Published in final edited form as:

Phys Med Biol. ; 63(16): 165012. doi:10.1088/1361-6560/aad47a.

Re-evaluation of pediatric ^{18}F -FDG dosimetry: Cristy-Eckerman versus UF/NCI hybrid computational phantoms

Kitiwat Khamwan^{1,2,6}, Shannon E O'Reilly³, Donika Plyku¹, Alison Goodkind⁴, Anders Josefsson¹, Xinhua Cao⁴, Frederic H Fahey⁴, S Ted Treves⁵, Wesley E Bolch³, and George Sgouros^{1,7,8}

¹Department of Radiology and Radiological Science, The Russell H Morgan Johns Hopkins University, School of Medicine, Baltimore, MD, United States of America ²Department of Radiology, Division of Nuclear Medicine, Faculty of Medicine, Chulalongkorn University, Bangkok, Thailand ³Department of Biomedical Engineering, J Crayton Pruitt Family University of Florida, Gainesville, FL, United States of America ⁴Division of Nuclear Medicine and Molecular Imaging, Boston Children's Hospital, Harvard Medical School, Boston, MA, United States of America ⁵Department of Radiology, Division of Nuclear Medicine and Molecular imaging, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, United States of America ⁶Department of Radiology, Chulalongkorn University Biomedical Imaging Group, Faculty of Medicine, Chulalongkorn University, Bangkok, Thailand ⁷Johns Hopkins University, School of Medicine CRB II, 4M61 1550 Orleans St., Baltimore, MD 21231, United States of America

Abstract

Because of the concerns associated with radiation exposure at a young age, there is an increased interest in pediatric absorbed dose estimates for imaging agents. Almost all reported pediatric absorbed dose estimates, however, have been determined using adult pharmacokinetic data with radionuclide S values that take into account the anatomical differences between adults and children based upon the older Cristy–Eckerman (C–E) stylized phantoms. In this work, we use pediatric model–derived pharmacokinetics to compare absorbed dose and effective dose estimates for ^{18}F -FDG in pediatric patients using S values generated from two different geometries of computational phantoms. Time–integrated activity coefficients of ^{18}F -FDG in brain, lungs, heart wall, kidneys and liver, retrospectively, calculated from 35 pediatric patients at the Boston's Children Hospital were used. The absorbed dose calculation was performed in accordance with the Medical Internal Radiation Dose method using S values generated from the University of Florida/ National Cancer Institute (UF/NCI) hybrid phantoms, as well as those from C–E stylized computational phantoms. The effective dose was computed using tissue–weighting factors from

⁸ Author to whom any correspondence should be addressed. gsgouros@jhmi.edu.

Compliance with ethical standards

Ethical approval

This article does not contain any studies with human participants or animals performed by the author.

Informed consent

Not necessary for this paper.

Conflict of interest

The authors declare that they have no conflict of interest.

ICRP Publication 60 and ICRP Publication 103 for the C–E and UF/NCI, respectively. Substantial differences in the absorbed dose estimates between UF/NCI hybrid pediatric phantoms and the C–E stylized phantoms were found for the lungs, ovaries, red bone marrow and urinary bladder wall. Large discrepancies in the calculated dose values were observed in the bone marrow; ranging between –26% to +199%. The effective doses computed by the UF/NCI hybrid phantom S values were slightly different than those seen using the C–E stylized phantoms with percent differences of –0.7%, 2.9% and 2.5% for a newborn, 1 year old and 5 year old, respectively. Differences in anatomical modeling features among computational phantoms used to perform Monte Carlo –based photon and electron transport simulations for ^{18}F , and very likely for other radionuclides, impact internal organ dosimetry computations for pediatric nuclear medicine studies.

