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Fabricating Pediatrics Bone Tissue Equivalent Materials for CT Quality Control Evaluation

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Abstract

Computed tomography (CT) imaging plays a critical role in diagnostic radiology, so they require pediatric or adult phantoms with high tissue equivalent material for accurate imaging, radiation dose optimization and radiation safety purposes and to assess and verify performance in CT quality control program. Yet the high cost of commercial alternatives limits their accessibility. The aim of this study was to fabricate skeletal bone equivalent materials useful in construction of pediatric phantom where low-cost bone equivalent materials were used. It provides a new composition and simple methodology for skeletal construction. The characteristics of developed bone equivalent material were evaluated by its physical density and Hounsfield unit (HU) of material. where Silicone rubber RTV (683) was used with $CaCO_3$ to fabricate bone equivalent material, which involves weighing of 50 g of silicon rubber RTV (683), then mixed with 17 g of $CaCo_3$ and 2 ml of the catalyst. This ratio was chosen based on prior research and the mixed quantity was improved after excessive experimental testing to fit the environmental condition and give better results. The production procedures have also been streamlined to create molds for each bone of the skeleton. Information regarding the new tissue-equivalent materials, as well as images of the construction process and completed skeletal were done. The average density measurements of samples manufactured from silicone rubber RTV with $CaCo_3$ fall within the range of human bone tissue concentration, which is (1.2 - 1.8) g/cm^3, indicating that the density values are comparable to those of human bone. The attenuation coefficients (HU) value on various computed tomography images of bone-equivalent materials (silicone rubber RTV with $CaCO_3$) also show findings that are within the range seen for human bone tissue. The human bone's HU calibration standard falls between 400 and 1000 HU. Therefore, silicone rubber RTV (683) with $CaCO_3$ can be used in construction of skeletal. This material can be applied to different diagnostic radiology quality applications and has produced great image quality. The majority of conventional phantoms used in quality control testing were constructed using CT slices, which may have made it difficult to see the skeletal vertebrae and all of their intricacies. Nonetheless, the suggested model provides a clear image of the spine's vertebrae and every skeletal component, including all of its intricacies, which can aid in the computation of dosages inside the human body.

Keywords

Bone Equivalent Material, Calcium Carbonate $CaCO_3$, Computed Tomography, Hounsfield Unit, Silicone Rubber RTV (683), Phantom, Pediatric

1. Introduction

Radiation diagnostics is an important area of clinical medicine, which makes it possible to detect diseases by non-invasive or minimally invasive methods using various kinds of radiation, while its useful in diagnostic and therapy fields, inadequate use of radiation can cause negative effect on the human body despite its usefulness in diagnostic and therapy fields. Therefore, it is quite important to carefully evaluate the distribution of radiation energy absorbed by human tissue during the radiological examination and taking in the account the enhancement of quality imaging systems.

CT is a medical imaging modality used to obtain detailed internal images of the body [1]. It diagnoses possibly life-threatening conditions such as hemorrhage, blood clots, or cancer. An early diagnosis of these conditions could potentially be lifesaving.

A patient is exposed to ionizing radiation for a brief period of time during a CT scan, the amount of radiation is greater than the amount from a plain X-ray because the CT scan gathers more-detailed information [1].

The low doses of radiation used in CT scans have not been found to cause long-term harm. However, the repeated scan or using contrast can lead to increase in the lifetime risk of cancer [2]. More children than adults may be impacted by this. Since using exposure settings intended for adults can result in a higher radiation dose than is required to create a meaningful image for a pediatric patient, it is especially crucial to ensure that CT scans performed on children are conducted with the proper exposure factors [2].

Anthropomorphic pediatric phantoms and the material made off play significant role in quality control, quality assurance and dosimetry measurements in medical imaging. It is used to evaluate actual radiation doses and estimate organ doses for protection purposes.

