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Development of Synthetic Bones for Advanced Radiation Dosimetry Applications

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Abstract

Background: the aim of this study is to develop synthetic bones from several variations of calcium carbonates and polyester resins for the ANSI chest phantom dosimetry. Material and method: eight samples of synthetic bones from calcium carbonate and polyester resin have been synthesized. The bonding material used was unsaturated polyester resin. The unsaturated polyester resin for each sample was 10 ml and the hardener was 6 drops. The calcium carbonate powder was mixed with unsaturated polyester resin. Degassing was carried out on 8 samples to reduce the bubbles that arise due to the mixing and stirring process. The samples were then put into a mold. The samples were scanned using a siemens somatom definition as CT scanner. Average ct numbers and their homogeneities were measured from their CT images. Result: the results of the eight samples constituted of 0, 10, 20, 30, 40, 50, 60, and 70% calcium carbonate and their CT numbers were +173, +309.1, +321.6, +591, +781.8, +982, +1180, and +1450.3 hus, respectively. However, for 70% calcium was very difficult to be molded. Therefore, the synthetic bones from 10% to 60% calcium carbonate percentages represent human bones from a cartilage (i.e. Hu < +400) to hard bone (i.e. Hu > +1000). For all synthetic bones, the homogeneities are more than 98%. Conclusion: the synthetic bones could be used as human bone in the ANSI chest phantom rather than aluminum sheet. Cartilage is used for young phantom and hard bone is used for adult phantom.

Indexed keywords: Computer Engineering, Advanced Computing, Technology, Open Access

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Key words: Synthetic Bone, ANSI Chest Phantom, Phantom Dosimetry

INTRODUCTION

The dose received by patient is a side effect of implementation of ionizing radiation for radiological examination [1-3] and it might be harmful to the patient [4,5]. The dose should be minimized with a note that the image obtained must be of high quality for medical purposes, such as to establish a diagnosis. The management of patient dose in Indonesia is regulated by the Nuclear Energy Regulatory Agency (BAPETEN). The BAPETEN issued the diagnostic reference level (DRL) for dose guidance in the practices of radiological examinations [6]. Therefore, measurement and recording the patient's dose are essential for dose optimization. In addition, measurement of dose is integral part of quality control (QC). Dose measurement needs equipment such as dosimeter and phantom.

A phantom attenuation that can resemble the condition of the human body is essential for dose measurement QC [7]. The American National Standards Institute (ANSI) chest phantom is a simple attenuation phantom and usually used for dose measurement [8]. The ANSI chest phantom is a

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square box with several layers to surrogate the body [8]. The ANSI chest phantom was undergone several modifications by many researchers, such as by Pina, et al [9,10] and Alves, et al [11]. The ANSI chest phantom substitutes soft tissue with acrylic / polymethyl methacrylate (PMMA) material, lungs with air, and bone with Aluminum (Al) sheet [12-13].

Aluminum is a cheap and easy to be obtained, but it does not accurately substitute the real bone of human [14]. Bone is one of the constituent tissues of the human body. It functions as a body support, shaping the body, and protecting the body's organs, as well as being the place of the process of blood hemopoiesis [14]. Bone tissue has an ability to store minerals, especially calcium and is mostly in a form hydroxyapatite. These materials distinguish bone from other connective tissue, including cartilage [15]. Based on its constituent structure, human bones consist of cartilage (less dense bone) and hard bone (solid bone) [16]. Cartilage is composed of cartilage cells (Chondrocytes) formed by

Chondroblast, with space between cartilage cells containing many adhesives and less lime. Cartilage is abundant in the bones of young children. In adults, cartilage is at the ends of the ribs, larynx, trachea, bronchi, nose, ears, and so on. While hard bone (true bone) is formed by bone-forming cells (osteoblasts) where the space between hard bone cells contains a lot of lime, little adhesive. The lime substances are in the form of calcium carbonate ($CaCO_3$) and calcium phosphate ($Ca (PO_4)_2$) which are carried by blood [17]. Hard bones function is to arrange the skeletal system. Bones become hard due to the deposition of calcium phosphate crystals in the osteoblast [18]. The bone mass densities are from 1100 kg/m^3 (cartilage bone) to 1920 kg/m^3 (cortical bone) [19]. The CT number for cartilage is < 400 HU, while for the hard bone is > 1000 HU [20].

