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Dose Estimation in Pediatric Nuclear Medicine

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Abstract

The practice of nuclear medicine in children is well established for imaging practically all physiologic systems but particularly in the fields of oncology, neurology, urology, and orthopedics. Pediatric nuclear medicine yields images of physiologic and molecular processes that can provide essential diagnostic information to the clinician. However, nuclear medicine involves the administration of radiopharmaceuticals that expose the patient to ionizing radiation and children are thought to be at a higher risk for adverse effects from radiation exposure than adults. Therefore it may be considered prudent to take extra care to optimize the radiation dose associated with pediatric nuclear medicine. This requires a solid understanding of the dosimetry associated with the administration of radiopharmaceuticals in children. Models for estimating the internal radiation dose from radiopharmaceuticals have been developed by the Medical Internal Radiation Dosimetry Committee of the Society of Nuclear Medicine and Molecular Imaging and other groups. But to use these models accurately in children, better pharmacokinetic data for the radiopharmaceuticals and anatomical models specifically for children need to be developed. The use of CT in the context of hybrid imaging has also increased significantly in the past 15 years, and thus CT dosimetry as it applies to children needs to be better understood. The concept of effective dose has been used to compare different practices involving radiation on a dosimetric level, but this approach may not be appropriate when applied to a population of children of different ages as the radiosensitivity weights utilized in the calculation of effective dose are not specific to children and may vary as a function of age on an organ-by-organ bias. As these gaps in knowledge of dosimetry and radiation risk as they apply to children are filled, more accurate models can be developed that allow for better approaches to dose optimization. In turn, this will

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lead to an overall improvement in the practice of pediatric nuclear medicine by providing excellent diagnostic image quality at the lowest radiation dose possible.

Introduction

Pediatric nuclear medicine has many applications within the fields of oncology, cardiology, neurology, endocrinology, urology, gastroenterology, and orthopedics.[1] According to the National Council on Radiation Protection and Measurements (NCRP) 160 report, nuclear medicine procedures have increased from 6.3 million in 1984 to 18 million in 2006 with approximately 1% of these procedures performed on children.[2] This has led to an increase in per capita annual radiation dose to the US population from nuclear medicine procedures from 0.14 mSv in 1982 to 0.8 mSV in 2006. However, it is important to note that the largest fraction of this dose is attributed to nuclear cardiology, a procedure not commonly performed in children. Table 1 lists the number and relative frequency of pediatric nuclear medicine procedures performed at 10 hospitals in 2005.[3] Approximately 25,500 studies were performed in the 10 hospitals surveyed that year. The most common procedures were for the evaluation of the kidneys and bone disorders, with smaller but significant numbers of procedures for oncology and neurology applications.

Nuclear medicine imaging provides potentially life-saving information regarding physiological and molecular processes. Such imaging can be particularly valuable in children and infants wherein the rapid and unequivocal diagnosis of developmental or pathological concerns is essential for the health of these patients. Because of the increased utilization of radiologic procedures, the resultant ionizing radiation exposure has become a topic of considerable discussion. While engaging in this discourse, it is important to consider the benefits of nuclear medicine, as well as the potential risk associated with radiation exposure when deciding what is best for the patient. In weighing these risks it is important to accurately estimate the radiation dose from the medical use of radiopharmaceuticals and the impact of reduced dose on image quality.

Providing the appropriate administered activity to pediatric patients is particularly important because of their increased risk from radiation exposure as compared with adults.[4,5] Children’s vulnerability to ionizing radiation is due in part to the enhanced radiosensitivity of their tissues. Additionally, there is a longer time period over which stochastic radiation effects may manifest. According to the Biological Effects of Ionizing Radiation (BEIR) VII Phase 2 Report of the U.S. National Academy of Sciences, the carcinogenic risk of radiation may be two to three times higher in children than in adults, although this risk varies according to organ and tissue type.[6] When estimating pediatric radiation dose it is also important to consider gender since there is a higher risk associated with dose to breast tissue in females than in males. Current effective dose-based metrics are not age or sex specific, tantamount to applying the radiosensitivity averaged over age and gender to that of a child. The authors of this article are currently addressing these limitations, as will be discussed. Finally, we have demonstrated that accounting for body habitus (height and weight) and organ-size differences yields greater accuracy than a weight only based model.[7]

In current clinical practice, dosing for pediatric molecular imaging is based on consensus guidelines that provide consistency while preserving adequate diagnostic image quality.[8] These guidelines do not rigorously consider the tradeoff between image quality, as measured by performance on the relevant diagnostic task, and potential risk to the patient. We are currently using state-of-the-art simulation, image quality evaluation and radiation dosimetry tools to examine dose optimization methods in a much more rigorous and scientifically validated manner. This approach can lead to clinically implementable administered activity and dose optimization techniques for pediatric, and potentially adult, nuclear medicine and molecular imaging on par with national efforts to reduce doses in pediatric and adult CT and fluoroscopically guided interventions.

