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An Easily Made, Low-Cost, Bone Equivalent Material Used in Phantom Construction of Computed Tomography

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Abstract

Computed tomography (CT) has become a routine imaging modality for numerous clinical applications due to its extensive availability, less invasiveness, short scanning time, excellent anatomical resolution, and superior diagnostic value. CT phantoms constructed from bone and tissue-equivalent materials have historically been used to provide a physical representation of the body's anatomy and attenuation characteristics for image quality. Correct diagnosis depends on accurate calibration of the CT scanner and the image interpretation. The aim of this study was to select a new, suitable, inexpensive, and available material that can be used as bone equivalent material in CT phantoms. The principal characteristics which should be considered for selecting the bone equivalent material are physical density and Hounsfield unit (HU) of material. The developed material which is composed of silicone rubber Room Temperature Vulcanizing (RTV) (683) and calcium carbonate ($CaCO_3$) was studied. The results show that the density and CT HU are similar to the human bone. Therefore, silicone rubber RTV (683) with $CaCO_3$ can be used as bone equivalent material in construction of CT phantoms for quality control. This material has demonstrated superior image quality and can be used in other radiology applications.

Keywords: Bone Equivalent Material, $CaCO_3$, Computed Tomography, Density, Hounsfield Unit, Silicone Rubber RTV.

INTRODUCTION

The clinical applications of computed tomography (CT) have increased due to the technological improvements such as multi-detector spiral CT and greatly reduced scan times for diagnosis of a variety of organ systems including lungs, liver, stomach, pancreas, colon, kidneys, and coronary vasculature [1,2]. Therefore, CT usage has expanded dramatically year after year over the last two decades worldwide [3]. The total number of CT examinations made annually in the United States has increased from approximately 3 million in 1980 to nearly 70 million in 2007 [4]. However, the rapid proliferation of computed tomography (CT) scanners has created a need for more documentation on the performance evaluation of a CT scanner [5].

Physical anthropomorphic phantoms have an important role in quality assurance and radiation dosimetry studies of medical imaging [6]. For a material to be considered tissue equivalent in these phantoms, it must have similar radiological proprieties as that of tissue (soft-tissue, muscle, bone, or fat), such as physical density and CT Hounsfield units (HU) [7,8]. Some phantom materials have been developed for this purpose such as the bone material recommended in ICRP70 [9].

Bone equivalent materials are widely used in anthropomorphic CT phantoms for quality control. These materials have historically been used to provide a physical representation of the body's anatomy and attenuation characteristics for image performance and radiation dosimetry studies. Bone equivalent material should be equivalent to human bone tissue in density and CT HU properties in the diagnostic energy 120 kVp. The materials chosen must be commercially available, relatively simple to fabricate and maintainable for a long period of time [8]. However, the widespread clinical use of these phantoms has been limited by their prohibitive costs [10]. Therefore, it is essential to search for new materials with bone equivalent properties for the quality control purposes, which can be used for different CT scanner machines.

Density is the degree to which matter is crowded together, or concentrated. For example, a tightly packed snowball has a higher density than a loosely packed one. Dense elements, those with a high atomic number, have many circulating electrons and heavy nuclei and, therefore, provide more opportunities for photon interaction than elements of less density. Density is the quantity of matter per unit volume, specified in units of kilograms per cubic meter (kg/m^3). In other words, mass density is mass divided by volume (m/l^3). Sometimes mass density is reported in grams per cubic centimeter (g/cm^3).

In general, the attenuation coefficient decreases with increasing photon energy and increases with increasing atomic number and density. It follows that if the kVp is kept constant, the linear attenuation coefficient will be higher for bone than it would be for lung tissue. This corresponds with what we commonly see in practice. That is, bone attenuates more of the x-ray beams than do the lungs, allowing fewer photons to reach the CT detectors. Ultimately, this results in an image in which bone is represented by a lighter shade of gray than that representing the lungs. Therefore, to differentiate an object on a CT image from adjacent objects, there must be a density difference between the two objects.

Differences in linear attenuation coefficients among tissues are responsible for x-ray image contrast. In CT, the image is a direct reflection of the distribution of linear attenuation coefficients. For soft tissues, the linear attenuation coefficient is roughly proportional to physical density. For this reason, the values in a CT image are sometimes referred to as density [11].

