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Original Article

Investigation of the suitability of new developed epoxy based-phantom for child's tissue equivalency in paediatric radiology

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ABSTRACT

In this study, tissue equivalency (TE) of a newly developed epoxy-based phantom to 3–5 years child's tissue was investigated in paediatric energy range. Epoxy-based TE-phantoms were produced at different glandular/adipose (G/A) ratios of 17/83%, 31/69%, 36/64% and 10/90%. A procedure was developed in which specific amounts of boron, calcium, magnesium, sulphur compounds are mixed with epoxy resin, together with other minor substitutes. In paediatric energy range of 40–60 kV_p half-value layer (HVL) values were measured and then Hounsfield Units (HU) were determined from Computed Tomography(CT) scans taken in the X-ray energy range of 80-120kV_p. It is found that radiation absorption properties of these phantoms in terms of the measured HVL values related to linear attenuation coefficients (μ) are very well mimicking a 3 years child's soft tissue in case a ratio of 10/90%G/A. Additionally, the HU values of phantoms were determined from the CT scans. The HU = 47.8 ± 4.8 value was found for the epoxy-based phantom produced at a ratio of 10/90%G/A. The obtained HVL and HU values also support the suitability of the new epoxy based-phantom produced at a ratio of 10/90%G/A for a satisfactory mimicking a 3 years child's soft tissue by 5%. Thus they can have a potential use to perform the quality controls of medical X-ray systems and dose optimization studies.

1. Introduction

For years, in medicine, ionizing radiation is used in paediatric radiology for diagnostic purposes such as imaging of fetuses, babies, children's and adolescents. Children must be kept away from ionizing radiations effects more than adults because, their cells with higher mitosis rate are more vulnerable to ionizing radiations effects and they have more time in their lifespan to be cancer. Therefore, it is important to evaluate radiation protection of the children and adolescents different from adults, as their tissues' radiation absorption properties are not the same.

The phantoms representing the patient are used in experimental dose measurements to determine the optimum radiation dose on medical imaging. Ideally, in view of absorbing radiation doses, the phantoms should be almost identical with the patient's tissues. Water is commonly adopted as tissue equivalent material in X-ray examinations. Although there are also commercially available phantoms, the new phantoms having different designs for new research purposes are still being developed [6,14]. In recent times, a low cost paediatric pelvis phantom based on the anatomy of a 5-year-old child is developed, and thus some findings are obtained through CT density comparison between the developed phantom and a 5 years child's tissue. Additionally, the phantoms are developed for optimization of paediatric chest and skull radiographs [2]. In this context, epoxy resin based tissue substitutes are also studied for years [18]. This study is limited to only paediatric energy range whether this new phantom can provide a satisfactory mimicking with the radiosensitivity properties of child's soft tissue because tissue equivalency of a phantom depends on not only radiation absorption properties of material but also relates to radiation beam quality.

The purpose of this study is to investigate the suitability of a newly developed epoxy-based tissue equivalent (TE)-phantom material to mimic a 3–5 year child's soft tissue. To achieve this, epoxy based solid TE-phantoms were produced at different glandular/adipose (G/A) ratios by means of simple, inexpensive laboratory equipment and techniques. The mean energy of the produced x-ray beam is measured by a CdTe spectroscopy system. In paediatric range of 40–60 kV_p, the produced phantoms are characterized in terms of half value laver HVL (cm) relating to linear attenuation coefficient, $\mu(cm^{-1})$ to quantify their satisfactory

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mimicking with a child's soft tissue. Additionally, Hounsfield Unit (HU) values representing the radiosensitivity are determined from Computed Tomography (CT) scans in the range of 80–120 kV_p for the characterization of the newly developed tissue equivalent phantom.

2. Materials and methods

2.1. X-ray device and measuring instruments

Dose measurements were performed in a complete X-ray calibration system installed on radiometric bench. As seen in Fig. 1, it consists of a 50 kW Italray Pixel HF Generator and a Varian RAD-21 x-ray tube assembly (Its focal spot size:0.6–1.2 mm, Tungsten anode, anode angle:12°) and a GiCi-PM-2000 High Voltage Divider (Greenwich Instrum. Corp.). It has two operation modes: radiography (40–150 kV_p voltage and 25–600 mA current) and fluoroscopy (40–125 kV_p voltage and 0.5–6 mA current). The used detector is a spherical ion chamber having a 27.9 cm^3 vented sensitive volume PTW (Type TM32005) certified by PTW(Germany) [15]. Its energy dependence is below %5 between 48 keV and 1.3 MeV. This ~28 cm^3 ion chamber was calibrated together with an UNIDOS Webline electrometer (T10021-0294) using ISO N beam qualities corrected by the factors, $k_Q = 0.960–1.000$ with a 2.5% uncertainty (PTW calibration certificate Nr. 0606295, traceable to PTB).

X-ray spectra were acquired with a XR-100T model CdTe semiconductor detector (Amptek, USA), associated with a PX4 digital pulse processor [3]. The detector is a 25 mm^2 area x 1 mm thick CdTe diode with a 100 μm thick Be window, built-in a preamplifier and a Peltier cooler for cooling its FET. Its measured energy resolution is FWHM = 1.3 keV@122 keV and FWHM = 0.38 keV@14.41 keV γ-rays of ^{57}Co.

2.2. Characterization of RQR and RQA standard beam qualities in paediatric radiology

The X-ray beams used for conventional radiograph (CR) and computed tomography (CT) applications must supply RQR and RQA beam qualities according to EN-IEC 61267 protocol [4,9]. RQR and RQA beams are characterized by the first and second HVLs, depending on additional filtration and thus beam homogeneity factor(h) is determined as an another characterizing parameter.

