Evaluating the Physical Properties of Epoxy Resin as a Phantom Material to Mimic the Human Liver in Computed Tomography Applications

Marwan Alshipli*[1], Norlaili A. Kabir[1], Abd Aziz Tajuddin[1], Rokiah Hashim[2], and M.W.Marashdeh[1,3]

Abstract— The aim of this study was to evaluate the physical properties of epoxy resin to be used as a phantom material to mimic the liver of human body in computed tomography (CT) protocols. The epoxy resin type of E-110I/H-9 was mixed uniformly with a ratio 2:1 of resin and hardener. The mass density, effective atomic number, linear and mass attenuation coefficients of the epoxy were calculated. The linear and mass attenuation coefficients were calculated at relevant CT photon energy 40-65keV using the FFAST database (NIST, USA). Then, the calculated measurements of fabricated epoxy were compared with the standard values of human liver. The results indicated that the mass density and effective atomic number had achieved good agreement with the liver values. The theoretical values of linear and mass attenuation coefficients were in strong agreement with the values reported in International Commission on Radiation Units and Measurements. Therefore, the results physically verify the suitability of epoxy resin E-110I/H-9 as a CT phantom material to mimic the human liver.

Keywords— Computed Tomography, Epoxy Resin, Phantom Material, Physical Properties.

I. INTRODUCTION

Computed tomography scan (CT) is a cross-sectional medical imaging modality; introduced in 1972 by Godfrey Hounsfield. It is the first radiologic modality that uses X-ray radiation and computer to produce detailed images of internal structures depending on the different attenuation proprieties of the scanned area [1].

The CT images of liver depend on the attenuation variation between the normal and abnormal liver regions. Consequently, CT scan provides more detailed images about the liver and related structures than other radiologic modalities. These images have more information related to liver lesions, injuries, infections and other diseases [2, 3]. However, CT examinations produce higher radiation dose compared to other radiological procedures [4]. CT procedures deliver more than a hundred times the radiation dose of a conventional X-ray. Further, the level of radiation dose from CT protocols has increased, in part due to the improved speed of image acquisition [5, 6]. Therefore, CT phantom materials are developed in this study for future dose monitoring and image quality purposes in order to produce higher image quality with lower radiation dose level in CT applications.

Phantom is a specifically designed object that simulates the human body in medical imaging procedures which can evaluate the effect of ionizing and non-ionizing radiations. The phantom materials interact with radiation beams in experimental studies to avoid direct risk of radiation and ease of application in radiological research, including image quality, dosimetry measurements and radiotherapy quality assurance protocols. Water has been developed as a reference and standard material to simulate soft tissue of human body in ionizing radiation studies. However, the physical state of water renders it not always an appropriate model for use in ionizing radiation studies. Thus, many solid equivalent materials such as tropical wood, polystyrene, paraffin wax, and Perspex have been developed as alternative phantom materials[7-10].

CT phantom materials should have similar X-ray attenuation properties to human structures to adjust CT image quality, radiation dose measurements and quality assurance programs. Therefore, fabricating a suitable CT phantom material to mimic a human soft tissue depends on many physical factors and measurements, including mass density, effective atomic number, and attenuation properties [10].Several phantom studies have used the CT modalities to evaluate and measure the physical CT image characteristics of abdomen liver region, such as image contrast, spatial resolution and signal noise ratio [11-13]. Other studies have employed abdominal liver phantom to assess image quality and measure the radiation dose using different algorithm

[1]School of Physics, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia.
[2] Division of Bioresource, Paper and Coatings Technology, School of Industrial Technology, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia.
[3] Department of Physics, College of Sciences, Al Imam Mohammad Ibn Saud Islamic University (IMSIU), P.O. Box 90950, Riyadh 11623, Saudi Arabia.

filters, tube energies, and tube current settings [14-19].Furthermore, many researchers have evaluated the role of single and dual energy CT scanners to detect liver lesions and increase the CT image quality using abdominal liver phantom and real patient studies at the same time (vitro and vivo study) [20-23]. Therefore, providing a suitable CT phantom material that mimics human liver will give more image information and details that supports abdomen/liver CT studies and research.

