DESIGN AND FABRICATION OF A 3D PRINTED THYROID PHANTOM FOR RADIATION DOSIMETRY

by

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LIST OF ABBREVIATIONS

3D	Three-dimensional
ABS	Acrylonitrile Butadiene Styrene (ABS
AMDI	Advanced Medical & Dental Institute
AP	Anterior-Posterior
CBCT	Cone beam CT
CNR	Contrast-to-noise ratio
CT	Computed Tomography
CTDI	CT Dose Index
D	Absorbed dose
DE	Dual Energy
DECT	Dual Energy Computed Tomography
DLP	Dose Length Product
E	Effective dose
EANM	European Association of Nuclear Medicine
eV	Electron volt
FOV	Field of view
GE	General Electric
h	hour
HIPS	High Impact Polystyrene
HpGe	High purity germanium detectors

HU	Hounsfield Units
I	Intensity of attenuated narrow beam of gamma-ray
I_0	Intensity of un-attenuated narrow beam of gamma-ray
ICRP	International Commission on Radiological Protection
ICRU	Radiation Units and Measurements
kVp	Peak kilo-voltage
LAO	Left Anterior-Oblique
MBq	Megabecquerel
MDCT	Multidetector Computed Tomography
min	minute
MIRD	Medical Internal Radiation Dose
MRI	Magnetic resonance imaging
NaI(Tl)	Sodium Iodide doped with Thallium
^{o}C	Degree Celsius
OSLD	Optically Stimulated Luminescence Dosimeters
PA	Polyamide-Nylon
PA	Posterior-Anterior
PC	Polycarbonate
PET	Positron Emission Tomography
PETG	Polyethylene terephthalate
PLA	Polylactic Acid
PMMA	Polymethyl-methacrylate

PVE	Partial volume effect.
QA	Quality assurance
QC	Quality control
RAO	Right Anterior-Oblique
SD	Standard Deviation
SE	Single Energy
SECT	Single Energy Computed Tomography
SEM-EDS	Scanning Electron Microscope - Energy Dispersive X-ray Spectroscopy
SNM	Society Nuclear Medicine
SNR	Signal noise ratio
SPECT	Single Photon Emission Computed Tomography
SSDE	Size-specific dose estimates
SSDE	Size-Specific Dose Estimates
Tc-99m	Technetium
TLD	Thermoluminescence Detectors
TPE	Thermoplastic elastomers
TPU	Thermoplastic Polyurethane
TSH	Thyroid-stimulating hormone
USM	Universiti Sains Malaysia
XCOM	Photon cross-section database
XRF	X-ray fluorescence
Z	Atomic number

Z_{eff}	Effective atomic number
α	Alpha particles
β	Beta particles
γ	Gamma-ray
μ	linear attenuation coefficients
μ/ρ	Mass Attenuation Coefficient
μ_w	linear attenuation coefficients of water
ρ	Density

