ORIGINAL ARTICLE

Comparison of Average Absorbed Dose Distributions of Organs in SPECT-CT Imaging Using Monte Carlo Simulation

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Abstract

Purpose: The use of ionizing radiation in medical research, treatment, and diagnosis is inevitable and expanding day by day. Meanwhile, in two modes of Computed Tomography (CT) and Single Photon Emission Computed Tomography (SPECT) imaging, the dose received by the organs is featured with limitations and problems, which are often referred to as the CT Dose Index volume (CTDIvol.) and the Dose Length Product (DLP). This study aimed to estimate the average dose of organs and compare them in each of these two modalities.

Materials and Methods: Using the GATE code to simulate the SPECT-CT system and the International Commission on Radiological Protection (ICRP) voxelized phantom as the patient was investigated. The mean dose distribution in three groups of children, adults, and obese people with different body thicknesses was estimated. The dose received by each of the two systems was evaluated separately and results were discussed and analyzed comparatively.

Results: In the kidney, bladder, intestine, colon, liver, and gallbladder, the dose received in CT is at least 10% more than nuclear medicine. For example, the ratio of the dose received in CT to the dose received in nuclear medicine in the lung was about 1.08 and in the esophagus was about 1.24. Subsequently, the ratio increased to 0.25 in the bladder and 0.19 in the colon and intestine. Moreover, the major organs that received the maximum dose, result in CT at least 10% more than nuclear medicine.

Conclusion: The dose received in organs such as the esophagus, breast, and lung during CT imaging protocol and also maximum dose were at least ten percent more than nuclear medicine.

Keywords: Computed Tomography Scan; Single Photon Emission Computed Tomography-Computed Tomography; Monte Carlo Simulation; Absorbed Dose.

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1. Introduction

The introduction of dual systems in the form of Single-Photon Emission Computed Tomography-Computed Tomography (SPECT-CT), Positron Emission Tomography (PET)-CT, etc. has created a great change in the implementation of conventional imaging protocols and improved the quality of the resulting images, so tomographic images from CT, SPECT and PET are important components in current medical imaging [1,2]. On the other hand, the revolution of dual imaging systems such as SPECT-CT and the achievement of new goals in the reconstruction of images based on various software has changed the attention of physicians from anatomical imaging to functional imaging [3]. One of the main reasons for using dual imaging systems is to reduce the shooting time [4] which is due to the reduction of the amount of rotation of each head and leads to a decrease in the depreciation of the device [5]; and also the patient's comfort and the consequent reduction of the error due to the patient's movement [6] because the CT imaging technique is based on ionizing radiation, the imaging protocol is performed by rotating the radiation source around the patient and recording the radiation reflected the detector during which the radiation source has one rotation per second, so the dose is originated from two modalities, SPECT and CT, that should be considered important and significant [7, 8], after rotating the radiation source, while a detector array is facing each other, photons passing through the patient's body are recorded, but in nuclear medicine, the radiation injection into the patient's body and its uneven distribution throughout the body will lead to images [1]. In both systems, the energy is estimated in the form of absorbed and scattered photons in the patient's body, so that the patient exposure is the sum of the beam distribution in both systems [7]. Calculating the dose emitted from CT is impossible and the estimated dose of the organs is always considered a criterion [9]. Due to the proliferation of dual imaging modalities around the world, the patient's exposure to radiation is the minimum dose received by the tissue, which is the lowest acceptable level for the tissue [3]. Dose in CT is expressed in terms of criteria such as CT Dose index volume (CTDIvol.) in mGy and Dose Length Product (DLP) in mGy per centimeter. [10]. As a major limitation, CTDIvol. cannot represent the dose received by the patient, so the estimate of the dose received by the tissue is discussed [11]. In nuclear medicine, low-dose absorption CT systems are commonly used, which impose a lower dose on the patient compared to diagnostic imaging, but in any case, the possibility of overdose is been. There are also CT scan systems used in nuclear medicine [12]; especially when a fixed protocol is used to image all the patients. Due to this problem, to control and be aware of the dose received by patients, indicators have been determined that can be used to estimate the patient dose [13,14].