The adjusted tube voltage was checked through a voltage divider and the indicated values were observed on a scope. The resulted differences in measured voltages are given in Table 1, and they are quite better than those (with an uncertainty of 1.5% or 1.5 kV at k = 2 coverage factor) for practical peak voltages specified in EN IEC 61267 standard [9]. For the presently used x-ray assembly, the inherent (permanent) filtration is measured at 60 kVp at a 100 cm distance according to the reference beam characterization procedure [10,19]. The inherent filtration is determined to be 1.45 mmAl. The output dose rates of the present X-ray device setup are measured with a monitor chamber to check the repeatability of the output dose rates. Exposures were performed perpendicular to the central axis of the beam at 0° angle, in a field size of at least 10 × 10 cm^2 where positioned at the centre of the chamber volume. After waiting a warming up time and zeroing the values of the electrometer, X-ray exposures are read in free-air kerma rate (mGy/h) and the doses (mGy) are indicated at a given, pre-defined mAs values. The irradiations are repeated at three times while measuring a ~28 cm^3 PTW ion chamber.

In this setup, the distance from focal spot to collimator and filter is kept at minimum to prevent beam scattering and the geometrical condition is set at a distance of 100 cm because the minimum source-to-detector distance between the focal point of X-ray tube and the detector surface must be ≥ 55 cm for achieving standardized radiation qualities [9]. The obtained RQR beam qualities are given Table 1, together with IEC requirements for first HVLs and homogeneity coefficients. The required Al filter thickness is determined for RQR beam qualities. Similarly, for simulating a child patient, one needs to achieve RQA beam qualities by adding Aluminium filters which represents phantom according to the IEC protocol [9]. The measured characteristics of the obtained RQA beam qualities are given in Table 2. The measured HVL values show that the beam requirements of EN IEC 61267 standard [9] are fully met within the experimental deviations of 0.45–1.85%.

2.3. Production of epoxy based tissue equivalent phantoms

Since we aimed to produce a new tissue equivalent (TE) phantom mimicking a child's tissue aged 3–5 years for use in paediatric applications, a special procedure was developed in which the amounts of boron, calcium, sulphur compounds are determined using a computational algorithm. The tissue equivalency of the developed mixtures for adipose and glandular agree well with those of ICRU-44 tissues [8] within 90–95%. Then they are mixed gently with a liquid form of epoxy resin and its hardener, together with other very small amounts of phenolic microspheres by means of a mechanical stirrer rod at a given rotation of 70–80 rpm. For solidification, they were waited in silicon moulds for 48 h at a normal room temperature conditions. As shown in Fig. 2, the present phantoms based on epoxy matrix were produced at the different ratios of 17/83%G/A, 31/69 %G/A, 36/64%G/A and 10/90%G/A, respectively. To mimic paediatric soft tissue closer, it was necessary for phantoms to have lower physical density. For this reason, the special epoxy resin and its hardener was chosen and their mixing ratio was proprietarily adjusted by increasing its phenolic ingredient, and thus a much lower physical density ($\rho \approx 1.02$ g/cm^3) was obtained for 10/90%G/A epoxy based-phantom. After the phantoms have gained enough rigidity in a few, they a days, they are ready for further analyses and to use in radiological tests. The elemental composition of custom epoxy resin was analysed for H, C, S elements by LECO CHNS 932

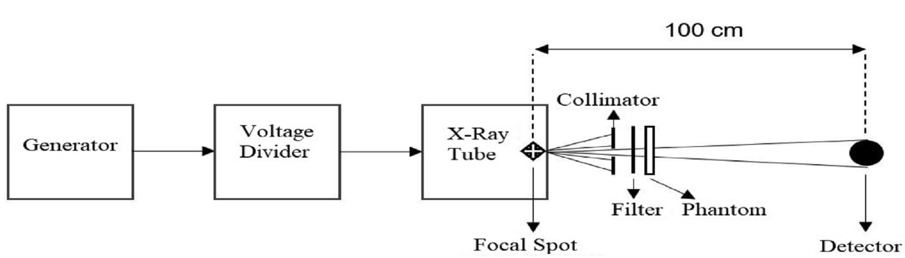


Fig. 1. A schematic diagram of X-ray beams for obtaining RQR and RQA beam qualities and HVL measurement of phantoms for use in paediatric radiology.

Table 1
The properties of the obtained RQR x-ray beam qualities for use in medical pediatric energy range.

Standard Radiation Quality[a]	X-ray Tube Voltage[b] (kVp)	Measured Tube Voltage Difference (Volt)	The used Al Filter Thickness[c] (mm Al)	IEC First HVL Value (mm Al)	Measured HVL Value (mm Al)	IEC Homogeneity Coefficient (h)	Measured Homogeneity Coefficient (h)	The percentage difference in homogeneity Coefficient (%)
RQR2	40	0	0.5	1.42	1.42	0.81	0.80	−1.2
RQR3	50	0.80	0.5	1.78	1.76	0.76	0.76	0
RQR4	60	1.33	0.5	2.19	2.21	0.74	0.68	−8.1

[a] As specified in EN IEC 61267 standard protocol.
[b] Voltages are measured by a voltage divider (GiCi-PM Dynalyzer, Model 2000 High Voltage Divider with a dividing ratio of 10000:1 or 1000:1 and a impedance of 1 MΩ or 10 MΩ) using a using a fast digital oscilloscope (LeCroy, Model 62xi, 600 MHz frequency and 10 GS/s max. sampling rate).
[c] The stated total filtration also includes the measured inherent (permanent) filtration of 1.45 mm Al, where the purity of the filters used are at least 99.5% which is nearly complying with the requirement of EN IEC 61267 standard protocol.

Table 2
The properties of RQA beam qualities representing the patient for use in paediatric energy range.

