An Investigation on Shielding Effect of Bismuth on Lung Ct Scan Using Monte Carlo Simulation

[1]Huseyin Ozan TEKIN, [2]Tugba MANICI, [3]Vishwanath P. SINGH

[1] Uskudar University, Vocational School of Health Service, Radiotherapy Department, Istanbul, 34672, Turkey

[2] Uskudar University, Medical Radiation Research Center (USMERA), Istanbul, 34672, Turkey

[3] Karnatak University, Department of Physics, Dharwad, 580 003, India

(Received : 15.07.2016 ; Accepted : 07.08.2016)

ABSTRACT

Computed tomography (CT) related to computer-processed combination or X-ray images obtained from different angles to create patient's cross-sectional body parts images. CT is mostly associated with high radiation dose to organs during the diagnostic process. To provide the probable effect of bismuth shielding on dose reduction to organs and investigation of applicability of Monte Carlo (MC) method. Monte Carlo (MC) method has been used for calculation of dose attenuation properties of bismuth. MCNPX (version 2.4.0) has been used during the calculations. In this study, validation of modeled MCNPX simulation geometry has been provided by calculating the mass attenuation coefficient values of lung and comparing with previous available studies in literature for lung. Our results agreed well with other results about mass attenuation coefficients of lung. By using the validated MC model, dose attenuation properties of bismuth have been investigated. Dose reduction rates of bismuth on lung have been compared with experimental studies. With bismuth shielding, absorbed dose amount in lung significantly reduced. It can be concluded from MC results that the bismuth shielding reduced lung dose significantly in x-ray CT examination of thorax region.

Key Words: Dose Reduction, Bismuth Shielding, Monte Carlo

1. INTRODUCTION

The use of X-ray in medical applications is the major artificial source for population recieved radiation. One of these applications is known as Computed Tomography (CT). CT is an imaging technique which produces cross-sectional images of body and representing in each pixel the local X-ray attenuation properties of the body. The imaging technology and capabilites of CT scanners have developed enormously in the early 1990's since the introduction of helical computed tomography (CT).The increasing requisition for CT examinations had a considerable impact on doses ensured to patients and on the exposure of the population completely [1]. Same as with the all medical applications utilizing ionizing radiation exposure, it is an important issue that reduce the exposure dose of patient and staff as low as reasonably achievable (ALARA). Different types of CT scans, are named for different uses or for what images they are trying to record and one of them is called as thoracic CT. Thoracic CT is an imaging method that uses x-rays to create cross-sectional pictures of the chest and upper abdomen. It turned out the most proper technique for lung examinations [2]. [DAM1]-. There are many steps that can be taken in order to reduce the radiation dose on a patient. One of such steps is to locate an absorbing materaial onto the patient surface and outside of the anatomy of interest [3]. Bismuth shielding was recommended for use in CT examinations in previous studies [4-9].This study aimed providing the validation of modeled Monte Carlo geometry and simulation setup by using MCNPX code during the investigation of radiation attenuation properties of bismuth shielding material in CT scans. MCNPX is a general purpose radiation transport code for modeling the interaction of radiation with materials and also tracks all particles at all energies. MCNPX is fully three-dimensional and it utilizes extended nuclear cross section libraries and uses physics models for particle types [10]. The capability of MCNPX as a suitable and strong code has been studied in literature. The capability of MCNPX Monte Carlo code on detection efficiency and using of different experimental and Monte Carlo studies has been studied by Akkurt et al. [11]. Also using conditions of MCNPX for dose distribution in PET-CT facility has been studied by Tekin et.al [12].

The effective performance of shielding used to reduce the unnecessary radiation dose of CT examinations has been reported by Kyung-Hwan et.al.[13]. The aim of the present study was to investigate effectiveness of bismuth shielding on lung during CT scan using Monte Carlo method simulation. Therefore, we defined a simulation geometry and provided the validity via comparing the calculated mass attenuation coefficients of lung with other studies. The mass attenuation coefficient μ_m is one of the most important parameter for characterizing the penetration and diffusion of gamma-rays in objective material [17]. In this study, validation of modeled MCNPX simulation geometry for calculation has been provided by comparing numerical simulation results on mass attenuation coefficients results for lung. Thus, validated simulation geometry of MCNPX has been used

*Corresponding Author
e-posta: huseyinozan.tekin@uskudar.edu.tr
Digital Object Identifier (DOI) : 10.2339/2016.19.4 617-622

for investigation of dose attenuation properties of bismuth and effects on absorbed dose amount in lung.