Many efforts have been made in clinical studies, which can be seen in various researches over the past years [15]; attempts have been made to estimate the dose of patients undergoing CT scans [16] or to estimate the dose of tissue received in a different age of groups [17], but the use of simulation systems, especially CT simulation and organ dose estimation using Monte Carlo, is not visible. CT simulation as a new challenge in the field of Monte Carlo studies and evaluation of results in the comparative phase alongside the nuclear medical imaging system highlights this research compared to other theoretical studies. The existence of simulation systems certainly will be of great help to theoretical studies, but it is also important to note that the design and implementation of a simulation protocol may take days or even weeks, which is certainly time-consuming and practically for clinical purposes is impossible and unusable over the next few years [18]. This can be one of the main limitations.

In this study, the absorbed dose of organs, especially trunk organs, was evaluated due to a large number of heart tests. The maximum absorbed dose by the organs in CT imaging and the use of technetium radiation as well as the approximate estimation of the absorbed dose in each of the two modalities used in the study objectives. Therefore, in the present study, the dose distribution due to CT imaging was calculated and compared with the dose distribution due to nuclear medicine imaging.

2. Materials and Methods

2.1. Monte Carlo Simulation, GATE Code

The best method of specificity dosimetry in nuclear medicine and the use of SPECT and PET images to determine the distribution of activity in the body and the use of CT images to determine the body attenuation map is the Monte Carlo method to estimate the dose in different areas of the body [19]. This study is based on the Monte Carlo simulation and implemented using the GATE code. The radionuclide used is ^{99m}Tc, the decay of which is obtained from the data provided by MIRD [20].

2.2. Simulation of CT

The SymbiaT6 SPECT-CT system manufactured by Siemens company base on Figure 1 has been simulated that the tube current intensity is 150 mAs and the voltage is considered at three peaks of 80, 110, and 130 kV. The X-ray tube is not simulated and only the output X-ray spectrum is used as a radiation source (voltage 80, 110, and 130 kV). 50 simulations were considered that have been inserted into a box with specific diameters for CT Scanner and also "Module", "Cluster" and, "Pixel" and finally attached. The Physics of the system was considered "standard" and also the type source was "Plane" with a "Rectangle" shape and the user spectrum was 130 keV-63 Al for the "energy type".

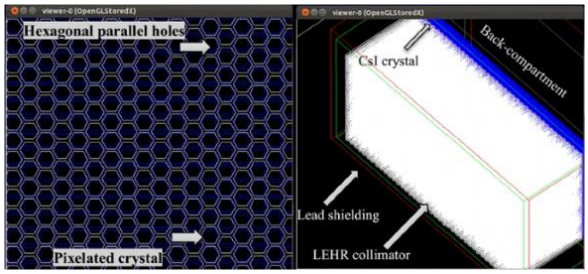


Figure 1. Gate Monte Carlo Simulation for SPECT

2.3. Simulation of SPECT

SPECT simulation, similar to CT, is performed base on Figure 2 using the information in the device manual, which is low energy all-purpose type collimator. The detector and electronics parts of the system are also simulated by GATE modules (module, cluster, pixel, …). The scanner has consisted of a Head, Shielding, Collimator, Holes of Air in the Collimator, Crystal, and also a Back-Compartment. Source has been defined as "Point Type" with "Cylinder Shape" and 130 keV energy gamma particles.

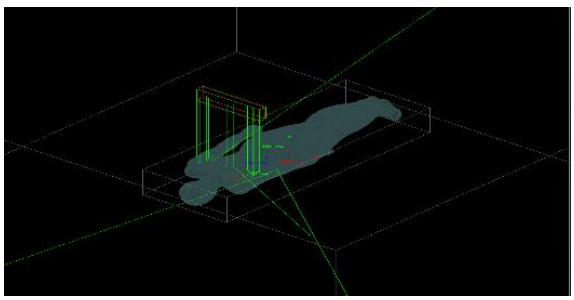


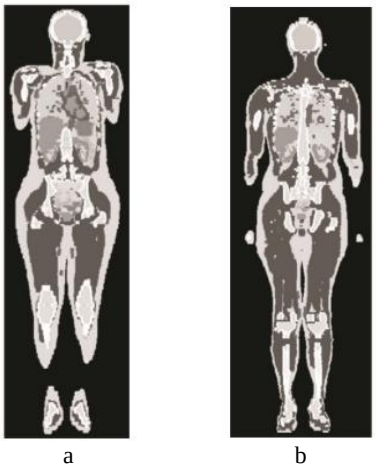
Figure 2. Gate Monte Carlo Simulation for CT

SPECT head has been considered a box with dimensions of about 22 cm, 63 cm, and 47 cm. Its material is Vacuum and simulated based on one ring which orbits with 2.81 deg/s. The next part, shielding, a box with dimensions of about 2 cm, 59 cm, and 38 cm has been set with Air material.

