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Development of a head CT dose index (CTDI) phantom based on polyester resin and methyl ethyl ketone peroxide (MEKP): a preliminary study

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Abstract

This paper aims to develop phantoms for measurement of computed tomography dose index (CTDI) based on a polyester resin mixed with methyl ethyl ketone peroxide (MEKP) as catalyst. CT number and CTDI values of the polyester resin phantoms were compared with a standard polymethyl methacrylate (PMMA) phantom as reference. The percentage of MEKP was varied from 0.3 to 0.6 wt%. The polyester resin phantoms had diameter of 160 mm, length of 150 mm and five cylindrical holes with diameter of 13.5 mm. One hole was positioned at the centre of the phantom and the other four near its periphery, 10 mm from the edge. The results show that the CT number of the polyester resin phantom was about 1%–9% higher than that of the standard PMMA phantom. Among the polyester resin phantoms, the one with 0.3 wt% MEKP is closest to the standard PMMA phantom in terms of CT number. In addition, the difference in weighted CTDI value between the 0.3 wt% polyester resin phantom and the PMMA is less than 5%. Thus, the 0.3 wt% polyester resin is potentially used as an alternative to the standard PMMA, with the advantage of a lower cost.

Keywords: development, CT dose index, phantom, polyester, resin, methyl ethyl ketone peroxide

(Some figures may appear in colour only in the online journal)

1. Introduction

Computed tomography (CT) is a medical imaging modality that contributes widely in the world for the diagnosis of disease and for treatment planning in the radiotherapy department [1, 2]. The International Commission on Radiological Protection (ICRP) reported that CT examinations comprise about 10% of all radiological examinations [3]. It seems that the trend toward more frequent CT examinations will continue. The CT scanner is the first device to use an x-ray beam to produce cross-sectional images of the human body that depend on the attenuation coefficients within the scanned area [4, 5]. The CT scanner produces images of the scanned object slice by slice. The result of the x-ray attenuation map is converted into digital data known as CT number on the Hounsfield unit (HU) scale [6, 7]. The CT scanner provides more detailed images than other radiological devices [8].

Because the radiation beam comes from various angles, the dose of CT radiation received by the patient is high [9, 10]. The technique for characterising CT radiation dose is different from other radiological modalities. The dose from CT at every point inside the body is a combination of the dose produced by the primary beam from various angles and the scattered beam from other slices [11]. The entrance skin dose (ESD) does not comprehensively reflect the output dose of the CT scanner or the dose received by patients [12]. The CT dose index (CTDI) has been introduced to characterise the output dose [12, 13], and the size-specific dose estimate (SSDE) has been proposed to estimate the patient dose [1, 9]. Generally, the measurement of CTDI uses a pencil ion chamber with length of 100 mm and a specially designed phantom [14]. Since such diagnostic equipment delivers a high dose, the CTDI should be regularly measured as part of the quality control (CT) program [15, 16].

The phantom for CTDI measurement is specifically designed from equivalent tissue materials that simulate the human body [17]. The standard phantom widely used is made from polymethyl methacrylate (PMMA). The standard PMMA phantom has two diameters, one of 160 mm as a surrogate for the patient's head and one of 320 mm as a surrogate for the patient's body [18]. The PMMA phantom has a homogeneous composition and a cylindrical geometry of length 150 mm. The PMMA phantom has one hole in the center and four holes in the peripheral area. The phantom is extensively used in a clinical setting, protocol evaluation or research purposes [19]. However, the standard phantom might be very costly for many hospitals in developing countries, such as Indonesia. Thus, efforts to find an alternative cheaper material with similar results to the standard PMMA phantom are essential. An alternative material for the phantom has been developed previously [20]. Sookpeng *et al* used nylon as a material for head and body phantoms for CTDI measurements, and reported that the values of CT number are about 20 HU lower than those of the standard PMMA phantom [20]. In addition, nylon also reduced production costs to about one-fifth compared to the PMMA phantom [20].