Standard Beam Quality	Tube Voltage (kVp)	Measured Tube Voltage Difference (Volt)	IEC Additional Filter Thickness (mm Al)[a]	Used Al Filter Thickness[b] (mm)	IEC HVL Value (mm Al)	Measured HVL Value (mm Al)	The Percentage Difference in HVL values (%)
RQA2	40	0	4	4	2.2	2.21	+0.45
RQA3	50	0.80	10	10	3.8	3.87	+1.84
RQA4	60	1.33	16	16	5.4	5.50	+1.85

[a] As specified in EN IEC 61267 standard protocol.
[b] The purity of Aluminum filter is at least 99.5% which is nearly complying with the requirement of 99.9% of EN IEC 61267 standard protocol.

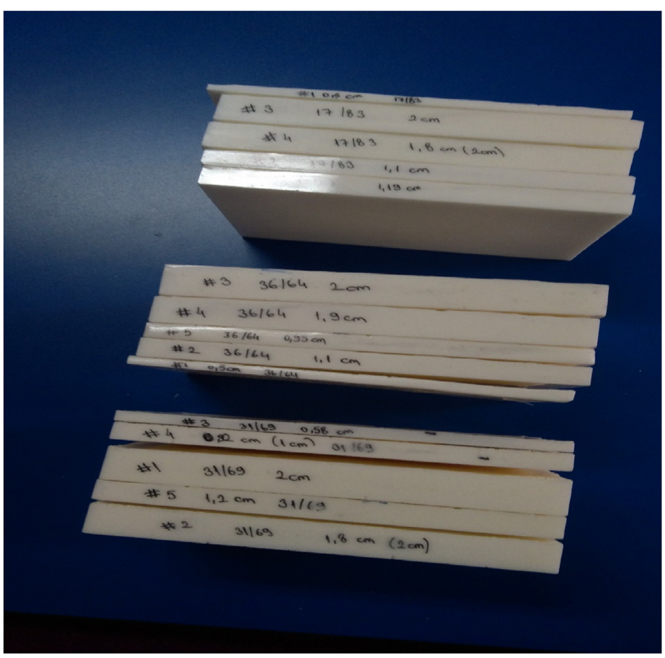


Fig. 2. Examples of epoxy based slab phantoms produced at different glandular/adipose (G/A) ratios [20].

elemental analyzer and the other elements were analysed by EVO-40 SEM-EDX analysis system in Middle East Technical University (Ankara). The elemental composition of epoxy is determined to be 68.25%C, 14.67%O, 7.91%H, 4.56%N, 1.11%Ca, 1.48%Cl, 0.456%Zn and 1.56%Si in weight. Its effective atomic number is calculated to be $Z_{eff} \cong 6.1$. The densities of the produced solid epoxy phantoms were determined to be 1.16 g/cm^3 for 17/83%G/A, 31/69 %G/A, 36/64%G/A phantoms and 1.02 g/cm^3 for 10/90%G/A phantom by using a RADWAG density measuring kit (PS 1000.R2 Model) with an accuracy of 0.001 g, where small pieces of phantom are immersed in ethyl-alcohol and pure water, respectively. The thicknesses of the phantoms were measured by use of a Vernier calliper (precision:+0.01 mm) and a micrometer screw gauge (within 0–25 mm, precision:+0.001 mm), respectively. The produced phantoms are normally in rigid form, however a Vernier calliper or a digital micrometer are used very gently its thimble screw and fixed with the help of its ratchet-stop. The thickness measurements of the phantoms are made from at least three to five different points on phantoms and hence the mean thickness values are reported together with their standard deviations in Table 3, thus resulting in an quantitative knowledge on thickness variation for any slab phantom. The other physical parameters of the produced phantoms such as durability, colorization, resistance to breakage, tensile strength, etc are reported in our TÜBİTAK 115S108 research project final report [20]. Depending on the different G/A ratios, the densities of produced solid phantoms and their thicknesses given in Table 3 are reported with the uncertainties at the confidence level of 95%.

2.4. Determination of HVL values of the phantoms by using a CdTe X-ray spectroscopy technique

The developed epoxy based phantoms were characterized in terms of μ and HVL corresponding to mean photon energy, and HU values. Alternatively, a radiation field can be specified by using X-ray spectroscopic method [5,9] because the spectral distribution of the photon fluence is nearly equal to pulse height spectrum. In this study, it aimed to determine μ and HVL by using x-ray spectra. This is because the HVL value of any material is directly related the attenuation coefficient $\mu(\overline{E})$, i.e., $HVL = \ln 2/\mu(\overline{E})$ at any beam quality, it explicitly requires to be known spectrum average (mean) energy, $\overline{E}$ (keV). In our case, we used RQA beams representing patient, i.e. each beam corresponds to a continuous, filtered radiation field (Bremsstrahlung radiation), so that the average spectrum energy can be determined at the given radiation conditions. Thus the mean photon energies for RQA paediatric beam qualities were determined from the X-ray spectra collected by CdTe detector with a 1.5 inch EXVC Collimator Kit (Amptek, USA) in which 2 mm thick tungsten disks (400 μm and 1000 μm are used to collimate the primary X-ray beam under high photon flux. The energy calibration of CdTe detector was performed by using the point sources of

Table 3
Physical densities and their thicknesses of the produced solid phantoms for different Glandular/Adipose ratios.

