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Phase-contrast imaging for body composition measurement

Huajie Han[a,b], Renfang Hu[b], Faiz Wali[b], Zhao Wu[b], Kun Gao[b], Shenghao Wang[c], Yonggang Gu[d], Yi Jin[d], Chao Zhai[d,*]

[a] Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei 230027, China
[b] National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230027, China
[c] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Science, Shanghai 201800, China
[d] Experimental Center of Engineering and Material Science, University of Science and Technology of China, Hefei 230027, China

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ABSTRACT

Purpose: In this paper, we propose a novel method for human body composition measurement, especially for the bone mineral density (BMD) measurement. The proposed method, using the absorption and differential phase information retrieved from X-ray grating-based interferometer (XGBI) to measure the BMD, has potential to replace dual-energy X-ray absorptiometry (DEXA), which is currently widely used for body composition measurement.

Methods: The DEXA method employs two absorption images acquired at two different X-ray spectra (high energy and low energy) to calculate the human body composition. In this paper, a new method to calculate BMD using a single X-ray measurement is proposed. XGBI is a relatively new X-ray technique that provides absorption, phase and scattering information simultaneously using a single X-ray spectrum. With the absorption and differential phase information retrieved from XGBI, BMD can be measured using only one single X-ray spectrum. Numerical simulations are performed with a body phantom of bone (Cortical, ICRU-44) surrounded by soft tissue (Soft, ICRU-44). BMD is calculated with both the DEXA method and the proposed method.

Results: Results show that BMD can be measured accurately with the proposed method; moreover, better signal-to-noise ratio (SNR) is obtained compared to DEXA.

Conclusion: With the proposed method, BMD can be measured with XGBI setup. Further, the proposed method can be realized using current X-ray phase-contrast imaging (XPCI) apparatus without any hardware modification, suggesting that this technique can be a promising supplementary function to current XPCI equipment.

1. Introduction

Measurements of human body composition are valuable in a wide variety of clinical fields. For example, the ongoing epidemic of obesity in children and adults has highlighted the importance of body fat for short-term and long-term health [1]. Quantifying the body composition has played an important role in monitoring the performance and training regimens for athletes [2]. Recently, aging has emerged as an increasingly serious problem all over the world, and much attention has been focused upon the health condition of the aging population. Osteoporosis is one of the most common diseases affecting the middle-aged and elderly population, and patients suffering from this disease are more susceptible to bone fracture. Since there is no obvious symptom at the early disease stage, the early diagnosis of osteoporosis by measuring the bone mineral density (BMD) is of great importance for reducing bone fracture risk [3].

The past few decades have seen the rapid evolution of new techniques for body composition measurement (e. g. the single photon absorptiometry, the quantitative computerized tomography and the quantitative ultrasound bone measurements), but only the dual-energy X-ray absorptiometry (DEXA) is preferred in clinical applications owing to its advantages of high precision, short scanning time, and low radiation dose [3]. Differential absorption of X-ray by human bones and soft tissues is the fundamental principle of the DEXA method. Two absorption equations are acquired when the human body is scanned with X-ray beams of two different energy spectra [4]. There are two commercial methods to acquire dual-energy X-ray absorption information (GE Lunar and Stratec models & Hologic models). However, complicated hardware modifications to the conventional radiology apparatus, including X-ray tubes and detectors, are necessary for performing DEXA measurements [4].

X-ray phase-contrast imaging (XPCI) has the potential to

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[*] Corresponding author.
E-mail address: zhaichao@ustc.edu.cn (C. Zhai).

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significantly improve the image contrast of weakly absorbing materials compared to the conventional absorption-based X-ray imaging methods [5,6]. Several XPCI methods have been developed during the past few decades including crystal interferometric methods, free-space propagation method, diffraction enhancing method, grating interferometer method, and edge illumination method [5–10].

Currently, X-ray grating-based interferometer (XGBI) is the most widely applied tool for XPCI. Since phase information is available using low-brilliance X-ray sources, this technique have the potential for medical and industrial applications [6]. Furthermore, this method enables the simultaneous extraction of multiple information (absorption, refraction, and dark-field). The differential phase and small-angle scattering contrasts provide valuable supplementary information for clinical and industrial examinations. Quantitative X-ray radiography for volumetric breast density (VBD) estimation by combining the absorption and scattering information and quantitative measurement of the electron density and effective atomic number by combining the absorption and differential phase information have been reported [11,12]. Theoretically, phase information, which can be retrieved simply by integration from the differential phase image (DPI), can also be applied for quantitative measurement. However, due to the presence of noise in directly-retrieved DPI, reliable phase image remains an open challenge. Recently, effective phase retrieval algorithms have been proposed, which enable quantitative measurement with phase radiography [13,14].

In this study, at first, non-linear regularized phase retrieval method is used to acquire the phase image [13]. Subsequently, a novel method to measure BMD is proposed by combining the absorption and phase information acquired simultaneously with an XGBI setup. Simulation results show that the BMD can be measured with an improved accuracy compared to the DEXA method. Moreover, the complicated technique of the X-ray source and detector for the DEXA are greatly simplified.