2. MATERIAL AND METHODS

2.1. Validation of MCNPX

The coefficient μ_m is a density independent coefficient and determined for investigated attenuator materials by transmission method according to Lambert-Beer's law $\mu_m \cdot x = \ln (I_0/I)$; where I_0 and I are the incident and attenuated photon intensity, respectively. $\mu_m(cm^2.g^{-1})$ is the mass attenuation coefficient and x is the thickness of the slab. To provide the validation of modeled MCNPX simulation geometry, the gamma-ray mass attenuation coefficients of lung were calculated at 60 keV, 80 keV, 150 keV, 400 keV, 500 keV, 600 keV, 1000 keV, 1250 keV, 1500 keV, 2000 keV photon energies. In Fig. 1, a modeled and defined lung section has been located between the lead (Pb) collimated gamma-ray source and detection area. The geometric center of detection area was considered for location of point source.

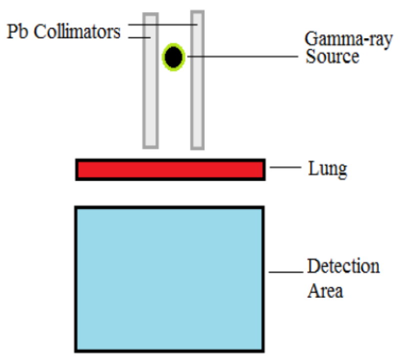

Figure 1. Schematic view of geometry for mass attenuation coefficient of lung

Gamma-ray sources at different energies have been defined in data card section of MCNPX input by considering different variable such as CEL, ERG, DIR, POS, and PAR. The geometric center of detection cell has been considered for location of point source. Each variable has different abilities during Monte Carlo simulation. In present study, our variables commanded source cell, energy, direction, source position and particle type, respectively. On the other hand, one of important definition is material specification by considering atomic number, mass number and density (d) for pure elemental materials and atomic number, elemental mass concentrations and density for compounds or mixtures. By considering these variables, we defined the lung, radiation sources, Pb collimators and detection area in input file respectively. The elemental mass concentrations and density of lung [18] have been presented in Table 1.

As a variance reduction technique, the mother volume cell has been optimized by considering total simulation area to reduce statistical error and unnecessary particle tracking in simulation. In the MCNPX simulation process 106 photons were used as a number of particle. MC calculations were done by using Intel® Core ™ i7 CPU 2.80 GHz computer hardware. The calculated mass attenuation coefficients results of this study and results from the previous studies in literature are presented in Table 2. Moreover, the uncertainties have been calculated via standard deviation and reported in Table 2. The simulation geometry of MCNPX will be used for assessment of effect shielding effect of bismuth on lung during thoracic CT scan.

Table 1. Elemental concentrations of lung (d= 1.05 g/cm^3)

Element	Elemental concentrations (%)
H	0.10127
N	0.02865
Na	0.00184
O	0.75707
Cl	0.00266
Mg	0.00073
P	0.00080
Fe	0.00037
Ca	0.00009
Zn	0.00001
K	0.00194
C	0.10231
S	0.00225

2.2. Bismuth Shielding, Lung Phantom and Simulation

In the next step, validated simulation geometry has been used for investigation of dose reduction effect of bismuth shielding on lung. As the energy source in input file, the X-ray spectrum energies from 100 keV to 160 keV have been used to obtain spectrum of the CT system. SpelCalc program [20] has been used to obtain spectrum to simulate the beam of CT system. SpekCalc is primarily designed to be used in medical physics for both research and education aims. Noteworthy is the particularly wide range of tube potentials (40-300 keV) and anode angles that can be modeled: the program can therefore be potentially useful to those working in superficial and orthovoltage radiotherapy, as well as in diagnostic radiology. The obtained X-ray sprectrum has been defined as a source spectrum in MCNPX input. A lung phantom and Pb shielding materials to reduce backscattered photons have been defined respectively.