Polyester resin is a widely used polymer. Its density is similar to that of human tissue, i.e. approximately 1.10–1.15 g cm^{-3} [21]. Additionally, polyester resin offers a combination of mechanical performance and cost-effectiveness. Some of the advantages of polyester resin are that it is non-toxic, insoluble, resistant to the absorption of water, transparent and effortless to manipulate without tangled equipment [22]. It is also cheaper and easier to obtain in developing countries. Polyester resin mixed with a certain catalyst may be effective for use as an alternative phantom. Up to now, polyester resin has not been proposed as a phantom material. Because of its potential application as an alternative phantom for CTDI measurement, it is necessary to develop and evaluate it. In this study, we developed a head phantom for CTDI measurement made from polyester resin mixed with methyl ethyl ketone peroxide (MEKP). MEKP is an organic peroxide used in the composites industry for polyester resin. It reacts with the resin to

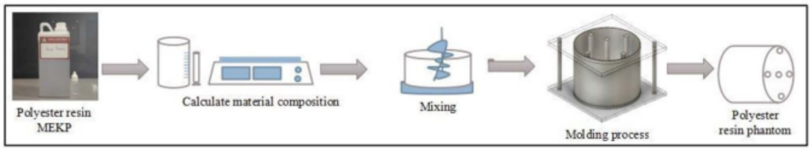

Figure 1. Schematic diagram of the phantom development.

turn it from a liquid to a solid as a catalyst. We varied the composition of the polyester resin and the MEKP to find an optimal composition. As preliminary study, we only evaluated the CT number and CTDI value in one CT scanner.

2. Materials and methods

2.1. Synthesis of the alternative head phantom

The standard head phantom for CTDI measurement was made from PMMA material. The phantom consisted of cylinders, one with a diameter of 160 mm to represent the human head. The length of the phantom was 150 mm. It had five cylindrical holes along the cylinders. One hole was positioned at the centre and the other four at the periphery, a distance of 10 mm from each edge of the phantom.

Alternative phantoms were developed. It was made from polyester resin mixed with MEKP and with the same shape and size as the standard PMMA phantom. Synthesis of polyester resin–MEKP was begun by mixing polyester resin with MEKP of various mass fractions (0.3, 0.4, 0.5 and 0.6 wt%). A schematic diagram of the experiment is depicted in figure 1. A sample was mixed and slowly stirred. The mixing process was completed in 3 min using a spatula. Afterwards, the resin was placed in cylindrical moulds (diameter of 170 mm) for several hours to dry at room temperature (27 °C). Thus, the range of drying time of polyester resin for each phantom was about 36 h. The polyester resin phantoms had been lathed to make small holes. Each phantom had five holes, one at the centre and four at the periphery. The inner diameter of the holes was 13.5 mm. The peripheral holes were located 10 mm from the edge of the phantom. The polyester phantoms were then lathed to turn down their diameters to 160 mm.

2.2. Evaluation of the developed head phantom

As a preliminary study, the developed phantoms were evaluated from their CT numbers and CTDI values.

The CT number was in HU units and indicated the linear attenuation coefficient of the material to the x-ray beam. Comparisons of the CT number between images of the standard PMMA phantom and the polyester resin phantoms with different materials were carried out. The phantoms were scanned using a Philips Brilliance 16 Slice CT scanner with parameters tabulated in table 1. All measurements were made in helical mode.

A circular region of interest (ROI) was used to obtain the average and standard deviation of the CT number. Five ROIs were drawn in the image of each phantom. One ROI was placed around the centre of the image of the head phantom and four ROIs were placed at edge positions close to each hole as shown in figure 2. After measuring the average and standard deviation

Table 1. Scan parameters of CT.

Parameter	Setting
Tube current	150 mA
Tube potential	120 kVp
Rotation time	1 s
Beam width	5 mm
Field of view	250 mm
Projection angle range	360°

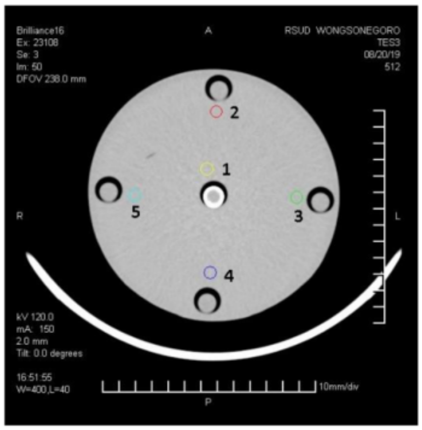

Figure 2. Positions of the ROIs inside the phantom. The number of pixels for each ROI was about 178, corresponding to an area of 42.4 mm^2.