Fabrication of a skeletal bone with materials useful to construct pediatric phantom for X-ray imaging, requires careful attention of a number of factors such as the selection of materials, the capacity to physically resemble human body parts [3] [4] and providing a representative interfacing between bone and soft tissue [5]. Phantoms representing children aged between 1 and 15 years are urgently needed.

The design of skeletal bone materials should take into account the likeness to real bone tissue, and the shape should often mimic the shape of a human bone.

It must have similar radiological proprieties as those in the bone such as physical density and CT Hounsfield units (HU) in the diagnostic energy 120 - 130 kVp [6] [7]. Some materials have been developed for this purpose such as the bone material recommended in ICRP70.

The materials selected must be easily obtained, simple to handle and durable for a long time [8].

Silicone rubber is an elastomer, which means a polymer with the physical property of elasticity composed of silicone itself a polymer containing silicon together with carbon, hydrogen, and oxygen. They are widely used and have multiple formulations. They are generally non-reactive, stable, and resistant to extreme environments and temperatures from −55˚C to 300˚C (−70˚ to 570˚F) while still maintaining its useful properties. Due to these properties and its ease of manufacturing and shaping, silicone rubber can be found in a wide variety of products. It's a highly adhesive gel or liquid. To convert it to a solid, it must be cured, vulcanized, or catalyzed. It can be made as mold [9].

RTV (Room Temperature Vulcanized) silicone rubber is a type of silicone rubber made from one-part (RTV-1) or two-component (RTV-2) systems. Their hardness ranges from very soft to medium.

It has 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 [10].

Calcium carbonate ($CaCO_3$) is common substance found in rocks as the minerals calcite. Most notably, it could be found in chalk and shellfish skeletons. It has medical use as a calcium supplement or as an antacid [11].

Calcium carbonate appears as white, odorless, tasteless, and microcrystalline powder or colorless crystals [12]. Practically insoluble in water. 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 [13].

A material's density is defined as its mass per unit volume. Density is essentially a measurement of how tightly matter is packed together.

The linear attenuation coefficient indicates the degree of penetration of the light beam or particle to the material [13]. The attenuation of X-rays in tissues is generally affected by several factors such as the energy of the photon, the thickness of the bodily tissue, atomic number, and density of the tissue [14]. In general, the attenuation coefficient become less when the photon energy is larger and directly proportional with increasing atomic number and density, so bone attenuates more of the x-ray beams than do the lungs tissue so less photons to reach the CT detector [15]. A radiographic image is composed of different absorption rates because X-rays either passed freely through the body or absorbed or scattered by anatomical structures. The denser the tissue, the more X-rays are attenuated, so this gives the contrast of the image [16].

Table 1. Hounsfield Scale for different kinds of tissue.

Matter	Hounsfield value (HU)
Cortical bone	>1000
Trabecular bone	300 to 800
Water	0
Fat	−50 to −100
Lung	−1000 to −800
Air	−1000
White matter	20 to 30 HU
Kidney	20 to 40 HU
Spleen	35 to 55 HU
Grey matter	37 to 45 HU
Blood	45 to 65 HU
Liver	45 to 65 HU

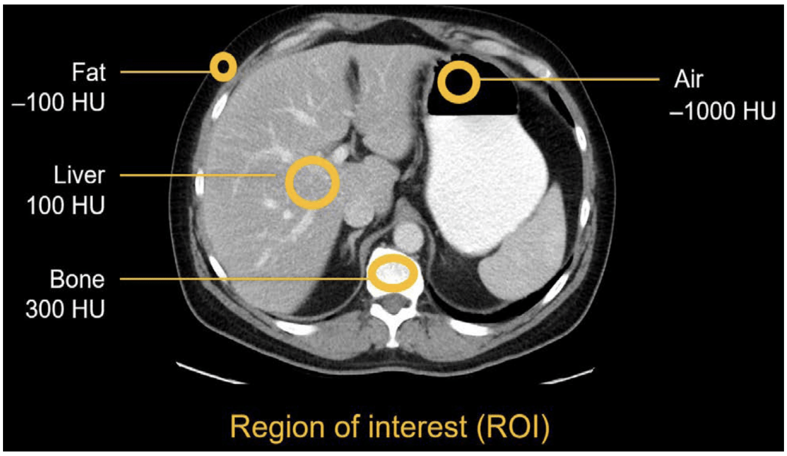


Figure 1. The drawing of (ROI) over the structure.