Aluminum is a metal which has a light density, corrosion resistance, and good electrical conductivity. Generally, aluminum is mixed with other metals to form aluminum alloys. This material is used not only for household appliances, but also for industrial, construction, and so on [21]. The mass value of Aluminum is 2700 kg / m^3 [19], and its CT number is +2100 to +2300 HU [22].

In this study, bone substitutes will be developed using calcium carbonate and polyester resin as a binder. Calcium carbonate is an inorganic mineral in a stable phase and is available at cheap prices [23-24]. Calcium carbonate has a density of 2711 kg / m^3 [25]. Calcium carbonate has been used in many studies [26, 27]. Jones, et al [26] mixed several materials over two types of materials including epoxy resin (36.4% Araldite GY6010 and 14.6% Jeffamine T-403) with25.5% silicon dioxide and 23.5% calcium carbonate to obtain tissue equivalent material as a phantom dosimetry construction in pediatric radiology [26]. Whereas Winslow, et al [27] mixed material to produce a bone-like material with a CT number of 622 HU [27]. However, this value does not indicate the range of variations in the CT number of human bones. The polyester resin is a widely used polymer. Polyester resins have a density in range of 1.10–1.15 g/cm^3 [28, 29]. Therefore, polyester resin can be used as an alternative material for soft tissue phantom. Rumaisya, et al [29] used polyester resin and methyl ethyl ketone peroxide (MEKP) to develop a head phantom of CT dose index (CTDI). Some of the advantages of polyester resin include: insoluble, non-toxic, transparent, resistant to water absorption, and easy to manipulate without tangled equipment [29, 30].

In this study, several bone composites have various CT numbers will be developed as synthetic bones for the ANSI chest phantom dosimetry. Several bone composites will be achieved by various calcium carbonate contents in unsaturated polyester resins.

DESIGN, MATERIAL, PROCEDURE, TECHNIQUE OR METHODS Synthesis of Synthetic Bone

This study developed eight samples of synthetic bone from calcium carbonate and unsaturated polyester resin (UPR) (Table 1). The UPR was for bonding material. The UPR for each sample was 10 ml and the hardener was 2% of the volume of the UPR.

Table -1 Composition of composites for various synthetic bones

Sample	UPR (ml)	Calcium Carbonate (gram)	Calcium carbonate percentage	Catalyst
		-	0%	2% UPR
		1.1	10%	2% UPR
		2.5	20%	2% UPR
		4.3	30%	2% UPR
		6.7	40%	2% UPR
			50%	2% UPR
			60%	2% UPR
		23.3	70%	2% UPR

Synthesize procedure of synthetic bones was shown in Figure 1. Samples were stirred for 5 minutes. The resulting composites were then carried out a vacuum process to remove air bubbles for 5 minutes. After the vacuum process, the composites were given a hardener of 2% of the volume of UPS. The composites were stirred again for 2 minutes. The curing process took approximately 4 hours.

Evaluation of Synthetic Bones

After the synthesis process, eight samples were scanned in Radiology Department of Kraton General Hospital using the Siemens Somatom Definition AS CT scanner (Figure 2). Scan parameters used in this study are as follows:

kVp : 120 kVp
mAs : 350 mAs
Dose modulation : Yes
CARE dose : Yes
Rotation time : 0.5 s
Colimation : 6 mm Acq. 64 x 6 mm
Pitch : 0.55