of the CT number, the homogeneity of the CT number for each phantom was then calculated using equation (1) [23].

$$H = \left(1 - \frac{|HU_{\mathrm{max}} - HU_{\mathrm{min}}|}{HU_{\mathrm{min}}}\right) \times 100\%. \quad (1)$$

To evaluate CTDI values of the developed polyester resin phantoms, a CT dose profiler detector (RTI Electronic, Sweden) and Black Piranha electrometer (RTI Electronic, Sweden) were used [24]. The profile doses measured by the CT dose profiler were then integrated over 100 mm and divided by the beam collimation to obtain the CTDI value in each hole. The weighted CTDI ($\mathrm{CTDI_w}$) was calculated using equation (2):

$$CTDI_{\mathrm{w}} = \frac{1}{3} CTDI_{\mathrm{c}} + \frac{2}{3} \overline{CTDI_{\mathrm{p}}} \quad (2)$$

where $\mathrm{CTDI_c}$ is CTDI measured at the cental hole of the phantom and $\mathrm{CTDI_p}$ is the average value of CTDI at the peripheral holes.

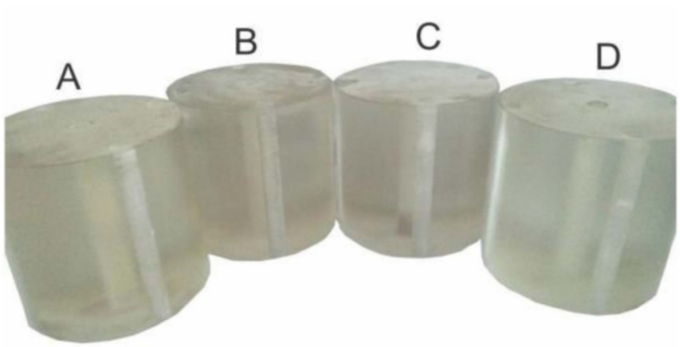

Figure 3. Polyester resin phantoms with various compositions: (A) 0.6 wt%, (B) 0.5 wt%, (C) 0.4 wt% and (D) 0.3 wt%.

Finally, *k*-factors were computed by a comparison between $CTDI_w$ measured using the standard PMMA phantom ($CTDI_{w,PMMA}$) and the polyester resin phantom ($CTDI_{w,PR}$).

$$k = \frac{CTDI_{w,PMMA}}{CTDI_{w,PR}} \tag{3}$$

Multiplying this *k*-factor by the $CTDI_w$ value measured with the polyester resin will produce the $CTDI_w$ value as measured using the standard PMMA phantom.

3. Results

Head phantoms for CTDI measurement with various mass fractions have been successfully synthesised. A photograph of the polyester resin phantoms is shown in figure 3. Air bubbles are only found at surface of the 0.5 wt% polyester resin phantom. This occurs because of imperfect stirring and environmental factors during the printing process. However, visual observation shows that all phantoms have a homogeneous structure.

The CT numbers and their standard deviations of the polyester resin phantoms with various mass fractions (0.3, 0.4, 0.5 and 0.6 wt%) are tabulated in table 2. Comparisons of the average values of the CT number between the polyester resin phantoms and the standard PMMA phantom are shown in figure 4. This shows that all CT numbers measured in the polyester resin phantoms are slightly higher (up to 6%) than those in the standard PMMA phantom. The differences in CT number are less than 10 HU. The standard deviations of each phantom are comparable, being slightly higher in the polyester resin phantom than in the standard PMMA phantom. The standard deviation represents the image noise.

The CT numbers measured in the centre are slightly higher than those at the periphery for each polyester resin phantom. This is because the effective energy of an x-ray in the centre of the phantom is slightly different than at the periphery. This is caused by the beam hardening phenomenon. Thus, the radiation reaching the centre of the phantom has a mean energy greater than at the periphery because the low energy is attenuated in the periphery of the phantom. To investigate the extent of the difference in average HU values between the polyester resin and the standard PMMA phantoms, a statistical test was conducted. Based on the graph and

Table 2. Values of the CT number measured in ROIs at five positions.