Epoxies are strong adhesive materials referring to a class of polymer and pre-polymer. They react with themselves or with co-reactant materials (hardeners) to form a thermosetting plastic polymer with excellent mechanical and chemical properties. Therefore, epoxies contribute to a wide range of applications, including protective surfaces and metal coatings, structural adhesives, constructions, and electrical insulators and components. Furthermore, epoxies are commonly available, not toxic materials, and can bond with other materials[24, 25]. On the other hand, epoxies are becoming common materials in the fields of medical physics and imaging as phantom materials with higher quality and greater reproducibility [26-31]. These properties and advantages of epoxies make them appropriate materials to be used as a liver equivalent phantom material in CT procedures. Therefore, the main contribution and objective of this study is to evaluate the physical properties of epoxy resin E-110I/H9 to be characterized as an equivalent CT phantom material of the human's liver.

II. MATERIALS AND METHODS

A. Sample Preparations and Density Measurements

The epoxy resin product type of E-110I/H-9 was acquired from Pan Asel Chemicals (M) Sdn Bhd Company, Kuala Lumpur, Malaysia. It is a two-component (resin and hardener), non-volatile, colorless and low viscosity liquid high gloss epoxy resin which combines to form hard enamel. In the present study, the epoxy E-110I/H-9 was prepared by mixing resin and hardener uniformly (by weight) with a ratio of 2:1. The sample was mixed and vigorously stirred using an electrical mixer (Pensonic PM-163 Hand Mixer). After that, the epoxy was placed in rectangular shape molds (4 cm × 3 cm × 0.5 cm) for 16 hours at temperature 22 ±1°C. The density was measured as the ratio of mass to volume (g/cm³) by weighing 10 mL of the epoxy using class A volumetric flask. Then, the average density values of five test samples were taken to achieve high precision.

B. Effective Atomic Number and Elemental Composition Analysis

The effective atomic number (Zeff) plays a vital role in phantom material fabrication, particularly for low photon energy interactions where the photoelectric effect is more dominated. Therefore, it gives an indication about the interaction between the radiation beam and the matter [32]. In this study, the Zeff was calculated based on elemental composition analysis. The PE 2400 CHNS/O series II Elemental Analyzer was employed to determine the percentages of carbon, hydrogen, nitrogen, sulphur, and oxygen for the fabricated epoxy. Then, the chemical technique described by Mayneord was used to determine Zeff of epoxy as shown in the following equations [33].

$$Zeff=\left[\sum_{i=1}^{n}\left(aiZ_{i}^{m}\right)\right]^{(1/m)} \tag{1}$$

where ai is the fraction of electron in element i, Zi is the atomic number of the element i and m is an experimental coefficient (between 3 and 5)[34] .

$$ai=\frac{wi\left(\frac{Zi}{Ai}\right)}{\sum wi\left(\frac{Zi}{Ai}\right)} \tag{2}$$

The electronic fraction is given by Equation 2. Where wi and Ai are the fractional weight and the atomic mass of the element i, respectively.

C. Using X-Ray Form Factor, Attenuation and Scattering (FFAST) Database to Calculate the Linear and Mass Attenuation Coefficients.

linear attenuation (μ) and mass attenuation ($\mu\ /\rho$) coefficients of phantom materials can be expressed by calculating the attenuated photons dependence with the energy of radiation beam [35]. The attenuation properties are useful in computerized tomography, diagnostic radiology and in evaluating the characteristics of a material [36]. The linear attenuation coefficient can be calculated for sample with thickness x, as given by the Beer Lambert law (Equation 3) ,then, the mass attenuation coefficient can be measured by dividing the linear attenuation coefficient value by density of the sample.

$$I=I_0e^{-\mu x} \tag{3}$$

where I is the intensity of photons transmitted through thickness x, $I_0$is the initial photon intensity and μ is the linear attenuation coefficient.

The attenuation coefficients for any body part or material can be derived linearly from its chemical structure. The data for many materials over a wide energy photon range can be determined online by FFAST. FFAST is a database software program developed by the National Institute of Standards and Technology (NIST), physical measurement laboratory, USA. These are theoretically constructed data sets, but they are providing adequately accurate values about the total attenuation cross section measurements in photon energy range up to 433 keV. In comparison with experimental results, the alternate theory data demonstrated that the FFAST measurements as a function of energy were in strong agreement [37-39]. However, in this study, the FFAST was performed to calculate the linear and mass attenuation coefficients of epoxy resin in photon energy level related to the tube energies of CT scan protocols in the energy range 40–65 keV (80–140 kVp) [40]. Afterward, the calculated linear and mass attenuation coefficients values of epoxy were compared with those of human liver at the same energy levels.