HU is represented both by the gray scale appearance in the image and can measure as numerical value. The higher the number, the more x-rays the structures absorb. Therefore, a high attenuation structure like bone will have a higher HU value than low attenuation structures like fat or air [17] ("as illusterated in **Table 1**").

By drawing region of interest ("as shown in **Figure 1**"), obtaining of the attenuation value and information about the structure's density will be precise.

(HU) are a dimensionless unit universally used in to express CT numbers in a standardized and convenient form. It 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, and obtained from a linear transformation of the measured attenuation coefficients [18]. This transformation is based on the arbitrarily-assigned radio densities of air and pure water.

The values displayed in table [1] is determined by the application of specific window and level values. The software of all CT scanners and PACSs has the ability to measure the density of a region of interest (ROI) electronically overlaid the image [19].

Much research was conducted in the field of phantom construction with different methodology and materials. A methodology for fabrication series of three different adult phantoms at the University of Florida was carried. All phantoms were constructed in 5 mm transverse slices using materials designed to mimic human tissue at diagnostic photon energies: soft tissue-equivalent substitute (STES) made from the commercially available, two-part urethane rubber compound "PMC 121/30 Dry", (Smooth-On, Easton, PA), was combined with 2.8% by weight of powdered $CaCO_3$ (Fisher Scientific, Hanover Park, IL). The calcium carbonate was added to the two parts of urethane and mixed with an electric mixer, with care being taken to ensure a homogeneous mixture with no undissolved $CaCO_3$, lung tissue-equivalent substitute (LTES) was designed by combining uncured urethane-based STES along with poly-fil polystyrene micro beads (Fairfield Processing, Danbury, CT) in a 10:1 ratio by weight. Bone tissue-equivalent substitute (BTES) used was the epoxy resin based material, the mixture of the BTES is as follows: 36.4% Araldite GY6010 and 14.6% Jeffamine T-403 (Huntsman Corp., Woodlands, TX), as well as 25.5% Silicon dioxide and 23.5% Calcium carbonate (Fisher Scientific, Hanover Park, IL). It was designed to represent a homogenous mixture of cortical and trabecular spongiosa (bone trabeculae and bone marrow). The production process has also been streamlined with the use of an automated machining system to create molds for the phantom slices from bitmap images based on the original segmented computed tomography (CT) datasets [20].

Another study describes the development and validation of a low cost pediatric pelvis phantom based on the anatomy of a 5-year-old child. In that study, tissue equivalent materials representing pediatric bone (Plaster of Paris; PoP) and soft tissue (Poly methyl methacrylate; PMMA) were used. PMMA was machined to match the bony anatomy identified from a CT scan of a 5-year-old child and cavities were created for infusing the PoP. Phantom validation comprised physical and visual measures. Physical included CT density comparison between a CT scan of a 5-year old child and the phantom and Signal to Noise Ratio (SNR) comparative analysis of anteroposterior phantom X-ray images against a commercial anthropomorphic phantom. The mass attenuation coefficients can be calculated after entering the compound proportions of any material using web-based software. All tissues in the pelvic area are of comparable linear attenuation coefficients when compared to soft tissue, except for cortical bone [21].

This paper aim was to obtain a new suitable combination of bone equivalent material to help in designing of pediatric phantoms with diagnostic energy 120 kVp (The kilovolt age setting was high because x-ray output increases with increasing kilovolt age, the highest rate of x-ray production possible was helpful to obtain optimal image quality and minimal scanning time) [22]. These materials are available, environmental friendly and with law cost, which are silicone rubber RTV (683) and calcium carbonate ($CaCO_3$).