To be able to simulate the collimator in the GATE interface, since the shape of the arrays was considered hexagonal, the thickness of the array edges, as well as the distance between the arrays, were considered by the device manual. The lead collimator has been simulated as a box with dimensions of about 2.40 cm, 59 cm, and 43 cm. Height of the holes is 24.05 mm with a 1.75 mm radius which rotates 90 degrees in the Y-axis each simulation. Holes have been repeated in X, Y, and Z axes with the number of 1, 160, 68 arrays, respectively. NaI crystal and also Glass back compartment were the last parts that have been simulated with dimensions of about 2.15 cm, 59 cm, and 40 cm and 2 cm, 59 cm, and 35 cm, respectively.

2.4. ICRP Phantom

Figure 3 indicate the International Commission on Radiological Protection (ICRP) tuned phantom is used as an "input file" in the simulation, which is used in adult size with both sexes. According to it, 141 organs or tissues in the body are embedded according to their specific anatomical structure. By changing the dimensions of the waxes, the phantom has been prepared in two sizes, smaller (used for children) and larger (used for obese people).



a b

Figure 3. ICRP phantom image: a) female and b) male

The change in the size of the original phantom is based on a theory of American Association of Physicists in Medicine (AAPM), recorded by clinical measurements of the AP and Lateral body thickness of patients in the SPECT-CT imaging. All possible interactions for the

photon, including Photoelectric Absorption, Compton Scattering, and Riley, as well as possible interactions for the electron, such as the production of Bremsstrahlung, Ionization, Specific Radiation, and Auger electron production are considered. Electron and photon cut-off energy are defined as the minimum acceptable value for the Gate code (25% kV). Phantom activity is based on the distribution of Technetium-99m-Sestamibi radiation in the patient's body and the Gate code is used to calculate the dose [21].

Phantom has been prepared for 50 simulation models in three groups of children, adults, and obese people based on different thicknesses. These thicknesses are taken from the published AAPM results based on the effective thickness obtained from both AP and Lateral thicknesses of the body [1,22]. This simulation is intended for children with a voltage of 80 kV, adults with a voltage of 110 kV, and for obese people with a voltage of 130 kV, which corresponds to the amount of voltage applied in imaging protocols. The binary file obtained from the simulation of the SPECT-CT system containing the absorption dose of different phantom organs that cannot be read in the GATE environment was executed using MATLAB software and the average absorption dose of the trunk organs was obtained.

2.5. Validation of the Simulation

The system is validated experimentally using the Siemens executive protocol. Validation of the simulated system is done in two steps. In the first stage, the imaging was performed using simple geometric phantoms. This phantom is the CTDI reference phantom, which was purchased by the German company Siemens and is available in two sizes, Head and Body, with two diameters of 16 cm and 32 cm [23].

The phantom is a chemical-polymeric compound (Polymethyl Methacrylate) or PMMA, which has a density of 1.19 g/cm^3 and a weight of about 20 kg. In this validation, the Phantom Head part is used, which consists of 5 cylindrical holes with a maximum diameter of 1.31 cm, and the detector sensor is installed in the middle hole. CTDP or CT dose profile is an advanced dose point that is used in Helical systems in addition to evaluating the CT dose index in all units and also in determining the geometric efficiency of the system [24]. To check the validation of the system, in addition to the reference phantom, three other auxiliary tools have been used. A pencil-shaped sensor for beam detection, an electrometer attached to the sensor to record detected beams, and a software system called Ocean 2014 are involved. Each electrometer can record 2000 units of absorption dose per second, which is claimed to be the most suggested and safest method for evaluating the dose and plotting the graph. The basis of this process is to complete irradiation of the sensor inside the phantom, recording of information by the electrometric system connected to the detector, and then the entry of information wirelessly into the software used, which draws the dose profile graph on the screen. The input voltage is 120 kV and the current is 50 mA per second. It is also necessary to insert the pitch of the device at a rate of 1. The rotation time is 1 second and the scan time is 10 seconds. If, in addition to the CTDI estimate, the amount of DLP is significant, a scan length of 143 mm is required, which naturally covers the length of the phantom. As soon as the radiation starts, an indirect wireless connection is established between the software and the detector, and by moving the phantom bed, it is placed in the right place, which moves forward at a speed of 12 mm per second. After irradiation, the information about the CT dose index can be seen on the screen, and the relevant dose profile is drawn immediately. For the next step, the detector is placed outside the phantom to evaluate the ground dose and geometric performance of the sensor. The execution protocol is quite similar to the previous method, only the parameters used change slightly. At this stage, a current intensity of 200 mA is used, which increases the scan time to 14.4 seconds. Geometric efficiency obtained to check other cavities and working accuracy, more than 70% must be obtained to finalize the protocol used.