In this article, the most recent data describing the growing use of nuclear medicine in children will be described in addition to the basic concepts regarding the estimation of radiation dose in these patients. The biokinetic models developed by the authors to more accurately reflect pediatric dose risk will also be elucidated. Finally, the case of dose optimization will be presented as an example of how better dosimetric models can lead to improvements in pediatric nuclear medicine.

Dosimetry of Pediatric Nuclear Medicine

The models used for estimating the radiation dose to patients after the administration of radiopharmaceuticals will be discussed in this section. As will be discussed, these estimates do not apply to an individual patient but to models of patients assumed to be of a certain size and physiology. Representative anatomical models and derived pharmacokinetic data will be used that will not apply directly to any specific patient. Much of this discussion will center around the need for better agent-specific pharmacokinetic models that are derived from longitudinal measurements of agent distribution in children.

All dosimetric estimations for radiologic imaging, including pediatric nuclear medicine, begin with organ dose estimates. In nuclear medicine, this involves the radiation dose to a particular target organ (r_T) from a particular source organ (r_S). The radiation dose to the target organ, referred to as $D(r_T)$, can be summarized by the formalism developed by the Medical Internal Radiation Dosimetry Committee of the Society of Nuclear Medicine and Molecular Imaging:

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

where $\tilde{A}(r_S)$ is the time-integrated activity in a selected source organ (r_S) and $S(r_T \leftarrow r_S)$ is the radionuclide-specific quantity (ie, the S value) representing the mean dose to the target organ per unit activity present in the source organ.[9] The radiopharmaceutical of interest may distribute to a number of source organs. For example, ^{18}F FDG may distribute to the brain, heart, liver, kidneys, bladder, and the remaining soft tissue. Σ_S indicates summing over all source organs in which the radiopharmaceutical distributes to determine the total dose to the target organ.

$S(r_T \leftarrow r_S)$ is given by

$$S(r_T \leftarrow r_S) = \sum_i \Delta_i \varphi_i / M_T \quad (2)$$

where Δ_i is the mean energy per nuclear transformation for the ith radiation emitted by the radiopharmaceutical, φ_i is the fraction of energy emitted by the ith radiation from the source organ that is absorbed by the target organ, and M_T is the mass of the target organ. A particular radionuclide associated with a radiopharmaceutical typically emits several radiations. For example, ^{18}F emits positrons and 511-keV annihilation photons along with other less abundant radiations. Σ_i indicates summing over all radiations, i, emitted by the radionuclide. The S value is a physical parameter relying on the radionuclide's decay scheme as well as the size, orientation, and spacing of organs within the patient. There are different models for the various types of patients, such as men, women and children, to yield appropriate values for φ_i and M_T. For tissue self-dose, the absorbed fraction, φ_i is often considered to be 1.0 for nonpenetrating radiation (eg, beta particles including positrons) and less than 1 for gamma and x-rays. Also, φ_i/M_T is referred to as the specific absorbed fraction.

In simple cases, the time-integrated activity, $\tilde{A}(r_S)$, may be given by the following equation:

$$\tilde{A}(r_s) = 1.44\, A_o\, F\, T_{eff} \quad (3)$$

and represents the total number of decays. It depends on the amount of administered activity (A_o in Bq), the fraction of activity that goes to the source organ (F) and the clearance of the radiopharmaceutical (T_{eff}). F depends on the particular radiopharmaceutical administered and the specific uptake of the patient. T_{eff} is given by the following equation:

$$T_{eff} = T_B * T_P / T_B + T_P \quad (4)$$

where T_{eff} represents the effective clearance half-life, which accounts for both biological clearance, T_B, and the physical radioactive half-life, T_P. T_B is often exponential although there are exceptions such as the bladder. It is important to note that these estimates do not apply to a specific patient. In fact, the uncertainty of these estimates when applied to individual patients could be 100%.[10] This uncertainly could be even higher when applied to children.