In Fig.3a and Fig.3b schematic view of simulation setup with and without bismuth shielding for MCNPX simulation is shown. In the MCNPX simulation process 106 photons were used as a number of particle. To obtain absorbed dose amount in lung phantom, energy

Table 2. Mass attenuation coefficient values for lung (d= 1.05 g/cm^3)

Photon Energies (keV)	This Study (MCNPX)	FLUKA	GEANT4	XCOM	NIST
60	0,20270 ±0,00009	0.20323	0.18919	0.20520	0.20530
80	0,18110±0,00006	0.18380	0.17419	0.18240	0.18260
150	0,14900 ±0,00008	0.14833	0.14702	0.14910	0.14930
400	0,10350 ±0,00009	0.10461	0.10382	0.10510	0.10530
500	0,09520±0,00012	0.09585	0.09596	0.09592	0.09607
600	0,09010 ±0,00014	0.08911	0.08915	0.08869	0.08882
1000	0,06980±0,00007	0.07071	0.07006	0.07002	0.07013
1250	0,06010±0,00008	0.06182	0.06199	0.06262	0.06271
1500	0,05690 ±0,00006	0.05684	0.05649	0.05698	0.05706
2000	0,04930 ±0,00007	0.04909	0.04831	0.04893	0.04900

deposition mesh tally (F6) has been used as a mesh tally. This type of tally in MCNPX scores energy deposition data in which energy deposited per unit volume from all particles is included [21]. However, as an importance definition in input file, we defined the photon (imp:p 1) as a considered particle type to calculate energy deposition in lung phantom. Of course, this type of approach is a variance reduction method to reduce statistical error in simulation. Eventually, X-ray beam has been directed on to the lung phantom and energy deposition has been observed in both calculations.

3. RESULTS AND DISCUSSION

3.1 Mass Attenuation Coefficient

The mass attenuation coefficeints of the lung using MCNPX simulation are given in Table.2 along with previsously reported results in literature [14], XCOM data [15] and NIST values [16]. The values obtained using MCNPX compared at various energies from the 60 keV until 2000 keV photon energy. Here during the validation process the modeled MCNPX simulation geometry, not only well-known Monte Carlo code data such as GEANT4 and FLUKA have been used but also standard XCOM and NIST data also have been used for comparison. During the comparison, we obtained some small differences between results. It can be conluded that, since each Monte Carlo code has their own libraries for cross-section data, the results can be different from each other with small differences. Thus, we provided the opportunity to evaluate our results in a large data table. This approach provided accordance between the both studies such as validation of modeled simulation geometry and results. Mass attenuation coefficients versus different photon energies for lung have been presented graphically also in Fig.2.

During the validation, mass attenuation coefficients for lung were found comparable with NIST sandard data and other investigations. However, by this validation study,we provided an opportunity to compare our results not only with other well-known Monte Carlo codes such as FLUKA and GEANT4 but alsowith XCOM and NIST data. On the other hand, at some energy values,the results

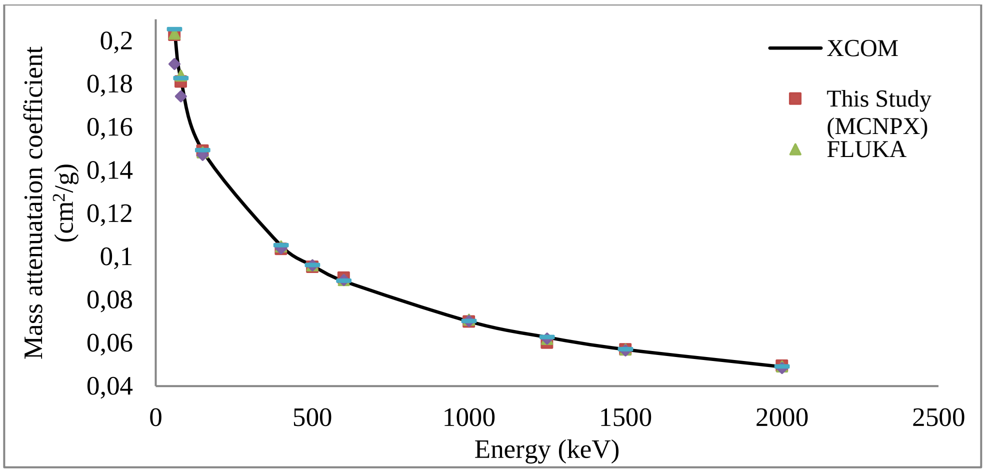

Figure 2. Mass attenuation coefficients versus different photon energies for lung

Table 3. Effect of bismuth shielding material and dose reduction.