Keywords

pediatric dosimetry; computational phantoms; Medical Internal Radiation Dose (MIRD); Monte Carlo calculations; ^{18}F –FDG

Introduction

Radiopharmaceutical dosimetry for diagnostic imaging agents typically provides absorbed dose estimates to a reference anatomic geometry rather than to individual patients or a particular patient population (Sgouros et al 2011, Treves 2014, Fahey et al 2017). The reference anatomic geometry is used with Monte Carlo–based radiation transport simulations to compute values of the radionuclide S value, defined as the absorbed dose to a target tissue per radionuclide decay in a source tissue. The total number of disintegrations or time–integrated activity, A , is obtained by integrating the time–activity curve for each tissue. Accordingly, absorbed dose estimates have two fundamental inputs: (1) the computational phantom used to obtain radionuclide–specific and source/ target organ–specific S values and (2) the tissue time–integrated activity coefficients $\tilde{a}$ or time–integrated activity coefficients (TIACs) ($=\tilde{A}/A_0$, where A_0 is the administered activity). The latter can be quantitatively obtained from patient imaging of the radiopharmaceutical (Fahey 2009, Stabin and Xu 2014).

Virtually all absorbed dose calculations over the past several decades have used Cristy –Eckerman (C–E) phantom–derived radionuclide S values. Reference geometries for newborn, 1 year old, 5 year old, 10 year old and 15 year old children are also described by the C–E phantom series and used to compute pediatric S values (Wayson et al 2012, Xie et al 2013, Xie and Zaidi 2014). Furthermore, all pediatric absorbed dose estimates reported by the International Commission on Radiological Protection (ICRP) use adult pharmacokinetic data coupled with pediatric reference phantom S values (Fahey et al 2011, 2016, Lassmann and Treves 2014, Treves et al 2014, 2016, Grant et al 2015, Mattsson et al 2015, Lassmann et al 2016). The reference geometry and corresponding S values for both adults and children were recently updated in ICRP Publication 128 (Mattsson et al 2015). Pediatric data for ^{18}F –FDG have recently been used to develop a pharmacokinetic model (PK model) of FDG applicable to newborn, 1 year old and 5 year old patients (Khamwan et al 2016). Time –integrated activities (TIAs) derived from this model were used with new pediatric S values

to obtain absorbed dose estimates that were compared with estimates published in ICRP Publication 128, which used an adult PK model with S values derived from the pediatric C–E phantoms (O’ Reilly et al 2017). An example of 3D views for a C–E stylized computational pediatric phantom is illustrated in figure 1 (Cristy and Eckerman 1987).

In this work, we used model–derived pediatric TIA to compare ^{18}F –FDG–absorbed dose estimates obtained using S values from the University of Florida/National Cancer Institute (UF/NCI) pediatric reference phantoms with absorbed dose estimates obtained using the older C–E pediatric phantom S values implemented by the OLINDA/EXM version 1.0 software (Stabin et al 2005), the most widely used software package for internal dosimetry calculations in nuclear medicine.

Methods

Patients

The retrospective data from 35 pediatric patients (19 males and 16 females; age range 2 weeks to 5 years; mean age 1 year 4 months; patient weight $\pm$ SD, 11.5 ± 4.7 kg) who underwent whole–body ^{18}F –FDG PET/CT scanning at the Boston’s Children’s Hospital between November 2009 and March 2015 were collected. Patients received ^{18}F –FDG intravenously as a bolus of 65 ± 27 MBq (range, 20–126 MBq). The scans were primarily for cancer diagnosis ($n=7$), staging evaluation ($n=22$) and other tumor types ($n=6$). The characteristics of the pediatric patients in this work and PET/CT image acquisition were published previously by Khamwan et al (2016).

Tissue TIACs for the newborn and 5 year old

As previously reported, pediatric PK model–derived TIACs for brain, heart wall, lungs, kidneys and liver (Khamwan et al 2016) were used in the C–E versus UF/NCI phantom–derived absorbed dose comparisons described in this work. Since retrospective data were used to derive the pediatric ^{18}F –FDG model, biokinetic data for urinary bladder contents were not available. Instead, the TIAC of FDG in the urinary bladder contents for the 1 year old and 5 year old was derived from the models given in ICRP Publication 128 (Mattsson et al 2015). However, the latest ICRP Publication 128 still lacks the TIAC data for urinary bladder in newborns. According to the biokinetic data published by Ruotsalainen et al (1996), the percentage of ^{18}F –FDG in the urinary bladder for newborns and for adults were 7% and 20%, respectively. We calculated, therefore, the TIAC in newborns by relating the TIAC from the adults ($\bar{t}=0.26$ h) (Mattsson et al 2015) to the newborns based on these assumptions. As a result, the TIAC for newborns used in this work was assigned as $0.26 \times 0.07/0.20 = 0.09$ h. The TIAC in the rest of the body was computed as the total body TIAC minus the sum of all TIAC source organs. Table 1 lists the TIAC used in the absorbed dose calculations of ^{18}F –FDG. These values were used for both phantoms. Other than the remainder of the body and the urinary bladder contents, these values are assumed for newborns and children up to the age of 5 years.