Validation of the simulation in the Gate interface has been considered by using a cylindrical phantom with one central detector and four peripheral dose actors. Scan time for running the simulation as well as rotation time has been adjusted the same as the experimental parameters demonstrated in Table 1, CTDI results in the practical exam indicated in Table 2 and the final results have been compared with the experimental results in Table 3.

Theoretical formulas have been used for CTDI calculations in the simulation environment which are as below [17,25].

$$CTDI_w = \frac{1}{3} CTDI_{100}^{center} + \frac{2}{3} CTDI_{100}^{periphery} \quad (1)$$

$$CTDI_{vol.} = \frac{CTDI_w}{pitch} \quad (2)$$

Table 1. CTDI Parameters in the validation calculation

CTDI Parameters in Experimental Exam	
mA	50
Kv	120
Total inherent filtration (mm)	7 AL
Scan time(s)	10
Delay (s)	4
Rotation time(s)	1
Collimation (mm)	12
Pitch	1
Scan length(mm)	143
Measuring time(s)	10
Scan speed(mm/s)	12

Table 2. CTDI results in the validation calculation

CTDI Results in Experimental Exam	
Kv	120
CTDI(100,C)	34.71 mGy
CTDI(W)	37.77 mGy
$CTDI_{vol.}$	37.77 mGy
DLP(mGy.cm)	838.4

Table 3. CTDI Comparison of simulated SPECT-CT and experimental SPECT-CT

CTDI (Gy) Based on Simulation	CTDI (Gy) Based on Experimental Results
2.98E-02	3.77E-02

3. Results

According to the examination of the mean absorbed dose (mGy) in two modalities of SPECT and CT, the results obtained from the simulation-based on Figure 4 can be displayed.

Given that these two modalities operate differently; the spectrum received by the organs varies as the SPECT participates as an internal emitter and the CT as an external emitter. In nuclear medicine, the organs responsible for the excretion of substances have the highest uptake and have a higher peak graph in the diagram [26,27]. For example, in organs such as the kidneys, bladder, intestines, colon, liver, and gallbladder, an increase in peak diagram can be seen as shown in Figure 4. In nuclear medicine centers, high-fat materials such as cream or high-fat milk are used before the imaging protocol to reduce the absorption of activity in the liver and gallbladder so as not to disturb the image, but providing this issue in simulation is not possible and is one of the limitations. In a comparative classification, the dose of CT in respiratory organs such as the lungs and esophagus and organs such as the breast is at a higher peak than in nuclear medicine, which is seen at 130 kV over the 110 kV energy spectrum. This dose increase has been estimated to be relative to the mean dose (mGy) in CT and nuclear medicine in the two phantoms, as shown in Table 4 below.

Table 4. Mean dose ratio (mGy) at different energies in CT and nuclear medicine in male and female phantoms

Organ	Average Dose (Female) /N.M	Average Dose (Male) /N.M
Bladder	0.10	0.25
Breast	1.17	0.00
colon	0.19	0.19
Gall bladder	0.07	0.00
Heart	0.66	0.58
Intestine	0.16	0.19
Kidney	0.19	0.17
Liver	0.61	0.58
Lung	1.08	1.02
Esophagus	0.94	1.24
Stomach	0.76	0.67