There are several factors that affect the radiopharmaceutical dose to children including the radiopharmaceutical administered, the organ distribution of the administered radiopharmaceutical and the clearance of the radiopharmaceutical.

Pharmacokinetic Modeling

The estimation of $\tilde{A}$ requires knowledge of the pharmacokinetics (PK) of the radiopharmaceutical in terms of both uptake and clearance represented by F and T_{eff}, respectively, in the previous equation. Typically, PK is initially based on animal experiments and later replaced by more accurate estimates from human data. To correctly assess absorbed dose for pediatric patients, age-specific PK are required. The International Commission on Radiological Protection (ICRP) has published an extensive set of absorbed dose estimates and corresponding PK data.[11] Though the available calculations include absorbed and effective doses to children, the biokinetic models used in these calculations are typically derived from adult data, and the applicability of these models to children has yet to be ascertained.

There are a number of studies that have reported PK data for FDG in pediatric patients[12–17]; however, these studies provide PK data only for the brain and, in one case, the bladder.[13] We have developed a pharmacokinetic model of FDG applicable to premature infants and small children (<5-year old), which may be used to generate model-derived time-integrated activity coefficients and absorbed dose calculations for these patients.[18]

To develop this PK FDG model applicable to pediatric patients, the FDG compartmental model developed by Hays and Segall for adults was adjusted according to a combination of published data from infants, as well as retrospective data collected at Boston Children's Hospital (BCH). We found that the developed PK models differed substantially from adult PK models, which can have considerable impact on the dosimetric models for pediatric patients. This approach may be used as a model for estimating dosimetry from other radiopharmaceuticals in children.

As part of an ongoing dose-optimization effort, we have measured the renal uptake of ^{99m}Tc- dimercaptosuccinic acid (DMSA), a renal cortical imaging agent, in a wide age-range of pediatric patients from BCH; the collection of these data are essential for the PK model development of this radiopharmaceutical. To establish a PK model for ^{99m}Tc-DMSA applicable to pediatric patients of different ages, we retrospectively evaluated the renal uptake of this agent in 36 children from BCH, ranging in age from 1–16 years old. The percent injected activity present in the kidneys was estimated and compared with model prediction. The measured percent injected activity in the kidneys was independent of age and weight at 3.0 ± 0.6 hours postinjection. Our preliminary PK model for ^{99m}Tc-DMSA successfully fits the renal imaging data from BCH and the pediatric clinical data on liver, spleen and whole-body found in literature reports. Measurements of renal uptake of ^{99m}Tc-DMSA in pediatric patients from BCH provide a valuable data set for further PK model development. Further validation of the PK model depends on the availability of longitudinal imaging data in pediatric patients for this agent. Ultimately, these approaches will be applied to other radiopharmaceuticals commonly used in children.

Computational Phantoms

Estimation of the S value requires knowledge of both the radionuclide used and a model of the patient that includes estimates of the size and orientation of the various organs as well as their distance to other organs or tissues of interest. Anthropomorphic phantoms are used to model patients of different sizes (Fig. 1).[19] Several groups, including the University of Florida and the RADAR Task Group of the Society of Nuclear Medicine and Molecular Imaging, have provided more realistic depictions of reference adult, pediatric and pregnant female bodies and organs by using non-uniform rational B-splines (NURBS), a surface representation technique.[20]

A series of computational phantoms have been developed that realistically portray the anatomy of the pediatric patient population, which can be used to develop and validate techniques to optimize pediatric nuclear medicine with respect to radiation dose and image quality. A population of 48 hybrid phantoms consisting of NURBS and polygon meshes was generated. The representative ages included the newborn, 1-, 5-, 10-, and 15-year-old males and females. For each age, the phantoms were modeled at their 10th, 50th, and 90th height percentile, each at a constant 50th weight percentile, to investigate the effect of body morphology at different ages. To test the impact of kidney size, the newborn phantoms were modeled with the following three kidney volumes: −15%, average, and +15%. To illustrate the impact of different organ morphologies on dose optimization, we calculated the effective dose for each phantom using weight-based ^{99m}Tc-DMSA activity administration.