Absorbed dose calculations

The absorbed dose, $D(r_T)$, to target region, r_T , was calculated in accordance with the methodology described by the Medical Internal Radiation Dose (MIRD) Committee Pamphlet No 21 (Bolch et al 2009). The following equations were used:

$$D(r_T) = \sum_{r_S} \tilde{A}(r_S) \cdot S(r_T \leftarrow r_S), \quad (1)$$

where $\tilde{A}(r_S)$ represents the TIA of the radiopharmaceutical in the source region. The S value is given by:

$$S(r_T \leftarrow r_S) = \frac{1}{M(r_T)} \sum_i E_i Y_i \phi(r_T \leftarrow r_S, E_i), \quad (2)$$

where E_i is the mean energy of the i^{th} radiation, $\phi(r_T \leftarrow r_S, E_i)$ is the fraction of radiation energy E_i emitted by the source region (r_S) that is absorbed by a target region (r_T), Y_i is the yield for the i^{th} radiation per nuclear transformation, and $M(r_T)$ is the mass of the target region.

Radionuclide S values were computed for all relevant source organs in the full series of UF/NCI pediatric reference phantoms as described by Lee et al (2010). Radiation transport simulated were completed using the MCNP version 2.7 code. Each simulation directly sampled the ^{18}F emission spectrum, accounting for annihilation photons emitted by the ^{18}F –FDG. The decay scheme for ^{18}F was obtained from the electronic database of ICRP Publication 107 (2008). Source regions considered were brain, lungs, kidneys, heart wall, urinary bladder contents and rest of body. Target organs were those used in the effective dose calculation. Sufficient particle histories were simulated to achieve statistical uncertainties below 1% for all source–target combinations. The radionuclide S values generated were then imputed to an Excel spreadsheet implementing the MIRD schema of equation (1). Figure 2 shows the front 3D views of the UF/NCI computational phantoms as a function of subject age used in this study. Estimates of both active marrow and skeletal endosteum absorbed dose were computed by fluence tallies in all regions of trabecular spongiosa for each phantom of the UF/NCI series, which were then convolved with age–dependent and bone–specific fluence–to–dose response functions assembled by Wayson et al (2012) using the same methodology as described by Johnson et al (2011) for the ICRP adult phantoms.

According to our previously developed pediatric PK model, the bidirectional exchange of FDG between the plasma and erythrocytes compartments was included in the simulation. The blood volume fraction in each compartment for brain, lungs, heart wall and liver was considered for the model fitting. Consequently, the time–integrated activity coefficient obtained in each source organ for dosimetric calculation was generated by including these blood volume fractions in each compartment.

OLINDA/EXM version 1.0 software was used to calculate absorbed doses utilizing the newborn, 1 year old and 5 year old anatomical models based on C–E S values (Cristy and Eckerman 1987). The effective dose calculations for C–E stylized phantoms and UF/NCI hybrid phantoms were determined by applying the tissue weighting factor from ICRP Publication 60 (1991) and ICRP Publication 103 (2007), respectively.

The percent difference in absorbed dose between the two phantom methods for the newborn, 1 year old and 5 year old was calculated as following:

$$\% \text{ Difference} = \frac{(D(r_T)_{UF/NCI} - D(r_T)_{C-E})}{D(r_T)_{C-E}} \times 100\%, \quad (3)$$

where $D(r_T)_{UF/NCI}$ is the absorbed doses to r_T calculated based on UF/NCI hybrid phantoms and $D(r_T)_{C-E}$ is the absorbed doses based on the C–E stylized phantoms.