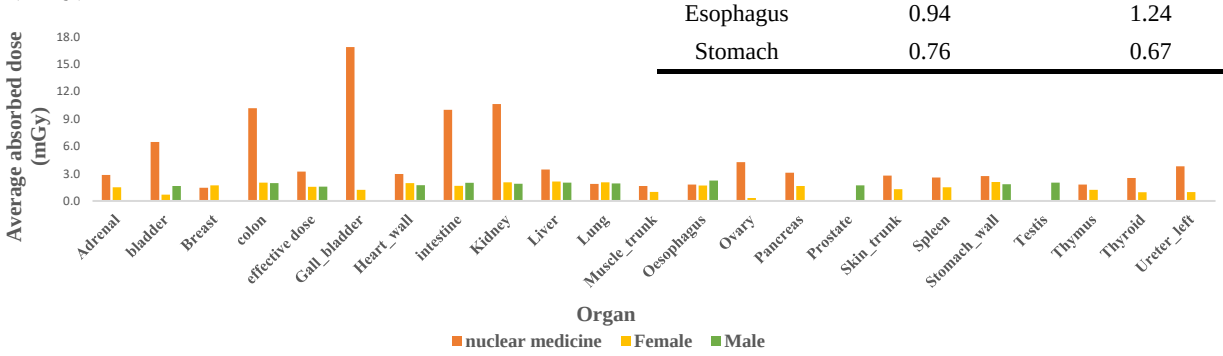


Figure 4. Graph of the average absorbed dose in different organs in the two modalities of SPECT and CT in terms of mGy in both groups of men and women

According to the above Table 4, the ratio of the average dose obtained in different energies in terms of mGy in CT is compared with the dose received in nuclear medicine, which has been separated into two separate columns, male and female phantom. Due to the increase in diagram peak in the excretory organs, other organs in CT have shown a higher dose increase than in nuclear medicine, which is visible by at least 10%, for example in the lungs and breast. Also, the maximum dose received by the organs in mGy according to Table 5 is as follows:

Table 5. Maximum dose of organs received (mGy) in CT and nuclear medicine during different energies in male and female phantoms

SPECT-CT	Organ	Max Dose (mGy)
Nuclear Medicine	Gall bladder	16.9
Female – 80 kV	Esophagus	2.11
Female – 110 kV	Spleen	2.18
Female – 130 kV	Spleen	2.28
Male – 80 kV	Esophagus	2.09
Male – 110 kV	Esophagus	2.28
Male – 130 kV	Esophagus	2.34

According to Table 5, the maximum dose received in nuclear medicine in the gallbladder is 16.9 mGy dose. In CT, the maximum dose received by a male phantom is 130 kV, which can be seen in the esophagus with a dose of 2.34 mGy. However, to compare the two modalities used in the study, the maximum dose was compared in similar organs, so that in the case of breast, esophagus, and lung, the maximum dose absorbed in CT was more than nuclear medicine and with a probability of at least 10% increase and gradually increases with increasing energy, so, as shown in the Table 6, the maximum dose received by the phantom in CT in an organ such as the esophagus is at least 10% higher than in nuclear medicine.

4. Discussion

Although in patients, there is no limit to the dose received and the only rule of cost-benefit is to determine whether or not to perform imaging, it should be noted that in any case, according to the protective principles the patient dose should be quantified to be able to determine the risk and complications of receiving radiation [28, 29]. The main purpose of this study was to estimate the dose absorbed by the organs in a SPECT-CT imaging protocol and to compare two modalities with each other. Based on

Table 6. Percentage increase in organ doses in the transition from 80 kV to 110 kV and also 110 kV to 130 kV

Sex	Female			Male		
Energy(kV)	80	110	130	80	110	130
Adrenal		%23	%8		%25	%10
Bladder		- %86	%10		%85	%9
Breast		%81	%5		-	-
Colon		%1.4	%4.6		%1.7	%5
Effective Dose		%0.7	%4.3		%0.8	%4
Gall Bladder		%12	%17		%12	%15
Heart Wall		%21	%5		%25	%5
Intestine		%18	%5		%18	%5
Kidney		%4	%6		%4.5	%6
Liver		%8	%5		%9	%6
Lung		%11	%5		%12	%6
Muscle Trunk		%19.5	%15		%20	%17
Oesophagus		%32	%7		%33	%5
Ovary		%73	%12		-	-
Pancreas		%12	%6		%12	%6
Prostate		-	-		%23	%7
Skin Trunk		%32	%2		%33	%1
Spleen		%24	%5		%25	%4.5
Stomach Wall		%22	%5		%21	%6

the results obtained from the simulation, in addition to the heart organ, several vital organs of the trunk such as the thyroid, spleen, lung, breast, etc. have also been examined. The aim was to calculate the CTDIvol. which according to the quantity and quality of X-rays be close (maximum 5% difference) to the actual system output. The simulated CT validation was performed using a simple cylindrical phantom design and CTDI output calculation. SPECT validation was performed to increase the accuracy of the final results and the final confirmation of the simulation using the absorption dose of the organs in the references. Due to the importance of heart exams and a large number of scans, the trunk organs have been examined and validated one by one with the items reviewed in articles and studies. According to the studies that are mostly clinical and there is no attempt to use simulation codes, especially CT simulation, the absorbed dose for each section of CT scan is 2 to 4 cGy [30, 31] and the average dose in nuclear medicine is approximately 0.5 to 1 cGy [32, 33]. In CT, the radiation is uniform as an external emitter but becomes non-uniform as soon as it enters the tissue, whereas, in nuclear medicine, which is an internal emitter, the distribution of radionuclide in the body is uneven [34]. Excretory organs that are responsible for controlling and expelling substances