For a given patient weight, body habitus had a considerable effect on effective dose. Substantial variations were observed in the risk index between the 10th and 90th percentile height phantoms from the 50th percentile phantoms for a given age, with the greatest difference being 18%. There was a dependence found between kidney size and the risk with the highest risk indices observed in patients with smaller kidneys. Overall, the phantoms and techniques in this study can be used to refine dosing guidelines for pediatric nuclear imaging studies while taking into account the effects on both radiation dose and image quality.

Effective Dose

Effective dose (ED) was developed by the ICRP to provide a single number parameter for radiation-risk to allow different enterprises involving radiation exposure to be compared.[21] ED is equivalent to the absorbed dose given to the whole body of the patient that would result in the same stochastic biological effect as the actual collection of organ absorbed doses. It is calculated by taking a weighted sum of the absorbed doses delivered to individual organs, where each organ is weighted by its radiation sensitivity to stochastic effects. The formula is as follows:

$$\mathrm{ED} = \sum H_T \times W_T \quad (5)$$

where H_T is the equivalent dose to organ T and W_T is the radiosensitivity weight assigned to that organ. The radiosensitivity weights were recently updated.[22] Effective dose is based on

a population-based estimate of radiation risk and does not apply to a specific patient (Table 2). Equivalent dose is the absorbed dose adjusted by the appropriate radiation weighting factors to account for the differential biological effects of different radiation types. For photons and electrons this factor is 1 so that for all diagnostic imaging agents equivalent dose, *H*, is equal to absorbed dose, *D*. The ICRP has published standardized dose estimates for many radiopharmaceuticals.[11] Table 3 presents data for five procedures commonly performed in children.

Dosimetry of CT

Over the past 15 years, hybrid imaging has gone from a technological advance to an essential component of the diagnostic armamentarium. The combination of the ability to image physiologic and molecular processes along with the outstanding anatomical detail provided by CT provides invaluable clinical information, particularly in oncology. In fact, PET/CT has been so successful that whole-body PET-only devices have not been marketed by any major manufacturer for over a decade. The application of SPECT/CT has also been very successful, particularly for certain clinical applications. In many cases, a second, diagnostic CT scan is obtained in addition to that acquired during the hybrid imaging session. The application of CT in the context of hybrid imaging is quite variable. In some cases, the hybrid-based CT is acquired as a low-dose study only for attenuation correction and anatomical correlation; in other instances, it is acquired as a fully diagnostic study extended over the entire PET or SPECT field of view.

There are many factors that affect CT dose such as tube voltage (in kVp), tube current time product (in mAs), collimation and regional extent.[23] By reducing the current, fewer x-rays are emitted. This is useful when imaging thinner or less attenuating parts of the body (ie, the lungs). Table speed or “pitch” also affects CT dose. Pitch is defined as the distance traversed by the bed during 1 rotation of the x-ray tube divided by the collimated beam width. Thus, a higher pitch is equivalent to a faster bed speed and a lower dose. The use of automated exposure control can also affect CT dose. Dose can also be reduced by constraining exposure to a limited field of view, which is especially appropriate for high-dose applications. One example would be a parathyroid scan when the clinician is solely interested in the neck and the thorax. In comparison, an oncologic PET/CT scan may extend from the base of the patient’s skull to mid-thighs.

The CT dose index (CTDI) is defined as the dose delivered at certain locations within standard acrylic, cylindrical phantoms (16- and 32-cm diameter for the head and whole-body phantoms, respectively). If CTDI is averaged over several locations within the phantom (central and peripheral) and normalized by the pitch, it is referred to as $CTDI_{vol}$. The dose-length product (DLP in units of mGy cm) is the product of the $CTDI_{vol}$ and the axial length of the CT acquisition. Values of $CTDI_{vol}$ and DLP are typically displayed on the CT operator’s console during an acquisition.[23]

These values do not represent the radiation dose to a particular patient, but to the standard phantoms. However, if the size of the patient is known, the CTDI can be modified and reported as the size-specific dose estimate.[24] A series of anthropomorphic phantoms

composed of tissue-equivalent material has been used to estimate the radiation dose to patients of varying sizes from CT in both PET/CT and SPECT/ CT (Table 4).[25] For the same CT acquisition parameters, the dose to a newborn is approximately twice that of a medium-sized adult. Several groups have developed and used computerized phantoms for the estimation of CT dose to children and have corroborated these findings.[26,27] Therefore, CT acquisition parameters should be reduced for smaller patients.[28,29] As with radiopharmaceutical dosimetry, these estimates are averages for patients of different ages, and the radiation dose to a particular individual may vary.