Energy (keV)	Deposited Energy with Bismuth Shielding (a.u)	Deposited Energy without Bismuth Shielding (a.u)	Dose Reduction (%)
100	5,50E-05	1,08E-04	49,25722615
120	1,00E-04	1,30E-04	22,76889719
140	1,21E-04	1,43E-04	15,74533164
160	1,32E-04	1,51E-04	13,05602896

shows that our data are more closer to NIST values than FLUKA and GEANT4.

3.2 Bismuth Shielding Effect

The validated simulation geometry has been used during the investigation of bismuth shielding and its effect on deposited energy reduction in lung. As shown in Fig.4, both calculation that no shielded lung phantom energy deposition and bismuth shielded lung phantom energy deposition have been presented. For modeled lung phantom, the average deposited energy amounts have been compared respectively. A progressive decrease in deposited energy amount in lung phantom was achieved by the addition of bismuth shielding material. However, dose reduction rates have not been achieved in same rates because of relationship between increasing energy values and dose attenuation properties of attenuator material. Lung absorbed dose rates have been presented in Table 3. As it can be seen from the Table 3, dose reduction rates have been decreased by increased energy.

The results showed that bismuth is a well attenuator material for mentioned energyrange between 100 keV and 160 keV which is the average CT energy range in diagnostic scans for patients. The results generally agreed with some other experimental studies undertaken on bismuth shielding [22-23]. On the other hand, effect of attenuator materials on image quality is an important subject to consider. However, Chang K-H et.al 2010, reported that by using the bismuth shielding, the dose of the critical organs could be considerably reduced without degrading the image quality. This study considered only the attenuation properties of bismuth shielding in the energy range of 100 keV to 160 keV on lung. Certainly, in a thoracic CT examination breast tissue could be the first attenuator before the lung but since the breast and lung have almost the similar densities and previous bismuth shielding studies achieved significant dose reduction on breast tissue, it can be concluded that dose attenuation properties of bismuth is significant.

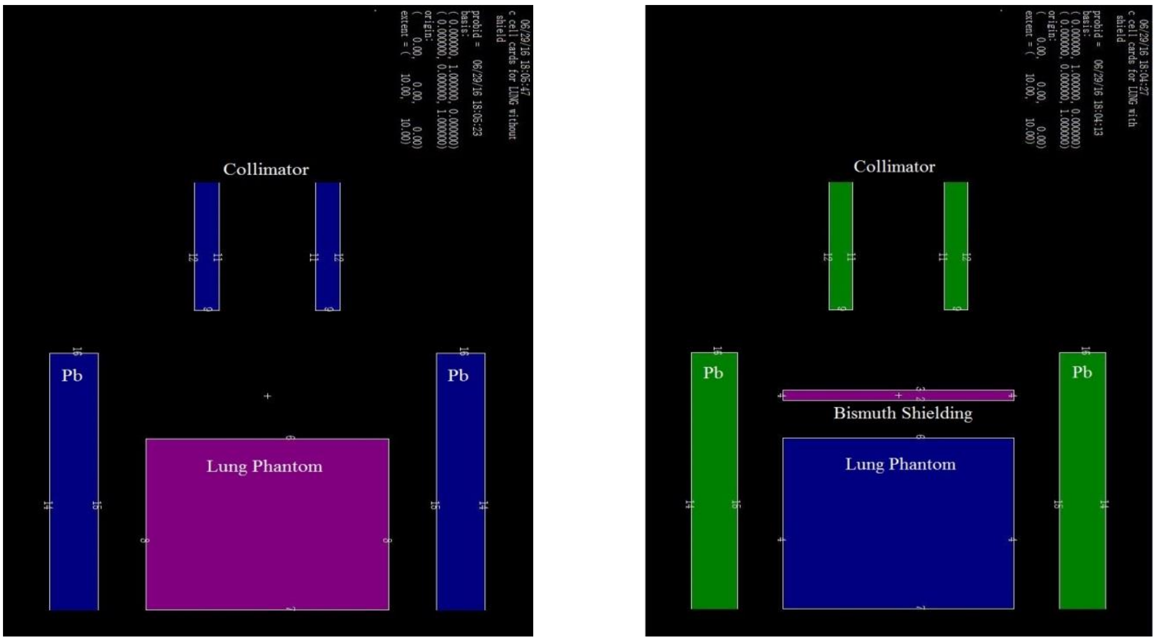

Figure 3 (a) Schematic view of simulation setup without bismuth shielding **(b)** Schematic view of simulation setup with bismuth shielding