Results

Table 2 shows the individual organ absorbed dose coefficients in 15 target organs for the newborn, 1 year old and 5 year old patients based on the UF/NCI hybrid computational phantoms and the C–E stylized computational phantom S values. The absorbed dose coefficients listed for the UF/NCI hybrid phantoms are for a pediatric female, whereas these gender-specific pediatric models are not available for C–E stylized phantoms. As shown in the table, the highest organ absorbed doses were seen in brain and urinary bladder wall in both the UF/NCI and C–E computational phantoms. The estimated absorbed dose coefficients to the brain and UB wall for the newborn were 0.72 mGy MBq^{−1} and 0.28 mGy MBq^{−1} for the UF/NCI hybrid phantoms. For the C–E phantoms, these same absorbed dose coefficients were 0.66 mGy MBq^{−1} and 0.67 mGy MBq^{−1}, respectively. Absorbed dose coefficients for salivary glands and esophagus could not be compared as these are not described in the C–E phantoms. The effective dose coefficients for the UF/NCI phantoms were slightly different to those from C–E phantoms for all three ages.

Figure 3 depicts the differences in absorbed dose coefficients computed by the UF/NCI –phantom based and C–E phantom-based S values in 11 different target organs. The UF/NCI S value–based absorbed doses to the urinary bladder wall were 58%, 41% and 63% lower for the newborn, 1 year old and 5 year old, respectively, than the corresponding value obtained from C–E S value–based calculations. Since the bladder wall is the critical organ for ¹⁸F–FDG, this is a change that has important implications in terms of recommended administered activities. On the other hand, the UF/NCI hybrid pediatric phantom lung dose calculations were substantially higher than the corresponding values obtained using the C–E phantoms. Stomach wall and ovaries also gave higher UF/NCI absorbed doses across all ages. The difference in absorbed dose for all the other tissues was age–dependent. The strongest age dependence was seen for the bone marrow and ovaries. The newborn red marrow dose calculations using UF/NCI S values gave an almost 26% lower absorbed dose to the marrow; the 1 year old's marrow dose was approximately 21% higher while the 5 year old's marrow dose was more than 199% higher.

Discussion

Because of the limited computing power available in the late 1980s, the C-E pediatric phantom represented organs with idealized geometric shapes; correspondingly, the electron absorbed fractions calculated for this phantom were made reasonably conservative with *ad hoc* assumptions regarding electron energy deposition. Emissions were classified as penetrating (i.e. photons) versus non-penetrating (i.e. electrons). Non-penetrating emissions were assumed fully absorbed in the source tissue with no energy deposition in adjacent tissue (i.e. absorbed fraction (ϕ) = 1 for self-dose and ϕ = 0 for cross-organ electron dose) (Wayson et al 2012, Xie et al 2013, Stabin and Xu 2014, Xie and Zaidi 2014). In the special case of walled organs such as the bladder and GI, the absorbed fraction for the contents of the organ was set to 1/2. Such simplifications were not necessary in the UF/NCI hybrid phantom-based calculations (Wayson et al 2012, Xie et al 2013, Xie and Zaidi 2014). Differences in the dose estimates represent a balance between the effects of radiation transport calculations in a phantom geometry with contiguous tissue contact and one in which tissues are isolated geometric shapes. In light of these differences in geometry and the implementation of electron transport in the newer phantoms, one might expect that the C-E versus UF/NCI phantom-derived dose estimates to be dependent on the electron emission spectrum of the radionuclide energy.

Comparing the current report to a similar comparison made for the ^{68}Ga electron emission spectrum, this is, in fact, what is observed (Andersson et al 2014). ^{18}F has a relatively simple decay scheme with a single transition to the ground state via emission of a positron (β^+) with an average energy of 249.5 keV (maximum energy of 633.9 keV) and a yield of 0.97 (Hays et al 2002). On the other hand, ^{68}Ga decays via three β^+ emissions having average energies of 836.0, 352.6 and 107.6 keV with corresponding yields of 0.8768, 0.0120 and 0.000 0026, respectively. There are also Auger and monoenergetic electron emissions, but these are all at energies in which complete absorption is expected and the assumption of ϕ = 1 is confirmed by electron transport calculations (Bolch et al 2009, Wayson et al 2012, Xie et al 2013, Xie and Zaidi 2014). Accordingly, ^{68}Ga -absorbed dose estimates based on the newer phantoms tended to be lower than those based on the C-E stylized phantoms because higher energy electrons are more likely to escape tissue if electron transport is considered than would be the case for lower energy electron emissions (Josefsson et al 2018). In both cases, a thin-walled organ such as the urinary bladder wall would give a result showing that the assumption of 1/2 absorption is too conservative.