Epoxy based phantom	Depending on Glandular/Adipose (G/A) ratio			
	G/A, 10/90%[a]	G/A, 17/83%	G/A, 31/69%	G/A, 36/64%
Mean physical densities (g/cm^3)	1.02 ± 0.01	1.16 ± 0.01	1.16 ± 0.01	1.16 ± .01
Thicknesses of the phantoms[b] (cm)	0.67 ± 0.02;	0.54 ± 0.02;	0.60 ± 0.02;	0.55 ± 0.02;
	1.41 ± 0.02;	1.22 ± 0.02;	0.97 ± 0.02;	1.00 ± 0.02;
	2.08 ± 0.04;	1.23 ± 0.02;	1.26 ± 0.02;	1.21 ± 0.02;
	2.80 ± 0.04;	1.81 ± 0.02;	1.71 ± 0.02;	1.77 ± 0.02;
	3.47 ± 0.06	1.97 ± 0.02;	2.00 ± 0.02;	2.10 ± 0.02;
		2.51 ± 0.04;	2.60 ± 0.04;	2.65 ± 0.04;
		3.19 ± 0.04;	2.97 ± 0.04;	3.10 ± 0.04;
		3.78 ± 0.04	3.26 ± 0.04	3.31 ± 0.04

[a] It is found to be most suitable phantom in terms of glandular/adipose ratio used for use in paediatric energy range.
[b] Different thickness combinations of the phantoms are used in HVL measurements to provide the thicker phantom material in irradiations. Here the reported thickness uncertainties are standard deviation from the mean value from several thickness measurement from the different regions of the slab surfaces by using an electronic digital micrometer (its resolution:0.001 mm in the thickness measuring rage:25 mm) or a caliper Vernier with a 0.01 mm precision.

14.41 keV (^{57}Co), 59.54 keV (^{241}Am), 88.03 (^{109}Cd), and 122.06 keV (^{57}Co) γ-ray energies as follows:

$$E(\mathrm{keV}) = 0.309 + 0.194\cdot x_i\text{-}1{,}993\mathrm{x}10^{-7}\cdot x_i{}^{2} \quad (1)$$

where, x_i is channel number and E is the energy corresponding to channel, x_i. The energy response of the present CdTe detector is almost linear up to ≈200 keV. The deviation from its linearity is only 0,1 keV at 1024th channel. Thus, the present x-ray spectrometer with a CdTe detector was set up to acquire the x-ray spectrum data in 1024 spectral channels with an amplifier gain of k = 0.194 keV/channel, thus covering up to exactly ≈198.7 keV. The CdTe x-ray detector is mounted in an EXCV collimator having Tungsten discs which have holes to collimate the primary x-ray beams to the detector window. Then, the x-ray spectra were acquired through Amptek ADMCA 2.0 software at 40, 50 and 60 kV_p tube voltages at a defined total filtration. The average spectrum energy, $\overline{E}$(keV) of the measured spectrum is calculated as follows:

$$\overline{E}(keV) = k \times \frac{\sum_{1=1}^{n} x_i \cdot C_i}{\sum_{i=1}^{n} C_i} \quad (2)$$

where k is energy calibration constant (keV/channel), x_i is channel number (i = 1 … 1024) and C_i the counts at ith channel.

An example of the measured x-ray spectrum at 60 kV_p and 10 mAs irradiation condition at a given distance of 100 cm is shown in Fig. 3. Thus, this X-ray spectrometer with a CdTe detector is firstly used to measure energy spectrum of RQA2, RQA3 and RQA4 beam qualities and then used for the characterization of the epoxy based-phantoms, so that the results for HVL and μ were evaluated to decide whether a phantom meets a satisfactory mimicking to the equivalency of child's tissue.

Fig. 3. A CdTe detector for x-ray spectroscopy on the radiometric bench (The detector side is in a tungsten EXCV collimator from Amptek Inc).

2.5. Measurement of the HVL values of the phantoms by ion chamber

As described in Section 2.2, RQA standard beam qualities were employed for irradiation of the produced epoxy based phantoms. From 40kV_p to 60kV_p with increasing a voltage step of 5 kV, the phantoms are placed in front of primary x-ray beam with increasing their slab phantom thicknesses, as shown in Fig. 1. Then, the dose values (in free air kerma, K_a) were measured by a 28 cm^3 PTW calibrated ion chamber with an UNIDOS Webline electrometer at a predefined radiation conditions (mAs, distance, etc).

2.6. Determination of HU values of phantoms from CT scans

In this step, the produced epoxy phantoms were scanned in a X-ray CT system to determine HU values. The CT device is a Siemens Definition Flash Straton MX-P model which has 70, 80, 100, 120, 140 kV steps, 2 × 100kW generator, 2xSteallar Detector, 2x128Slices) installed in Eskişehir Osmangazi University Oncology Department. In case of CT applications, the tube voltages of up to 120 kVp can be used for pediatric radiology. In this work, the CT images of phantoms are taken at 80, 100 and 120 kVp voltages to investigate the suitability of the produced phantoms for CT applications. The HU values of the phantoms are determined from analyses of scans through image evaluation programs.

3. Results and discussion

3.1. Physical properties of obtained RQR and RQA paediatric beam qualities

The accuracy of the parameters related to the studied phantom requires using a proper geometrical setup of X-ray assembly to obtain medical X-ray beams stipulated by standard protocols. As given in Table 1, the RQR standardized beam qualities are obtained with good agreement of those IEC protocols by 1.2%–8.1% in terms of the percentage differences between those in beam homogeneity coefficients. Thus, each of RQA beam qualities, is sufficiently filtered and continuous X-ray radiation field for representing a child or young adult patient irradiation in paediatric range. As seen in Table 2, the obtained RQA beams meet very well the requirements