III. RESULTS AND DISCUSSIONS

A. Density and Effective Atomic Number Measurements

The average mass density of the fabricated epoxy samples were determined using gravimetric calculation. The results showed that the epoxy had an average density value 1.11 g/cm³.The density of liver as reported in International Commission on Radiation Units and Measurements (ICRU, Report 44, 1989) is 1.06 g/cm³. In comparison with this study's results, the density of epoxy was in high agreement with the mass density of the liver within a difference of 4.7 %. Furthermore, the results indicated that the average density of epoxy is close to the mass density values of liver that were reported in the previous studies and no significant variation was observed [41-44].

The Zeff value of epoxy was measured depending on the chemical composition results. The percentages of H, C, O N, and S of epoxy were 4.68%, 68.48%, 23.14%, 2.4% and 1.3%, respectively. This shows that, the elemental analysis resembles the composition of human liver tissue, which mainly consists of carbon and oxygen. The results indicated that the calculated Zeff of epoxy is 7.11whichis in agreement with the Zeff value of the human liver tissue within a range difference of8.61–8.85% as calculated in previous studies by Kim (1974) [45], McCullough (1975) [41] and Watanabe (1999) [44].

The calculated results in this part of the study demonstrated the potential of using epoxy as a CT phantom material and are thus considered a good match for human liver tissue. This consistency between density and Zeff values of epoxy and liver can be considered as an early assumption of equivalent property of epoxy as a phantom material. In addition, it is important to note that the density and Zeff values of epoxy are close to those of water and this verifies the suitability of epoxy resin to be used as a phantom material in ionizing radiation applications.

B. Attenuation Properties Measurements

Table 1 shows the results of the linear and mass attenuation coefficient values from the FFAST data sets (NIST, USA) over energy range 40–65 keV. It was observed that all results decrease with increasing beam energy. The calculated results of epoxy were compared with previous values reported by Böke, 2014 [46]; King *et al*., 2011 [42] ; and ICRU Report 44, 1989 [47]. The linear attenuation coefficient results calculated in the present study are in agreement with the results reported by Böke (2014) within 2.72–10.31 %, King *et al.* (2011) within 6.17–6.44% and ICRU (1989) within 0.44 – 7.37 %. The mass attenuation coefficient results also agreed with the results reported by Böke (2014) within 0.44–5.46 %, King et al (2011) within 10.48–15.6 % and ICRU (Report 44, 1989) within 3.02 – 11.52 %.

Figures 1 and 2 show the linear and mass attenuation coefficients measurements against the energy. The graphs illustrate that the epoxy has linear and mass attenuation coefficients close to that of liver over photon energy range 40–65 keV. The curves similarity demonstrates that the epoxy attenuation coefficients results are in good agreement with previous studies of Böke, King *et al.* and ICRU. In comparison with ICRU measurements, it was observed that this study's results had much better agreement when the photon energy was increased. In other words, the results showed good matching with attenuation prosperities of liver, particularly in photon energies between 50–65 keV. However, the overall attenuation prosperities results demonstrated the suitability of epoxy to be used as a substitute material for human liver tissue over all the CT energy levels.

TABLE I
COMPARISON BETWEEN CALCULATED LINEAR AND MASS ATTENUATION COEFFICIENTS FOR EPOXY RESIN AND LIVER TISSUE

	Linear Attenuation Coefficient (μ) (cm^{-1})				Mass Attenuation Coefficient (μ/ρ) (cm²/g)			
E (keV)	**Epoxy Resin**	Böke (2014)	King *et al.* (2011)	ICRU (1989)[a]	**Epoxy Resin**	Böke (2014)[b]	King *et al.* (2011)[b]	ICRU (1989)
40	**0.264**	0.257	0.299	0.285	**0.238**	0.242	0.282	0.269
45	**0.251**	0.238	0.275	0.263	**0.225**	0.226	0.259	0.248
50	**0.237**	0.220	0.256	0.241	**0.214**	0.208	0.242	0.227
55	**0.228**	0.209	0.243	0.229	**0.205**	0.197	0.229	0.216
60	**0.218**	0.199	0.233	0.217	**0.196**	0.188	0.220	0.205
65	**0.214**	0.194	0.229	0.211	**0.193**	0.183	0.216	0.199

[a]Calculated value of (μ) is given by International Commission on Radiation Units and Measurements (ICRU) by multiplying the mass attenuation coefficient by the mass density of liver [47].