In both cases of the C-E and UF/NCI phantoms, activity in the blood contained in the lungs is included in the residence time; no explicit blood in the lung-to-lung parenchyma S value was used. For the UF/NCI phantoms, the lung was treated as a single homogeneous tissue region in the simulation, similar to that in the C-E phantom. The simulation considered the lungs as both a homogenous mixture of tissue and air in a defined volume as both source and target.

The more than two-fold greater lung dose across all three ages for the UF/NCI phantom compared to the C-E phantom reflects the greater rest of body contribution to the lung dose for each of these ages. In both cases, rest of body dose contribution is obtained by uniformly

distributing TIA that has not already been specifically assigned to tissue and using rest of body to lung S values to account for dose contributions not already specifically allocated. The total body (used for C–E phantom to approximate rest of body) to lung S values for C–E phantoms are 7.59×10^{-6} , 3.64×10^{-6} and 2.06×10^{-6} mGy (MBq s) $^{-1}$ for the newborn, 1 year old and 5 year old, respectively. Corresponding values for the UF/NCI phantom are 3.19×10^{-5} , 1.59×10^{-5} , and 8.35×10^{-6} mGy (MBq s) $^{-1}$. These substantial differences in rest of body to lung S value are most likely due to the better anatomical representation in UF/NCI phantom where tissues are in contact with each other.

Since hermaphrodite C–E phantoms are used to represent the newborn, 1 year old and 5 year old anatomies, the OLINDA/EXM output for these age groups provides organ–absorbed doses for both pediatric male and female tissues. In contrast, the UF/NCI hybrid phantoms are gender-specific and these tissues are specifically modeled at each age, accordingly, the dose estimates for breast and ovaries obtained by the UF/NCI hybrid phantom were higher for all three ages. The effective dose coefficient computed by OLINDA/EXM version 1.0 is based on radiation and tissue weighting factors specified in ICRP Publication 60 (1991). In ICRP Publication 103 (2007), the tissue weighting factor for breast was increased to 0.12 from 0.05, and was dramatically decreased from 0.20 to 0.08 for gonads. The effective doses for breast in the UF/NCI were about three-fold greater than the C–E phantoms, whereas the two-fold, 1.5-fold and 1.2-fold lower effective doses in ovary were found for all three ages. Additionally, the effective dose in lungs for the UF/NCI was greater than C–E phantoms by close to a factor of two. However, the major contribution of effective doses computed by the C–E stylized phantom was obtained from the urinary bladder wall with values of 23%, 33% and 40%, and greater than the UF/NCI about three, two, and 3.5 times for the newborn, 1 year old and 5 year old, respectively. Therefore, the significant change in tissue–weighting factors for breast and gonads from ICRP 60 to ICRP 103 may partially explain the close similarity in whole–body effective dose between the two phantoms even though the breast and ovary absorbed doses are higher with the newer phantoms.

The purpose of development of the UF/NCI pediatric hybrid phantoms is to address the issue of older stylized and voxel phantoms (Nipper et al 2002, Lee et al 2010, Wayson et al 2012, Xie et al 2013, Xie and Zaidi 2014). The UF/NCI hybrid computational phantoms are neither voxel–based nor stylized, but they retain the anatomical fidelity of voxelized phantoms with the scaling flexibility of geometric stylized phantoms. This is through the use of non–uniform rational B-spline (NURBS) technology, which combines the flexibility of mathematical organ geometry representation with the anatomical reality. OLINDA/EXM version 2.0 was recently released and this version employs NURBS–style phantoms. This work focuses on understanding the impact of transitioning from the older phantoms and tissue–weighting factors to the most recently updated phantoms that will be adopted by ICRP in the near future (Menzel et al 2009). Historically, the bladder wall has been the critical organ for ^{18}F –FDG. The results presented in this paper suggest that this conclusion was likely an artifact of the electron-absorbed fraction used for walled organs.