In CT scans, HU is proportional to the degree of x-ray attenuation and it is allocated to each pixel to show the image that represents the density of the tissue [12]. Godfrey Hounsfield arbitrarily assigned distilled water the number 0. He assigned the number 1000 to dense bone and −1000 to air. Objects with beam attenuation higher than that of water have an associated positive number. Conversely, substances with attenuation lower than that of water have a proportionally negative Hounsfield value [11,13]. All values higher than those in the selected range will appear white on the image. All values lower than those in the selected range will appear black on the image [11]. Bone HU ranges between 850 and 970 [14].

The aim of this study was to introduce a new suitable practical bone equivalent material with diagnostic energy 120 kVp, which will be used in manufacturing of the quality control (QC) CT phantoms. These materials are inexpensive, environmental friendly and easily obtainable, which are silicone rubber RTV (683) and calcium carbonate ($CaCO_3$).

MATERIALS AND METHOD

In this study, the material proposed was bone equivalent material consisting of silicone rubber RTV (683) with $CaCO_3$. The developed bone-equivalent material should match the physical density and CT HU of human bone within the diagnostic energy 120 kVp.

Silicone rubber (SR, or sometimes SIR or SiR) is a generic term used for a group of materials with the common feature that the backbone of the basic polymer is a silicon/oxygen chain. Silicone rubber is an elastomer, meaning that it can be deformed within very wide limits with comparatively low forces, and then returns to its original shape when the force is released. The material is elastic, but incompressible [15]. An elastomer is a polymer with the physical property of elasticity. Elastomer is a term derived from elastic polymer, which is often used interchangeably with the term rubber. Each of the monomers which link to form the polymer is usually made of carbon, hydrogen, oxygen and/or silicon. Elastomers are usually thermosets requiring a curing process involving heat and the addition of sulfur or other equivalent curatives. In addition, elastomers might also be thermoplastic [16].

Silicone rubber – Room Temperature Vulcanizing (RTV) has valuable properties such as availability, biocompatibility, temperature and chemical resistance, workability, and dimensional stability which make it possible to use with $CaCO_3$ as a bone equivalent material in construction of the anthropomorphic CT phantoms. CT number or HU from CT images provides information on the attenuation characteristics of X-ray beam in a particular volume element in a patient’s body [17].

Calcium carbonate is a chemical compound with the formula $CaCO_3$. It is a common substance found in rocks as the minerals calcite and aragonite (most notably as limestone, which contains both of those minerals) and is the main component of pearls and the shells of marine organisms, snails, and eggs. $CaCO_3$ is the active ingredient in agricultural lime and is created when calcium ions in hard water react with carbonate ions to create lime scale. It is medicinally used as a calcium supplement or as an antacid, but excessive consumption can be hazardous [18].

$CaCO_3$ is a white, odorless powder or colorless crystals. It’s practically insoluble in water. It occurs extensively in rocks world-wide. Ground calcium carbonate results directly from the mining of limestone. The extraction process keeps the carbonate very close to its original state of purity and delivers a finely ground product either in dry or slurry form. According to the United States Pharmacopeia (USP), $CaCO_3$ is fine, white, odorless, tasteless, and microcrystalline powder, while it is described as a white or almost white powder in the European Pharmacopeia (Eur. Ph.) [19].

SAMPLE PREPARATION

200 gm of silicone rubber RTV (683), 125 gm CaCO3 with 2ml catalyst material were mixed together for about 2 minutes. The air bubbles were eliminated by using a vacuum machine at 29 mericuri at room temperature 24-25 C. The resulting material was divided into 5 cubic 1cm^3 samples to measure the density, and a cylinder sample (2.5 cm in diameter and 4cm in depth) for measuring the HU [14], and the shape of the samples was designed by a 3d printer. These samples were left to dry for about one month to make sure that they cured completely.

PHYSICAL DENSITY

Density measurements of each sample were taken by utilizing Archimedes's principle. Each group of sample was weighed on a scale with 0.01/gram precision and the average was taken to find the dry mass of a piece sample. The density of each sample was calculated using Eq. (1).

$$\rho = \frac{m}{v} \tag{1}$$

Where ρ is density of material, v is volume of the object, and m is mass of the object.
The bone equivalent material was chosen to have a density analogous to that of human bone (1.2 - 1.8 g/cm^3) and to obtain a target x-ray attenuation coefficient based on the ICRU-44 reference for soft tissue composition [20].

HOUNSFIELD UNITS

To determine the average Hounsfield unit (HU) of proposed tissue equivalent materials, CT images of developed material were investigated using a calibrated 128 slice Philip CT scanner at the academic hospital of the Universitas Gadja Mada (*Rumah Sakit Akademik*) - Yogyakarta, Indonesia, operated at a tube voltage of 120 kVp. The main CT scan parameters according to CT accreditation phantom instructions [14] are shown in Table 1.

