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Combining 3D optical imaging and dual energy absorptiometry to measure three compositional components

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Abstract

We report on the design of the technique combining 3D optical imaging and dual-energy absorptiometry body scanning to estimate local body area compositions of three compartments. Dual-energy attenuation and body shape measures are used together to solve for the three compositional tissue thicknesses: water, lipid, and protein. We designed phantoms with tissue-like properties as our reference standards for calibration purposes. The calibration was created by fitting phantom values using non-linear regression of quadratic and truncated polynomials. Dual-energy measurements were performed on tissue-mimicking phantoms using a bone densitometer unit. The phantoms were made of materials shown to have similar x-ray attenuation properties of the biological compositional compartments. The components for the solid phantom were tested and their high energy/low energy attenuation ratios are in good correspondent to water, lipid, and protein for the densitometer x-ray region. The three-dimensional body shape was reconstructed from the depth maps generated by Microsoft Kinect for Windows. We used open-source Point Cloud Library and freeware software to produce dense point clouds. Accuracy and precision of compositional and thickness measures were calculated. The error contributions due to two modalities were estimated. The preliminary phantom composition and shape measurements are found to demonstrate the feasibility of the method proposed.

Keywords

3d optical imaging; dual-energy absorptiometry; body composition

1. INTRODUCTION

Dual-energy x-ray absorptiometry (DXA) systems can be used to quantify lean and fat tissues for many regions of the body including the arms, legs, trunk, and whole body¹. Michael and Henderson² proposed an extended DXA method to solve for three components using the total tissue thickness. They used Monte Carlo modelling to compare the standard and extended DXA techniques. Another three-material decomposition approach used a mass conservation equation for dual-energy computed tomography³. According to Wang⁴ water, lipid, and protein define approximately 99% of the mass of most soft tissue in humans. As these three components form the major part of soft tissues, it is supposed be reasonable

solution to decompose soft tissues into those three components. Knowing of local composition could be helpful in diagnostics of cancer tumor or other diseases. In our prior work⁵, we created images of water, lipid, and protein of the breast by combining dual-energy X-ray mammography with an estimate of the breast attenuating thickness for each pixel. We accomplished this by creating three independent equations to solve for the three unknown molecular constituents of soft tissue: water, lipid, and protein. Low- and high-energy X-ray attenuations were directly measured from digital mammograms and the breast attenuating thicknesses were estimated using the distance from the top compression paddle to the lower compression surface. The output was three separate compartment images (water, lipid and protein) with a measured calibration accuracy of 2% to known standards. The method proposed in this paper differs from our previous work by source of the X-rays (whole body DXA densitometry versus digital mammography) and method used to measure attenuation thickness (3D supine optical scanning versus mammographic paddle compression thickness). It should be noted that DXA images and standing optical volume scans have been fused in the past by others for the purposes of gait analysis⁶. We report on the design of the technique combining 3D optical imaging and dual-energy absorptiometry body scanning to estimate local body area compositions of three compartments. Dual-energy attenuation and body shape measures are used together to solve for the three compositional tissue thicknesses: water, lipid, and protein. The method was validated using calibration phantom covered a wide range of water, lipid and protein thicknesses.

2. COMPOSITIONAL MODEL

2.1 Dual-energy absorptiometry

The review of physical concepts of body composition model for dual-energy x-ray absorptiometry is presented by Pietrobelli⁷. He operated with the ratio of the low to high energy attenuation of x-ray emissions through an absorber, commonly referred to as R-value. For a homogeneous absorber in case of monochromatic light, an R value is defined as the ratio of the low to high attenuation or the ratio of mass absorption coefficients,

$$R = \frac{\ln(I/I_o)_L}{\ln(I/I_o)_H} = \frac{(-\mu_m M)_L}{(-\mu_m M)_H} = \frac{(\mu_m)_L}{(\mu_m)_H} \quad (1)$$

where μ_m = mass attenuation coefficient, I_o = unattenuated photon intensity, I =attenuated photon intensity, M =absorber mass, L =low energy emission, and H =high energy emission. Each element and thus each molecule will have a unique R -value based on its atomic number and weight. Equation (1) is not thickness dependent so R is constant for a particular composition and not dependent on the attenuator mass or thickness. Eq. 1 can be extended to account for multiple absorbers. In case of the polychromatic source DXA densitometer a ratio (R_{DXA}) of I , passing through a tissue sample to the unattenuated x-ray intensity, I_o continuously changes as a function of thickness due to the preferential higher attenuation of x-rays and the energy decreases, commonly referred to as beam hardening or other reasons such as detector spectral response. Usually the R_{DXA} for materials of a constant composition smoothly change as a function of absorber mass. In this case the problem of extraction of composition of two components could be solved empirically by using non-linear functions of two known variables: R_{DXA} and high energy attenuation.