There are some limitations in our comparison of effective dose estimates for pediatric patients. Since the study of healthy children for dosimetric calculation purposes alone is not practical and cannot be ethically justified, the TIACs were calculated based on a model-

derived PK that was validated by relating clinical PET/CT diagnostic imaging (Khamwan et al 2016). Accordingly, the uncertainty in absorbed and effective doses cannot be reported from this work.

Conclusions

As pediatric pharmacokinetic data are collected for diagnostic imaging agents that are relevant to pediatric studies and as the field transitions from older stylized phantoms to more detailed computation hybrid phantoms, comparisons of the type presented in this work are important in helping understand the implications of new data and tools for prior absorbed dose estimates.

Acknowledgments

Kitiwat Khamwan was supported by the Chulalongkorn University Office of International Affairs Scholarship for Short-term Research, Thailand.

Funding

This study was funded by NIH grant number R01 EB013558.

References

- Andersson M, Johansson L, Minarik D, Leide–Svegborn S and Mattsson S 2014 Effective dose to adult patients from 338 radiopharmaceuticals estimated using ICRP biokinetic data, ICRP/ICRU computational reference phantoms and ICRP 2007 tissue weighting factors *EJNMMI Phys.* 1 1–13 [PubMed: 26501443]
- Bolch WE, Eckerman KF, Sgouros G and Thomas SR 2009 MIRD pamphlet no. 21: a generalized schema for radiopharmaceutical dosimetry—standardization of nomenclature *J. Nucl. Med.* 50 477–84 [PubMed: 19258258]
- Cristy M and Eckerman KF 1987 Specific absorbed fractions of energy at various ages from internal photon sources: part I Methods ORNL/ TM-8381/(Oak Ridge, TN: Oak Ridge National Laboratory)
- Fahey FH 2009 Dosimetry of pediatric PET/CT *J. Nucl. Med.* 50 1483–91 [PubMed: 19690036]
- Fahey FH et al. 2017 Dose estimation in pediatric nuclear medicine *Semin. Nucl. Med.* 47 118–25
- Fahey FH, Treves ST and Adelstein SJ 2011 Minimizing and communicating radiation risk in pediatric nuclear medicine *J. Nucl. Med.* 52 1240–51 [PubMed: 21764783]
- Fahey FH, Treves ST and Lassmann M 2016 Dose optimization in pediatric nuclear medicine *Clin. Transl. Imaging* 4 5–11
- Grant FD, Gelfand MJ, Drubach LA, Treves ST and Fahey FH 2015 Radiation doses for pediatric nuclear medicine studies: comparing the North American consensus guidelines and the pediatric dosage card of the European Association of nuclear medicine *Pediatr. Radiol.* 45 706–13 [PubMed: 25367355]
- Hays MT, Watson EE, Thomas SR and Stabin MG 2002 MIRD dose estimate report no. 19: radiation absorbed dose estimates from ^{18}F -FDG *J. Nucl. Med.* 43 210–4 [PubMed: 11850487]
- International Commission on Radiological Protection (ICRP) 1991 Recommendations of the International Commission on Radiological Protection (ICRP publication 60 Ann. ICRP) (Oxford: Pergamon)
- International Commission on Radiological Protection (ICRP) 2007 The 2007 Recommendations of the International Commission on Radiological Protection (ICRP publication 103 Ann. ICRP) vol 37 pp 1–332 [PubMed: 18082557]
- International Commission on Radiological Protection (ICRP) 2008 Nuclear Decay Data for Dosimetric Calculations (ICRP publication 107 Ann. ICRP) vol 38 pp 7–96 [PubMed: 19285593]