REKABENTUK DAN FABRIKASI FANTOM TIROID BERCETAK 3D UNTUK DOSIMETRI SINARAN

ABSTRAK

Penganggaran dos radiasi dalaman dan luaran daripada prosedur SPECT/CT amat bergantung pada kaedah pengiraan Dos Radiasi Dalaman Perubatan. Pada masa ini, tiada fantom tiroid dinamik dengan bentuk geometri yang tepat yang boleh mensimulasikan biokinetik radiofarmaseutis di dalam tiroid. Kajian ini bertujuan untuk mereka bentuk dan membuat fantom tiroid dinamik tiga dimensi (3D) untuk mendapatkan kualiti imej dan dosimetri yang tepat. Mesin Spektroskopi Tenaga Serakan X-ray (SEM-EDS) digunakan untuk mendapatkan pecahan unsur jisim untuk mengevaluasi sembilan bahan bercetak 3D. Hasil yang didapati digunakan dalam pangkalan data keratan rentas foton XCOM versi dalam talian untuk memperoleh nilai pengecilan jisim bagi setiap bahan. Dua teknik CT yang berbeza (pengimejan tenaga tunggal dan pengimejan dwitenaga) digunakan untuk meneliti ciri-ciri pelemahan bagi setiap bahan dengan mengukur angka CT. Hasil daripada semua kaedah dibandingkan dengan nilai pelemahan tiroid. Hasil kajian menunjukkan bahan polikarbonat boleh digunakan sebagai bahan yang menyerupai tisu tiroid manusia. Fantom leher-tiroid bercetak 3D direka bentuk dengan menggunakan teknologi cetakan 3D. Fantom tiroid jenis pepejal dan berongga direka dengan menggunakan perisian 3D Max. Dimensi tiroid yang digunakan diperoleh daripada sorotan kajian. Kedua-dua fantom mempunyai dua lubang pada setiap lobus untuk pemasangan dosimeter radiasi (contohnya dosimeter pendarcahaya rangsangan optik dan termopendarcahaya). Fantom tiroid mengambil masa selama 30 minit untuk menghasilkan cetakan berbanding dengan kaedah konvensional yang memakan masa lebih lama. Pam picagari infusi digunakan untuk mensimulasikan data biokinetik Tc-99m daripada sorotan kajian bagi dosimetri dalaman semasa pengimejan SPECT/CT. Tujuh peratus daripada isi padu 370 MBq dan 74 MBq masing-masing dimasukkan ke dalam fantom tiroid orang dewasa dan kanak-kanak berumur 10 tahun. Hasil yang diperoleh dibandingkan dengan nilai Suruhanjaya Antarabangsa bagi Perlindungan Radiologi (ICRP) dan perisian Pemodelan Eksponen/Penilaian Dos Dalaman Aras Organ (OLINDA/EXM). Keputusan menunjukkan perbezaan yang agak kecil berbanding dengan hasil dosimeter ICRP (7.43 % untuk orang dewasa dan 20.37% untuk kanak-kanak). Ini boleh dirujuk kepada data pembersihan ginjal teknetium dan taburannya dalam badan dengan menggunakan data eksperimen yang dijalankan terhadap manusia dan haiwan pada tahun 1960-an. Perbezaaan peratus antara perisian OLINDA/EXM dengan dos purata daripada kajian dosimetri menunjukkan perbezaan yang ketara (84.11 % untuk orang dewasa dan 107.45 % untuk kanak-kanak). Hal ini kerana perisian OLINDA/EXM bergantung pada pengiraan nilai eksponen dan input model kinetik dalam pengiraan dos radiasi dalaman. Hasil kajian menunjukkan teknik biokinetik ini boleh digunakan untuk mendapatkan dos terserap sebagai alternatif dan kaedah yang praktikal bagi pendekatan dosimetri individu berbanding dengan pengiraan atau perisian simulasi. Kesimpulannya, kajian ini menunjukkan bahawa pengkuantitian dos radiasi dalaman dan luaran bagi tiroid boleh diperoleh dengan menggunakan fantom leher-tiroid bercetak 3D rekaan.

DESIGN AND FABRICATION OF A 3D PRINTED THYROID PHANTOM FOR RADIATION DOSIMETRY

ABSTRACT

Estimation of internal and external radiation dose from SPECT/CT procedures depends mainly on calculations of Medical Internal Radiation Dose (MIRD) methods. Currently, there is no dynamic thyroid phantom with a precise geometrical shape which can simulate the biokinetics of the radiopharmaceuticals in the thyroid. The goal of this study was to design and fabricate a three-dimensional (3D) dynamic thyroid phantom for dosimetry and image quality evaluation. Nine 3D printing materials were evaluated in terms of elemental composition, mass attenuation coefficients, CT numbers and mass density, where The Energy Dispersive X-ray Spectroscopy (SEM-EDS) machine, CT scanner of two different CT modes (single-energy and dual-energy imaging) and online version of the XCOM photon cross-section database were used. The results were compared with the attenuation values of the thyroid, where polycarbonate (PC) material shows a good match and can be used as a tissue-equivalent material for human thyroid to 3D print the thyroid phantom in this study. Hollow and solid thyroid phantoms were designed using 3D Max software. Both thyroid models have two holes on each lobe for installation of radiation dosimeters (i.e. thermoluminescence and optically stimulated luminescence dosimeters). The infusion syringe pump was used to simulate the biokinetics data of Tc-99m for internal dosimetry during SPECT/CT imaging. Seven percent of 370 MBq and 74 MBq were administered into the thyroid phantoms of adult and paediatric of 10 years old, respectively. The results were compared with International Commission on