from the body, have a higher uptake than the other organs and have a high accumulation of injectable radionuclides [23, 35]. This is in organs such as the liver or gallbladder with a higher peak ratio [24]. On the other hand, it is obvious that the dose received due to CT imaging depends on the patient's physical size [36-38]; Of course, it was necessary to consider three energy spectra to evaluate this study. For this purpose, the main phantom corresponds to the size stated in the ICRP report with an energy spectrum of 110 kV. The energy spectrum of 80 kV is equal to the tests used in children and 130 kV is for the study of obese people. According to the obtained results, in passing the energy spectrum of 80 to 110, with the increase in the amount of voltage, an increase in the absorbed dose of the organs in both female and male phantoms has been seen. This issue has appeared in the transition from the energy range of 110 to 130 with a smaller percentage increase than the first case and indicates a lower dose increase than the first one. Also, by juxtaposing two modalities of SPECT and CT imaging, the percentage of increase in CT dose compared to SPECT in organs such as the esophagus, breast, and lung can be expressed by at least 10%, and the maximum dose received in these two modalities in organs like esophagus, breast, lung and thymus, CT has resulted in more than nuclear medicine, leading to an approximately 10% increase in dose. So, the need to pay attention to the dose received by the patient resulting from a SPECT-CT imaging protocol requires attention to the dose of output from each of these two systems. Monte Carlo simulation, combined with medical phantoms and simulation tools, significantly reduces the potential risks and allows the user to use the available facilities and implement the real world as much as possible [37]. It is important to note that the design and implementation of a simulation protocol may take days or even weeks, which is certainly time-consuming and practically impossible, and unusable for clinical purposes in the next few years. This has been one of the main limitations of this study, which has made the study time-consuming and lengthy.

5. Conclusion

The dose received in organs such as the esophagus, breast, and lung during CT imaging protocol is at least 10% more than in the case of technetium radiopharmaceuticals. Also, the maximum dose received in these two imaging modalities in organs such as the esophagus, breast, lung, and thymus is approximately a 10% increase dose in CT resulted more than nuclear medicine.

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References

1- Jodie A Christner, Natalie N Braun, Megan C Jacobsen, Rickey E Carter, James M Kofler, and Cynthia H McCollough, "Size-specific dose estimates for adult patients at CT of the torso." *Radiology*, Vol. 265 (No. 3), pp. 841-47, (2012).

2- Yingzhen N Zhang *et al.*, "Liver fat imaging—a clinical overview of ultrasound, CT, and MR imaging." *The British journal of radiology*, Vol. 91 (No. 1089), p. 20170959, (2018).

3- Hamid Abdollahi *et al.*, "Radiation dose in cardiac SPECT/CT: An estimation of SSDE and effective dose." *European journal of radiology*, Vol. 85 (No. 12), pp. 2257-61, (2016).

4- A. K. Buck *et al.*, "Spect/Ct." *J Nucl Med*, Vol. 49 (No. 8), pp. 1305-19, Aug (2008).

5- Price A Jackson, Michael S Hofman, Rodney J Hicks, Mark Scalzo, and John Violet, "Radiation dosimetry in 177Lu-PSMA-617 therapy using a single posttreatment SPECT/CT scan: a novel methodology to generate time- and tissue-specific dose factors." *Journal of Nuclear Medicine*, Vol. 61 (No. 7), pp. 1030-36, (2020).

6- RD Khawaja *et al.*, "Simplifying size-specific radiation dose estimates in pediatric CT." *AJR Am J Roentgenol*, Vol. 204 (No. 1), pp. 167-76, (2015).

7- James A Brink and Richard L Morin, "Size-specific dose estimation for CT: how should it be used and what does it mean?," Vol. 265, ed: *Radiological Society of North America, Inc.*, (2012), pp. 666-68.