Type of phantom	Mean pixel value (HU) ± Standard deviation (HU)					Homogeneity (%)	*P*-value
	ROI 1 (center)	ROI 2 (top)	ROI 3 (right)	ROI 4 (bottom)	ROI 5 (left)		
PMMA	133 ± 4.6	133 ± 2.7	132 ± 3.2	131 ± 4.2	131 ± 3.7	83.82	–
Polyester resin–MEKP							
0.6 wt%	139 ± 6.5	136 ± 4.4	136 ± 4.6	136 ± 6.0	136 ± 4.4	78.61	<0.001
0.5 wt%	142 ± 6.0	135 ± 4.0	135 ± 5.4	135 ± 5.7	135 ± 4.9	76.28	0.032
0.4 wt%	140 ± 6.3	133 ± 5.5	134 ± 4.1	135 ± 4.1	136 ± 4.8	79.38	0.038
0.3 wt%	141 ± 6.4	134 ± 5.3	134 ± 4.3	134 ± 5.2	135 ± 4.8	79.87	0.055

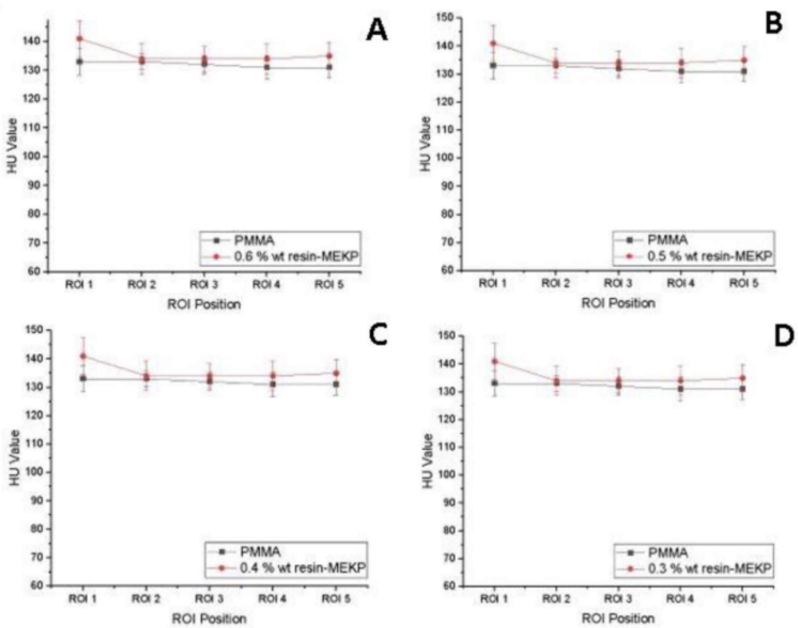

Figure 4. Values of the CT number of the polyester resin phantom for each composition compared to a standard PMMA phantom: (A) 0.6 wt%, (B) 0.5 wt%, (C) 0.4 wt% and (D) 0.3 wt%.

statistical analysis, it seems that the polyester resin phantom with 0.3 wt% MEKP is closest to the standard PMMA phantom.

The homogeneities of CT number in the polyester resin and the standard PMMA phantoms are shown in table 2. The homogeneities of the polyester resin phantoms are slightly lower than those of the standard PMMA phantom, but the differences are insignificant. The highest homogeneity is in the standard PMMA phantom (83.8%). Among the polyester resin phantoms, the one with 0.3 wt% has the highest homogeneity, approximately 80%.

The values of CTDI at the centre and periphery and the weighted CTDI for all phantoms are shown in table 3 together with *k*-factors for all polyester resins. In general, all doses measured in the polyester resin were slightly higher than those in the standard PMMA phantom. Based on statistical analysis, the phantom with 0.3 wt% polyester resin was comparable to the standard PMMA phantom.

4. Discussions

This work has developed an alternative phantom for CTDI measurement based on a polyester resin with MEKP as catalyst. Polyester resin is transparent, so it easy to observe inside the material during its synthesis. In addition, this material is chosen because of its simple synthesising process, and it has supportive properties such as being non-toxic, insoluble and effortless

Table 3. CTDI values for all phantoms and *k*-factors for all polyester resin phantoms.

