FABRICATION OF *RHIZOPHORA* SPP. HEAD PHANTOM FOR EXTERNAL BEAM RADIOTHERAPY APPLICATIONS

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by

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LIST OF SYMBOLS AND ABBREVIATIONS

%	Percentage
°C	Degree in Celcius
µC	Micro-Coulomb
µm	micrometer
^{60}Co	Cobalt-60
2D	2-Dimensional
3D	3-Dimensional
3D-CRT	3-Dimensional Conformal Radiation Therapy
AAPM	American Association of Physicist in Medicine
Al_2O_3	Aluminium oxide
AMDI	Advanced Medical and Dental Institute
Ar	argon
BR	Brazil
C	carbon
C++	C Object-Oriented Programming Language
C-C	Carbon-carbon bond
C-O-C	Carbon-oxygen-carbon bond
Ca	calcium
CaF_2	Calcium flouride
CAN	Canada
cGy	centiGray
CHN	Carbon, hydrogen, nitrogen
Cl	Chlorine
CT	Computed Tomography
Cu	Copper

cm	centimeter
DE	Germany/Deutschland
DICOM	Digital Imaging and Communication in Medicine
d_{max}/D_{max}	Dose at maximum depth dose
D_{mean}	Mean dose
Dy	dysprosium
EBRT	External Beam Radiotherapy
EDX	Energy dispersive X-ray
EGSnrc	Electron Gamma Shower by National Research Council
FLUKA	Fluktuierende Kaskade
FR	France
FTIR	Fourier Transform Infrared
g	gram
$g \cdot cm^{-3}$	gram per centimeter cubic
GATE	Geant4 Application for Tomographic Emission
GEANT	Geometry and Tracking
GLOBOCAN	Global Cancer Observatory: Cancer Today
H	hydrogen
h	hour
HU	Hounsfield Unit
IC	Ionisation chamber
ICRU	International Commissioning of Radiation Units and Measurement
IMRT	Intensity Modulated Radiotherapy
IND	India
JIS	Japanese International Standard
JNP	Japan
JPA	Jabatan Perkhidmatan Awam

K	potassium
KBr	Potassium bromide
keV	Kilo electron Volt
kg	kilogram
LEGe	Low Energy Germanium
LiF	Lithium fluoride
LINAC	Linear Accelerator
MA	Massachusetts
mAs	milliAmpere-second
MARA	Majlis Amanah Rakyat
MC	Monte Carlo
MCNP	Monte Carlo Neutron Positron
MeV	Mega electron Volt
MF	Melamine-formaldehyde
mL	millilitre
MLC	Multileaf collimator
min	minute
Mg	magnesium
Mn	Manganese
Mo	Molybdenum
MOR	Modulus of rupture
MPa	Mega-Pascal
MR	Magnetic Resonance
MRI	Magnetic Resonance Imaging
MU	Monitor unit
MV	Megavoltage
N	nitrogen

Na	sodium
NaCl	Sodium chloride
NO	Norway
Nb	Niobium
nC	Nano-Coulomb
NIST	National of Institute Standard Technology
O	oxygen
OAR	Organ at risk
OSB	Oriented Strand Board
P	phosphorus
P	Maximum load
P_{max}	maximum load at fracture time
PET	Positron Emission Tomography
Pd	Palladium
PDD	Percentage depth dose
PENELOPE	Energy loss of positron and electron
PF	Phenol-formaldehyde
pH	Potential of hydrogen
pMDI	polymeric diphenylmethane diisocyanate
PMMA	Polymethylethacrylate
PRF	Phenol resorcinol formaldehyde
PVA	Polyvinyl alcohol
QA	Quality Assurance
QUANTEC	Quantitative analysis of normal tissue effects in the clinic
R_a	Average roughness
ROI	Region of interest
RT	Radiotherapy

R_z	Mean peak-to-valley height
S	sulfur
SD	Standard deviation
SE	Sweden
sec	second
SEM	Scanning electron microscopy
Sn	Tin
spp.	species
SPECT	Single photon emission computed tomography
SSD	Source to surface distance
Ti	Titanium
TLD	Thermoluminescent dosimeter
TGA	Thermogravimetric analysis
TPS	Treatment planning system
TS	Thickness swelling
UF	Urea-formaldehyde
UKM	Universiti Kebangsaan Malaysia
USA	United States of America
USM	Universiti Sains Malaysia
UTM	Universiti Teknologi Malaysia
WA	Water absorption
WBRT	Whole brain radiotherapy
XCOM	X-ray computed
XRD	X-ray diffraction
XRF	X-ray fluorescence
Z	Atomic number
Z/A	atomic number/mass number of an atom