- Johnson PB, Bahadori AA, Eckerman KF, Lee C and Bolch WE 2011 Response functions for computing absorbed dose to skeletal tissues from photon irradiation—an update *Phys. Med. Biol.* 56 2347–65
- Josefsson A et al. 2018 Comparative dosimetry for ⁶⁸Ga-DOTATATE: impact of using updated ICRP phantoms, S values, and tissue-weighting factors *J. Nucl. Med.* 59 1281–8 [PubMed: 29439017]
- Khamwan K et al. 2016 Pharmacokinetic modeling of [¹⁸F]fluorodeoxyglucose (FDG) for premature infants, and newborns through 5 year- olds *EJNMMI Res.* 6 1–11 [PubMed: 26728358]
- Lassmann M and Treves ST 2014 Pediatric radiopharmaceutical administration: harmonization of the 2007 EANM paediatric dosage card (version 1.5. 2008) and the 2010 North American consensus guideline *Eur. J. Nucl. Med. Mol. Imaging* 41 1636 [PubMed: 24893792]
- Lassmann M, Eberlein U, Lopci E and Chiti A 2016 Standardization of administered activities in paediatric nuclear medicine: the EANM perspective *Eur. J. Nucl. Med. Mol. Imaging* 43 2275–8 [PubMed: 27497694]
- Lee C, Lodwick D, Hurtado J, Pafundi D, Williams JL and Bolch WE 2010 The UF family of reference hybrid phantoms for computational radiation dosimetry *Phys. Med. Biol.* 55 339–63 [PubMed: 20019401]
- Mattsson S et al. 2015 ICRP Publication 128: Radiation dose to patients from radiopharmaceuticals: a compendium of current information related to frequently used substances *Ann. ICRP* 44 7–321
- Menzel H, Clement C and DeLuca P 2009 ICRP Publication 110. Realistic reference phantoms: an ICRP/ICRU joint effort. A report of adult reference computational phantoms *Ann. ICRP* 39 1–164
- Nipper J, Williams J and Bolch WE 2002 Creation of two tomographic voxel models of paediatric patients in the first year of life *Phys. Med. Biol.* 47 3143–64 [PubMed: 12361215]
- O'Reilly S E et al 2017 Dosimetry for pediatric ¹⁸F-FDG molecular imaging studies (abstract) The 2017 Annual Meeting of the Association of Physics in Medicine¹⁸
- Ruotsalainen U et al. 1996 Estimated radiation dose to the newborn in FDG-PET studies *J. Nucl. Med.* 37 387–93 [PubMed: 8667081]
- Sgouros G, Frey EC, Bolch WE, Wayson MB, Abadia AF and Treves ST 2011 An approach for balancing diagnostic image quality with cancer risk: application to pediatric diagnostic imaging of ^{99m}Tc-dimercaptosuccinic acid *J. Nucl. Med.* 52 1923–9 [PubMed: 22144506]
- Stabin MG and Xu XG 2014 Basic principles in the radiation dosimetry of nuclear medicine *Semin. Nucl. Med.* 44 162–71
- Stabin MG, Sparks RB and Crowe E 2005 OLINDA/EXM: the second-generation personal computer software for internal dose assessment in nuclear medicine *J. Nucl. Med.* 46 1023–7 [PubMed: 15937315]
- Treves ST 2014 *Pediatric Nuclear Medicine and Molecular Imaging* 4th edn (New York: Springer)
- Treves ST, Gelfand MJ, Fahey FH and Parisi MT 2016 Update of the North American consensus guidelines for pediatric administered radiopharmaceutical activities *J. Nucl. Med.* 57 15N–8N [PubMed: 26514173]
- Treves ST, Lassmann M and Group ESPDHW 2014 International guidelines for pediatric radiopharmaceutical administered activities *J. Nucl. Med.* 55 869–70 [PubMed: 24744446]
- Wayson MB, Lee C, Sgouros G, Treves ST, Frey EC and Bolch WE 2012 Internal photon and electron dosimetry of the newborn patient—a hybrid computational phantom study *Phys. Med. Biol.* 57 1433–75 [PubMed: 22354044]
- Xie T and Zaidi H 2014 Evaluation of radiation dose to anthropomorphic paediatric models from positron-emitting labelled tracers *Phys. Med. Biol.* 59 1165–87 [PubMed: 24557029]
- Xie T, Bolch WE, Lee C and Zaidi H 2013 Pediatric radiation dosimetry for positron-emitting radionuclides using anthropomorphic phantoms *Med. Phys.* 40 102502 [PubMed: 24089923]

Figure 1.
3D visualization of C—E stylized phantoms.