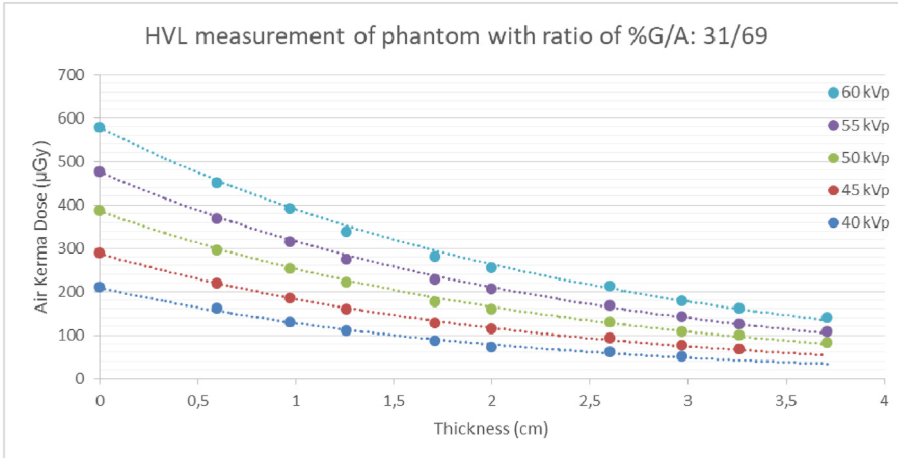


Fig. 4. An example of air kerma measurements with increasing phantom thickness for determination HVL values at different x-ray beam energies for the epoxy based slab phantoms with a 31/69% Glandular/Adipose (G/A) ratio.

stipulated by IEC 61267 protocol when we compared the measured HVL values with those HVL values required by IEC protocol by 0.45–1.85%.

3.2. Measured HVL values of epoxy based phantoms

As an example is shown in Fig. 4, the HVL values are determined by plotting the attenuation curve $f(x) = \log_e(K_{a,x})$ where $K_{a,x}$ is the value of the air kerma which is transmitted through a studied phantom having a thickness, x. In dose measurements, the required correction factor (p-T) was applied to any variation in PTW ion chamber response (K_a) due to possible changes in measured air pressure (p = 1013-1015 hPa) and temperature (T = 23.2–23.4 °C), but the effect of humidity factor is very negligible for a 100 cm thick air layer at relative humidity (26–39%) measured in room. The dose measurements were repeated at least three times at each slab thickness, thus resulted in low variation coefficients by 0.1–0.5% from their mean values. From the attenuation curves at different tube voltages of 40–60 kVp, the measured HVL values of the produced phantoms are given in Table 4. The uncertainties in HVL values are estimated to be 5.3–7.6%, The uncertainty components are due to tube voltage stability of 1.6–2.2% during irradiation sessions, the purity of filtration material (Al) of 0.5%, the variation of mean filter thickness of 0.5–1%, variation of mean phantom thicknesses of 0.1–0.2%, deviation of 0.5–1% from the fixed distances, scattered radiation of less than 0.1%, and other systematic ones of 5–6%. As shown in Fig. 5, HVL values of the phantoms are increased with increasing beam energies. In paediatric energy range, the HVL values are measured to be between 1.63 cm and 2.01 cm for the phantom produced at a 10/90%G/A ratio. As seen in Table 4, when adipose tissue ratio is increased, the resulted HVL value is increasing. Thus the produced phantom approaches relatively to the soft tissue of a child. This means that the produced phantom is more mimicking with the a child's tissue in terms of HVL (i.e., relating to photon linear attenuation coefficient, $\mu(cm^{-1})$).

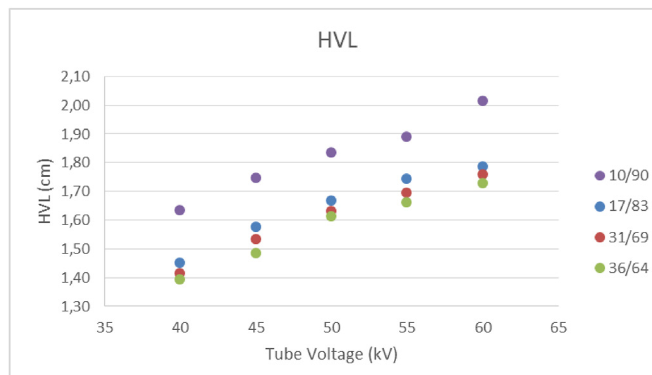


Fig. 5. A variation of HVL values of epoxy based tissue equivalent -phantoms produced at different G/A% ratios in paediatric energy range by using RQA beam qualities.

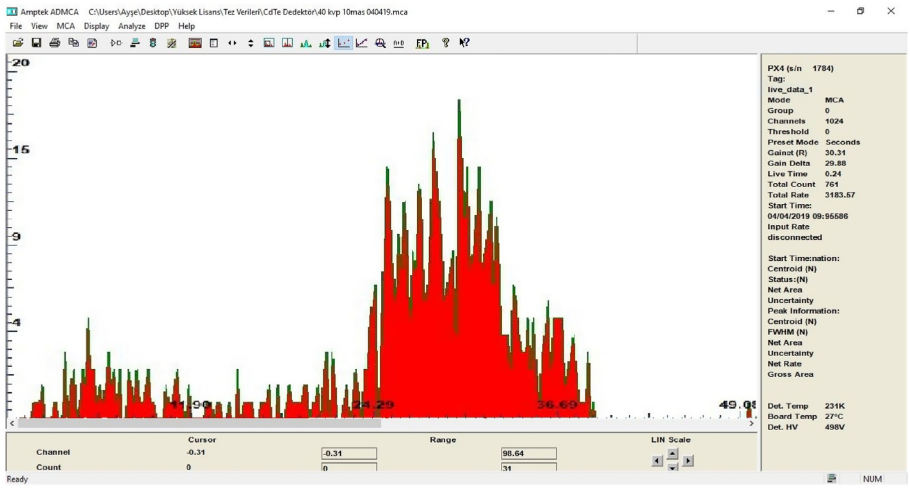
3.3. Determination of Hounsfield Units(HU) of the phantoms from their linear attenuation coefficients

In pediatric energy range of 40–60 kVp, the pulse height spectra are obtained by a 25 mm^2 CdTe detector by the irradiation of RQA X-ray beams as described in Section 2.4. The examples of X-ray

