in dual-energy mammography.

2 Theory

2.1 Physical Model of Dual-Energy Imaging

In mammography, the breast is compressed to the thickness T which is to be composed of adipose tissue (thickness t_a), glandular tissue (thickness t_g) and MC (thickness t_c). As the total breast thickness T is known and the contribution of MCs to the total breast thickness can be ignored, the three unknowns of t_a , t_g , t_c can be expressed as two: glandular ratio $g = t_g/(t_a + t_g) \cong t_g/T$ and MC thickness t_c .

If $P_0(E)$ is the incident x-ray photon fluence of energy E and $P(E)$ is the transmitted fluence, then:

$$P(E) = P_0(E) \exp [-\mu_a(E)T - g(\mu_g(E) - \mu_a(E))T - \mu_c(E)t_c] \quad (1)$$

$\mu_a(E)$, $\mu_g(E)$ and $\mu_c(E)$ are the linear attenuation coefficients of adipose tissue, glandular tissue and MCs, respectively.

In dual-energy imaging calculations, a reference signal I_r is needed to increase the dynamic range of the logarithmic intensity value. Now we define the exposure data f as the log-value of ratio of the transmitted exposure I and reference signal I_r . The low- and high-energy log-value $f_l(t_c, g)$, $f_h(t_c, g)$ are measured independently using x-ray beams of different kVps:

$$\begin{cases} f_l = \ln(I_{rl}) \\ \quad - \ln\left\{ \int P_{0l}(E) \exp [-\mu_a(E)T - g(\mu_g(E) - \mu_a(E))T - \mu_c(E)t_c] Q(E) dE \right\} \\ f_h = \ln(I_{rh}) \\ \quad - \ln\left\{ \int P_{0h}(E) \exp [-\mu_a(E)T - g(\mu_g(E) - \mu_a(E))T - \mu_c(E)t_c] Q(E) dE \right\} \end{cases} \quad (2)$$

$Q(E)$ is the detector response.

The goal of dual-energy mammography is to convert the log-value functions $f_l(t_c, g)$ and $f_h(t_c, g)$ to MC thickness $t_c(f_l, f_h)$ and $g(f_l, f_h)$. Polynomials are

often used to describe the relationship between (f_l, f_h) and (t_c, g) in diagnostic dual-energy imaging calculations. In this paper, cubic polynomials are used to describe the inverse-map functions:

$$\begin{cases} t_c = k_{c0} + k_{c1}f_l + k_{c2}f_h + k_{c3}f_l^2 + k_{c4}f_h^2 + k_{c5}f_l f_h + k_{c6}f_l^3 + k_{c7}f_h^3 \\ g = k_{g0} + k_{g1}f_l + k_{g2}f_h + k_{g3}f_l^2 + k_{g4}f_h^2 + k_{g5}f_l f_h + k_{g6}f_l^3 + k_{g7}f_h^3 \end{cases} \quad (3)$$

Coefficients k_{ij} ($i = c, g; j = 0, 1, \dots, 7$) are approximated numerically by least-squares technique according to calibration data.

2.2 Calculation Errors from Calibration Materials

After necessary correction procedures, the image data (f_l, f_h) are free of scatter and noise; systemic calculation bias Δt_c of MC thickness still exists in dual-energy imaging. Δt_c is composed of two portions: first, it is an approximation that MC thickness and glandular ratio represented by polynomials. Substituting the log-values (f_l, f_h) into the calibrated polynomials to calculate MC thickness is an interpolation of calibration data intrinsically which results in *fitting error* Δt_{cp} . Secondly, materials for calibration always differ from materials imaged. The differences of linear attenuation coefficient between calibration materials and imaged human breast lead to *calibration material error* Δt_{cc} of MC thickness.