Radiological Protection (ICRP) values and Organ Level Internal Dose Assessment/Exponential Modelling (OLINDA/EXM) software. The results showed slightly lower difference from dosimeters than ICRP results (7.43 % and 20.37% for adult and children, respectively). The percentage differences between the OLINDA/EXM dosimetry study showed a significant difference (84.11 % and 107.45 % for adult and paediatric, respectively). The close results from ICRP may refer to that the ICRP using the experimental data on humans or animals that was published in the 1960s, while OLINDA/EXM software applies complicated calculations using hypothetical and standardised phantoms and models of the human body with simple geometry shapes. The biokinetics procedure results reveal that the technique applied can be used to quantify internal and external radiation dose to thyroid as an alternative and practical method for an individualised dosimetric approach other than using calculations or simulation software.

CHAPTER 1 INTRODUCTION

1.1 Introduction

Since the discovery of X-rays by Rontgen in 1895 and decay of radioactivity by Becquerel in 1896, many tools and instruments used in diagnostic radiology and nuclear medicine have evolved. In general, nuclear medicine studies the function of the body, using different imaging techniques, such as producing a 3-dimensional image using single-photon emission computed tomography (SPECT), which shows better detection of lesions than with planar imaging.

Although it is weak in showing the anatomical details which can lead to uncertain interpretations due to a lack of localisation information of the lesion (Jacene et al., 2008). Many software tools have been used to integrate the function of images from nuclear medicine with the anatomical images from computed tomography (CT), and this enhances the patient care and management decisions. This is called hybrid imaging.

Computed tomography can be utilised in nuclear medicine for three major different purposes: attenuation correction, radiopharmaceutical's anatomical localisation and for diagnostic examination (STUK - Radiation and Nuclear Safety Authority, 2012). Further work on this technique continues to enhance the sensitivity of the camera, spatial resolution and image reconstructions. In these hybrid imaging techniques, radiation exposure catches more attention due to the increase of dose level from CT and high effective dose from radionuclides in nuclear medicine. Attention is now leading towards reducing the patient absorbed dose especially in paediatric imaging, besides keeping a high-quality image. This indicates the importance of in vivo radiation dose measurement of radiosensitive organs like the thyroid during a clinical procedure.

The right choice of radionuclides and suitable activity are essential to assess the internal dosimetry for different organs. This will assist to optimise the quality of images as well (Chaichana and Tocharoenchai, 2016). The injection, inhalation or oral intake of these radioisotopes to patients are considered as the primary contents of nuclear medicine practice, whether for diagnostic, therapeutic or research purposes.

Thus, new procedures and strategies are improved side by side with presenting of new radiopharmaceuticals (ICRP, 2015). It has also helped to discover new types of radiopharmaceuticals, develop the production of the radioisotopes and to innovate new techniques, which have enhanced the quality of patient care with a clear understanding of the nature of radioactive materials and how they are detected (IAEA, 2015).

Using ionising radiation is essential for all diagnostic procedures, and this involves the risk of cancer development later in life. The thyroid is considered as a radiosensitive organ, and is exposed to a direct beam during neck examination in a CT scan, which increases the lifetime risk of inducing cancer, especially for paediatric patients.

For the dosimetry purposes, the external exposure of a radiation beam can be directly measured using many real-time dosimetric tools such as skin dose or dose area product to evaluate the patient's dose.