2.2 Three compositional dual-energy absorptiometry approach

For polychromatic sources, the log-signal function is no longer linear with thickness. The following equation was used to relate high-energy X-ray attenuation, A_{HE} , to the thickness of each mass

$$A_{HE} = \ln \left(\frac{\int I_O(E) e^{(-\mu_w(E)t_w - \mu_l(E)t_l - \mu_p(E)t_p)} dE}{\int I_O(E) dE} \right) \quad (2)$$

where $I_O(E)$ is incident spectrum, t_x is tissue component thickness, and $x=w/l/p$ correspond to water/lipid/protein. A similar equation exists for the low-energy attenuation, A_{LE} . Although these equations cannot be solved analytically, the inverse relationships for thickness were modeled as a power series in three variables: A_{HE} , the ratio value ($R_{DXA}=A_{LE}/A_{HE}$), and total tissue thickness (T). The power series for material thickness was expressed in three equations

$$t_j = \sum_{(\alpha, \beta, \gamma) \in N} a_{\alpha\beta\delta, j} A_{HE}^\alpha R^\beta T^\gamma \quad (3)$$

where j is water, lipid, or protein. One of the three equations was solved by substitution of the total thickness equation,

$$T = \sum_{j=1}^3 t_j \quad (4)$$

The coefficients of the two other equations were determined empirically by scanning a calibration test object made from three bioequivalent materials. This method can be referred to as an extended DXA method since it is using two energy attenuations with the measured total thickness to calculate three compositions.

3. METHODOLOGY

3.1 Calibration phantoms

We constructed calibration phantom made from three materials representing the three compositional compartments. These materials had energy-dependent ratio R_{DXA} values similar to the stoichiometric ideal materials: water (plastic water by CIRS (CIRS, Norfolk, VA)), lipid (machinable wax, Mac Master Carr, Inc., Elmhurst, IL), and protein (Delrin®) materials. This calibration phantom had fifty-two regions of interest each with unique thicknesses and compositions. The calibration phantom was constructed as a stack of the wax and plastic water materials with total thicknesses of 2, 4 and 6 cm and water/wax ratios of 0, 25, 33, 50, 66, and 100%. On top of these stacks, strips of Delrin with area of $1 \times 2 \text{ cm}^2$ were added. The protein mass percent was 0, 5, 10, 20, and 30%. These concentrations were chosen as they are in the range of biological tissues concentrations⁴. The set of Delrin thicknesses was used to match these concentrations. The solid plastic water will be referred to as water, the wax as lipid, and the Delrin as protein. The measurements of low and high attenuation of phantom materials and biological components in dependence of

thickness were performed. The linear low energy μ_{LE} and high energy μ_{HE} coefficients were calculated as slopes of the attenuation vs thickness dependences.

3.2 DXA imaging and data processing

All phantom scans were acquired using the research scan protocol and software version 9.3 on a GE Lunar Prodigy Bone Densitometer (GE Healthcare). The scan options were set to research mode, standard X-ray technique, and scan width equal to 20 cm and length of 30 cm. Low-energy and high-energy attenuation images were saved for each scan using the options available from GE Lunar for the research scan mode. R_{DXA} was calculated as the ratio of the low-energy to high-energy attenuation images after the background subtraction. The paired R_{DXA} value and high-energy attenuation value are unique for each component thicknesses. The calibration coefficients were estimated numerically as the solution to the power series in Eq. 3 in terms of R_{DXA} , A_{HE} , and T . The quadratic model had ten coefficients per equation, which led to a total of 20 coefficients for water and lipid. Quadratic form is represented by Eq. 5. The multiple regression fitting was applied to the averaged images from the calibration measurements. The fitting accuracy to the data was reported through the study of the estimated values from the fit. In addition, we studied the effects of the accuracy of the total thickness measurement by manually varying the total thickness of ± 0.1 cm.