Z_{eff}	Effective atomic number

PEMFABRIKATAN FANTOM KEPALA DARIPADA *RHIZOPHORA* SPP. UNTUK APLIKASI RADIOTERAPI ALUR LUAR

ABSTRAK

Kajian ini bertujuan untuk memfabrikat fantom kepala daripada *Rhizophora* spp. terikat dengan soya dan lignin untuk aplikasi dosimetrik dalam radioterapi alur luar (EBRT) otak. Tiga saiz zarah yang berbeza (0–103 µm, 104–210 µm, 211–500 µm) dan peratusan pelekat berbeza (0, 6 and 12%), digunakan untuk pengeluaran papan partikel pada ketumpatan sasaran 1.0 $g \cdot cm^{-3}$. Papan partikel juga dikaji pada tiga campuran lapisan yang berbeza untuk kelicinan permukaan. Pencirian papan partikel dilakukan untuk menentukan kekuatan fizikal, kimia dan mekanikal. Pencirian ini merangkumi analisis termogravimetri (TGA), analisis inframerah transformasi Fourier (FTIR), analisis mikroskopi elektron imbasan (SEM), spektroskopi dispersi sinar-X (EDX), analisis nitrogen karbon hidrogen (CHN), ikatan dalaman, penyerapan air, pembengkakan ketebalan, analisis kehabluran dan analisis komposisi elemen. Papan partikel juga dikaji dari segi nombor tomografi (CT), sifat pengecilan, serakan Compton dan peratusan dos kedalaman (PDD). Seterusnya, fantom kepala dibina menggunakan formulasi papan partikel yang terbaik. Untuk penyinaran otak, teknik terapi sinaran konformal tiga dimensi (3D-CRT) digunakan, dengan dos yang ditetapkan sebanyak 30 Gy dalam 10 pecahan. Sistem perancangan rawatan (TPS) digunakan untuk merancang rawatan, di mana dos yang diserap pada setiap kawasan penting (ROI) dianggarkan. Dosimeter termoluminesen (TLDs) digunakan untuk mengukur cas yang dikumpul daripada penyinaran. Seterusnya, kit GATE Monte Carlo (MC) digunakan untuk mensimulasikan rawatan untuk mengesahkan dos yang diserap. Mengikut pencirian, *Rhizophora* spp. (dengan saiz zarah 0–103 µm) diikat dengan 12% soya dan lignin, dan disalut dengan kemasan berkilat, dipilih sebagai rumusan optimum untuk fabrikasi fantom kepala. Papan partikel *Rhizophora* spp. terikat pelekat dari segi nombor CT dan pengecilan adalah berada dalam persetujuan erat dengan nilai XCOM air, mempamerkan potensinya sebagai bahan fantom yang setanding dengan tisu. Untuk penyinaran otak, purata dos TLD yang direkodkan dalam PTV ialah 283.13 cGy, iaitu dalam lingkungan ±5.6% daripada dos yang ditetapkan. Dos yang diserap dianggarkan melalui simulasi GATE berada dalam anggaran yang hampir dengan TPS, dengan 1.6% perbezaan untuk isipadu sasaran perancangan (PTV). Ketidakpastian statistik untuk simulasi GATE adalah kurang daripada 1%, mematuhi ketidakpastian yang disyorkan <2%. Kesimpulannya, kajian ini berjaya menunjukkan potensi dosimetrik fantom kepala yang diperbuat daripada *Rhizophora* spp. terikat dengan soya dan lignin dalam rawatan radioterapi otak.

FABRICATION OF *RHIZOPHORA* SPP. HEAD PHANTOM FOR EXTERNAL BEAM RADIOTHERAPY APPLICATIONS

ABSTRACT

The aim of this study was to fabricate a head phantom made from soy-lignin *Rhizophora* spp. for dosimetric applications in external beam radiotherapy (EBRT) of the brain. Three different particle sizes (0–103 µm, 104–210 µm, 211–500 µm) and different percentages of adhesives (0, 6 and 12%) were studied for the production of the particleboards at target density of 1.0 g·cm^{-3}. The particleboards were also evaluated with three different coating mixtures for surface smoothness. Characterisation of the particleboards were carried out to determine the physical, chemical and mechanical properties of the fabricated particleboard. This includes thermogravimetric analysis (TGA), Fourier transform infrared (FTIR), scanning electron microscopy (SEM), energy dispersive X-ray (EDX), carbon hydrogen nitrogen (CHN), internal bonding, water absorption, thickness swelling, crystallinity and elemental composition analyses. The particleboards were also investigated in terms of computed tomography (CT) number, attenuation, Compton scattering and percentage depth dose (PDD). Next, a head phantom was constructed using the best particleboard formulation. For brain irradiation, three-dimensional conformal radiation therapy (3D-CRT) technique was used, with a prescribed dose of 30 Gy in 10 fractions. Treatment planning system (TPS) was used to plan the treatment, where absorbed dose at each region of interest (ROI) was estimated. Thermoluminescent dosimeters (TLDs) were used to measure the charges collected from the irradiation. Next, GATE Monte Carlo (MC) toolkit was used to simulate the treatment to verify the absorbed dose. Following characterisations, *Rhizophora* spp. (with particle size of

0–103 µm) bonded with 12% soy flour and lignin, and coated with gloss finish, were chosen as the optimum formulation for the fabrication of the head phantom. The adhesive bonded *Rhizophora* spp. particleboard in terms of CT number and attenuation were in agreement with the XCOM value of water, exhibiting its potential as a tissue-equivalent phantom material. Following brain irradiation, the average TLD dose recorded in PTV is 283.13 cGy, which is within ±5.6% of the prescribed dose. The absorbed doses estimated via GATE simulation were within close approximation with that of the TPS, with 1.6% difference for planning target volume (PTV). The statistical uncertainty for the GATE simulation was less than 1%, adhering to the recommended uncertainty of <2%. In conclusion, this study successfully demonstrates the dosimetric potential of the head phantom made from soy-lignin *Rhizophora* spp. in external beam radiotherapy of the brain.