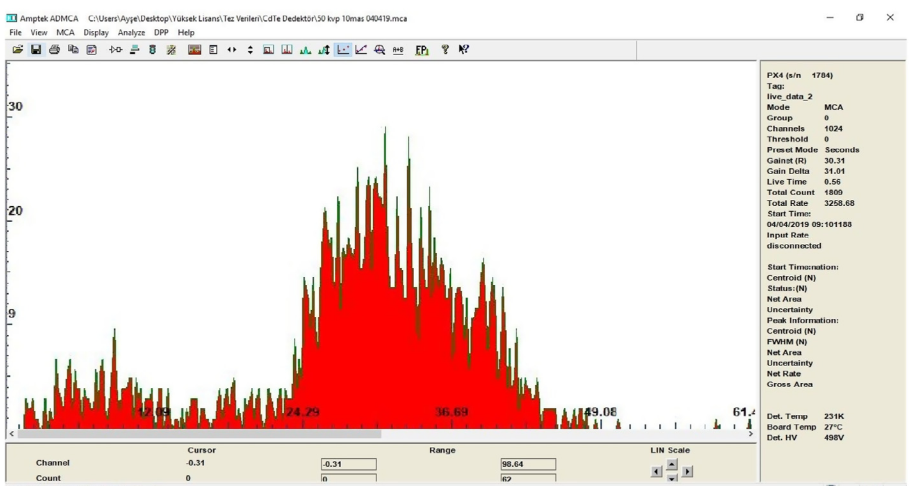
Table 4
HVL values of the produced epoxy based phantoms in paediatric energy range of 40–60 kVp.

Tissue equivalent phantoms[a] based on different (G/A) Ratio	Measured Half Value Layer, HVL (cm)					
	Applied tube voltage[b] →	40 kV	45 kV	50 kV	55 kV	60 kV
	(Standard beam quality) →	(RQA2)		(RQA3)		(RQA4)
10/90%		1.63	1.75	1.83	1.89	2.01
17/83%		1.45	1.58	1.67	1.74	1.79
31/69%		1.41	1.53	1.63	1.69	1.76
36/64%		1.39	1.48	1.61	1.66	1.73

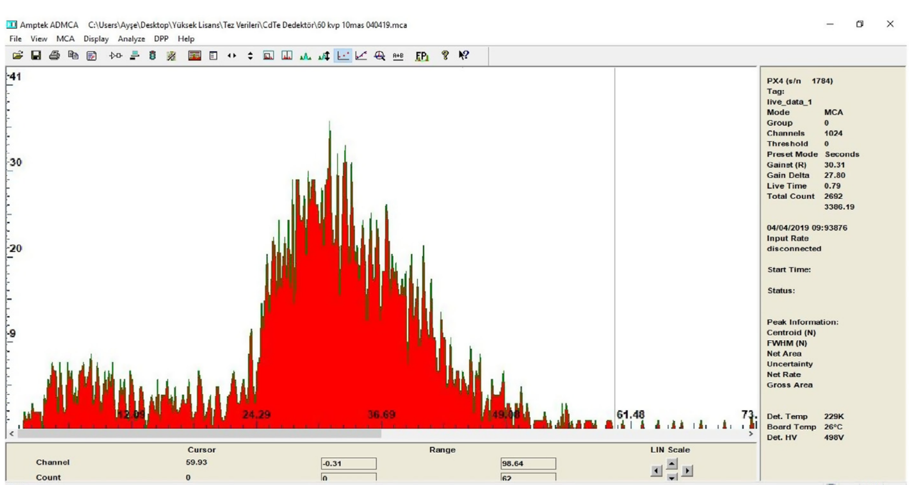
[a] Phantoms produced at different percentage glandular/adipose (G/A) tissue ratio using a special epoxy/ingredient mixtures by employing a suitable production process.
[b] Phantoms are irradiated by using RQA paediatric-beam qualities.



a)RQA2 beam quality (40kV$_p$)



b)RQA3 beam quality (50kVp)



c) RQA4 beam quality (60kVp)

Fig. 6. X-ray pulse height spectra of different RQA beam qualites measured by a CdTe detector.

spectra acquired with a CdTe detector are shown in Fig. 6. Each X-ray spectrum data in 1024 channels was evaluated and then the spectrum average energy is determined by Eq. (2). The resulted mean energies are 26.7 keV for RQA 2, 29.3 keV for RQA 3 and

Table 5
Hounsfield Units (HU) values of the produced epoxy based phantoms in paediatric energy range of 40–120 kV.

Tissue equivalent phantoms[a] based on different glandular/adipose (G/A) Ratio	Hounsfield Units (HU) values						
	Applied tube voltage[b]→	40 kV[c]	50 kV[c]	60 kV[c]	80 kV[d]	100 kV[d]	120 kV[d]
	(Standard beam quality)→	(RQA2)	(RQA3)	(RQA4)			
10/90%		94.8	37.7	62.8	30.7	46.8	47.8
17/83%		20.6	59.2	57.3	101.4	115.2	120.6
31/69%		46.2	82.1	73.7	109.8	119.5	126.1
36/64%		63.3	94.9	92.7	105.5	119.7	126.1

[a] Phantoms were produced at different percentage glandular/adipose (G/A) tissue ratio.
[b] Phantoms are irradiated by using RQA paediatric range beam qualities.
[c] HU vales were calculated from Eq. (3) in which the linear attenuation coefficients of air and water are taken from NIST XCOM database [13] for corresponding to mean energy of RQA beams.
[d] HU values obtained via CT scans.

30.6 keV for RQA 4.

In fact, there are known two semi-empirical methods to estimate the HU values of any tissue equivalent materials. One of the methods for determination of HU value is that we can use the obtained linear attenuation coefficients (μ_x) of the phantoms produced at different G/A% ratios by the following equation:

$$HU = 1000 \cdot \left[\frac{\mu_x - \mu_{water}}{\mu_{water} - \mu_{air}} \right] \tag{3}$$

where the linear attenuation coefficients of water (μ_{water}) and air (μ_{air}) are obtained from NIST XCOM database [13], considering mean X-ray energies mentioned above. In pediatric energy range, the HU values given in Table 5 were calculated for epoxy based phantoms at different G/A ratios.