$$t_j = a_{1,j} + a_{2,j}A_{HE} + a_{3,j}R_{DXA} + a_{4,j}T + a_{5,j}A_{HE}^2 + a_{6,j}R_{DXA}^2 + a_{7,j}T^2 + a_{8,j}A_{HE}R_{DXA} + a_{9,j}A_{HE}T + a_{10,j}R_{DXA}T \quad (5)$$

3.3 Three dimensional optical imaging

Accurate X-ray path lengths or thicknesses are required for the three composition method. To accomplish this, we optically scanned the phantom by a manual scanning technique. The 3D scanner, a Microsoft Kinect⁸ (Redmond, WA), is hand held, inexpensive and readily available. In this paper we validated our approach using three material calibration phantoms. In clinical usage, each participant will be scanned while they are having their DXA scan using this hand held scanner. Images of the phantom or participant are generated in real time so the technician can verify that all aspects of the body not in contact with the table are accurately scanned and that there are no movement artifacts. The Kinect scanner measures 3D shape using an infrared depth projector and depth sensor. We used two software programs: open source Point Cloud Library (“Kinfu” application)⁹ and free version of “ReconstructMe” software program¹⁰. The software program generated three-dimensional shape as a mesh object. 3D point cloud and mesh is created in real time during scanning. It takes a few minutes to complete the scan. For the patient studies, 3D optical images for the scanner will be registered to DXA images using least square minimization; pixel-specific X-ray path lengths will be determined from the known geometric configuration of the DXA system. The end result is a unique and accurate total tissue thickness, T , for each pixel.

4. RESULTS AND DISCUSSIONS

4.1 Phantom material characterization

The Table 1 demonstrates R values of the materials used in our calibration phantoms and their biological components. The R values for water, fatty acids, and protein, as showed in the review⁷, are 1.36, 1.29, and 1.22 respectively. As one can see from the Table 1 our measurements demonstrate satisfactory correspondence between plastic water ($R=1.37$) and water ($R=1.36$), wax ($R = 1.2$) and Canola Oil ($R = 1.22$), and Delrin ($R = 1.31$) and Gelatin powder ($R = 1.29$). These R values also correspond well with values of water, fatty acids, and protein published in⁷. Thus, we can conclude that the calibration phantom materials can mimic well the biological human body composition.

Fig. 1 represents R_{DXA} dependence of thickness for plastic water, wax, Delrin and gelatin powder. As one can see the R_{DXA} values are thickness-dependent for all materials. The thickness dependence seems to be a result of combination of different factors including detector spectral response and beam hardening. The R_{DXA} values of Delrin and Gelatin powder are very close to each other and located between solid water and wax. The R_{DXA} values for the three components are well separated and distinguishable. For example at the thickness equal to 5 cm the protein (1.3) stands between lipid (1.7), the lower value, and water (1.37), the higher value.

4.2 Error estimation

The plastic water/wax phantom of 2, 4 and 6 thicknesses, and its reconstructed 3D mesh representation created from the Kinect sensor depth maps, are presented at the Fig. 2. The scanning was implemented using 0.5 m³ cube space. The average error of the step thickness estimation was around 1 mm. This result corresponds to the accuracy measurements of Kinect sensor¹¹ achieved by scanning from a distance of 0.5 m. Using known phantom thicknesses and quadratic eq. 5 for fitting of 52 ROIs of the calibration phantom we achieved the average standard deviation (and percent error calculated as a standard deviation divided by a component maximal thickness) of 0.09 cm (1.6 %), 0.08 cm (1.4 %), and 0.05 cm (4.1 %) for water, lipid, and protein respectively. If the total ROI thicknesses are different from the real ROI thicknesses by ± 0.1 cm, the quadratic fitting thickness outputs has the average standard deviations (percent errors) were 0.19 cm (3.2 %), 0.16 cm (2.7 %), and 0.3 cm (22 %) for water, lipid, and protein, respectively. The estimated values for protein were 6 times higher than the ones with the correct total thicknesses. This result showed the importance of the total thickness measurement accuracy for three component analysis. The additional efforts have to be undertaken to further improve accuracy of the shape reconstruction including either application of different types of scanners with better accuracy or reconstruction algorithm modifications.

