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A method to determine the density of foods using X-ray imaging

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ABSTRACT

Density of foods is an important physical property, which depends on structural properties of food. For porous foods such as baked foods, accurate measurement of density is challenging since traditional density measurement techniques are tedious, operator-dependent and incapable of precise volume measurement of foods. To overcome such limitations, a methodology was developed using both digital radiography (DR) and computed tomography (CT) X-ray imaging to directly determine density of foods. Apparent density was determined directly from X-ray linear attenuation coefficients by scanning at 40, 60, 80 kVp on DR and 45, 55, 70 kVp on CT. The apparent density can be directly determined using CT however sample thickness is needed to determine density using DR. No significant difference ($p < 0.05$) was observed between density obtained from traditional methods, with density determined from X-ray linear attenuation coefficients. Density determined on CT for all foods with mean 0.579 g/cm^3 had a standard deviation, SD = 0.0367 g/cm^3. Density determination using X-ray linear attenuation was found to be a more efficient technique giving results comparable with conventional techniques.

1. Introduction

Density of foods is a physical property that is used to determine quality of foods and many-a-times used as a conversion factor to determine volume of foods. There are several measurement techniques for density that involve separately determining mass and volume of the food sample. However, traditional volume measurement is commonly associated with drawbacks such as repeated calibration, laborious, inaccuracy and subject to operator dependence (Rahman, 2009). Solid displacement technique using rapeseed commonly used for volume determination of baked foods (AACC, 2000) encounters a number of such problems and more including seed clutter, sticking of seed to food, seed clumping and the subsequent need for cleaning of seeds before reuse. This necessitates the need for a more reliable and efficient method to directly determine density of any food materials.

Numerous non-destructive imaging methods have been developed in recent decades for the evaluation of foods. Imaging techniques can now characterize food products based on physical, mechanical, optical, electro-magnetic, thermal properties (Gunasekaran et al., 1985; Kotwaliwale et al., 2011; Kelkar et al., 2011). But none have been developed that can directly determine the density of foods. Since absorption of X-rays are directly proportional to the material's inherent density (Phillips and Lannutti, 1997) this work proposes a methodology using X-ray imaging technology for the direct measurement of density of foods X-ray imaging has been widely used in the food industry for quality control purposes (Haff and Toyofuko, 2008). In X-ray digital radiography (DR), a single image consisting of a projection of transmitted X-rays through an object is acquired. DR is widely used commercially for the detection of contaminants in foods (Nicolaï et al., 2014). A few studies have employed DR for the investigation of infestation damage in fruits (Jiang et al., 2008) and understanding quality attributes of nuts (Kim and Schatzki, 2001). Recently, computed tomography (CT) has been proven to be a useful technique for quantitative and qualitative analysis of the constituents of many food items. It has been used to quantitatively analyze the geometrical distribution of fat and proteins in meat products (Frisullo et al., 2009), to understand the role of sugar and fat in cookies (Pareyt et al., 2009), apple tissue (Mendoza et al., 2007), and to investigate the rise of dough (Bellido et al., 2006). Recently, micro CT was used to generate high-resolution 2D and 3D microstructures of bread (Besbes et al., 2013; Cafarelli et al., 2014; Demirkesen et al., 2014; Van Dyck et al., 2014), and extruded starch products (Horvat et al., 2014) in order to characterize the structure of product to its ingredients properties, or processing conditions. In all these cases, image processing tools and algorithms were utilized to quantify structural characteristics of the food products.

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In medical physics, CT has been commonly used for diagnosis based on relative changes in attenuation contrast. Absolute values of attenuation are used only for calcium recording based on thresholding technique, and bone densitometry where calibrated tables are used to determine density values (Heismann et al., 2003). Monte Carlo algorithms relating tissue density to Housenfield CT numbers (Schneider et al., 2000) and electron density, atomic number using dual-energy CT (Hünemohr et al., 2014) have been demonstrated. However little or no work has focused on using X-ray imaging to directly determining the density of a wide range of foods.

1.1. Theory

Beer–Lambert's law relates the absorption of light to the material through which the light passes. Similarly, the absorption of X-rays is related to the material through which the beam passes by the following equation (Jackson and Hawkes, 1981),

$$\frac{I}{I_0} = e^{(-\mu t)} \tag{1}$$

where I = intensity of transmitted X-rays,
I_0 = intensity of incident X-rays,
μ = linear attenuation coefficient of the material,
t = thickness of material through which X-rays have traveled.