3.4. *Determination of Hounsfield Units(HU) of the phantoms from CT scans*

Hounsfield unit (HU) is a dimensionless unit and used in CT scanning to express CT numbers [7]. A HU value can be obtained from a linear transformation of the measured attenuation coefficients as defined in Eq. (3). However, in the HU scale, the radiodensity of distilled water at standard temperature and pressure conditions (STP) is defined as 0 HU, while the radiodensity of air at STP is defined as −1000 HU. This results in a scale running from −1000 HU for air to approx. +2000 HU for very dense bone. Hence, Hounsfield units are used to compare dose comparison in paediatric and adult phantoms at low- and standard voltages in CT [16]. One of the well known uses is the evaluation of the fat content of the liver, with fatty liver diagnosed by the presence of a liver-to-spleen ratio of <1.0 or 0.8, and the other uses are guiding the management of kidney stones, bone mineral density measurement and brown adipose tissue radiodensity in young adults [12,17].

In this study, for the suitability of the produced phantoms to a child tissue, HU values are determined from their CT scans taken at available 80, 100 and 120 kVp voltages by a Siemens CT device. The obtained CT images of the phantom produced at different glandular/adipose ratios (from 17/83%G/A, 31/69%G/A, 36/64%G/A and 10/90% G/A) were analysed to calculate HU values and the mean HU values of those produced epoxy phantoms are given in Table 5. The mean HU values obtained for the phantom produced at a %10/90 G/A ratio are fluctuated by 10–21% as standard deviations. As given in Table 6, when the HVL values for the newly developed soft tissue equivalent phantom based on epoxy is compared with those of a reference paediatric soft tissue phantom produced by ORNL [21], the results agree with our HVL values in the paediatric energy rage. The percentage differences in HVL values between our phantom and a referenced phantom are lower than %7 in 40–60 kV interval. The present results expressed in terms of HVL and HU values show that the presently developed soft tissue phantom is a new paediatric phantom especially for a satisfactory mimicking a 3 years child's soft tissue by 5%. This novelty presents an advantage over existing phantoms such as simply standard phantoms such as the ACR calibration phantom. The presently ingredient constituents used in epoxy base material yielded to track paediatric tissue regarding the change in HU as a function of kVp.

4. Conclusions

In this study, a new epoxy based phantom was developed at different glandular/adipose (G/A) ratios to mimic a child's soft tissue equivalency in paediatric radiology. The radiation absorption properties of the phantoms investigated by using standardized X-ray beams representing the patient. The produced phantoms are characterized in the 40–60 kVp energy range in terms of both HVL and HU values and they were also characterized in terms of only HU values in 80–120 kVp CT energy range. For a satisfactory mimicking of a 3 years child's tissue, the best epoxy based phantom was produced at a %10/90 G/A ratio for mimicking paediatric soft tissue. As given in Table 6, our newly developed soft tissue equivalent (TE) phantom is compared in terms of HVL values with those of a reference paediatric soft tissue phantom produced by ORNL in paediatric energy range, and the good agreement is achieved by 7% difference in HVL values for the paediatric energy range of 40–60 kV. Additionally, as given in Table 7, when the mean HU = 47.8 ± 4.8 of this new soft TE-epoxy based- phantom with a % 10/90 G/A ratio is compared with that HU = 45.6 ± 7.9 of a 3 years

Table 6
A comparison of HVL values for the present paediatric soft tissue phantom with those of a reference paediatric soft tissue phantom.

Phantom	HVL (cm)		
	40 kV	50 kV	60 kV
The present paediatric soft tissue phantom produced at %10/90 G/A	1.63	1.83	2.01
Reference paediatric soft tissue phantom by ORNL[a]	1.53	1.77	1.88
The percentage difference	+%6.5	+%3.4	+%6,9

[a] Taken from Ref. [21].

Table 7
A comparison of Hounsfield Unit (HU) of the presently developed epoxy based phantoms with those HU values for child's soft tissue obtained from CT scans.

Paediatric purpose phantom/Child's soft tissue	Tube voltage used for CT scan	Mean HU±SD
G/A ratio: 10/90% soft TE epoxy based-phantom (in this work)	120 kV	47.8 ± 4.8
3 years old child's soft tissue [11]	120 kV	45.6 ± 7.9
% G/A ratio: 17/83 soft TE-epoxy based-phantom (in this work)	80 kV	101.4 ± 5.6
5 years old child's soft tissue [1]	80 kV	74.0 ± 25.4

SD: Standard Deviation.

old child's soft tissue determined at 120 kVp CT scans in the study of Kasraie et al. [11], the obtained HU values agree well with each other by ~5%, although their standard deviations varied by 10–17%. On the comparison to the paediatric phantom produced by Kasraie et al., %10/90 G/A phantom mimics paediatric soft tissue much more closer, where the competitor existing phantoms soft tissue material has HU value of 9.8 ± 11.0 [21]. Additionally, the HU = 101.4 ± 5.6 value obtained for other soft TE-epoxy based phantom was produced at a 17/83%G/A ratio might be approximated to HU = 74.0 ± 25.4 of a 5 years old child's soft tissue determined at 80 kVp CT scans by 37%. The latter result for HU obtained for the phantom (17/83% G/A ratio) is roughly mimicking for a 5 years child's soft tissue in the study of Ali et al. [1].

In conclusion, it is shown that newly developed soft tissue equivalent epoxy based phantoms produced at a %10/90 G/A ratio are more suitable for mimicking a 3 years child's tissue in paediatric radiology. Thus they can have a potential use to perform the quality controls of medical X-ray systems as alternative to standard ACR phantom and their beneficial use in dose optimizations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2021.07.002.