2. Materials and Method

The materials utilized in this study were bone-equivalent materials made of silicone rubber RTV (683) and $CaCO_3$. Both of these materials expected to be similar to the physical density and CT HU of human bone within the diagnostic energy 120 kVp.

2.1. Sample Preparation

Firstly, the methodology described by Abu Arrah *et al.* in the construction of bone equivalent material was used with some modifications in the quantity of the materials [23]. The first stage involves weighing 50 g of silicon rubber RTV (683) and then mixed with 17 g of $CaCo_3$ and 2 ml of the catalyst, then the material was mixed together for about 2 minutes, the air bubbles were eliminated by using a vacuum machine at room temperature 24˚C - 25˚C. The resulting material was divided into 6 cubic $3cm^3$ samples to measure the density and was left to completely cured for 3 days. The cubic sample that the prepared material fill with was made and designed from red wax that was usually used in the field of dentistry for taking the dimension of the patient teeth with wax mold.

After the samples were dry, the density of each sample was measured by the mathematical formula of density. Each sample was weighed on a digital balance that has scale with 0.001/gram precision and the mass of each piece was found. The density of each sample was calculated using equation (1).

$$\rho = mv \quad (1)$$

where ρ is density of material, v is volume of the object, and m is mass of the object. The bone equivalent material was selected to give a density similar to that of human bone (1.2 - 1.8 g/cm^3) and to obtain x-ray attenuation coefficient based on the ICRU-44 reference for soft tissue composition [24].

2.2. Attenuation Coefficients

To determine the attenuation coefficient, (the average Hounsfield unit (HU)) of suggested tissue equivalent materials, CT images of developed material were investigated using a calibrated 128 slice Philip CT scanner at the Ibn ALhaytham diagnostic center, ALhawadith Street, Khartoum, Sudan operated at a tube voltage of 130 kVp.

The computed tomography scanning protocol and scan parameters according to CT accreditation phantom instructions [25] ("are shown in **Table 2**"):

Table 2. Test CT scanning parameters for the samples and ACR parameters instructions.

Items	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	33.5
KVP	120 - 130	130
Region of Interest (ROI)	Approximately 200 mm^2	200 mm^2
Window Width (WW)	400	400
Window Level (WL)	0	0

2.3. Pediatric Skeletal Construction Methodology

After the selected material passed the tests as tissue equivalent material for bone, the construction and composition of the skeletal which was done by manufacturing each part of skeletal bone alone (spine (vertebra chain), thorax, pelvic areas and parts of hands and legs) one by one vertebra, then gathering them to give the final shape of the spine and the skeletal from neck to pelvic and some part of the legs (trunk).

A pediatric skeleton for study purposes in Khartoum university, faculty of medicine was chosen after subjected to many dimension measurements, which are length of the ribs in the chest region, length of the arms, legs, neck and spine and was compared with the dimension of real pediatric population and with the number in the reference in that field. According to those measurements which agree with dimension of a three years old children boys, our phantom size based on the size of the three years old child body and was represented the children of age category (0 - 5) years. This age three-year was chosen because the data available are rich for that age category. This model cannot be generalized to other pediatric age group but the same methodology, materials and concept can be used to create other model with different ages.

Bone Tissue Construction

First of all, the skeleton was disintegrated from neck to pelvic so each bone become alone and marked by number, then a mold from epoxy resin based material (MIXFLEX PS205) was made. The idea of mold was taken from the way that the dentists take the impression and the dimension of the teeth for the patient with silicon impression. The mold was consisted from two part, front and back one so the mold can take the shape and all the details of the bone from the both sides.

Epoxy resin based material was used for manufacturing the molds for each vertebra.

For each bone, there were two parts of mold front part for the front details of the bone and back part for the lower details of the bone, then the epoxy resin material was enveloped with plastic cylinder around epoxy resin that contains the bone to insure the combination of two parts so every detail of each bone can appear.

The way that the front and back mold from the epoxy resin was made is that the mold was made using pug, epoxy resin, and plastic cylinder open from both sides.