The linear attenuation coefficient (μ) of a material responsible for the X-ray image contrast is dependent on the density of a material (Falcone et al., 2005).

The Beer–Lambert's law is ideally valid for monochromatic X-ray source since low energy X-ray beams are more strongly adsorbed than the higher energy beams. For polychromatic sources, it results in attenuation of a homogenous sample being not proportional to its thickness. This produces distortions and false density gradients due to the hardening of the beam. Hence, polychromatic X-ray sources normally used in commercial X-ray devices filter out low energy X-rays and apply mathematical algorithms to correct such artifacts (Busignies et al., 2006).

X-ray attenuation for energies, $E < 511$ keV is due to the principle mechanisms of photoelectric absorption, Compton scattering, and Rayleigh scattering (Cho et al., 1975). X-ray attenuation is dominated by both Compton scattering and photoelectric absorption, while Rayleigh scattering photon interaction is negligible (Phillips and Lannutti, 1997). Thus, the total spectral attenuation as given by Heismann et al. (2003) is,

$$\mu = \rho\alpha\frac{Z^k}{E^l} + \beta\rho \tag{2}$$

where μ is the linear attenuation coefficients at X-ray energy level E,
$\rho\alpha\frac{Z^k}{E^l}$ = Photoelectric absorption term,
$\beta\rho$ = Compton Scattering term,
Z = atomic number of the absorber,
β = scattering attenuation constant,
and α = photoelectric constant.

Typically $k = 3$ (Heismann et al., 2003); $l = 3.1$ (Cho et al., 1975); and $\beta \approx 0.02$ m^2/kg for $E < 140$ keV (Heismann et al., 2003).

1.2. Density measurement

1.2.1. Linear attenuation coefficient method

Linear attenuation coefficient can be normalized by dividing it by the density (ρ) of the element or compound, results in (μ/ρ), a constant known as the mass attenuation coefficient (cm^2/g) (Bushberg et al., 2002) for any given material at a given energy level. Thus, the mass attenuation coefficient is only dependent on the composition of a given material and independent of density while linear attenuation coefficient increases with increasing density.

The density of a material can be determined from the linear attenuation coefficients of the sample measured at two different X-ray energies E_1 and E_2,

Given that at E_1,

$$\mu_1 = \rho\alpha\frac{Z^k}{E_1^l} + \beta\rho \tag{3}$$

And at E_2

$$\mu_2 = \rho\alpha\frac{Z^k}{E_2^l} + \beta\rho \tag{4}$$

Since Z^k is constant at all energy levels for a given material, and since β and l are constant for all materials, equating Eqs. (3) and (4),

$$\left(\frac{\mu_1}{\rho} - \beta\right)\left(E_1^l\right) = \alpha Z^k = \left(\frac{\mu_2}{\rho} - \beta\right)\left(E_2^l\right) \tag{5}$$

$$\frac{\mu_1 - \rho\beta}{\mu_2 - \rho\beta} = \frac{E_2^l}{E_1^l} = \left(\frac{E_2}{E_1}\right)^l \tag{6}$$

Rearranging in terms of density,

$$\rho = \frac{(\mu_1 - c\mu_2)}{\beta(1 - c)} \tag{7}$$

where

$$c = \left(\frac{E_2}{E_1}\right)^l \tag{8}$$

The linear attenuation coefficient method gives the basic X-ray absorption Eq. (7) that shows apparent density is a direct function of the X-ray linear coefficients determined at least two different energies. This energy dependence of μ depends on the principle shown by Heismann et al. (2003) where density is expressed as a direct function of two attenuation values μ_1 and μ_2 obtained at two different energies E_1 and E_2 with different spectral weighting.

1.2.2. Intercept method

Density can also be determined from the intercept of Eq. (2) determined at various $\frac{1}{E^l}$ energy levels. The term $\rho\alpha Z^k$ is the slope, with the Compton Scattering term $\beta\rho$ being the intercept. Since β is a constant and independent of the material, the apparent density (ρ) can thus be determined.

Although direct determination of density using X-ray radiography (DR) requires the knowledge of thickness of the food material, this limitation can be overcome by using computed tomography (CT), which can determine linear attenuation through a material at any thickness. Since most industrial DRs and CTs contain filters at the X-ray source and detector to eliminate any lower energy photons to avoid beam hardness with the object, precise reproducibility that can be obtained in its measurements over a large number of scans (Phillips and Lannutti, 1997).

1.3. Objective

The main objective of the study is to develop a methodology to directly determine apparent density of foods using X-ray imaging systems such as X-ray radiography and computed tomography.