[b]Calculated value of $(\mu/\rho)$are given by Böke [46] and King *et al.* by dividing the linear attenuation coefficient by the mass density of liver.

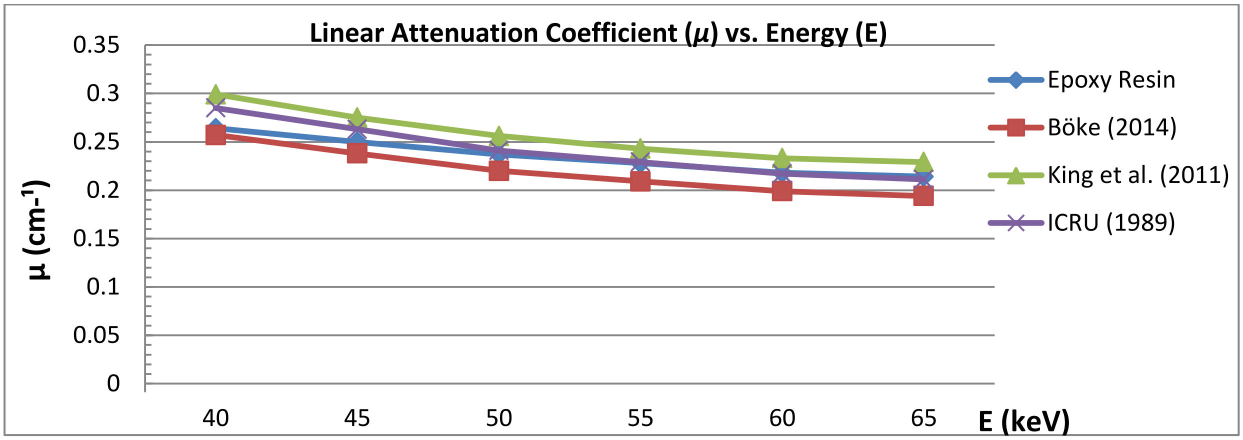

Fig. 1 Comparison of the linear attenuation coefficients (μ) versus photon energy for epoxy resin and human liver tissue

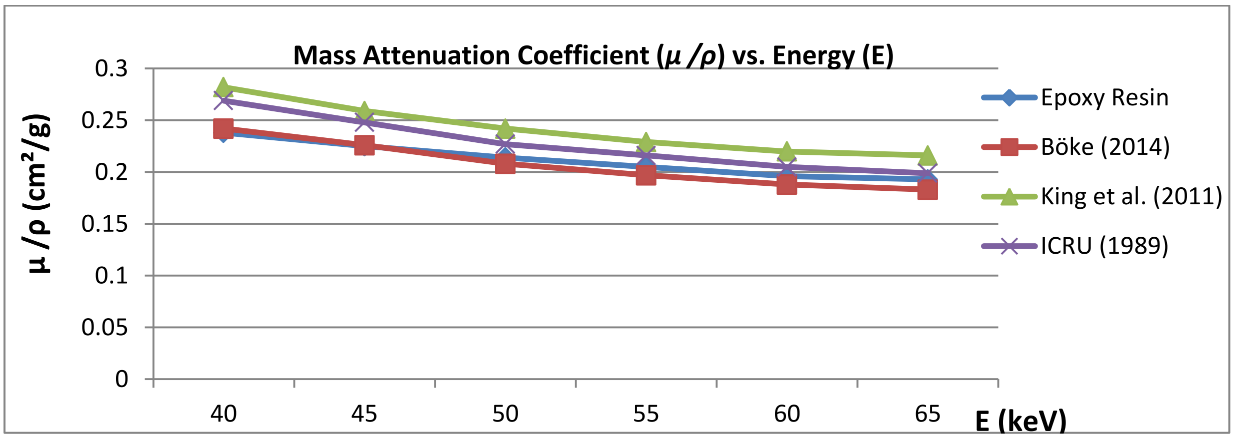

Fig. 2 Comparison of the mass attenuation coefficients (μ /ρ) versus photon energy for epoxy resin and human liver tissue