The variation of dose reduction rate from 100 keV to 120 keV has been observed as highest decrease as % 27±. In addition, variation of dose reduction rate from 120 keV to 140 keV was around %7± and from 140 keV to 160 keV was around %2± respectively. In thi sstudy, relative error has been achieved less than % 0.1 and it can be considered as small relative error rate for a medical application based Monte Carlo simulation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

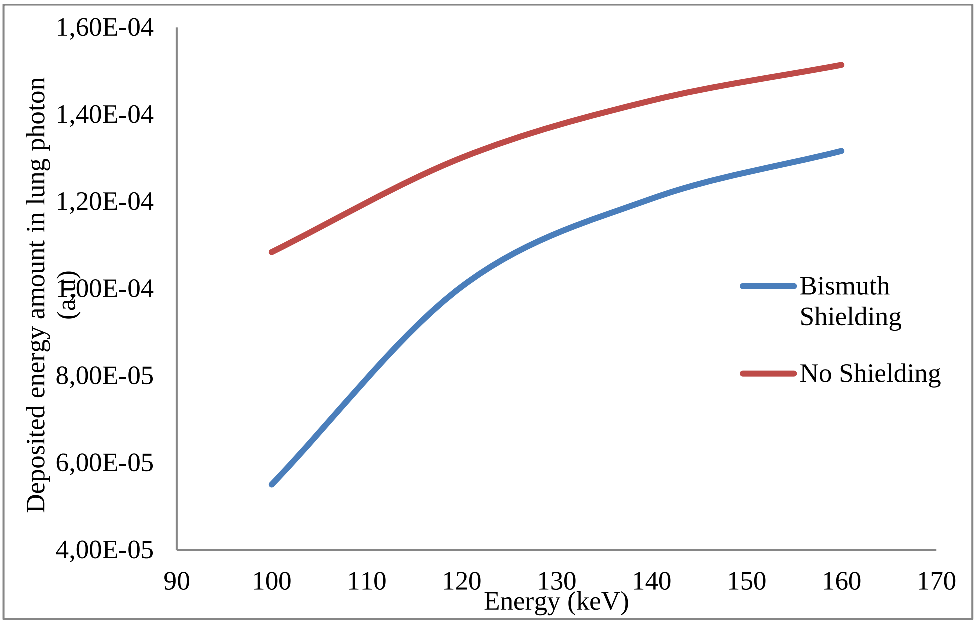

Figure 4. Comparison of deposited energy amount in lung photon versus energy

4. CONCLUSION

In this study, effect of bismuth shielding on lung during CT scan using Monte Carlo simulation has been reported. During the validation, mass attenuation coefficients for lung were found comparable with NIST standart data and other investigations. The values obtained using MCNPX compared at various energies from the 60 keV until 2000 keV photon energy. The standarted simulation geometry has been used for investigation of bismuth shielding and its effect on deposited energy reduction in lung. The results showed that bismuth is a very effective shielding materias for CT energy range (100 keV to 160 keV) in diagnostic scans for patients energy. It can be concluded that the Monte Carlo simulation is a strong tool and it is an alternate method for experiment due to flexibility and convenience in defining geometry. This standart geometry can be utilised for investigation of shielding effects on other human organ for radiation protection, medical diagnostic and discussion with ICRP and IAEA.

REFERENCES

[1] Goldman, L.W.,PrinciplesofCT:radiationdoseandimagequality.***J.Nucl. Med. Technol***.: ,213–225, (2007).

[2] Kalra,M.K.,Maher,M.M.,Toth,T.L.,Hamberg, L.M., Blake, A.M.,Shepard, J.A.,Saini,S.-, 2004. Strategiesfor CTR adiation Dose Optimization.***J. Radiol.*** 230: 619–628, (2004).

[3] Iball, G. R.,& Brettle, D. S. Organ and effective dose reduction in adult chest CT using abdominal lead shielding. ***The British Journal of Radiology***,84:(1007), 1020–1026, (2011) http://doi.org/10.1259/bjr/53865832.