Table 1: Test CT parameters in comparing with ACR parameters instructions

	ACR parameters instructions	Test parameters
Protocol	Adult abdomen	Adult abdomen
Patient orientation	Supine, head first	Supine, head first
Image thickness	≤ 2 mm	2 mm
Field of view	Not smaller than 21 cm	35 cm
kVp	120 – 130	120
Region of interest (ROI)	Approximately 200 mm^2	200.13
Window Width (WW)	400	400
Window Level (WL)	0	0

RESULTS

Measurements of the density samples are given in Table 2.

Table 2. The density measurements

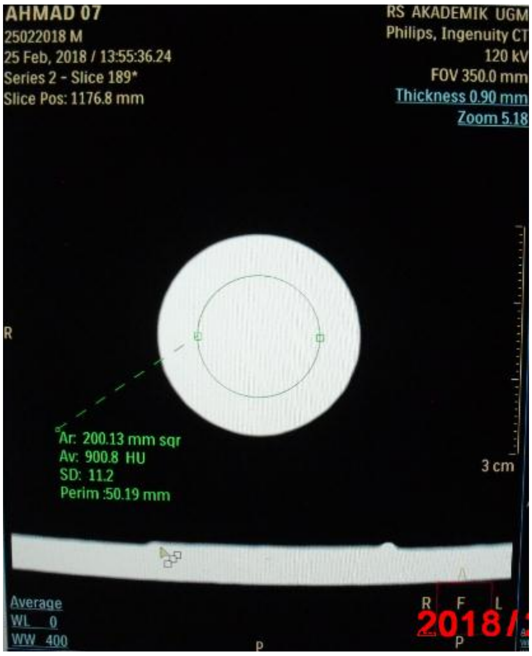
Number of sample	1	2	3	4	5
Mass / g	1	1	1	1	1
Volume / cm^3	0.62	0.62	0.65	0.63	0.64
Density / g/cm^3	1.61	1.61	1.54	1.59	1.56
Average density g/cm^3			**1.58**		

The results of the average density indicate that the density of silicone rubber RTV with $CaCO_3$ fall inside the range obtained for human bone tissue. As known, the density of the human bone range 1.2 - 1.8 [14].

CT HU on different CT images in different locations from the sample are shown in Table 3 and the images are shown in Figure 1.

Table 3: HU of CT images

Number of CT image	HU
1	900.8
2	898.3
3	895.9
4	893.5
5	890.4
6	890.5



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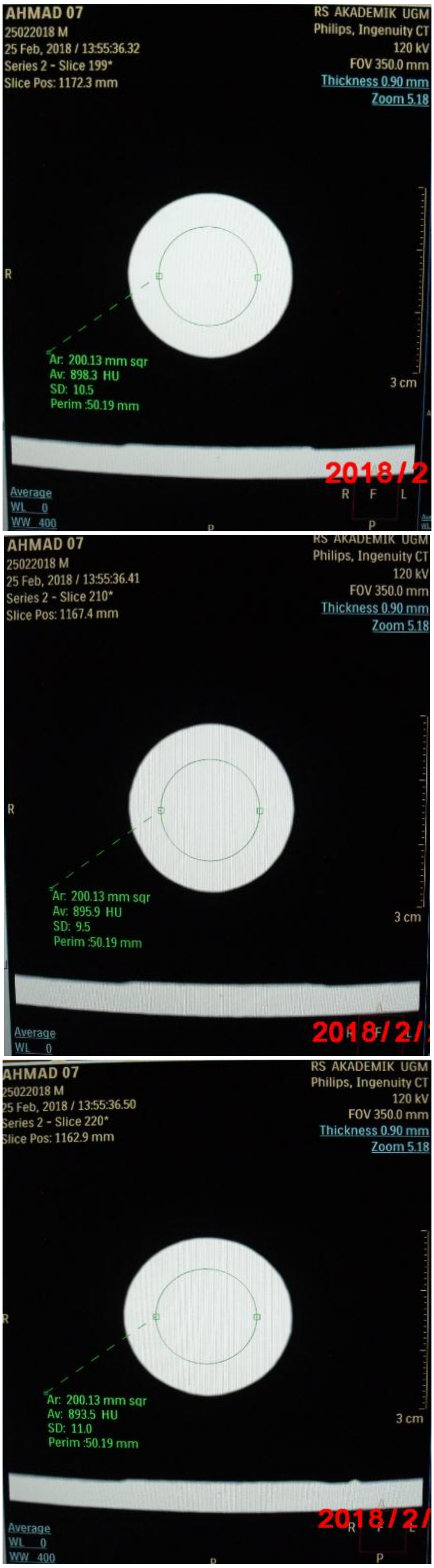

Figure 1: CT HU of the bone equivalent material

The results of HU determination indicate that the CT numbers of silicone rubber RTV with $CaCO_3$ fall inside the range obtained for human bone tissue. As known, the HU calibration criteria of the human bone range from 850 to 970 [14].