Isolated calibration material error Δt_{cc} could not be obtained directly from inverse-map polynomials Eq.3, but can be deduced from dual-energy physical model Eq.2. Physically, the differences between calibration materials and imaged human breast can be represented in Eq.2 where f_l and f_h are log-values of imaged human breast and $\mu_a(E)$, $\mu_g(E)$ and $\mu_c(E)$ are linear attenuation coefficients of calibration materials. At the energy of E , the partial derivative of t_c with respect to $\mu_a(E)$ can be deduced from dual-energy physical model Eq.2 using differential method for implicit function:

$$\frac{\partial t_c}{\partial \mu_a(E)} = \frac{-\frac{\partial f_l}{\partial \mu_a(E)} \times S_g + \frac{\partial f_h}{\partial \mu_a(E)} \times R_g}{R_c \times S_g - R_g \times S_c} \quad (4)$$

where:

$$R_c = \partial f_l / \partial t_c \quad R_g = \partial f_l / \partial g \quad S_c = \partial f_h / \partial t_c \quad S_g = \partial f_h / \partial g$$

The partial derivatives of t_c with respect to $\mu_g(E)$ and $\mu_c(E)$ can be obtained in the same way. As we know, the first-order terms of a Taylor's series expansion can be used for error estimation. And then, the magnitude of calibration material error in MC thickness Δt_{cc} can be approximated using the first-order terms of a Taylor's series expansion of t_c in terms of the variables $\mu_i(E)$ ($i = g, a, c$):

$$\Delta t_{cc} \approx \sum_E \frac{\partial t_c}{\partial \mu_g(E)} \times \Delta \mu_g(E) + \sum_E \frac{\partial t_c}{\partial \mu_a(E)} \times \Delta \mu_a(E) + \sum_E \frac{\partial t_c}{\partial \mu_c(E)} \times \Delta \mu_c(E) \quad (5)$$

where $\Delta \mu_i(E)$ ($i = g, a, c$) are the differences of the linear attenuation coefficient between calibration materials and imaged human breast.

3 Materials and Methods

The simulation conditions which are in accordance with the clinical equipments are as same as those in papers [2] [4] of Kappadath.

The x-ray spectra used for low- and high-energy measurements were 25 kVp and 50 kVp. The spectra data were taken from *Handbook of Mammographic X-ray Spectra* [6] with resolution of 1 keV.

The detector consists of a CsI:Tl converter layer coupled with an aSi:H flat-panel detector. All photons transmitted through the imaged object were assumed to be absorbed completely in the perfectly efficient converter layer [7].

Hammerstein [5] has determined the elemental compositions of glandular and adipose tissues in a human breast. The composition per weight of H, N, and P seems to be well determined; however, those of C and O present a wide range of possible values. Table 1 lists two extreme compositions 1 and 2, one general composition 3. In this paper, the composition per weight of C and O refer to composition 3 without specific notification. The densities equal to 0.93 g/cm^3 for adipose tissue and 1.04 g/cm^3 for glandular tissue.

Table 1. Elemental compositions (percentage per weight) of C and O for glandular and adipose tissues

Element	Composition 1		Composition 2		Composition 3	
	Adipose	Glandular	Adipose	Glandular	Adipose	Glandular
C	68.1	30.5	51.3	10.8	61.9	18.4
O	18.9	55.6	35.7	75.3	25.1	67.7

Phantom materials were used for calibration. In the simple way, polyethylene (CH_2) was commonly used for adipose phantom material, PMMA ($\text{C}_5\text{H}_8\text{O}_2$) and acrylic ($\text{C}_3\text{H}_4\text{O}_2$) were often used for glandular phantom material. Breast-tissue-equivalent materials can be available commercially. For example, breast-tissue-equivalent materials from CIRS (Computerized Imaging Reference Systems, Inc., Norfolk, VA, USA) are based on Hammerstein and those from RMI (Radiation Measurements Inc., Madison, WI, USA) are based on White [8]. The elemental compositions of phantom materials [9] and human breast are listed in Table 2.

In this paper, MCs were assumed to be composed mainly of calcium oxalate (CaC_2O_4). The density is 2.20 g/cm^3 . Aluminum was used to calibrate MCs.

Mass attenuation coefficients of the materials in this paper were computed by XCOM software from NIST [10].

The calibration data consisted of 30 different combinations of MC thicknesses and glandular ratios. Glandular ratio was in five steps 0%, 25%, 50%, 75% and 100% at a fixed total breast thickness 5 cm; MC thickness was in six steps 0, 380, 760, 1140, 1520, $1900 \mu\text{m}$. The reference signal I_r was measured through 50% glandular ratio of 5 cm breast phantom.