8- Ivo Rausch, Frank G Füchsel, Corinna Kuderer, Michael Hentschel, and Thomas Beyer, "Radiation exposure levels of routine SPECT/CT imaging protocols." *European journal of radiology*, Vol. 85 (No. 9), pp. 1627-36, (2016).

9- M Lecchi, S Malaspina, C Scabbio, V Gaudieri, and A Del Sole, "Myocardial perfusion scintigraphy dosimetry: optimal use of SPECT and SPECT/CT technologies in

stress-first imaging protocol." *Clinical and translational imaging*, Vol. 4 (No. 6), pp. 491-98, (2016).

10- Kelvin Kwok-Ho Yap, Ganesh Ramaseshan, Tom Sutherland, Raymond Shafik-Eid, Kim Taubman, and Stephen Schlicht, "Prevalence of incidental or unexpected findings on low-dose CT performed during routine SPECT/CT nuclear medicine studies." *Journal of medical imaging and radiation oncology*, Vol. 59 (No. 1), pp. 26-33, (2015).

11- Duo Zhang, Bang-Hung Yang, Nien Yun Wu, and Greta Seng Peng Mok, "Respiratory average CT for attenuation correction in myocardial perfusion SPECT/CT." *Annals of nuclear medicine*, Vol. 31 (No. 2), pp. 172-80, (2017).

12- Richard J Palyo, Albert J Sinusas, and Yi-Hwa Liu, "High-sensitivity and high-resolution SPECT/CT systems provide substantial dose reduction without compromising quantitative precision for assessment of myocardial perfusion and function." *Journal of Nuclear Medicine*, Vol. 57 (No. 6), pp. 893-99, (2016).

13- Karine Assie *et al.*, "Monte Carlo simulation in PET and SPECT instrumentation using GATE." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Vol. 527 (No. 1-2), pp. 180-89, (2004).

14- Kalpana M Kanal, Priscilla F Butler, Debapriya Sengupta, Mythreyi Bhargavan-Chatfield, Laura P Coombs, and Richard L Morin, "US diagnostic reference levels and achievable doses for 10 adult CT examinations." *Radiology*, Vol. 284 (No. 1), pp. 120-33, (2017).

15- Johannes Zeintl, Alexander Hans Vija, Amos Yahil, Joachim Hornegger, and Torsten Kuwert, "Quantitative accuracy of clinical 99mTc SPECT/CT using ordered-subset expectation maximization with 3-dimensional resolution recovery, attenuation, and scatter correction." *Journal of Nuclear Medicine*, Vol. 51 (No. 6), pp. 921-28, (2010).

16- Akihiko Takahashi, Kazuhiko Himuro, Yasuo Yamashita, Isao Komiya, Shingo Baba, and Masayuki Sasaki, "Monte Carlo simulation of PET and SPECT imaging of 90Y." *Medical physics*, Vol. 42 (No. 4), pp. 1926-35, (2015).

17- Choirul Anam, Freddy Haryanto, Rena Widita, Idam Arif, and Geoff Dougherty, "A fully automated calculation of size-specific dose estimates (SSDE) in thoracic and head CT examinations." in *Journal of Physics: Conference Series*, (2016), Vol. 694 (No. 1): *IOP Publishing*, p. 012030.

18- Sébastien Jan *et al.*, "GATE: a simulation toolkit for PET and SPECT." *Physics in Medicine & Biology*, Vol. 49 (No. 19), p. 4543, (2004).

19- Marie-Paule Garcia, Julien Bert, Didier Benoit, Manuel Bardiès, and Dimitris Visvikis, "Accelerated GPU based spect Monte Carlo simulations." *Physics in Medicine & Biology*, Vol. 61 (No. 11), p. 4001, (2016).

20- Emma O'Shaughnessy and Kat L Dixon, "Reducing CT dose in myocardial perfusion SPECT/CT." *Nuclear Medicine Communications*, Vol. 36 (No. 11), pp. 1150-54, (2015).

21- G Zhang, N Marshall, Ria Bogaerts, Reinhilde Jacobs, and Hilde Bosmans, "Monte Carlo modeling for dose assessment in cone beam CT for oral and maxillofacial applications." *Medical physics*, Vol. 40 (No. 7), p. 072103, (2013).

22- SC Blankespoor *et al.*, "Attenuation correction of SPECT using X-ray CT on an emission-transmission CT system: myocardial perfusion assessment." *IEEE Transactions on Nuclear Science*, Vol. 43 (No. 4), pp. 2263-74, (1996).