CHAPTER 1

INTRODUCTION

1.1 Background

Tissue-equivalent phantom is an important tool for dosimetric applications in the field of medical physics. In medical physics, especially in radiotherapy setting, unnecessary exposures to human should always be avoided, to prevent stochastic effects of radiations. This is when phantoms, i.e., materials that represent human tissues, will be used as a replacement for humans. The phantom can be manufactured in the shape of a human body or part of it, with density and radiation properties similar to that of the actual human tissues (Ramos et al. 2017). The purpose of a phantom in medical physics applications is often to simulate human tissue in a given procedure or experiment according to its form and its composition. While the shape and composition of a phantom can vary drastically, they generally fall into one of two categories, dosimetry phantoms and imaging phantoms (Zuber et al., 2021b). Dosimetry phantoms are designed to be able to quantify the amount of radiation received at a given point, whether it be during a therapy or imaging procedure. Imaging phantoms are used to test the limits of an imaging system and to assess the quality of the images being produced by that system. When selecting or designing a phantom, one must carefully consider the materials to be used, the physical shape, and how these will affect what is trying to be measured in the situation of interest.

Tissue substitute materials have been extensively used in experimental dosimetry (Damilola et al., 2020; Mohd Fahmi Mohd Yusof et al., 2017a). AAPM TG-51 protocol recommended the use of water as a phantom material (Almond et al., 1999), as water is the most abundant component of the human soft tissue. Water has a mass density value close to that of muscle tissue, with similar properties towards ionising radiation. However, the use of water as a phantom in dosimetric studies is not always practical, due to its physical state being liquid, and the limited availability of radiation dosimeters to measure radiation in water. Thus, numerous water-equivalent materials such as acrylics and solid water have been developed (Banjade *et al.* 2001). Commercially available but expensive tissue-equivalent anthropomorphic phantoms include RANDO® phantom (Alderson Research Labs, Standford, CA) and recently, the ATOM® phantom (CIRS, Norfolk, VA), are often used for dosimetric radiation measurements.

Rhizophora spp. in the form of particleboards have been investigated for the fabrication of tissue-equivalent phantom (Bradley et al., 1991; Marashdeh et al., 2011; Sudin et al., 1988; M F Mohd Yusof et al., 2017; Mohd Fahmi Mohd Yusof et al., 2017a). The physical and mechanical properties of phantoms for radiation studies have been improved by extensive research (Abuarra et al., 2014b; Marashdeh et al., 2011; Ehsan Taghizadeh Tousi et al., 2014). Among many other tissue-equivalent materials, e.g., Perspex®, and epoxy resin (Sudin *et al.* 1988; Bradley et al. 1991), the attenuation properties of *Rhizophora* spp. wood has been shown to be closer to that of water (Banjade et al., 2001; Bradley et al., 1991).

When physical phantoms are used, the dose received by the organs or ROIs can be measured using a dosimeter. TLD, either of lithium fluoride (Karaçam et al., 2009; Sneed et al., 1995) or calcium fluoride (Kourinou et al., 2015; M Mazonakis et al., 1999; Michael Mazonakis et al., 1999) are often used due to their high sensitivity. The TLDs are placed within the assigned holes at each of the phantom slice (Mazonakis and Damilakis, 2017), providing dose distribution representing the ROIs. Large volume ionisation chamber (IC) can also be used for organ dose measurements. However, the used of IC is limited to phantoms that can accommodate its relatively larger dimension. Also, rather than providing a dose distribution, IC only allows for a single point measurement to be made within the organ volume.

Other than physical approach, development of new treatment techniques can also be validated virtually, via MC simulations. Mathematical phantoms can be constructed to simulate a patient, for both diagnostic (Motavalli et al., 2016) and therapeutic purposes (Geng et al., 2015; Kry et al., 2017). Other than that, tomographic images, e.g., CT images, can also be incorporated into MC codes, as input to simulate an inhomogeneous phantom. Various MC codes can be used, which include MCNP (Bednarz and Xu, 2008; Motavalli et al., 2016), Geant4 (Geng et al., 2015) and EGS (Sheeraz and Chow, 2021). MC simulations can also be used to verify the absorbed dose measured via dosimeters, e.g., TLDs and IC.

1.2 Problem statement

Despite the increasing development of phantom for use in diagnostic and radiotherapy, extensive works have not been done on the existing *Rhizophora*-based phantom in radiotherapy setting. *Rhizophora*-based phantom has been studied for its comparable characteristics to water and soft tissue, and thus showing its potential as a dosimetric phantom. Several types of adhesives had been incorporated in order to improve the physical and mechanical properties of the particleboard; however, a single adhesive addition may not meet the minimum requirement especially in the properties of the particleboard. Thus, formulations of two adhesives can be investigated to further improve these properties. Commercially available RANDO® phantom has been widely used to measure absorbed dose in the clinical setting. However, RANDO®

phantom consists of slabs with 2.5 cm thickness, which may affect its sensitivity in terms of measurement of dose in a specific organ of interest with a smaller volume. This limitation may affect the performance and the detectability of absorbed dose at different volume size within the phantom.

1.3 Aim & objective of research

The aim of this study was to develop a head phantom made of *Rhizophora* spp. particleboard, for dosimetric applications in brain EBRT. This can be achieved by fulfilling the following objectives:

i. To fabricate *Rhizophora* spp. particleboard with the incorporation of two organic adhesives and surface coating.
ii. To investigate the attenuation and computed tomography (CT) study for the *Rhizophora* spp. particleboard at various energy ranges.
iii. To demonstrate the feasibility of the head phantom for dosimetric applications in brain EBRT via TPS, TLD measurements and MC simulation.