2. Materials and methods

2.1. Basic physical principles

When monochromatic or quasi-monochromatic X-ray beam transmits through an object under examination, the absorption contrast can be described by the following equation, known as the Lambert-Beer law:

$$I = I_0 exp(-u_0 t). \tag{1}$$

where I_0 and I denote intensity of incident and emergent X-rays, respectively and $u_0 = 4\pi\beta/\lambda$ is the attenuation coefficient of the object, β is the absorption index, λ is the wavelength of the X-rays and t represents the transmission length.

The fundamental physical principle for DEXA is to measure the absorption of the human body penetrated by dual-energy X-ray spectra (high energy and low energy), which can be expressed as [3]:

$$I_L = I_{0L}\exp(-\mu_{LS}M_S - \mu_{LB}M_B), \tag{2}$$

$$I_H = I_{0H}\exp(-\mu_{HS}M_S - \mu_{HB}M_B). \tag{3}$$

where the subscripts L and H represent low and high photon energy, and B and S represent the bone and the soft tissue, respectively. Here $\mu = u_0/\rho$, is the mass attenuation coefficient, where ρ is the density of the object. The mass attenuation coefficient (μ), independent from the physical state of the observed sample, is only determined by the sample material. On the other hand $M = \rho t$ is the areal density representing the projection mass of the material on an observation plane perpendicular to the X-ray transmission direction. Particularly, M_B is the absolute BMD, which is usually expressed with unit of g/cm^2. We would like to point out that, the absolute BMD, as one of the expressions of the BMD results, is a preliminary but necessary measurement, based on which other unambiguous and meaningful expressions (e. g. the T score or Z score) can be obtained. In the following parts, this expression will be used for the evaluation of our method. Eqs. (2) and (3) can be simplified by replacing J of the logarithmic transmission factor $-\ln(I/I_0)$:

$$J_L = \mu_{LS}M_S + \mu_{LB}M_B, \tag{4}$$

$$J_H = \mu_{HS}M_S + \mu_{HB}M_B. \tag{5}$$

Thus, the areal densities of the soft tissue and the bone can be obtained from Eqs. (4) and (5) as follows:

$$M_B = \frac{\mu_{HS}J_L - \mu_{LS}J_H}{\mu_{HS}\mu_{LB} - \mu_{LS}\mu_{HB}}, \tag{6}$$

$$M_S = \frac{\mu_{HB}J_L - \mu_{LB}J_H}{\mu_{HB}\mu_{LS} - \mu_{LB}\mu_{HS}}. \tag{7}$$

On the other hand, the shift in the phase of the incident X-rays Φ can be described by the decrement of the refractive index δ. Thus the phase shift measured in XGBI can be written as [6]:

$$\Phi(x,y) = -\frac{2\pi}{\lambda}\int \delta(x,y,z)dz. \tag{8}$$

where (x,y,z) are the Cartesian coordinates of the XGBI system.

If the observed sample is a homogeneous block, the phase shift caused by the block with thickness t can be further written as:

$$\Phi = \frac{2\pi}{\lambda}\delta t. \tag{9}$$

Similarly, we define mass refraction coefficient as $\upsilon = 2\pi\delta/\lambda\rho$. By writing T in place of the phase shift Φ, then the dual-energy X-ray refraction equations can be deduced from Eq. (9) as follows:

$$T_L = \nu_{LS}M_S + \nu_{LB}M_B, \tag{10}$$

$$T_H = \nu_{HS}M_S + \nu_{HB}M_B. \tag{11}$$

Therefore, the areal densities of the bone and soft tissue can be measured with phase information by combining Eqs. (10) and (11), expressed as:

$$M_B = \frac{\nu_{HS}T_L - \nu_{LS}T_H}{\nu_{HS}\nu_{LB} - \nu_{LS}\nu_{HB}}, \tag{12}$$

$$M_S = \frac{\nu_{HB}T_L - \nu_{LB}T_H}{\nu_{HB}\nu_{LS} - \nu_{LB}\nu_{HS}}. \tag{13}$$

Eqs. (12) and (13) form the fundamental of the dual-energy phase-contrast method for body composition measurement. As a recently proposed method, the technique is superior to the conventional absorption-based DEXA with advantages of higher soft tissue measurement sensitivity and accuracy, and lower radiation dose, as reported [15].

However, the disadvantages caused by requirement of the dual-energy X-ray spectra still exist for the dual-energy refraction method. Actually, using Eqs. (4) and (10) or Eqs. (5) and (11), we can also solve the BMD M_B and areal density of the soft tissue M_S through simultaneous equations, as follows:

$$M_B = \frac{\nu_S J - \mu_S T}{\mu_S\nu_B - \mu_B\nu_S}, \tag{14}$$

$$M_S = \frac{\nu_B J - \mu_B T}{\mu_B\nu_S - \mu_S\nu_B}. \tag{15}$$

Eqs. (14) shows that the BMD can be solved with a single energy X-ray spectrum by combining the absorption information and the phase information, which can be retrieved by XGBI simultaneously. Consequently, the complicated techniques used to generate dual-energy X-ray spectra are simplified.