An example of low energy attenuation image is presented at the Fig. 3. The image demonstrates seven composition ROIs with wax/water proportion of 0, 50 and 100%, and protein mass of 0, 20 and 30%. The extracted water, lipid, and protein component maps and their profiles in horizontal direction are shown in the Fig. 4. The algorithm successfully extracted compositional maps with proper proportions of component thicknesses. You can

see also noise profiles. The noise amplitude is typical for this densitometer in research regime because it uses very small dose for measurements. Thus, our phantom studies of the error contributions due to two modalities clearly demonstrate the feasibility of combining dual-energy absorptiometry and 3D optical scanning for three composition measurements. The next step is to apply the elaborated technique for regional composition estimation of human subjects.

5. CONCLUSIONS

We report on the design of the technique combining 3D optical imaging and dual-energy absorptiometry scanning to estimate local body area compositions of three compartments. The components for the solid phantom were tested, and their high energy/low energy attenuation ratios are in good correspondence to water, lipid, and protein for the densitometer x-ray region. The error contributions due to two modalities were estimated. The preliminary phantom composition and shape measurements are found to demonstrate the feasibility of the method proposed.

References

- [1]. Dual energy X-ray absorptiometry for bone mineral density and body composition assessment. International Atomic Energy Agency; Vienna: 2010.
- [2]. Michael GJ, Henderson CJ. Monte Carlo modeling of an extended DXA technique. *Phys. Med. Biol.* 1998; 43(9):2583–2596. [PubMed: 9755947]
- [3]. Xin, Liua; Lifeng, Yu; Primak, Andrew N.; McCollough, Cynthia H. Quantitative imaging of element composition and mass fraction using dual-energy CT: Three-material decomposition. *Med. Phys.* 2009; 36(5):1602–1609. [PubMed: 19544776]
- [4]. Wang ZM, Pierson RN, Heymsfield SB. The 5-level model—A new approach to organizing body-composition research. *Am. J. Clin. Nutr.* 1992; 56(1):19–28. [PubMed: 1609756]
- [5]. Laidevant AD, Malkov S, Flowers CI, Kerlikowske K, Shepherd JA. Compositional breast imaging using a dual-energy mammography protocol. *Med. Phys.* 2010; 37(1):164–174. [PubMed: 20175478]
- [6]. Lee MK, Le NS, Fang AC, Koh MT. Measurement of body segment parameters using dual energy X-ray absorptiometry and three-dimensional geometry: an application in gait analysis. *Journal of Biomechanics.* 2009; 42(3):217–222. [PubMed: 19106000]
- [7]. Pietrobelli A, Formica C, Wang Z, Heymsfield SB. Dual-energy X-ray absorptiometry body composition model: review of physical concepts. *Am J Physiol.* 1996; 271(6):941–951.
- [8]. <http://www.microsoft.com/en-us/kinectforwindows/>
- [9]. <http://pointclouds.org/news/2011/12/08/kinectfusion-open-source/>
- [10]. <http://reconstructme.net/>
- [11]. Khoshelham K, Elberink SO. Accuracy and Resolution of Kinect Depth Data for Indoor Mapping Applications. *Sensors.* 2012; 12(2):1437–1454. [PubMed: 22438718]

Figure 1.
 R_{DXA} dependence of thickness for plastic water, wax, Delrin and gelatin powder.

Figure 2. Plastic water/wax phantom of 2, 4 and 6 thicknesses (left) and its reconstructed 3D mesh representation (right).

Figure 3. Attenuation image of the 6 cm thickness calibration phantom consisted of wax/water proportion of 0, 50 and 100%, and protein mass of 0, 20 and 30%.

Figure 4. Lipid (a), water (b) and protein (c) component thickness maps reconstructed by algorithm (upper) and their profiles in horizontal direction (low).

Table 1

Linear coefficients from slope of A_{LE} and A_{HE} thickness dependences and their ratios

Composition	slope μ_{LE}	slope μ_{HE}	$R = \mu_{LE}/\mu_{HE}$
Wax	0.447	0.373	1.2
Plastic Water (CIRS)	0.573	0.418	1.37
Delrin	0.758	0.577	1.31
Canola Oil	0.441	0.359	1.22
Gelatin powder	0.512	0.395	1.29