Estimation of absorbed dose from internal exposure involves complicated procedures, and it depends on the dose calculation that is usually performed using Medical Internal Radiation Dose (MIRD) methods based on measurement of the biokinetic data of different organs. The manual calculation is time-consuming and highly operator-dependent, which leads to the development of software tools including the Organ Level INternal Dose Assessment/EXponential Modeling (OLINDA/EXM) software to ease these calculations. Evaluating the dose using phantoms provides many advantages over the mathematical methods since the irradiation geometry and the energy spectrum of the photon are always changing and need to be considered when calculating the dose.

Numerous studies have developed many cumulative dose assumptions and theoretical hypotheses, where each radionuclide has its characteristic in the body. Although many of these studies and assumptions applied the calculations of the MIRD model, their assessments and results have varied widely over the years. Performing practical studies is rare, and the results could conflict with the theoretical studies, which may lead to incorrect research evaluations (Chu et al., 2012).

There are several factors and difficulties in internal dosimetry compared to external dosimetry such as the absence of a direct method to measure the internal radiation dose to a patient, the distribution of the radioactive substances inside the body or inside the organ itself as it is not homogeneous, and each radiopharmaceutical has its own biokinetics inside the body. Besides that, the internal dose is complicated and takes a prolonged period since nuclear medicine examination takes a somewhat lengthy time as well.

Anthropomorphic phantoms are constructed from various tissue substitute materials, which have been used widely for radiation dosimetry purposes. These phantoms consider the attenuation properties and the actual physical shape and size of the organ which mainly affects the results of the adsorbed dose. In commercially available anthropomorphic phantoms, there is no specific geometry of thyroid and it is considered as a homogenous organ with the same tissue substitute with soft tissue, which cannot be a precise representative of an actual thyroid gland.

In general, phantoms can be classified into two categories; imaging or dosimetric phantoms based on their applications in diagnostic radiology (White, 1993; Jones et al., 2006). To assess image quality for optimizing acquisition procedures, the imaging phantoms are used as a primary tool to fit this need, where this will lead to radiation dose reduction for the patients. In contrast, dosimetric phantoms are used to evaluate the dose in a patient's organs during a clinical procedure.

Generally, the dosimetric phantoms are designed using different tissue equivalent materials, based on a patient's body characteristics such as, size, weight and gender. Different tissue compositions, such as water, protein and lipids are changed with age for both males and females (White, 1993). This has revealed the importance of considering age in designing and fabricating phantoms for dosimetric purposes. Several anthropomorphic phantoms are fabricated to simulate the anatomical structure of human organs based on age and gender, and have similar attenuation properties for radiation dosimetry studies.

During the clinical procedure, computational simulation methods become very complicated. This provides the advantage for using anthropomorphic phantoms over mathematical methods. Currently, there are no dynamic anthropomorphic thyroid phantom, which can simulate the injection and retention of the radioactive material. The fabrication of such dynamic phantom is important to measure the absorbed dose directly to the human thyroid gland from SPECT/CT.

In CT scan procedures, several dose reduction techniques can considerably lower the dose, such as automatic current modulation, low kVp and with the use of post-reconstruction algorithms.

It is important to consider the variation of acquired dose in CT due to various types of CT scanner, scanning protocols and the divergence of scan length selected. Therefore, a standard recommendation regarding good practice in CT scans especially for paediatric patients should be taken into account, especially as the use of CT is still increasing.

The understanding of the biological effect in the future has not matured yet, particularly when a series of CT tests may apply, and the possibility of having cancer risk later in life may increase as well. Therefore, assessment of cancer induction risk allows for choosing of more efficient CT protocols to decrease the dose.