Figure 2.
3D visualization of UF/NCI computational hybrid phantoms for various age groups.

Figure 3. Percent difference of absorbed dose coefficient of ^{18}F -FDG in 11 target organs based on the S values computed by UF/NCI hybrid phantoms and C—E stylized phantoms (positive = UF/NCI calculated absorbed doses are greater).

Table 1.

TIAC derived for newborns to 5 year olds: FDG model used to calculate the organ absorbed dose for ^{18}F –FDG.

Organ	TIAC (h)
Brain	1.150
Heart wall	0.032
Lungs	0.019
Kidneys	0.046
Liver	0.109
Rest of the body	
Newborn	1.20
1 year old	1.13
5 year old	1.06
Urinary bladder contents	
Newborn	0.09 ^a
1 year old	0.16 ^b
5 year old	0.23 ^b

^aData computed from Ruotsalainen et al (1996).

^bBiokinetic data from ICRP Publication 128 (Mattsson et al 2015).

Table 2.

^{18}F -FDG absorbed dose coefficient based on UF/NCI and C-E pediatric phantoms for the newborn, 1 year old and 5 year old.

Target organ	Absorbed dose coefficient (mGy MBq ⁻¹)					
	Newborn		1 year old		5 year old	
	UF/NCI phantom	C-E Phantom	UF/NCI phantom	C-E phantom	UF/NCI phantom	C-E phantom
Colon	1.13×10^{-1}	1.07×10^{-1}	5.06×10^{-2}	4.54×10^{-2}	2.58×10^{-2}	2.72×10^{-2}
Lungs	2.07×10^{-1}	1.01×10^{-1}	9.28×10^{-2}	4.13×10^{-2}	4.77×10^{-2}	2.15×10^{-2}
Stomach wall	1.22×10^{-1}	1.02×10^{-1}	5.02×10^{-2}	4.07×10^{-2}	2.45×10^{-2}	2.09×10^{-2}
Ovaries	1.30×10^{-1}	1.10×10^{-1}	8.00×10^{-2}	4.97×10^{-2}	5.87×10^{-2}	2.82×10^{-2}
Urinary bladder wall	2.82×10^{-1}	6.77×10^{-1}	2.63×10^{-1}	4.49×10^{-1}	1.23×10^{-1}	3.36×10^{-1}
Esophagus	1.27×10^{-1}	—	5.02×10^{-2}	—	2.63×10^{-2}	—
Liver	1.93×10^{-1}	1.97×10^{-1}	8.38×10^{-2}	8.82×10^{-2}	4.96×10^{-2}	4.75×10^{-2}
Thyroid	1.28×10^{-1}	1.10×10^{-1}	4.79×10^{-2}	4.58×10^{-2}	2.52×10^{-2}	2.49×10^{-2}
Brain	7.23×10^{-1}	6.64×10^{-1}	2.72×10^{-1}	2.92×10^{-1}	2.13×10^{-1}	2.16×10^{-1}
Salivary glands	1.33×10^{-1}	—	5.27×10^{-2}	—	3.14×10^{-2}	—
Breast	9.87×10^{-2}	8.20×10^{-2}	3.54×10^{-2}	3.21×10^{-2}	1.86×10^{-2}	1.59×10^{-2}
Skin	8.47×10^{-2}	9.00×10^{-2}	3.27×10^{-2}	3.65×10^{-2}	1.72×10^{-2}	1.84×10^{-2}
Remainder	1.16×10^{-1}	—	4.75×10^{-2}	—	2.30×10^{-2}	—
Red bone marrow	1.36×10^{-1}	1.85×10^{-1}	6.79×10^{-2}	5.62×10^{-2}	7.05×10^{-2}	2.36×10^{-2}
Bone surface	1.57×10^{-1}	—	6.72×10^{-2}	—	6.29×10^{-2}	—
Effective dose coefficient (mSv MBq ⁻¹)	1.46×10^{-1}	1.47×10^{-1}	6.98×10^{-2}	6.78×10^{-2}	4.21×10^{-2}	4.11×10^{-2}