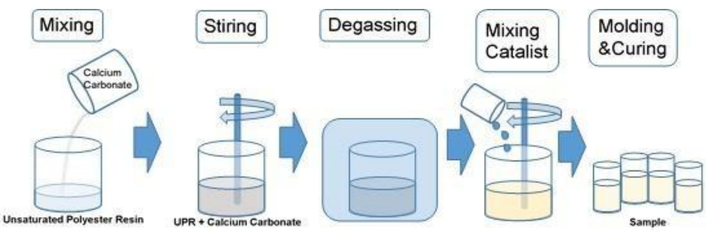

Fig. 1 Synthesize procedure of bone substitutes material

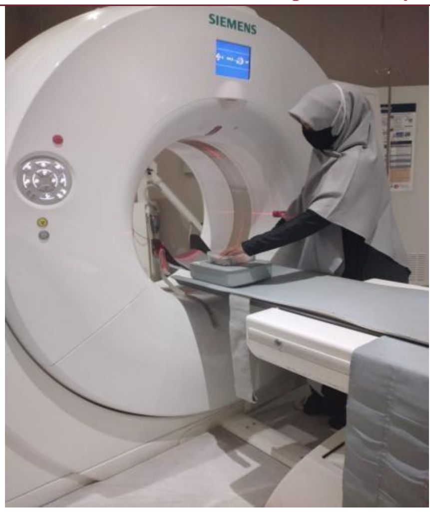

Fig. 2 Siemens Somatom Definition AS CT scanner

CT numbers of eight samples were measured from obtained CT images (Figure 3). Average and uniformity CT numbers were calculated. CT number in Hounsfield unit is a relative comparison between linear attenuation coefficient of a tissue and water. CT number was computed using equation (1).

$$CT\ number = 1000\frac{(\mu j-\mu a)}{\mu a} \quad (1)$$

Where μj is the linear attenuation coefficient of a tissue and μa is the linear attenuation coefficient of water. Based on the equation (1), CT number of the water will be 0. The CT number is directly proportional to the tissue density and expressed in Hounsfield unit (HU) [33].

CT number must also be uniform throughout the image. Therefore, the homogeneity of CT number was measured. Thehomogeneity was calculated by measuring the average CT number in some Region of Interest (ROI) distributed throughout the phantom (Figure 4) [34]. The homogeneity was calculated using equation (2) [35].

$$H = \left(1 - \frac{|CT_{max} - CT_{min}|}{CT_{min}}\right) x100\% \quad (2)$$

Where CT_{max} is maximum CT number in one ROI, and CT_{min} is minimum CT number in another ROI.

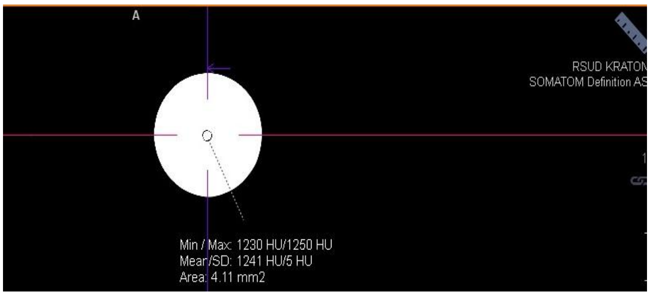

Fig. 3 Example of CT image of one synthetic bone. A circular region of interest (ROI) is drawn for average CT number calculation.

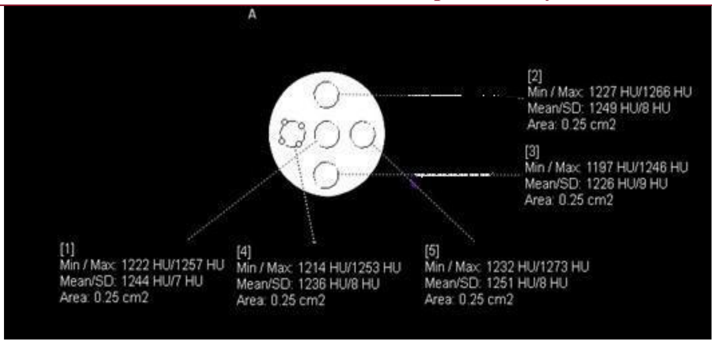

Fig. 4 Homogeneity is calculated from 5 ROIs drawn in the image

RESULTS AND DISCUSSION

Relationship between percentage of calcium carbonate and CT number of synthetic bones is shown in Figure 5. It is seen that there is linear relationship between both with $R^2 = 0.9749$. It means that calcium carbonate percentage linearly and strongly correlates to the its CT number [25].