1.4 Significance of study

For the very first time, a homogenous head phantom made from *Rhizophora* spp. will be constructed. This phantom will be useful to estimate the absorbed dose that will be received by a brain tumour and organ at risk (OAR), following EBRT. This phantom can accommodate the placement of TLDs for absorbed dose measurement, within cylindrical pegs that will be drilled at several points in each particleboard slabs constructed at the thickness of 1.0 cm, to represent the ROIs.

1.5 Outline of thesis

There are five chapters in this thesis. Chapter 1 consists of the introduction, which include the background of study, problem statement, aim and objectives of research, and the significance of study. Chapter 2 consists of the literature review, which covers theoretical aspects related to dosimetric phantoms, *Rhizophora* spp., brain cancer, EBRT and MC method. Chapter 3 describes the practical aspects related to the fabrication of soft tissue-equivalent *Rhizophora* spp. particleboard, where the formulation, in terms of particle sizes and percentage of adhesives, were thoroughly investigated. Physical and mechanical characterisations of the particleboard were also presented in this chapter. Other than that, attenuation properties and CT study were also investigated, followed by the validation of radiation dose by TLD, TPS and GATE simulation in EBRT of the brain, by utilising the head phantom. The results and discussions were reported in Chapter 4. Finally, the study is concluded in Chapter 5, along with recommendations to improve this study.

CHAPTER 2

THEORY & LITERATURE REVIEW

2.1 Phantom materials

2.1.1 Phantom for dosimetry

Dosimetric phantom is a model phantom that was developed following the evolvement of computational phantoms in order to measure and evaluate organ doses post irradiation either internally or externally. The apparent need to simulate the human body and features in radiation study invites researchers to study and explore various materials as phantom that were deemed suitable based on the investigation of physico-mechanical, attenuation and scattering. Phantom is often acknowledged as model that resembles the human body and anatomy, made up of medium with close equivalent to human soft tissue in terms of size, shape, positioning, density and radiation interaction with matter (Ramos et al., 2017).

Research and development on tissue-equivalent materials had been carried out by many researchers to study the radiation dosimetric effects within and surrounding the irradiated tissues (White et al., 1992). The introduction of adult-sized phantom mimicking human body in the early 1960 allows the continuation of innovative approach in the fabrication of phantom for radiation study. Homogeneous phantoms presented with comparable similarity to human soft tissue in terms of absorption and attenuation are the first step of making a proper heterogeneous phantom for use in radiation study. Alderson RANDO® phantom was among the first anthropomorphic phantoms presented in slabs (Alderson et al., 1962; Stacey et al., 1961). RANDO® phantom is the universally commercialised dosimetric phantom for use in various radiation study, which include radiotherapy. This phantom is made from moulded tissue-equivalent material, and often used in organ specific dosimetry for all dosimeters such as thermoluminescent dosimeter (TLD), optically stimulated luminescence (OSL) nanodots, metal-oxide-semiconductor field-effect transistor (MOSFET), film, ion chambers, and diodes. However, RANDO® presented with 2.5 cm slab thickness, which may affect the dose distribution with limited number of holes for dosimeter. Previous study analysed the dose in the lung area for radiotherapy in breast cancer cases, with the dose distribution only measured in one or two TLDs for each left and right lung (Abdemanafi et al., 2020). With the complexity of radiation treatment in radiotherapy and nuclear medicine, physicists and oncologists demand better and superior phantom with ever-increasing degrees of realism in order to adhere to the requirement and to remove the dependence on simple block of solid phantom or liquid tank. These phantoms have also been used for experimental studies to validate computer simulations by comparing the dosimetric data from both physical and simulated phantom (De Craene et al., 2012; Kim et al., 2015, 2010; Long et al., 2013; Sun et al., 2010).

2.1.2 Water equivalent material for phantom

Water has shown to be within similar affinity to soft tissue with acknowledgement from IAEA as standard phantom (Arib et al., 2006). Water is often presented with reproducible properties suited for radiation study and widely available, thus it is recommended for dosimetry purposes in radiotherapy. One of the main reasons is its close proximity of mass density to soft tissue (Samson et al., 2020a). The usage of water, in liquid form as phantom in every dosimetry procedure, however, is quite inflexible, considering its inconsistent shape and size. The limitation includes the difficulties of locating several types of radiation dosimeters as many of them are not compatible to be used in water. Therefore, solid phantoms were introduced and developed as a substitute to water.

ICRU Report 44 suggested some properties that can be considered for solid phantom material in order to achieve similar and comparable properties to human tissue (44, 1989). Table 2.1 summarises the relevant investigation of *Rhizophora* spp. as phantom material. Plastic water, polystyrene, poly(methyl methacrylate) (PMMA) and solid water are among the materials that were proposed to replace water as tissue substitute materials. Each of these materials was believed to provide the closest performance to water. Table 2.2 shows the atomic composition of various tissues in human body whereas Table 2.3 provides the atomic composition of various water-equivalent materials which are used for radiotherapy phantoms.