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References

[1] A.M. Ali, P. Hogg, S. Johansen, A. England, Construction and validation of a low cost paediatric pelvis phantom, Eur. J. Radiol. 108 (2018) 84–91.
[2] A.F.F. Alves, J.R.A. Miranda, F.A.B. Neto, S.B. Duarte, D.R. Pina, Construction of pediatric homogeneous phantoms for optimization of chest and skull radiographs, Eur. J. Radiol. 84 (8) (2015) 1579–1585, https://doi.org/10.1016/j.ejrad.2015.05.015.
[3] Amptek Inc., XR-100CdTe X-ray ve gamma ray detector. http://amptek.com/products/xr-100cdte-x-ray-and-gamma-ray-detector/. Access Date: 28.04.2019.
[4] J.L. Rodriguez-Ibarra, P.L. Hernandez-Adame, H.R. Vega-Carrillo, T. Rivera, X-ray spectra and doses, Appl. Radiat. Isot. 117 (2016) 32–35, https://doi.org/10.1016/j.apradiso.2016.04.001.
[5] S. Cubukcu, H. Yücel, Characterization of paraffin based breast tissue equivalent phantom using a CdTe detector pulse height analysis, APESM (Australas. Phys. Eng. Sci. Med.) 39 (4) (2016) 877–884, https://doi.org/10.1007/s13246-016-0487-1.
[6] M. Freed, J.A. Zwart, J.T. Loud, R.H. El Khouli, K.J. Myers, M.H. Greene, J.H. Duyn, A. Badano, An anthropomorphic phantom for quantitative evaluation of breast MRI, Med. Phys. 38 (2) (2011) 743–753.
[7] G.N. Hounsfield, Computed medical imaging, Science 210 (1980) 22–28, https://doi.org/10.1126/science.6997993.
[8] ICRU 44, International comission on radiation units and measurements. ICRU report 44: tissue substitutes in radiation dosimetry and measurement, J. Int. Comm. Radiat. Units Meas. os-23 (1) (1989).
[9] EN IEC 61267, Standard for Medical Diagnostic X-Ray Equipment –Radiation Conditions for Use in the Determination of Characteristics, International Electrotechnical Commission(IEC), Switzerland, 2006, 3, rue de Varembé, PO Box 131, CH-1211 Geneva 20.
[10] ISO 4037-1, Standard for Radiological Protection-X and Gamma Reference Radiation for Calibrating Dosemeters and Doserate Meters and for Determining Their Response as a Function of Photon Energy- Part 1: Radiation Characteristics and Production Methods, 2019. CP401 Ch de Blandonnet 8, CH-1214 Vernier, Geneva, Switzerland.
[11] N. Kasraie, A. Robinson, S. Chan, Construction of an anthropomorphic phantom for use in evaluating pediatric airway digital tomosynthesis protocols, Radiol. Res. Pract. 3835810 (2018) 1–9, https://doi.org/10.1155/2018/3835810.
[12] B. Martinez-Tellez, G. Sanchez-Delgado, M.R. Boon, P.C.N. Rensen, J.M. Llamas-Elvira, Distribution of Brown adipose tissue radiodensity in young adults: implications for cold [18F]FDG-PET/CT analyses, Mol. Imag. Biol. 22 (2) (2020) 425–433, https://doi.org/10.1007/s11307-019-01381-y.
[13] NIST XCOM, X-ray mass attenuation coefficients. https://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/air.html. Acces date: 05.05.2019.
[14] P.D. Price, A.P. Gibson, L.T. Tan, G.J. Royle, An elastically compressible phantom material with mechanical and x-ray attenuation properties equivalent to breast tissue, Phys. Med. Biol. 55 (4) (2010) 1177–1188.
[15] PTW, Freiburg, PTW farmer ionization chambers. https://www.ptw.de/farmer_chambers0.html. Acces Date: 05.05.2019.
[16] T. Shimonobo, Y. Funama, D. Utsunomiya, T. Nakaura, S. Oda, M. Kiguchi, T. Masuda, D. Sakabe, Y. Yamashita, K. Awai, Low-tube-voltage selection for non-contrast-enhanced CT: comparison of the radiation dose in pediatric and adult phantoms, Phys. Med. 32 (2016) 197–201, https://doi.org/10.1016/j.ejmp.2015.12.005.
[17] B.W. Ullrich, P. Schenk, U.J. Spiegl, T. Mendel, G.O. Hofmann, Hounsfield units as predictor for cage subsidence and loss of reduction: following posterior-anterior stabilization in thoracolumbar spine fractures, Eur. Spine J. 27 (12) (2018) 3034–3042, https://doi.org/10.1007/s00586-018-5792-9.
[18] D.R. White, R.J. Martin, R. Darlison, Epoxy resin based tissue substitutes, Br. J. Radiol. 50 (599) (1977) 814–821, https://doi.org/10.1259/0007-1285-50-599-814.
[19] H. Yücel, E. Güllüoglu, S. Çubukçu, Y.A. Üncü, Measurement of the attenuation properties of the protective materials used as a thyroid guard and apron for personnel protection against diagnostic medical X-rays, J. Phys. Sci. 27 (1) (2016) 111–128.
[20] H. Yücel, Development of a Tissue Equivalent Phantom Used for Quality Control Tests of Mammography Systems and its Characterization by Using X-Ray Spectroscopy, 2017 (in Turkish), Final Project Report, 1003TÜBİTAK, Project No:115S108.
[21] A.K. Jones, D.E. Hintenlang, W.E. Bolch, Tissue-equivelant materials for construction of tomographic dosimetry phantoms in pediatric radiology, Med. Phys. 30 (8) (2003) 2072–2081.