Type of Phantom	$CTDI_c$ (mGy)	$CTDI_p$ (mGy)	$CTDI_w$ (mGy)	*k*-factor
PMMA	26.14	25.40	25.65	–
Polyester resin–MEKP				
0.6 wt%	27.74	27.64	27.67	0.927
0.5 wt%	26.97	27.36	27.23	0.942
0.4 wt%	27.95	27.70	27.78	0.923
0.3 wt%	26.60	27.00	26.87	0.955

to combine with other materials. Another material that had been used as an alternative for the phantom for CTDI measurement was nylon. This material reduced the production cost to about one-fifth of that of the standard PMMA phantom. The results demonstrated that the CT number of the nylon phantom was 20 HU lower than that of the standard PMMA phantom [20], yet the findings of this study have provided convincing results.

In the current study, the developed polyester resin phantoms were evaluated. The results for theaverage CT number, its standard deviation and its homogeneity obtained in the polyester resin phantom for each variation were compared to the standard PMMA phantom. It is found that the polyester resin phantoms are homogeneous. This could be visually observed from the absence of formed air bubbles, because the polyester resin material is transparent and so one can easily observe if bubbles exist.

In the five ROIs, the CT number was higher in the central position for each mass fraction than at the other positions. The CT numbers for the polyester resin phantoms were in the range 130–140 HU. Hence, the differences in CT number measured between the polyester resin and the standard PMMA phantom were less than 10 HU. This indicated that the polyester resin is more suitable than nylon as an alternative phantom [20].

To evaluate the difference of each mass fraction of the phantom composition, an independent *t*-test was carried out from the normalised test results. The 0.3 wt% polyester resin phantom showed p-value > 0.05. This means that the difference in CT number between that phantom and the standard PMMA phantom was not significant. It was also found that the value of $CTDI_w$ measured in the polyester resin phantom was within 5% of that measured in the standard PMMA phantom. These small differences in $CTDI_w$ values are caused by the small change in attenuation of the polyester resin material. By multiplying the *k*-factor (table 3) and the $CTDI_w$ values measured using the polyester resin, the $CTDI_w$ value will become similar to that measured using the standard PMMA phantom.

It seems that a phantom made from the polyester resin can be used for further studies as an alternative material. The polyester resin was chosen since the phantom could be produced with lower cost. Its price is approximately $2–5/kg, whereas the price of PMMA has reached $8/kg. A standard phantom made of PMMA costs more than $1000. In addition, the advantage of the polyester resin is itssynthesis was simple and it is effortless to combine without tangled equipment. Therefore, it is possible for hospitals that do not yet have the standard PMMA phantom to synthesise it by themselves.

As a preliminary study, the evaluation was limited to only one CT scanner, one tube voltage and one slice thickness. For more comprehensive evaluation, CTDI values and CT number of the polyester resin phantoms should be measured and compared with the standard PMMA phantom in many CT scanners with various input parameters. The details of dose will be evaluated in a future study. It should be noted that our preliminary study was also limited to synthesis of the head phantom for CTDI measurement. Further study on development of the body phantom and also phantoms with various diameters for evaluation of size-specific dose estimate (SSDE) will be conducted. The SSDE is the patient dose indicator taking into account of both output dose and the patient characteristics [9, 25].

5. Conclusions

A head phantom for CTDI measurement based on a polyester resin material and MEKP with various compositions (i.e. 0.3–0.6 wt%) was successfully synthesised and evaluated. Comparisons of CT numbers measured in the polyester resin phantoms and in the standard PMMA phantom in each different composition showed that the CT numbers of the polyester resin were 1%–9% higher than those in PMMA phantom. A p-value > 0.05 between the standard PMMA phantom and the polyester resin phantoms was achieved in the 0.3 wt% polyester resin phantom. In addition, the $CTDI_w$ value of 0.3 wt% polyester resin was also relatively similar to the PMMA phantom. Its difference was less than 5%. This finding revealed that the 0.3 wt% polyester resin could be used as the phantom material for CTDI measurement. It might be considered as an alternative phantom for hospitals that do not own the standard PMMA phantom. One advantage of the polyester resin phantom is its lower cost.

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