Table 2.1 Summary of the *Rhizophora* spp. investigation as phantom material

Classification	Parameter	Description	Reference
Physical and mechanical properties	Mass and electron density	The measurement of sample's density in accordance to the target density by using gravimetric method and CT; The determination of relative electron density (RED) by CT number	(Ababneh et al., 2016; Damilola et al., 2020; Hamid et al., 2017; Marashdeh et al., 2012, 2011; Ngu et al., 2015; D O Samson et al., 2020a; Taghizadeh Tousi et al., 2015; Ehsan Taghizadeh Tousi et al., 2014; Yusof et al., 2015; Mohd Fahmi Mohd Yusof et al., 2017c, 2017a, 2017b)
	Internal bonding	The measurement of sample's bonding strength by applying specific load capacity in accordance to Japanese Industrial Standard (JIS) (Association, 2003)	(Abuarra et al., 2014b; Hamid et al., 2017; D O Samson et al., 2020b, 2020a; Taghizadeh Tousi et al., 2015; Ehsan Taghizadeh Tousi et al., 2014; Mohd Fahmi Mohd Yusof et al., 2017b)
	Modulus of rupture (MOR)	The determination of sample's strength before reaching the breaking point in flexion or torsion	(Hamid et al., 2017; D O Samson et al., 2020b, 2020a; Mohd Fahmi Mohd Yusof et al., 2017c)
	Water absorption & thickness swelling	The evaluation of sample's dimensional stability according to the JIS by using manual immersion in water; The analysis of sample's swelling ratio	(Abuarra et al., 2014b; Hamid et al., 2017; Omar et al., 2018; D O Samson et al., 2020b, 2020a; Taghizadeh Tousi et al., 2015; Ehsan Taghizadeh Tousi et al., 2014; Mohd Fahmi Mohd Yusof et al., 2017c)

	Surface roughness	The analysis of sample’s surface roughness using roughness profilometer	Performed in this study
Characterisation	Thermal decomposition	The evaluation of sample’s dissociation degree upon heating by using TGA	(D O Samson et al., 2020b, 2020a)
	Functional group	The determination of sample’s functional group by using FTIR	(D O Samson et al., 2020b)
	Crystallinity index	The analysis of sample’s crystallinity index by employing X-ray diffraction (XRD) analysis	(Marashdeh et al., 2011; D O Samson et al., 2020a)
	Microstructure	The investigation of sample’s microstructure and its spatial relationships by using SEM	(Abuarra et al., 2014b; Marashdeh et al., 2011; D O Samson et al., 2020b, 2020a; Ehsan Taghizadeh Tousi et al., 2014; Mohd Fahmi Mohd Yusof et al., 2017c)
	Elemental composition and effective atomic number	The determination of sample’s elemental composition for the measurement of effective atomic number by employing EDX or CHN analyses; the determination of sample’s elemental composition by employing X-ray fluorescence (XRF) analysis	(Damilola et al., 2020; Hamid et al., 2017; Omar et al., 2018; D O Samson et al., 2020b, 2020a; Taghizadeh Tousi et al., 2015; M F Mohd Yusof et al., 2018; Mohd Fahmi Mohd Yusof et al., 2017b, 2017a)
	Chemical response	The determination of chemical response of the sample (i.e adhesive) by using nuclear magnetic resonance (NMR)	(D O Samson et al., 2020b)

	Thermal behaviour and melting point	The determination of sample’s elemental interaction, thermal behaviour, melting point alongside the analysis of the quaternary, tertiary, and secondary structures by employing differential scanning calorimetry (DSC)	(D O Samson et al., 2020b; E T Tousi et al., 2014)
	Viscosity	The determination of viscosity of the sample (i.e adhesive and raw material) by using viscometer	(E T Tousi et al., 2014)
Attenuation properties and dosimetric evaluation	Linear and mass attenuation coefficient	The measurement of sample’s linear and mass attenuation coefficient by adopting the transmission study at various energy ranges, using the XRF spectroscopy or NaI (Tl) gamma spectroscopy	(Ababneh et al., 2016; Abuarra et al., 2014b; Alshipli et al., 2018; Hamid et al., 2017; Marashdeh et al., 2012; Ngu et al., 2015; Ngu, 2009; Safian, 2012; D O Samson et al., 2020a; Shakhreet et al., 2009; Sudin et al., 1988; Surani, 2008; E T Tousi et al., 2014; Mohd Fahmi Mohd Yusof et al., 2017b)
		The measurement of sample’s attenuation coefficient by CT number, and the determination of the mean ROI attenuation value	(Alshipli et al., 2018)
		The measurement of sample’s linear and mass attenuation coefficient based on Compton scattering method using Ludlum configuration	(Hamid et al., 2018; Mohd Yusof et al., 2019)

		The measurement of PDD to evaluate the attenuation properties of the sample at photon and electron energy ranges (eg. 6 MV, 10 MV, 5 MeV, 12 MeV)	(Banjade et al., 2001; Bradley et al., 1991; Marashdeh et al., 2012)
	Scattering properties	The determination of scattering properties based on count per second, channel shift and scattered photon energy using Compton scattering method	(Syazwina et al., 2012)
	Beam quality index	The measurement of beam quality index at photon and electron energy ranges using tissue phantom ratio (TPR) analysis	(M F Mohd Yusof et al., 2018)
	Depth dose	The determination of PDD using radiation dosimeter such as IC, TLD or Gafchromic film in comparison with water phantom to study the therapeutic depth dose of the phantom	(Damilola et al., 2020; Hamid et al., 2018; M F Mohd Yusof et al., 2018)
Image quality test	Image contrast	The analysis of phantom's image contrast in single photon emission computed tomography/computed tomography (SPECT/CT)	(Hamid et al., 2019)