Homogeneities of CT number for all synthetic bones are tabulated in Table 2. It shows that homogeneity levels of all synthetic bones are above 98%. Samples 1-4 have standard deviation of CT number below ± 4 HU. Samples 5-7 have deviation of CT number below ± 7 HU. Sample 8 has standard deviation of CT number above ± 10 HU.

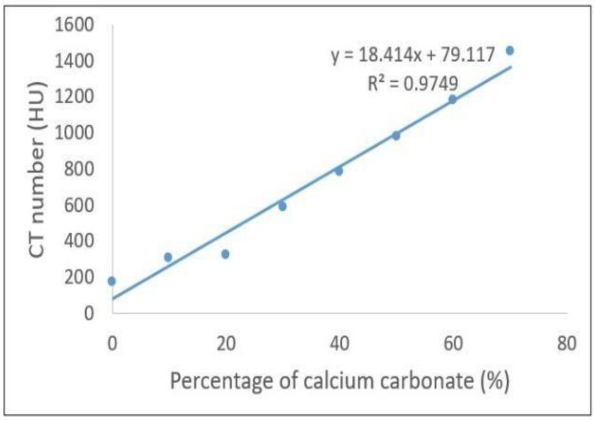

Fig. 5 The relationship of increasing calcium carbonate percentage in CT Numbers of synthetic bone

Table -2 Homogeneity test from polyester resin and calcium carbonate composite

Calcium carbonate percentage	CT number (HU)					H* (%)
	Left edge	Upper edge	Center	Lower edge	Right edge	
0%	174.0	175.6	170.0	171.4	173.0	98.6
10%	314.7	311.0	310.0	306.3	314.5	99.1
20%	327.0	321.0	325.9	324.1	327.6	99.2
30%	597.5	589.1	597.2	585.0	586.9	99.4
40%	772.5	773.2	774.2	776.9	774.6	99.7
50%	985.5	988.1	985.4	989.5	982.0	99.7
60%	1192.5	1194.4	1191.2	1187	1188.8	99.8
70%	1456.1	1461.7	1464.4	1456.2	1429.9	99.6

*) H is homogeneity of CT number

The study aims to develop he synthesis bones from calcium carbonate and polyester resin for the ANSI chest phantom dosimetry. The percentage of calcium carbonate is varied, i.e. from 0% to 70%.

At 0% calcium carbonate, the CT number is +173 HU, and at 10% calcium carbonate, the CT number is +309 HU and CT number linearly increase with the percentage of calcium carbonate. At 70% calcium carbonate, the CT number is +1450 HU.

Based on these findings, the synthetic bones from calcium carbonate and polyester resin is able to be used as bone surrogate from cartilage (with HU less than +400) for 10% calcium carbonate to hard bone (with HU more than 1000) for 60% calcium carbonate.

Sample 1 cannot be used as a bone replacement material because it has a CT number below 250 HU, while sample 8 (70% calcium carbonate) cannot be used because it has a high viscosity so it is very difficult to be molded. Overall, the homogeneity level of substitute bone substitute material is very good with an average of 99%. Unlike previous study [27] that used more than two component materials to produce one type bone-like material. The current study produces synthetic bones with wide range of CT number.

In this study, the authors have not yet classified synthetic bone for age and sex.

CONCLUSION

Eight synthetic bones have been developed and tested. The synthetic bones were composed from calcium carbonate and unsaturated polyester resin as bonding. The synthetics bones have CT numbers from of +309 HU to +1180 HU for calcium carbonate percentages from 10% to 60%. These synthetic bones with calcium carbonate percentages from 10% to 60% surrogate wide range of bones from cartilage to hard bones. These synthetic bones could be used as bone surrogate in the ANSI chest phantom dosimetry.

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