Dose Optimization

The practice of pediatric nuclear medicine should be optimized such that the diagnostic quality of the procedures is maintained at a high level while, at the same, minimizing any potential risk. As stated previously, this can be particularly problematic in children given the wide variation in both anatomy and physiology. As a result, pediatric procedures should be optimized as a function of patient size and age. For these reasons, it is essential to develop a more complete understanding of the radiation dosimetry and pharmacokinetics associated with the use of radiopharmaceuticals in children as described in this manuscript. Also, knowledge of the amount of the radiopharmaceutical going to the organ system of interest (eg, the amount of ^{99m}Tc DMSA that distributes to the renal cortex) can be helpful in optimizing both the acquisition and the reconstruction of the subsequent study, leading to further improvements in image quality.

In general, dose optimization of an imaging modality involves the evaluation of the radiation absorbed dose associated with the procedure and the relationship between dose and the diagnostic image quality. In many instances, the administered activity is used as a surrogate for absorbed dose to the patient since it is linearly related to the absorbed dose of an organ of interest, as shown in Eq. (1). This may be a reasonable approach for a series of patients of similar body size and physiology, but is less appropriate for a population of children of mixed ages. The effective dose could be calculated to account for varying size, distance, and orientation of individual organs within patients, but will not correct for variations in radiosensitivity of the organs as a function of age. Our group has sought to develop an optimization model that takes variations in both anatomy and radiosensitivity into account, and has found that this can change the optimization as a function of both body habitus and organ size.[7]

The diagnostic image quality can be characterized either subjectively or quantitatively. Observers could simply judge the level of image quality on a subjective scale such as 1 for poor and 5 for excellent. We have been involved in several investigations including dose optimization projects in children involving ^{99m}Tc DMSA SPECT, ^{99m}Tc MDP SPECT, ^{99m}Tc MAG3 renal scans and ^{99m}Tc IDA hepatobiliary scans.[30–33] In this regard, it may be helpful if this judgment is made by the observer in the context of rendering an interpretation that the referring physician will find useful. Alternatively, the image quality could be characterized by an observer performance study using either a model observer such as the Channelized Hotelling Observer model or a collection of trained human observers. This

approach has also been applied to dose optimization in pediatric nuclear medicine by our group.[34]

Conclusion

The goal for every pediatric molecular imaging study is to obtain the best diagnostic information employing the highest quality standards, in the shortest period of time, and with the lowest patient radiation exposure. Meeting this goal requires accurate anatomical and pharmacokinetic models of patients as a function of age, accurate dose estimates, and knowledge of the effect of dose on image quality. In this time of hybrid imaging, it is also important to understand the contribution to the patient's absorbed dose from CT. Although our ability to estimate radiation dosimetry has advanced quite significantly over the past few decades, gaps in the current knowledge still exist, particularly with respect to these estimates in children.

- The practice of pediatric nuclear medicine with respect to the amount of radioactivity administered as a function of patient size for the procedures commonly performed in children and the use of CT in the context of hybrid imaging needs to be better understood.
- The further development of anatomical models as a function of body size and habitus including radiation dosimetry at the sub-organ level must continue.
- The relationship between administered activity and patient size and weight needs to be better understood.
- The PK of radiopharmaceuticals routinely used in children needs to be better characterized as a function of age and physiologic maturity.
- Variations in organ radiosensitivity as a function of age and gender should be incorporated into models for dose optimization.
- Tools should be made available that can assist the practitioner of pediatric nuclear medicine to better optimize the imaging procedures in their individual clinics.

These advancements would not only lead to more accurate radiation dosimetry in these patients, and, ultimately, will lead to improvements in the clinical practice of pediatric nuclear medicine and better long term outcomes for patients.