Table 2.2 Atomic composition of various tissues in the human body

Element	Z	Z/A	Water	Air	Lung	Adipose	Tissue	Muscle	Cartilage	Bone
H	1	0.992	11.19	-	10.30	11.40	10.12	10.20	9.60	3.40
C	6	0.500	-	-	10.50	59.80	11.1-	14.30	9.90	15.50
N	7	0.500	-	75.50	3.10	0.70	2.60	3.40	2.20	4.20
O	8	0.500	88.81	23.20	74.90	27.80	76.18	71.00	74.40	43.50
Na	11	0.478	-	-	0.20	0.10	-	0.10	0.50	0.10
Mg	12	0.494	-	-	-	-	-	-	-	0.20
P	15	0.484	-	-	0.20	-	-	0.20	2.20	10.30
S	16	0.499	-	-	0.30	0.10	-	0.30	0.90	0.30
Cl	17	0.479	-	-	0.30	0.10	-	0.10	0.30	-
Ar	18	0.451	-	1.30	-	-	-	-	-	-
K	19	0.486	-	-	0.20	-	-	0.40	-	-

Ca	20	0.499	-	-	-	-	-	-	-	22.50
		$\rho\left(\frac{g}{cm^3}\right)$	1.000	1.203×10^{-3}	0.260	0.950	1.000	1.050	1.100	1.850
		$\langle Z/A \rangle$	0.555	0.499	0.550	0.556	0.550	0.550	0.547	0.515

H = hydrogen; C = carbon; N = nitrogen, O = oxygen; Na = sodium; Mg = magnesium; P = phosphorus; S = sulfur; Cl = chlorine; Ar = argon; K = potassium; Ca = calcium

Adapted from (Seco and Evans, 2006)

Table 2.3 Atomic composition of various water-equivalent materials which are used for radiotherapy phantoms

Sample	**Water[a]**	**Solid water[a]**	**Polystyrene[a]**	**PMMA[a]**	**Paraffin wax[c]**	**Acrylic[c]**	**Plastic water[d]**	**Virtual water[d]**	***Rhizophora* spp[c,b]**
H	11.19	8.09	7.74	8.05	15.0	8.0	9.25	7.70	5.37[c]
C	-	67.22	92.26	59.98	85.0	60.0	62.82	68.74	41.0[c]
N	-	2.40	-	-	-	-	1.0	2.27	0.89[c]
O	88.81	19.84	-	31.96	-	32.0	17.94	18.86	-
Other	-	Cl:0.13, Ca:2.32	-	-	-	-	Cl:0.96, Ca:7.95, Br:0.03	Cl:0.13, Ca:2.31	S:0.45[c]
Mass density ($g\cdot cm^{-3}$)	1.00	1.035	1.06	1.19	-	-	1.013	1.03	1.04[b]
Z/A	0.555	0.539	0.538	0.539	-	-	-	-	-

(Seco and Evans, 2006)[a]; (Bradley et al., 1991)[b]; (Abuarra et al., 2014)[c]; (Borcia and Mihailescu, 2007)[d]

H = hydrogen; C = carbon; N = nitrogen; O = oxygen; Cl = chlorine; Ca = calcium; Br = bromine; S = sulphur; Z/A = atomic number/mass number of an atom

2.2 *Rhizophora* spp.

Rhizophora spp. is a type of mangrove tree that grew abundantly in the muddy tidal plain mostly found in the coastal area in Malaysia. The genus *Rhizophora* contains many species of mangrove (Abuarra *et al.* 2014b). Although global mangrove distribution has fluctuated throughout geological history, *Rhizophora* spp. can be easily found in Malaysia, as Malaysia is the third among the top twenty Mangrove Holding Nation (Hamilton and Casey, 2016). Generally, *Rhizophora* spp. commonly reaches up to five to eight metres, approximately at 16 to 26 feet but sometimes can reach up to 30 to 40 metres in height with grows around 3.3 feet per year in height (Duke, 2006).

Rhizophora spp. often being used as charcoal or fuelwood and also as raw materials for chipboard, pulpwood and synthetic industries. *Rhizophora* spp. brings direct benefits owing to widespread use of stilt mangroves as wood for various purposes which includes cooking fuel, construction of homes and canoe parts (Duke, 2006). The wood of *Rhizophora* spp. is hard, heavy and strong, often used for structural components including poles, beams, flooring, wall-cladding, rafters for traditional homes and boat anchors (Shakhreet et al., 2013). The bark of *Rhizophora* spp. is also used to produce dyes and tannins (Percival, 1975). The tannins can be used together with formaldehyde adhesive commonly used to bond the wood slabs. These adhesives are acknowledged for their high moisture resistance and waterproof grades in the fabrication of particleboard (Duke, 2006). Other than that, the production of high quality papers from *Rhizophora* spp. can be used as newspaper, cardboard and chipboards (Marashdeh et al., 2011; Ehsan Taghizadeh Tousi et al., 2014). In Malaysia, the thirty-year rotation harvested yield of green wood of *Rhizophora* spp.

about 136 to 299 metric ton per hectare. *Rhizophora* spp. also had been proved to be suitable as phantom and previous studies proposed its propriety as phantom material mimicking human soft tissue (Abuarra et al., 2014b; Banjade et al., 2001; Bradley et al., 1991; Marashdeh et al., 2011; Munem et al., 2004; Tajuddin et al., 1996; Ehsan Taghizadeh Tousi et al., 2014; M F Mohd Yusof et al., 2017; Mohd Fahmi Mohd Yusof et al., 2017c).