DISCUSSION

Computed tomography (CT) has become an essential imaging method in clinical routines. It was the first procedure to non-invasively obtain images of the inside of the human body that were not biased by overlap of distinguished anatomical structures. This is due to the projection of all the information into a two dimensional imaging plane, as usually seen in planar X-ray fluoroscopy [21]. Hence, The main benefits of CT over conventional radiography are in the removal of superimposed structures, the ability to differentiate small differences in density of anatomic structures and abnormalities, and the higher image quality [11,21].

Diagnosis of changes in bone density and hard tissues is important in CT images because changes outside the normal range may indicate disease; early diagnosis is important for the patient's health. The diagnosis of density changes in all the body organs' CT techniques is based on the darkness and brightness of images, expressed with HU in CT scan and with gray scale.

Generally, diagnostic X-ray imaging depends on the maintenance of image quality that allows for proper diagnosis of medical conditions. Maintenance of image quality requires quality assurance (QA) programs on the various X-ray modalities, which consist of projection radiography (including mobile x-ray units), fluoroscopy, mammography, and CT scanning. Currently, a variety of modality-specific phantoms are used to perform QA tests. One of the main problems identified in the field of image QA is the concern of cost. The commercially available image quality assurance phantoms are expensive [22].

CT images are often described as "density distributions" because they provide a gray-scale display of linear attenuation coefficients that are closely related to the physical density of tissues [13]. The interaction of x-rays with tissue is proportional to the density of the tissue regardless of the type of interaction [23]. To differentiate adjacent objects on a CT image, there must be a density difference between the two objects. Moreover, one of the main advantages of CT over conventional radiography is the ability to differentiate small differences in density of anatomic structures and abnormalities [11].

In this study, silicone rubber RTV (683) was used with $CaCO_3$ to mimic the physical properties of human bone under CT scan by testing the density and HU. Density is related to the mass of each atom and basically tells how tightly the atoms of a substance are packed [23]. It was calculated by measuring the mass divided by volume. The resulting average density of the bone equivalent material is 1.58 g/cm^3. This is in the density range of bone (1.2 - 1.8 g/cm^3) [14]. So, the test of density was accepted.

CT scanners use HU (CT numbers) to account for tissue inhomogeneities within the human body [24]. HUs are a unit of measure that represent the different density levels of tissues and/or other substances [25]. The CT HU of each voxel is calculated from the transmission data collected as the beam passes through the patient at many different angles. Each pixel is displayed on the video monitor as a level of brightness which corresponds to the level of optical density in the pixel. The relative attenuation characteristics of a voxel are reported as HU. The HU range from −1,000 to +1,000 for each pixel [26].

The HU in CT images of the bone equivalent material was taken from different locations of the testing sample to prove that the results are similar. The resulting HU is located in a range from 890.4 to 900.8, which are in the range of HU bone calibration criteria (850 - 970) [14]. Therefore, the test of CT UH is passed and accepted.

A number of CT phantoms are available commercially for QC and image performance; they are very costly. Therefore, there is a need to produce a cheap bone-equivalent material to be used in CT phantoms for QC purposes with low cost. This study reveals a new field in inspection of the efficacy of employing the silicone rubber RTV with $CaCO_3$ as a bone-equivalent material which can be used in construction of QC CT phantoms, which are inexpensive, easily obtainable and easily made into molds. This work also simplifies additional research to extend the range of applications of new bone equivalent material in phantoms for different applications, such as dose calculation, either in CT scan or other radiology machines. This versatility will reduce the cost of purchasing commercial ones for each application.

CONCLUSION

The aim of this study was to find appropriate bone equivalent material for a physical phantom to be used in CT scan quality control. Silicone rubber RTV (683) can be used with $CaCO_3$ to formulate bone equivalent material which can be used in low-cost manufacturing of CT phantoms for quality control.

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