IV. CONCLUSIONS

This study has evaluated the physical properties of epoxy resin to be used as a substitute material in abdomen/liver CT protocols. The study's measurements were compared to values obtained by ICRU and previous published studies. The results demonstrated that the density and Zeff values of epoxy were in well agreement with the reported values of the human liver tissue. The differences between the theoretical measurements of linear and mass attenuation coefficients and the published data from ICRU were found to be 0.44–11.52% on average corresponding to the 40–65 keV photon energy. Thus, the findings of this study provide a compelling argument for the use of epoxy resin E-110I/H-9 as a substitute material for the human liver in CT procedures and applications.

ACKNOWLEDGEMENTS

The support of this study under USM RUI GRANT 1001/PFIZIK/811345 by Universiti Sains Malaysia is gratefully acknowledged.

REFERENCES

[1] Farncombe, T. and K. Iniewski, *Medical Imaging: Technology and Applications*. 2013: CRC Press.pp.

[2] Hounsfield, G.N., " Computed medical imaging," *Medical physics*, vol. 7, pp. 283-290, 1980.

[3] Ippolito, D., S. Sironi, M. Pozzi, L. Antolini, *et al.*, " Hepatocellular carcinoma in cirrhotic liver disease: functional computed tomography with perfusion imaging in the assessment of tumor vascularization," *Academic radiology*, vol. 15, pp. 919-927, 2008.

[4] Kalra, M.K., M.M. Maher, T.L. Toth, L.M. Hamberg, *et al.*, " Strategies for CT radiation dose optimization," *Radiology*, vol. 230, pp. 619-628, 2004.

[5] Linet, M.S., K. pyo Kim and P. Rajaraman, " Children's exposure to diagnostic medical radiation and cancer risk: epidemiologic and dosimetric considerations," *Pediatric radiology*, vol. 39, pp. 4-26, 2009.

[6] Mettler Jr, F.A., W. Huda, T.T. Yoshizumi and M. Mahesh, " Effective doses in radiology and diagnostic nuclear medicine: a catalog," *Radiology*, vol. 248, pp. 254-263, 2008.

[7] Winslow, J.F., D.E. Hyer, R.F. Fisher, C.J. Tien, *et al.*, " Construction of anthropomorphic phantoms for use in dosimetry studies," *Journal of applied clinical medical physics*, vol. 10, pp. 195-204, 2009.

[8] Yohannes, I., D. Kolditz, O. Langner and W.A. Kalender, " A formulation of tissue-and water-equivalent materials using the stoichiometric analysis method for CT-number calibration in radiotherapy treatment planning," *Physics in medicine and biology*, vol. 57, pp. 1173, 2012.

[9] Bradley, D., A. Tajuddin, C.W.A.C.W. Sudin and S. Bauk, " Photon attenuation studies on tropical hardwoods," *International Journal of*

Radiation Applications and Instrumentation. Part A. Applied Radiation and Isotopes, vol. 42, pp. 771-773, 1991.

[10] Yohannes, I., D. Kolditz, O. Langner and W.A. Kalender, " A formulation of tissue- and water-equivalent materials using the stoichiometric analysis method for CT-number calibration in radiotherapy treatment planning," *Phys Med Biol*, vol. 57, pp. 1173-90, 2012.

[11] Baker, M.E., F. Dong, A. Primak, N.A. Obuchowski, *et al.*, " Contrast-to-noise ratio and low-contrast object resolution on full-and low-dose MDCT: SAFIRE versus filtered back projection in a low-contrast object phantom and in the liver," *American Journal of Roentgenology*, vol. 199, pp. 8-18, 2012.

[12] Ghetti, C., F. Palleri, G. Serreli, O. Ortenzia, *et al.*, " Physical characterization of a new CT iterative reconstruction method operating in sinogram space," *Journal of Applied Clinical Medical Physics*, vol. 14, pp. 263-271, 2013.