The cylinder was closed with pug in one direction and left the other side opened, then the desire bone was put and first half of it planted inside the pug, the epoxy resin material was poured inside after was mixed with its catalyst and let it dry for 3 days.

Once the epoxy resin was dry, the side with pug was cleaned and the dry epoxy resin face that hold the desire bone details was polished with insulator and the epoxy resin was poured again inside the rest of the plastic cylinder to give the other half of the bone shape. After the complete dry of the mold, the plastic cylinder was removed and the mold open to extract the bone inside the mold that contain the precision details of the bone.

The next step that follow the preparation of the mold for each bone of the skeleton (from the bone of the neck to the pelvic and legs) is that, each mold for each part of skeletal was filled with the mixture of bone equivalent materials (17 g of $CaCo_3$ + 50 g of Silicon RTV (683) + 2 mm of catalyst) using injection and left to dry for 3 days. After that, the vertebra bone and each part of skeletal were removed from the mold to make the skeletal of pediatric phantom ("see **Figure 3** and **Figure 4**").

The thorax mold was made using plaster materials, it was made by pouring plaster on the front part of the chest carefully and let it dry for 3 days to make it sure it was totally dry, then that part was polished with light insulator to make it easy to be disintegrated from the second part (back part). The other face of thorax was made by also pouring plaster on it, after that the bone was removed from the plaster mold also to composed together with other parts of skeleton.

All parts of the vertebrae spine were assembly together using thin cylindrical metal that inserted inside the hole in vertebrae of the vertebral spine, the bones were connected together using transparent waxy adhesive and thin thread.

The bone was arranged similar as the arrangement of the human skeletal bone. The skeleton was then imaged using x-ray radiographic unit to see the shape of the skeletal ("as shown in **Figure 5**") and to investigate the absorption and the efficiency of the bone equivalent materials.

3. Results

Before the fabrication of the skeletal is constructed it has to pass the density and the attenuation tests, so the first test to be passed is the density test and the results were as follows.

Density Measurements:

Table 3. The density values of the bone equivalent material based on the volume and the mass measurements.

Samples	Mass (g)	Volume cm^3	Density (G/cm^3)
1	34	23.548	1.44
2	35	24.389	1.43
3	35	25.23	1.38
4	35	25.23	1.38
5	34	23.548	1.44
6	36	26.1	1.37

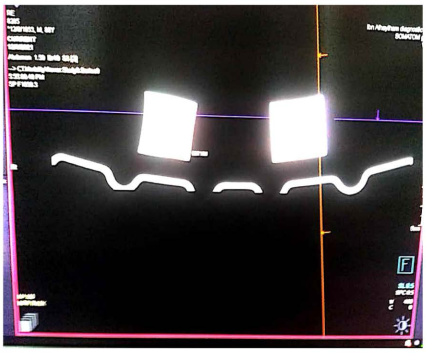
Average density was = (1.40 ± 0.03) g/cm^3.

Attenuation Coefficient Measurements:

Table 4. The value of the attenuation coefficients (Hounsfield value HU) for each sample.