Table 2. Elemental compositions (percentage per weight) of phantom materials and human breast

Materials	Density (g/cm ³)	Elemental compositions								
		H	C	N	O	F	Cl	Ca	P	Al
For adipose										
Polyethylene	0.93	14.4	85.6	-	-	-	-	-	-	-
CIRS	0.924	11.8	76.0	1.2	9.8	-	1.2	-	-	-
RMI	0.92	8.4	69.1	2.4	16.9	3.1	0.1	-	-	-
Human	0.93	11.2	61.9	1.7	25.1	-	-	-	0.1	-
For glandular										
PMMA	1.19	8.0	60.0	-	32.0	-	-	-	-	-
Acrylic	1.19	5.6	50.0	-	44.4	-	-	-	-	-
CIRS	1.04	10.9	70.2	1.2	12.5	-	1.1	0.6	-	3.5
RMI	0.99	8.4	68.0	2.3	18.9	-	0.1	2.3	-	-
Human	1.04	10.2	18.4	3.2	67.7	-	-	-	0.5	-

4 Results

4.1 Calibration Material Errors

After calibration, substitute the log-values (f_l, f_h) into the calibrated polynomials and calculate MC thickness t'_c , the *systemic calculation bias* is $\Delta t_c = t'_c - t_c$. When calibration materials are identical to human breast, the *calibration material error* Δt_{cc} is zero and the *fitting error* Δt_{cp} equals Δt_c . When calibration materials are phantom materials, Δt_c consists of Δt_{cp} and Δt_{cc} , Δt_{cc} can be calculated according to Eq.5.

Tables 3 lists Δt_{cc} , Δt_{cp} and Δt_c when different calibration materials used where MC is 250 μm and glandular ratio is 70%. In the first three rows, only one calibration material is different from the composition of human breast. Then we can get the MC thickness errors where 1% linear attenuation coefficient differences exist. In the last three rows, phantom materials were adopted.

In Table 3, fitting error is only -2 μm . The calibration material errors are -33%(-83 μm), -138%(-346 μm) and 1.2%(3 μm) when 1% linear attenuation coefficient differences exist between the calibration materials for adipose, glandular, MC and human breast, respectively. The errors coming from the calibration materials for glandular and adipose tissues are more than errors from MC calibration material.

If CIRS phantoms and aluminum were adopted as calibration materials, the calibration errors of MC thickness are 169%(423 μm). CIRS phantoms are made based on the human breast composition; however, composition differences still exist. In the energy range 10 keV–50 keV, the average linear attenuation coefficient differences are 0.95% between CIRS adipose phantom and breast adipose, 1.14% between CIRS glandular phantom and breast glandular, 0.95% between aluminum and CaC₂O₄.

Table 3. MC thickness errors using various calibration materials ($t_c = 250\mu m$, $g = 70\%$)

Calibration materials			MC thickness errors (μm)		
Adipose	Glandular	Microcalcification	Δt_{cc}	Δt_{cp}	Δt_c
0.99HM	HM ¹	CaC ₂ O ₄	-83	-2	-84
HM	0.99HM	CaC ₂ O ₄	-346	-2	-310
HM	HM	0.99CaC ₂ O ₄	3	-2	-0.3
CIRS ²	CIRS	Al	423	-2	404
RMI ³	RMI	Al	-9419	-2	-9163
Polyethylene	PMMA	Al	2066	-2	2134

¹ human breast composition determined by Hammerstein

² phantom material produced by CIRS

³ phantom material produced by RMI

If RMI phantoms, polyethylene and PMMA were used for calibration, the tremendous calibration material errors make the calculated MC thickness insignificant.

4.2 Calibration Material Errors of Different Breast Compositions

The breast composition of different individuals is variable while the calibration materials are always fixed when dual-energy imaging. The variations in breast composition of different individuals also bring about the MC thickness errors. Table 4 lists the errors of the three compositions listed in Table 1. Calibration materials are CIRS phantoms and aluminum. The MC thickness errors are far apart when calibration materials fixed and breast compositions changing.