2.2.1 Discovery of *Rhizophora* spp. wood as potential phantom

Rhizophora spp. was first discovered as potential phantom material from the study by Sudin et al., (1988). The research works had since becoming an increased interest as it studied the potential of natural wood as phantom that can potentially simulate the properties of human soft tissue towards ionising radiation (Bradley et al., 1991; CWA, 1993; Sudin et al., 1988). Twenty-five different types of wood species were investigated in term of mass density and attenuation in accordance to the requirement for soft tissue equivalency. Encouraging outcomes from the research lead to further evaluation of *Rhizophora* spp. in terms of radiographic and scattering conducted in 1996 (Tajuddin et al., 1996). The study of radiographic and scattering were performed, for different kinds of hardwoods, water and modified rubber at different angles were studied. The outcomes revealed that *Rhizophora* spp. has indistinguishable properties compared to water and modified rubber in terms of radiographic and scattering, thus providing a compelling argument for *Rhizophora* spp. as potential phantom material (Tajuddin et al., 1996).

2.2.2 Binderless *Rhizophora* spp. particleboard

The studies on *Rhizophora* spp. as potential phantom material began with the investigation of the raw solid wood, however, the idea of grinding the wood into wood flakes for fabrication of particleboard came into attention as solid wood presented with some limitations. Solid raw wood has the tendency to warp and split over time, and due to its inhomogeneous density, the desired properties of a phantom material cannot be achieved. The inflexibility of raw solid *Rhizophora* spp. wood in term of shape and size also makes it harder for the wood to be made into the desired feature. The improved condition of *Rhizophora* spp. in particleboard open the possibilities in response to its favourable characteristics including homogeneity, malleability and can be fabricated using different particle sizes and shapes (D O Samson et al., 2020b).

Investigations in 2011 and 2012 were conducted and particleboards were fabricated to replace solid wood (Marashdeh et al., 2012, 2011). This study evaluated the internal bond strength and dimensional stability based on various particle sizes of binderless samples. Profile density distribution was also investigated using CT. The outcomes showed that particle size has an effect on the dimensional stability which could be improved by hot pressing. Fabrication of particleboards at smaller particle sizes also proved to show better bonding strength (Marashdeh et al., 2011). Improvement on raw *Rhizophora* spp. wood is indeed essential before it can be appointed as phantom material.

In 2001, a study was conducted focusing on the solid *Rhizophora* spp. raw wood as tissue-equivalent phantom material. The attenuation properties of the wood was evaluated by measuring the PDD at 6 MV photon beam, 5 and 12 MeV electron beams (Banjade et al., 2001). The results demonstrated percentage discrepancy of less than 2.6% in comparison to water, hence suggesting the potential of *Rhizophora* spp. as phantom material to substitute water.

Radiographic and scattering analyses for water, modified rubber and various hardwoods were analysed at different angles between 10˚ to 45˚. Point source of 1.67

GBq of Americium was detected by employing 5 cm NaI(TI) detector and a 1024 multichannel analyser. The result revealed that *Rhizophora* spp. has similar properties to water and modified rubber in terms of radiographic and scattering (Tajuddin et al., 1996). The work leads to more attempt in providing a complete characterisation of *Rhizophora* spp. as a potential dosimetric medium, with possible application at both diagnostic and therapeutic energies.

2.2.3 The use of adhesives in the fabricated *Rhizophora* spp. particleboards

Adhesive acts as binding agent that holds other materials together, mechanically or chemically to form a coherent bond. Conventionally, materials such as wax, casein, gum and protein often employed as adhesive agent in food and building industries. The strength of the adhesion between the binding agent and the material depends on the intermolecular forces of the adhesive used. Some binding agents allow chemical bond to occur between the adhesive and substrate, whereas other formulations of adhesives and substrates allow electrostatic forces to hold the substances together. The incorporation of adhesive will improve the physical and mechanical strength of the fabricated particleboard, boosting its durability.

The petroleum-based adhesives, commonly known as synthetic adhesives are made of formaldehyde-based compounds, and are widely used in wood industries especially in the particleboards manufacturing. In many industrial practices, particleboards are often make use of petroleum-based resin such as phenol-formaldehyde (PF), phenol resorcinol formaldehyde (PRF) and urea-formaldehyde (UF) as adhesives (Owodunni et al., 2020; Surani, 2008; Syazwina et al., 2012). In a study conducted by Syazwina et al., same scattering outcomes were observed in the investigation of three different resins (PF, UF, and PRF) based on their channel shift, measured scattered photon energy and count per second.

Previous study also investigated the use of PF at different percentages to be incorporated into the fabricated R*hizophora* spp. particleboards. The attenuation properties of the particleboards at photon energy range of 15.77 to 25.27 keV was measured. The results revealed that the measured mass attenuation coefficients of particleboards were found to be very close to the calculated XCOM values for old-age breast when compare with young-age, middle-age, old-age breast and water from XCOM database (Shakhreet et al., 2013).

Previous literature also investigated the use of UF and PF as adhesives for the fabricated *Rhizophora* spp. particleboards (Ngu et al., 2015). The result revealed that sample treated with 10% of PF has the best potential compared to others. In another study, the use of segregated phenol-rich fraction of bio-oil was included into the formulation of PF resin in an effort to create an environmentally friendly type of PF resin, known as bio-oil-phenol-formaldehyde (BPF) as an adhesive (Omar et al., 2017). The physical and mechanical properties of the fabricated particleboards revealed to be within excellent condition with little and satisfactory formaldehyde emission. Attenuation of the sample exhibited close attenuation value to breast tissue, indicating its potential as phantom material in radiation study.