References

1. Treves, ST. Pediatric Nuclear Medicine and Molecular Imaging. 4. New York: Springer; 2014.
2. Schauer DA, Linton OW. NCRP Report No. 160, ionizing radiation exposure of the population of the United States, medical exposure—Are we doing less with more, and is there a role for health physicists? Health Phys. 2009; 97:1–5. [PubMed: 19509507]
3. Conway JJ. Quo vadis pediatric nuclear medicine. Semin Nucl Med. 2007; 37:242–248. [PubMed: 17544624]
4. Fahey FH, Bom HH, Chiti A, et al. Standardization of administered activities in pediatric nuclear medicine: A report of the first nuclear medicine global initiative project, part 1—statement of the issue and a review of available resources. J Nucl Med. 2015; 56:646–651. [PubMed: 25766899]

5. Fahey FH, Bom HH, Chiti A, et al. Standardization of administered activities in pediatric nuclear medicine: A report of the first nuclear medicine global initiative project, part 2—current standards and the path toward global standardization. J Nucl Med. 2016; 57:1148–1157. [PubMed: 27033894]
6. Radiation CtAHRfEtLLoI. Health Risks From Exposure to Low Levels of Ionizing radiation: BEIR VII Phase 2. Washington, DC: The National Academies Press; 2006.
7. O'Reilly SE, Plyku D, Sgouros G, et al. A risk index for pediatric patients undergoing diagnostic imaging with (99m) Tc-dimercaptosuccinic acid that accounts for body habitus. Phys Med Biol. 2016; 61:2319–2332. [PubMed: 26930549]
8. Gelfand MJ, Parisi MT, Treves ST. Pediatric radiopharmaceutical administered doses: 2010 North American consensus guidelines. J Nucl Med. 2011; 52:318–322. [PubMed: 21233182]
9. Bolch WE, Eckerman KF, et al. MIRD pamphlet no. 21: A generalized schema for radiopharmaceutical dosimetry—Standardization of nomenclature. J Nucl Med. 2009; 50:477–484. [PubMed: 19258258]
10. Stabin MG. Uncertainties in internal dose calculations for radiopharmaceuticals. J Nucl Med. 2008; 49:853–860. [PubMed: 18413398]
11. ICRP. Radiation dose to patients from radiopharmaceuticals: A compendium of current information related to frequently used substances. ICRP publication 128. Ann ICRP. 2015:44.
12. Hua C, Merchant TE, Li X, et al. Establishing age-associated normative ranges of the cerebral 18F-FDG uptake ratio in children. J Nucl Med. 2015; 56:575–579. [PubMed: 25745092]
13. Esa URHS-P, Eronen AK, Teras JBMHM, et al. Estimated radiation dose to the newborn in FDG-PET studies. J Nucl Med. 1996; 37:387–393. [PubMed: 8667081]
14. London K, Howman-Giles R. Normal cerebral FDG uptake during childhood. Eur J Nucl Med Mol Imaging. 2014; 41:723–735. [PubMed: 24323306]
15. Chugani HT, Phelps ME. Maturational changes in cerebral function in infants determined by 18FDG positron emission tomography. Science. 1986; 231:840–843. [PubMed: 3945811]
16. Chugani HT, Phelps ME, Mazziotta JC. Positron emission tomography study of human brain functional development. Ann Neurol. 1987; 22:487–497. [PubMed: 3501693]
17. Van Bogaert P, Wikler D, Damhaut P, et al. Regional changes in glucose metabolism during brain development from the age of 6 years. Neuroimage. 1998; 8:62–68. [PubMed: 9698576]
18. Khamwan K, Plyku D, O'Reilly SE, et al. Pharmacokinetic modeling of [18F] fluorodeoxyglucose (FDG) for premature infants, and newborns through 5-year-olds. EJNMMI Res. 2016; 6:1–11. [PubMed: 26728358]
19. Marine PM, Stabin MG, Fernald MJ, et al. Changes in radiation dose with variations in human anatomy: larger and smaller normal-stature adults. J Nucl Med. 2010; 51:806–811. [PubMed: 20395339]
20. Stabin M, Gelfand M. Dosimetry of pediatric nuclear medicine procedures. Q J Nucl Med Mol Imaging. 1998; 42:93.
21. ICRP. Recommendations of the International Commision on Radiaiton Protection. ICRP Publicaiton 26. Ann ICRP. 1977:1.
22. ICRP. The 2007 Recommendations of the International Commission on Radiaiton Protection ICRP Publicaiton 103. Ann ICRP. 2007:37.
23. Fahey FH. Dosimetry of pediatric PET/CT. J Nucl Med. 2009; 50:1483–1491. [PubMed: 19690036]
24. Boone J, Strauss K, Cody D. AAPM Report No. 204: Size-specific dose estimates (SSDE) in pediatric and adult body CT examinations. 2013
25. Fahey FH, Palmer MR, Strauss KJ, et al. Dosimetry and adequacy of CT-based attenuation correction for pediatric PET: Phantom study 1. Radiology. 2007; 243:96–104. [PubMed: 17293575]
26. Xu, XG., Eckerman, KF. Handbook of Anatomical Models for Radiation Dosimetry. New York: CRC Press; 2009.
27. Whalen S, Lee C, Williams JL, et al. Anthropometric approaches and their uncertainties to assigning computational phantoms to individual patients in pediatric dosimetry studies. Phys Med Biol. 2007; 53:453. [PubMed: 18184999]