The combination of hybrid imaging with SPECT/CT is commonly increasing, where stand-alone SPECT in many applications being replaced with this new scanning technique (Fahey, Treves, and Adelstein, 2012). SPECT/CT provides useful information about cellular functions and the anatomical structures of the human body. However, the use of such sources of radiation contributes to a high dose to the radiosensitive organs under test as well as increasing the effective dose to the patient. This requires investigations to assess these kinds of diagnostic procedures especially in children.

Thus, this study focused on fabrication of a dynamic 3D printed thyroid-neck phantom to evaluate the absorbed dose to the thyroid gland in SPECT/CT imaging.

1.2 Problem statement

Generally, the importance of dosimetry of patients comes from estimating the radiation absorbed by different types of tissues and organs in the body. By estimating the dose received by organs, the protocols applied can be enhanced to lower the dose especially for paediatric patients (Hranitzky and Stadtmann, 2011).

For diagnosis and therapy purposes in nuclear medicine, the internal dosimetry is crucial, where usually, MIRD method is used to assess the internal radiation dose in nuclear medicine. This approach depends on the biokinetic organ model and the kind of radiopharmaceuticals used. Several commercial software programs have been developed to help calculate the radiation dose to different organs, where the manual calculations are time-consuming and highly operator dependent (ICRP, 2015; Chaichana and Tocharoenchai, 2016).

Notwithstanding, the literature on previous researches (Hranitzky and Stadtmann, 2011; Aw-Zoretic et al., 2014; Spampinato et al., 2015; Fahey et al., 2017) indicate that, although the importance of patients' radiation safety in nuclear medicine procedures has been stressed, only limited studies have directly measured the radiation dose received by the patients' thyroid during diagnosis procedures.

Many phantoms were fabricated for image quality in scintigraphy images or SPECT-CT images, but only a few static phantoms were designed for internal dosimetry in the thyroid. Application of the thyroid's pharmacokinetics data of each radionuclide for accurate internal dose measurements is considered as a challenge. Currently, there is no dynamic thyroid phantom with a precise geometrical shape which can simulate the biokinetics information, and which can mimic the injection, retention and the excretion of the radiopharmaceuticals in the thyroid.

These concerns emphasise the problems of a patient's thyroid dose during regular scintigraphy procedures or during utilisation of the CT in the SPECT proceedings and the lack of knowledge about the contribution of exposure parameters on a patient's dose.

The current in vivo dose evaluation methods are used as a post evaluation of the internal dose and do not provide any real-time measurements for the thyroid during the diagnostic or therapeutic procedures in nuclear medicine.

The current commercial anthropomorphic phantoms mainly simulate the human thyroid as a homogenous organ with basic geometrical shapes like small cylinders, which does not precisely represent the actual human thyroid. This may cause inaccuracy in the radiation dose to the patient's thyroid, and in particular for different group ages.

In this project, we aimed to design and fabricate an affordable and dynamic 3-dimensional thyroid phantom, which simulates the real shape of thyroid gland. The phantom can fit different ages and genders as it has the feature of fast fabrication and dimension alternation using the 3D printing technology and commercially available material.

1.3 Research objectives

The main objective of this study was to fabricate a cost-effective 3-dimensional dynamic thyroid phantom for evaluation of radiation dosimetry and image quality.

The specific objectives of this study are listed as follows:

1. To evaluate different 3D printing materials as a thyroid tissue substitute using a new and a conventional method.
2. To design and fabricate a cost-effective, dynamic anthropomorphic thyroid phantom by using the 3D printing technology.
3. To evaluate biokinetics data of technetium pertechnetate for internal dosimetry in SPECT/CT imaging.
4. To evaluate the radiation dose to the thyroid for adult and paediatric SPECT/CT examinations.

1.4 Research scope

This research would introduce nine different types of 3D printing materials (i.e. PLA, ABS, PC, PETG, TPE, TPU, HIPS, PA and Wood-like) for evaluation as equivalent to human tissues in terms of elemental compositions, CT numbers and mass attenuation coefficients. Two different method will be used to evaluate the mass attenuation coefficients of the 3D printing materials using Scanning Electron Microscope - Energy