Despite commonly used as resin in the fabrication of particleboard across the world, formaldehyde is not among the highly favoured adhesive in the wood industry (Owodunni et al., 2020). Although formaldehyde has been acknowledged for their excellent performance as bonding material, there are some significant disadvantages of formaldehyde including environmental and health issues (Hashim et al., 2011; Owodunni et al., 2020). Current trend in particleboard industry suggests the use of particleboard with little or no formaldehyde in order to omit the unnecessary exposure to harmful substances as such usage is a detriment to the environment especially the air quality. Table 2.4 tabulates some of the past and current works on *Rhizophora* spp. particleboard as phantom material.

Table 2.4 Past and current works on *Rhizophora* spp. wood and particleboard as phantom material

Author, year of publication	**Adhesive consideration/treatment**
(Sudin et al., 1988)	Solid raw wood
(Bradley et al., 1991)	Solid raw wood
(CWA, 1993)	Solid raw wood
(Tajuddin et al., 1996)	Solid raw wood
(Banjade et al., 2001)	Solid raw wood
(Surani, 2008)	Treated with PF, UF, PRF
(Syazwina et al., 2012)	Treated with UF, PF, PRF
(Safian, 2012)	Bonded with tannin
(Marashdeh et al., 2012)	Binderless
(Shakhreet et al., 2013)	Treated with PF
(Ehsan Taghizadeh Tousi et al., 2014)	Bonded with *Eremurus* spp. root
(Abuarra et al., 2014b)	Bonded with natural gum Arabic
(Taghizadeh Tousi et al., 2015)	Bonded with *Serishoom* adhesive
(Ngu et al., 2015)	Treated with PF and UF
(Rabaiee et al., 2015)	Bonded with soy protein
(M F Mohd Yusof et al., 2017; Yusof et al., 2016, 2015)	Bonded with tannin
(Ababneh et al., 2016)	Bonded with almond gum
(OMAR, 2017)	Treated with PF and bio-oil PF (BPF)
(Hamid et al., 2018)	Bonded with corn starch
(Alshipli et al., 2018)	Bonded with epoxy resin
(D. Samson et al., 2020; D O Samson et al., 2020b, 2020a; Damilola Oluwafemi Samson et al., 2020)	Treated with defatted soy four (DSF) and soy protein isolate (SPI) modified by sodium hydroxide and itaconic acid polyamidoamine-epichlorohydrin (IA-PAE) adhesive

Previous studies often focused on fabricating homogenous phantom for use in radiation study. Previous study by Yusof et al., investigated *Rhizophora* spp. particleboard incorporated with tannin for use in dosimetric study. In this study, homogenous phantom was fabricated and attenuation properties of the samples at 6 MV and 6 MeV energies were carried out and finding demonstrated that the dose distribution of the particleboards were within close agreement when compared with the solid water and water phantom (Mohd Yusof et al., 2019; M F Mohd Yusof et al., 2018; Mohd Fahmi Mohd Yusof et al., 2017c; Yusof et al., 2016).

In 2014, a study was conducted with the incorporation of Arabic gum as natural-based adhesive material in the fabrication of homogenous *Rhizophora* spp. particleboard (Abuarra et al., 2014b). Positive results were seen as Arabic gum as adhesive distributed homogenously within the cells and between compressed fibers of the particleboard. The study was further extended by evaluating the attenuation coefficients of the samples within energy range of 17.4 to 26.7 keV. The mass attenuation coefficients were revealed to be very close to the water (XCOM), thus recommended as tissue equivalent material for phantom in dosimetric applications.

In 2015, a study on the utilisation of soy protein as adhesive in the fabrication of homogenous *Rhizophora* spp. particleboard was conducted by Rabaiee et al. (2015). The soy protein bonded with *Rhizophora* spp. particleboard demonstrated suitability as phantom material in the aspect of mass attenuation coefficient at low energy ranges in comparison with water (XCOM). Extensive studies were also carried out by another researcher, adopting the potential of soy protein as adhesive in the fabrication of *Rhizophora* spp. particleboard as homogenous phantom material (D. Samson et al., 2020; D O Samson et al., 2020b, 2020a; Damilola Oluwafemi Samson et al., 2020).

Soy protein isolate (SPI) was further treated with sodium hydroxide (NaOH) and itaconic acid polyamidoamine-epichlorohydrin (IA-PAE) to enhance the adhesion properties and water resistance. The result showed that the mass attenuation coefficients of the samples were in good agreement to theoretical value, proving its potential as phantom material.

2.3 Potential adhesives

2.3.1 Soy flour

Soy protein is one of the natural resources to produce natural wood adhesive (Ferdosian et al., 2017). Soy products as adhesives are safe and perform well as dominant bonding portion (Frihart and Lorenz, 2013). Other than that, soy protein also can withstand hot or cold condition during the fabrication process, and more efforts had been done to study soy protein as adhesive in order to improve the wood bond strength (Frihart and Hunt, 2010; Frihart and Lorenz, 2013; Frihart and Satori, 2013; Frihart and Wescott, 2004; Hojilla-Evangelista, 2002; Khosravi et al., 2010).

Despite its environmentally friendly characteristic, protein-based adhesives have high viscosity, short pot life and poor water resistance (Li et al., 2012). Thus, more methods were employed to improve the performance of protein-based adhesives such as cross-linking (Lei et al., 2014; Liu and Li, 2007), enzymatic modification (Hettiarachchy et al., 1995; Kalapathy et al., 1995), chemical denaturation (Rassam, 2008) and addition of additive (Chen et al., 2013). A study reported that water resistance of soy-based adhesives improved after cross-linking with epoxy resin, melamine-formaldehyde or both (Lei et al., 2014).