28. Donnelly LF, Emery KH, Brody AS, et al. Minimizing radiation dose for pediatric body applications of single-detector helical CT: strategies at a large children's hospital. AJR Am J Roentgenol. 2001; 176:303–306. [PubMed: 11159061]

29. Frush DP. Radiation, CT, and children: The simple answer is… It's Complicated 1. Radiology. 2009; 252:4–6. [PubMed: 19561246]

30. Sheehy N, Tetrault TA, Zurakowski D, et al. Pediatric 99mTc-DMSA SPECT performed by using iterative reconstruction with isotropic resolution recovery: Improved image quality and reduced radiopharmaceutical activity. Radiology. 2009; 251:511–516. [PubMed: 19304919]

31. Stansfield EC, Sheehy N, Zurakowski D, et al. Pediatric 99mTc-MDP bone SPECT with ordered subset expectation maximization iterative reconstruction with isotropic 3D resolution recovery. Radiology. 2010; 257:793–801. [PubMed: 20858847]

32. Hsiao EM, Cao X, Zurakowski D, et al. Reduction in radiation dose in mercaptoacetyltriglycerine renography with enhanced planar processing. Radiology. 2011; 261:907–915. [PubMed: 21900613]

33. Fahey F, Zukotynski K, Zurakowski D, et al. Beyond current guidelines: Reduction in minimum administered radiopharmaceutical activity with preserved diagnostic image quality in pediatric hepatobiliary scintigraphy. Eur J Nucl Med Mol Imaging. 2014; 41:2346–2353. [PubMed: 25097073]

34. Sgouros G, Frey EC, Bolch WE, et al. An approach for balancing diagnostic image quality with cancer risk: Application to pediatric diagnostic imaging of 99mTc-dimercaptosuccinic acid. J Nucl Med. 2011; 52:1923–1929. [PubMed: 22144506]