23- NA Baharul Amin, Nadin Jamal Abualroos, and R Zainon, "Fabrication of anthropomorphic thyroid-neck phantom for dosimetry study in nuclear medicine." *Radiation Physics and Chemistry*, Vol. 166p. 108462, (2020).

24- Maria Zankl, "Adult male and female reference computational phantoms (ICRP Publication 110)." *Japanese Journal of Health Physics*, Vol. 45 (No. 4), pp. 357-69, (2010).

25- I George Zubal, Charles R Harrell, Eileen O Smith, Zachary Rattner, Gene Gindi, and Paul B Hoffer, "Computerized three-dimensional segmented human anatomy." *Medical physics*, Vol. 21 (No. 2), pp. 299-302, (1994).

26- Olivier Gayou, Ellen Day, Seyed Mohammadi, and Alexander Kirichenko, "A method for registration of single photon emission computed tomography (SPECT) and computed tomography (CT) images for liver stereotactic radiotherapy (SRT)." *Medical physics*, Vol. 39 (No. 12), pp. 7398-401, (2012).

27- Martin Law *et al.*, "Evaluation of patient effective dose from sentinel lymph node lymphoscintigraphy in breast cancer: a phantom study with SPECT/CT and ICRP-103 recommendations." *European journal of radiology*, Vol. 81 (No. 5), pp. e717-e20, (2012).

28- Andreas Deresch, Gerd-Rüdiger Jaenisch, Carsten Bellon, and Alexander Warrikhoff, "Simulating X-ray spectra: from tube parameters to detector output." in *Proceedings of 18 th World Conference on Nondestructive Testing (WCNDT), Durban, South Africa*, (2012), pp. 16-20.

29- Yuni K Dewaraja, Scott J Wilderman, Michael Ljungberg, Kenneth F Koral, Kenneth Zasadny, and Mark S Kaminiski, "Accurate dosimetry in 131I radionuclide therapy using patient-specific, 3-dimensional methods for SPECT reconstruction and absorbed dose calculation." *Journal of Nuclear Medicine*, Vol. 46 (No. 5), pp. 840-49, (2005).

30- Mathieu Charest and Chantal Asselin, "Effective dose in nuclear medicine studies and SPECT/CT: dosimetry survey across Quebec Province." *Journal of nuclear medicine technology*, Vol. 46 (No. 2), pp. 107-13, (2018).

31- M Gabusi, L Riccardi, C Aliberti, S Vio, and M Paiusco, "Radiation dose in chest CT: assessment of size-specific dose estimates based on water-equivalent correction." *Physica Medica*, Vol. 32 (No. 2), pp. 393-97, (2016).

32- Nahid Dehghan and Sedigheh Sina, "Measurement of Operational Dosimetry Quantities for Nuclear Medicine Staff." *Radiation Protection Dosimetry*, Vol. 190 (No. 2), pp. 119-24, (2020).

33- R Figueroa, J Guarda, J Leiva, F Malano, and M Valente, "Dosimetry of tumor targeting imaging by convergent X-ray beam as compared with nuclear medicine." *Applied Radiation and Isotopes*, Vol. 167p. 109451, (2021).

34- Andrik J Aschoff, Carlo Catalano, Miles A Kirchin, Martin Krix, and Thomas Albrecht, "Low radiation dose in computed tomography: the role of iodine." *The British journal of radiology*, Vol. 90 (No. 1076), p. 20170079, (2017).

35- Astrid Gosewisch, "Patient-specific bone marrow dosimetry in Lu-177-based radionuclide therapy: investigation of efficient data acquisition protocols and a clinical Monte Carlo dosimetry workflow for 3D absorbed dose modelling." *lmu*, (2020).

36- Giovanni Cabass and Fabian Schmidt, "A new scale in the bias expansion." *Journal of Cosmology and Astroparticle Physics*, Vol. 2019 (No. 05), p. 031, (2019).

37- Lukas M Carter *et al.*, "PARaDIM: A PHITS-based Monte Carlo tool for internal dosimetry with tetrahedral mesh computational phantoms." *Journal of Nuclear Medicine*, Vol. 60 (No. 12), pp. 1802-11, (2019).

38- John Violet *et al.*, "Dosimetry of 177Lu-PSMA-617 in metastatic castration-resistant prostate cancer: correlations between pretherapeutic imaging and whole-body tumor dosimetry with treatment outcomes." *Journal of Nuclear Medicine*, Vol. 60 (No. 4), pp. 517-23, (2019).