Table 4. Calibration material errors of different breast compositions ($t_c = 250\mu m$, $g = 70\%$)

Breast compositions	MC thickness errors (μm)		
	Δt_{cc}	Δt_{cp}	Δt_c
Composition 1	-182	-6	-182
Composition 2	912	-6	905
Composition 3	423	-6	404

5 Discussion

In this paper, we analyze the MC thickness calculation errors brought by attenuation differences between calibration materials and human breast.

Comparing Δt_{cc} and Δt_{cp} , the fitting error Δt_{cp} is relatively small. The calibration material error Δt_{cc} occupies the dominant position in the systemic thickness bias Δt_c , it may be thousands of microns sometimes which makes the calculated MC thickness insignificant.

As can be seen in Table 3, it is impractical to use RMI phantoms or polyethylene, PMMA as calibration materials since they may bring about huge calibration material errors. In contrast, CIRS phantom materials are made based on human breast and approaching the compositions of human breast nearest in the published literatures. However, it will bring about 160% calibration material errors. Figure 1 presents the calibration material percent errors when glandular ratio ranges from 0% to 100%, MC thickness ranges from 0 μm to 1000 μm . The errors are almost positive which means that calibration using CIRS phantoms and aluminum will make the calculated MC thicker and will not cause the MC invisible. These calibration material errors may be ignored when dual-energy mammography is just used for the purpose to enhance the detectability of MCs. The calibration material percent error increases as the glandular ratio increasing, and decreases as the MC thickness increasing.

Fig. 1. MC thickness percent errors from calibration materials CIRS phantoms and aluminum

6 Conclusion

Since the attenuation characteristics of calibration materials are not exactly equal to those of human breast and the breast composition of different individuals is variable, MC thickness errors from calibration materials are unavoidable. From the point of imaging physics, this paper investigates the magnitude of calibration material error, ranging from dozens to thousands of microns. The errors from calibration materials can not be ignored when carrying out dual-energy calculations. The simple phantom materials, such as PMMA or polyethylene, are not suitable for calibration in dual-energy mammography in clinic. CIRS phantoms are the better choice.

In this paper, we analyze the physical model of dual-energy imaging and derive the expression that quantifies the calibration material error. Calculating

based on the physical model is an effective way to analyze errors in dual-energy imaging.

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References

1. Johns, P.C., Yaffe, M.J.: Theoretical Optimization of Dual-energy X-ray Imaging with Application to Mammography. *Med. Phys.* 13, 289–296 (1985)
2. Kappadath, S.C., Shaw, C.C.: Dual-energy Digital Mammography for Calcification Imaging: Scatter and Nonuniformity Corrections. *Med. Phys.* 32, 3395–3408 (2005)
3. Guillemaud, R., Robert-Coutant, C., Darboux, M., Gagein, J.J., Dinten, J.M.: Evaluation of Dual-energy Radiography with a Digital X-ray Detector. *Proc. SPIE* 4320, 469–478 (2001)
4. Kappadath, S.C., Shaw, C.C.: Dual-energy Digital mammography: Calibration and Inverse-mapping Techniques to Estimate Calcification Thickness and Glandular-tissue Ratio. *Med. Phys.* 30, 1110–1117 (2003)
5. Hammerstein, G.R., Miller, D.W., White, D.R., Masterson, M.E., Woodard, H.Q., Laughlin, J.S.: Absorbed Radiation Dose in Mammography. *Radiology* 130, 485–491 (1979)
6. Fewell, T.R., Shuping, R.E.: Handbook of Mammographic X-ray Spectra. HEW Publication (FDA), Washington. D.C. (1978)
7. Lemacks, M.R., Kappadath, S.C., Shaw, C.C., Liu, X., Whitman, G.: A Dual-energy Subtraction Technique for Microcalcification Imaging in Digital Mammography-A Signal-to-noise Analysis. *Med. Phys.* 29, 1739–1751 (2002)
8. White, D.R.: The Formulation of Tissue Substitute Materials Using Basic Interaction Data. *Phys. Med. Biol.* 22, 889–899 (1977)
9. Byng, J.W., Mainprize, J.G., Yaffey, M.J.: X-ray Characterization of Breast Phantom Materials. *Phys. Med. Biol.* 43, 1367–1377 (1998)
10. XCOM, <http://physics.nist.gov/PhysRefdata/Xcom/Text/XCOM.html>