[4] Nan-Ku et.al,. Real-time estimation of dosereductionforpediatric CT usingbismuthshielding. ***Radiation Measurements*** 46: 2039-204, (2011).

[5] Kenneth D. 2001. RadioprotectiontotheEyeDuring CT Scanning. ***AJNR Am J Neuroradiol***, 22: 1194–1198, (2001).

[6] Huggett J. A Phantom-Based Evaluation Of Three CommerciallyAvailablePatient Organ Shields for Computed Tomography X-Ray Examinations in Diagnostic Radiology. ***Radiation Protection Dosimetry*** 155(2): 161–168, (2013).

[7] Einstein A.J. et.al.,Effect of bismuthbreastshielding on radiationdose and imagequality in coronary CT angiography. ***Journal of Nuclear Cardiology***, 19(1): 100–108.

[8] Wang J. Radiationdosereductiontothebreast in thoracic CT: Comparison of bismuthshielding, organ-basedt ube current modulation, and use of a globally decreased tube current. ***Medical Physics*** 38, 6084 (2011).

[9] Wang J. Bismuth Shielding, Organ-based Tube Current Modulation, and Global Reduction of Tube Current for Dose Reduction to the Eye at Head CT. ***RSNA Radiology,*** 262: 191–198, (2012).

[10] RSICC Computer Code Collection (2002). MCNPX User's Manual Version 2.4.0. Monte Carlo N-Particle Transport Code System for Multiple and High Energy Applications.

[11] Akkurt I, Tekin H.O., Mesbahi A. Calculation of Detection Efficiency fort he Gamma Detector using MCNP-X" ***Acta Physica Polonica A.***, 128(2): 332-334, (2015).

[12] Tekin H.O. and Kara U."Monte Carlo Simulation for Distance and Absorbed Dose Calculations in a PET-CT Facility by using MCNP-X" ***Journal of Communication and Computer*** 13: 32-35, (2016).

[13] Chang K-H. et.al. Dose Reduction In CT Using Bismuth Shielding: Measurements And Monte Carlo Simulations. ***Radiation Protection Dosimetry***, 138(4): 382–388, (2010).

[14] Ermis E.E.et.al. 2016. A comprehensivestudyformass attenuation coefficients of different parts of thehuman body through Monte Carlo Methods. ***Nucl Sci. Tech.*** 27: 54, (2016).

[15] 2. M.J. Berger, J.H. Hubbell, 1987.Photon Cross section on a Personal Computer (XCOM). NBSIR87-3597 (NationalInstitute of Standards and Technology, Gaithersburg,

[16] NationalInstitute of Standards and Technology (NIST), X-ray mass attenuation coefficients. http://physics.nist.gov/PhysRef Data/XrayMassCoef/tab4.html.

[17] Abdel-Rahman MA, Badawi EA, Abdel-Hady YL, Kamel N. Effect of sample thickness on the measured mass attenuation coefficients of some compounds and elements for 59.54, 661.6 and 1332.5 keV c-rays. ***Nucl Instrum Methods Phys Res A*** 447: 432–436, (2000).

[18] ICRU, TissueSubstitutes in RadiationDosimetry and Measurement, Report 44 of the International Commission on RadiationUnits and Measurements (Bethesda, MD, 1989)

[19]Kubo T et.al., Radiation Dose Reduction in Chest CT: A Review. ***American Journal of Roentgenology*** 190: 335-343, (2008).

[20] Poludniowski G. Et al.,2009. SpekCalc: A Program to Calculate Photon Spectra from Tungsten Anode X-Ray Tube. ***Phys. Med. Biol.,***54(19): 433-438.

[21] RSICC ComputerCode Collection, 2002. MCNPX 2.4.0 Monte Carlo N-Particle Transport Code Systemfor Multiparticle and High Energy Applications, OAK Ridge National Laboratory.

[22] McCollough, C. et.al, 2009. Strategiesforreducingradiationdose in CT. Radiol. Clin. North Am. 47(1), 27–40.

[23] Wang, J. et.al., Radiationdosereductiontothebreast in thoracic CT: comparison of bismuthshielding, organ-basedtubecurrentmodulation, and use of a globally decreased tube current. ***Med. Phys.*** 38(11): 6084–6092, (2011).