[13] Holmquist, F., U. Nyman, R. Siemund, M. Geijer, *et al.*, " Impact of iterative reconstructions on image noise and low-contrast object detection in low kVp simulated abdominal CT: a phantom study," *Acta Radiologica*, vol. 57, pp. 1079-1088, 2016.

[14] Martinsen, A.T., H.K. Sæther, D. Olsen, P. Skaane, *et al.*, " Reduction in dose from CT examinations of liver lesions with a new postprocessing filter: a ROC phantom study," *Acta radiologica*, vol. 49, pp. 303-309, 2008.

[15] Grant, K.L., T.G. Flohr, B. Krauss, M. Sedlmair, *et al.*, " Assessment of an advanced image-based technique to calculate virtual monoenergetic computed tomographic images from a dual-energy examination to improve contrast-to-noise ratio in examinations using iodinated contrast media," *Investigative radiology*, vol. 49, pp. 586-592, 2014.

[16] Schindera, S.T., R.C. Nelson, S. Mukundan Jr, E.K. Paulson, *et al.*, " Hypervascular liver tumors: low tube voltage, high tube current multi–detector row CT for enhanced detection—phantom study," *Radiology*, vol. 246, pp. 125-132, 2008.

[17] Chen, B., D. Marin, S. Richard, D. Husarik, *et al.*, " Precision of iodine quantification in hepatic CT: effects of iterative reconstruction with various imaging parameters," *American Journal of Roentgenology*, vol. 200, pp. W475-W482, 2013.

[18] Marin, D., R.C. Nelson, S.T. Schindera, S. Richard, *et al.*, " Low-tube-voltage, high-tube-current multidetector abdominal CT: improved image quality and decreased radiation dose with adaptive statistical iterative reconstruction algorithm—initial clinical experience," *Radiology*, vol. 254, pp. 145-153, 2009.

[19] Husarik, D.B., S.T. Schindera, F. Morsbach, N. Chuck, *et al.*, " Combining automated attenuation-based tube voltage selection and iterative reconstruction: a liver phantom study," *European radiology*, vol. 24, pp. 657-667, 2014.

[20] Kim, K.S., J.M. Lee, S.H. Kim, K.W. Kim, *et al.*, " Image fusion in dual energy computed tomography for detection of hypervascular liver hepatocellular carcinoma: phantom and preliminary studies," *Investigative radiology*, vol. 45, pp. 149-157, 2010.

[21] Marin, D., J.C. Ramirez-Giraldo, S. Gupta, W. Fu, *et al.*, " Effect of a noise-optimized second-generation monoenergetic algorithm on image noise and conspicuity of hypervascular liver tumors: an in vitro and in vivo study," *American Journal of Roentgenology*, vol. 206, pp. 1222-1232, 2016.

[22] Husarik, D.B., S. Gordic, L. Desbiolles, B. Krauss, *et al.*, " Advanced virtual monoenergetic computed tomography of hyperattenuating and hypoattenuating liver lesions: ex-vivo and patient experience in various body sizes," *Investigative radiology*, vol. 50, pp. 695-702, 2015.

[23] Schindera, S.T., C. Zaehringer, D. Luigia, F. Schwartz, *et al.*, " Systematic radiation dose optimization of abdominal dual-energy CT on a second-generation dual-source CT scanner: assessment of the accuracy of iodine uptake measurement and image quality in an in vitro and in vivo investigations," *Abdominal Radiology*, vol., pp. 1-9, 2017.

[24] DeWerd, L.A. and M. Kissick, *The Phantoms of Medical and Health Physics*. 2014: Springer.pp.

[25] Strzelec, K., " Studies on the properties of epoxy resins cured with polythiourethanes," *International Journal of Adhesion and Adhesives*, vol. 27, pp. 92-101, 2007.

[26] Constantinou, C., F. Attix and B.R. Paliwal, " A solid water phantom material for radiotherapy x-ray and γ-ray beam calibrations," *Medical physics*, vol. 9, pp. 436-441, 1982.

[27] Singh, V., N. Badiger and N. Kucuk, " Assessment of methods for estimation of effective atomic numbers of common human organ and tissue substitutes: waxes, plastics and polymers," *Radioprotection*, vol. 49, pp. 115-121, 2014.