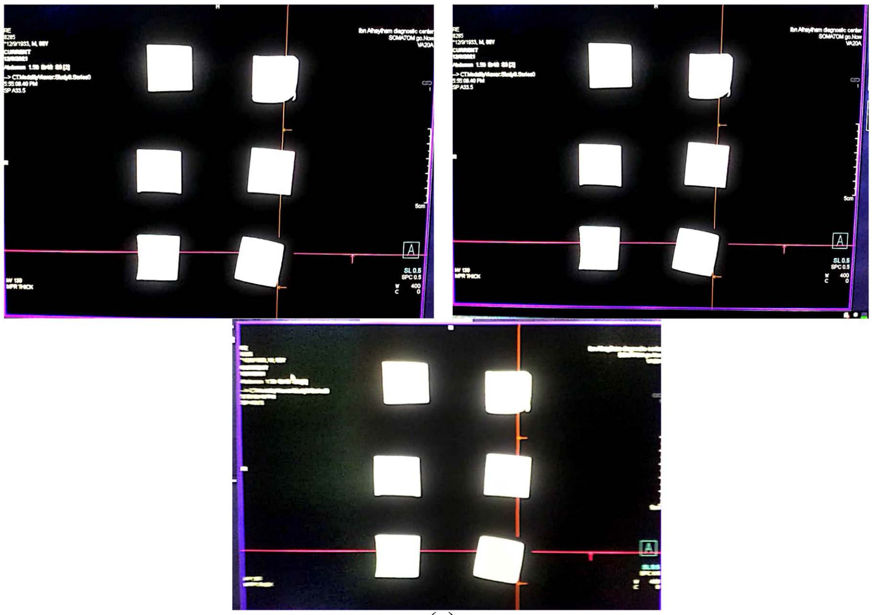
region of interest in CT image	samples 1 HU values	samples 2 HU values	samples 3 HU values	samples 4 HU values	samples 5 HU values	samples 6 HU values
1	841	666	685	699	679	690
2	867	672	694	667	665	688
3	775	705	675	689	685	684
4	856	668	667	698	694	678
5	779	688	671	694	688	695
6	827	655	644	665	686	689

The Image Quality Results Pictures for the Samples and Skeletal:



(a)

(b)



(c)

Figure 2. Images of the (Hounsfield value HU) during measurements: a) The attenuation coefficients for the first sample by drawing region of interest (ROI); b) The attenuation coefficients for the same sample with different region of interest (ROI); c) The appearance of all six samples in Computed tomography scanner during the attenuation coefficients measurements.

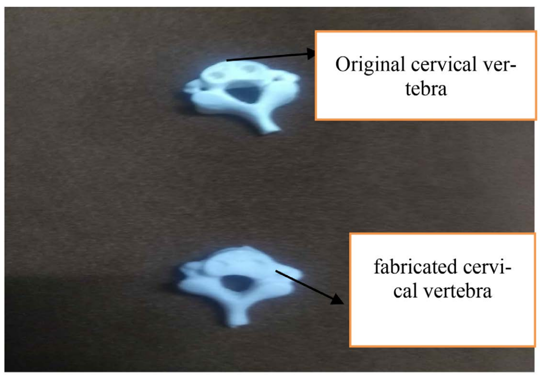


Figure 3. The shape of original cervical vertebrae and the fabricated vertebra.

Figure 4. The fabricated skeletal parts made with bone equivalent materials before the construction.

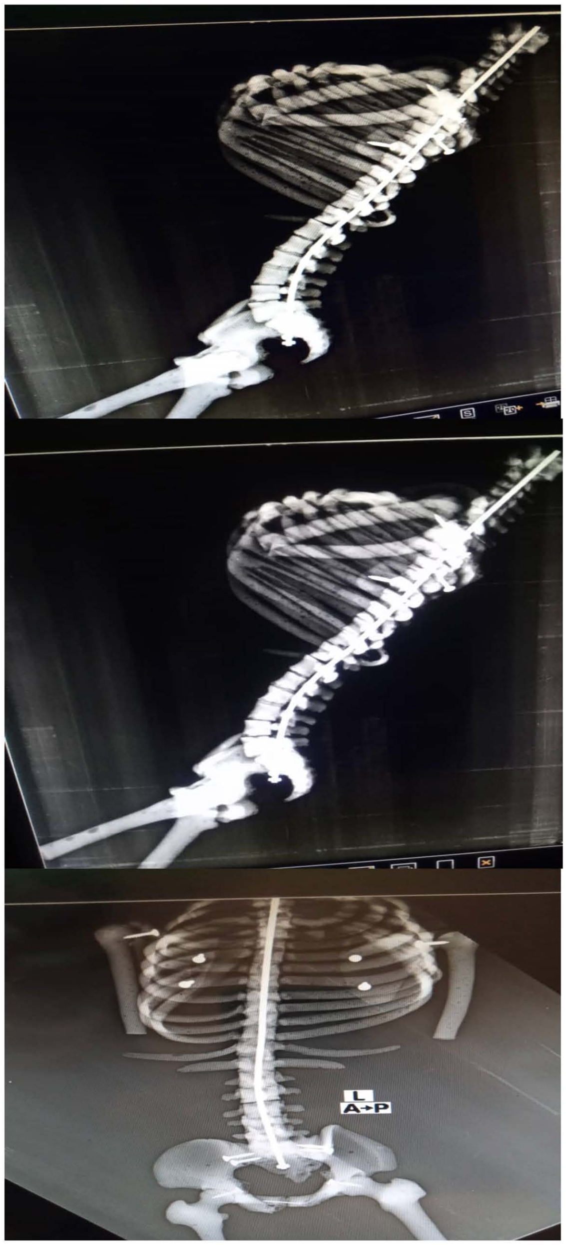


Figure 5. Group of images of skeletal after assembling using x-ray radiography unit.

4. Discussion

The particular interest of this publication is to fabricate skeletal that can be used in the manufacturing of anthropomorphic pediatric phantoms, where silicone rubber RTV (683) was utilized with $CaCO_3$ to simulate the physical properties of human bone under CT scan by testing the density and HU. Density was calculated by measuring the mass divided by volume. The resulting average density of the bone equivalent material is 1.44 g/cm^3 ("as shown in **Table 3**"). It was found that it falls in in the density range of bone (1.2 - 1.8 g/cm^3) [25]. So, the measurements of density were agreeing with reference level.

The CT scanners use HU to account for tissue in homogeneities within the human body [26]. The linear attenuation coefficient value or HU value in CT images of the bone equivalent material was measured from different position of the testing sample ("as shown in **Figure 2**") to confirm that the results are similar to that in reference level. The resulting HU is swinging in a range from (867 to 644) HU ("as summarized in **Table 4**"), which fall in the range of HU slandered value for bone which are (600 - 1000), Therefore the value of CT UH is passed the test and accepted.

There is an egret required to produce a cheap bone-equivalent material to be used in construction of pediatric phantoms. This study offers a new composition quantities and manufacturing methodology to prove the efficacy of the silicone rubber RTV with $CaCO_3$ as a bone-equivalent material. Which are cheap, easily to get, simple to handle with in making molds. This work also describes a new and simple way of manufacturing the skeletal with all its details illustrate clearly in the x-ray image as in human body. Strength and stability of the phantom material under repeated imaging depend on the radiation doses and radiation intensity, it can be used for many years in the case of law and moderate radiation dose quality control tests.

5. Conclusions

A new composition and methodology for designing skeletal part of pediatric phantom was successfully fabricated where Silicone rubber RTV (683) was used with $CaCO_3$ to fabricate bone equivalent material, which involves weighing of 50 g of silicon rubber RTV683, then mixed with 17 g of $CaCo_3$ and 2 ml of the catalyst can be used in low-cost manufacturing of CT phantoms for quality control and dosimetry studies purposes.

This work also describes a new and simple way of manufacturing the skeletal with all its details illustrated clearly in the x-ray image as in human body.

The methodology and the material used was passed the tests of the density and the attenuation coefficient measurements and achieved the required results, and when they compared with the slandered it was found that the density of the fabricated material (1.44 ± 0.03 g/cm^3) fall within the range of human bone tissue concentration which are (1.2 - 1.8) g/cm^3,the attenuation coefficients (HU) range from (644 up to 867 HU) on different CT images of bone equivalent materials also similar to that in reference level (400 - 1000 HU).

Most of the traditional phantoms that used in the quality control tests used CT slices in the construction of phantoms where the vertebrae of the skeletal and all its details may not be clearly observed. However, the model proposed offers to view the vertebrae of the spine and all the parts of the skeletal with all its details clearly with can help in the calculation of the doses inside human body (in vivo dosimetry).

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This dissertation is a reflection of my work as well as the combined efforts of all those who have influenced my academic and personal lives.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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