[28] Lee, C.I., J.W. Shin, S.-C. Yoon, T.S. Suh, *et al.*, " Percentage depth dose distributions in inhomogeneous phantoms with lung and bone equivalent media for small fields of CyberKnife," *arXiv preprint arXiv:1401.0692*, vol., pp., 2013.

[29] White, D., R. Martin and R. Darlison, " Epoxy resin based tissue substitutes," *The British journal of radiology*, vol. 50, pp. 814-821, 1977.

[30] Nisbet, A. and D. Thwaites, " An evaluation of epoxy resin phantom materials for electron dosimetry," *Physics in medicine and biology*, vol. 43, pp. 1523, 1998.

[31] Zivkovic, I., R. Mahou, K. Scheffler and C. Wandrey, " Candidate for tissue mimicking material made of an epoxy matrix loaded with alginate microspheres," *Progress In Electromagnetics Research C*, vol. 41, pp. 227-238, 2013.

[32] Taylor, M., R. Franich, J. Trapp and P. Johnston, " The effective atomic number of dosimetric gels," *Australasian Physical & Engineering Science in Medicine*, vol. 31, pp. 131-138, 2008.

[33] Singh, V.P., N.M. Badiger and N. Kucuk, " Assessment of methods for estimation of effective atomic numbers of common human organ and tissue substitutes: waxes, plastics and polymers," *Radioprotection*, vol. 49, pp. 115-121, 2014.

[34] Jackson, D.F. and D.J. Hawkes, " X-ray attenuation coefficients of elements and mixtures," *Physics Reports*, vol. 70, pp. 169-233, 1981.

[35] Hubbell, J., " Photon mass attenuation and energy-absorption coefficients," *The International Journal of Applied Radiation and Isotopes*, vol. 33, pp. 1269-1290, 1982.

[36] Rao, D.V., T. Takeda, Y. Itai, T. Akatsuka, *et al.*, " X-ray scattering cross sections for molecules, plastics, tissues, and few biological materials," *Journal of trace and microprobe techniques*, vol. 20, pp. 327-361, 2002.

[37] Chantler, C.T., " Theoretical form factor, attenuation, and scattering tabulation for Z= 1–92 from E= 1–10 eV to E= 0.4–1.0 MeV," *Journal of Physical and Chemical Reference Data*, vol. 24, pp. 71-643, 1995.

[38] Chantler, C.T., " Detailed tabulation of atomic form factors, photoelectric absorption and scattering cross section, and mass attenuation coefficients in the vicinity of absorption edges in the soft X-ray (Z= 30–36, Z= 60–89, E= 0.1 keV–10 keV), addressing convergence issues of earlier work," *Journal of Physical and Chemical Reference Data*, vol. 29, pp. 597-1056, 2000.

[39] Cengiz, E., " Determination of L III subshell photoelectric parameters of iridium," *Canadian Journal of Physics*, vol. 95, pp. 427-431, 2017.

[40] HUDA, W., E.M. SCALZETTI and G. LEVIN, " Technique factors and image quality as functions of patient weight at abdominal CT," *Radiology*, vol. 217, pp. 430-435, 2000.

[41] McCullough, E.C., " Photon attenuation in computed tomography," *Medical Physics*, vol. 2, pp. 307-320, 1975.

[42] King, B., K. Landheer and P. Johns, " X-ray coherent scattering form factors of tissues, water and plastics using energy dispersion," *Physics in medicine and biology*, vol. 56, pp. 4377, 2011.

[43] Kinase, S., M. Kimura, H. Noguchi and S. Yokoyama, " Development of lung and soft tissue substitutes for photons," *Radiation protection dosimetry*, vol. 115, pp. 284-288, 2005.

[44] Watanabe, Y., " Derivation of linear attenuation coefficients from CT numbers for low-energy photons," *Physics in medicine and biology*, vol. 44, pp. 2201, 1999.

[45] Kim, Y.S., " Human tissues: chemical composition and photon dosimetry data," *Radiation Research*, vol. 57, pp. 38-45, 1974.

[46] Böke, A., " Linear attenuation coefficients of tissues from 1keV to 150keV," *Radiation Physics and Chemistry*, vol. 102, pp. 49-59, 2014.

[47] Bethesda, M., " Tissue Substitutes in Radiation Dosimetry and Measurement, Report 44 of the International Commission on Radiation Units and Measurements," *Journal*, vol., pp., 1989.