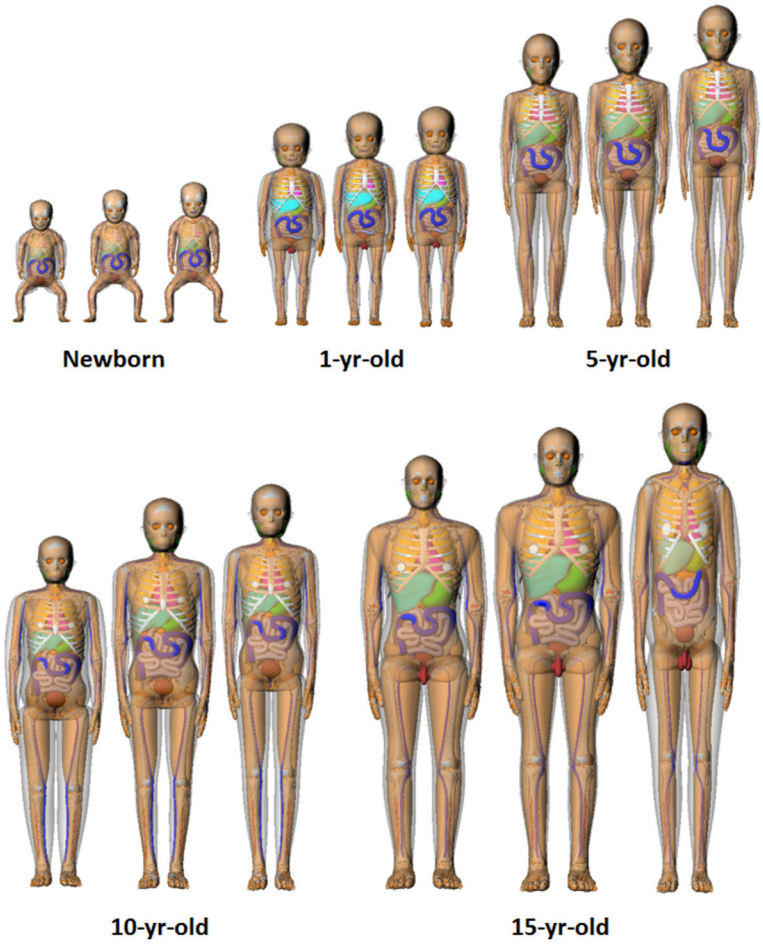

Figure 1.
Realistic CT-Based Scalable NURBS-Based Computational Phantom. (Adapted with permission from O'Reilly et al.[7] © IOP Publishing. Reproduced with permission. All rights reserved.)

Table 1

Pediatric Nuclear Medicine Practice in 2005[3]

	Brussels	Chicago	Sidney	Vancouver	Munich	Cincinnati	Paris	Boston	UK 1	UK 2
Exams	1300	1303	2259	3800	394	4013	2409	5719	1805	2340
Renal	50%	49%	43%	37%	57%	57%	29%	53%	90%	74%
Bone	20%	19%	22%	20%	6%	17%	44%	18%	4%	8%
Tumor-brain	5%	12%	15%	22%	24%	11%	7%	11%	3%	10%
GI	15%	15%	14%	17%	13%	8%	0%	6%	2%	3%
Heart-lung	10%	2%	6%	4%	0%	4%	20%	11%	1%	5%

Table 2

Effective Dose Organ Radiosensitivity Weights Based on ICRP Publication 103[22]

Tissue or Organ	Effective Dose Weights
Gonads	0.08
Red bone marrow	0.12
Lung	0.12
Colon	0.12
Stomach	0.12
Breast	0.12
Bladder	0.04
Liver	0.04
Esophagus	0.04
Thyroid	0.04
Skin	0.01
Bone surface	0.01
Brain	0.01
Salivary glands	0.01
Remainder	0.12
Total	1.00

Table 3

Effective Dose (in mSv) for Various Radiopharmaceuticals Based on Weight (Models Based on ICRP Publication 128[11])

	1 Year	5 Year	10 Year	15 Year	Adult
Mass (kg)	9.7	19.8	33.2	56.8	70
99mTc DMSA (3.5 mCi*)	0.7	0.8	0.9	1.2	1.1
99mTc-MDP (20 mCi*)	2.8	2.9	3.9	4.2	4.2
Tc-ECD (20 mCi*)	4.1	4.6	5.3	5.9	5.7
Tc-MAG3 (10 mCi*)	1.1	1.3	2.1	2.7	2.6
18-FDG (10 mCi*)	4.8	5.9	6.5	7.2	7.0

*Maximum administered activity.

Table 4

Radiation Dose to Anthropomorphic Phantom from CT Component of Hybrid Imaging as Function of Patient Size and Tube Current[23]

		$CTADI_{vol}$ (mGy)				
Phantom	**kVp**	**10 mA**	**20 mA**	**40 mA**	**80 mA**	**160 mA**
Newborn	80	0.42	0.85	1.69	3.39	6.78
Newborn	100	0.80	1.60	3.21	6.41	12.83
Newborn	120	1.26	2.53	5.05	10.10	20.20
Newborn	140	1.77	3.53	7.06	14.13	28.25
1-Year old	80	0.37	0.74	1.47	2.94	5.88
1-Year old	100	0.70	1.40	2.80	5.59	11.19
1-Year old	120	1.11	2.22	4.45	8.89	17.78
1-Year old	140	1.57	3.14	6.28	12.56	25.11
5-Year old	80	0.33	0.66	1.32	2.65	5.30
5-Year old	100	0.64	1.28	2.55	5.10	10.20
5-Year old	120	1.02	2.04	4.08	8.16	16.31
5-Year old	140	1.46	2.91	5.83	11.66	23.32
10-Year old	80	0.30	0.60	1.19	2.38	4.76
10-Year old	100	0.58	1.16	2.32	4.64	9.27
10-Year old	120	0.92	1.84	3.67	7.35	14.69
10-Year old	140	1.32	2.63	5.26	10.52	21.04
Med adult	80	0.20	0.40	0.80	1.61	3.22
Med adult	100	0.40	0.79	1.58	3.17	6.33
Med adult	120	0.64	1.27	2.55	5.10	10.19
Med adult	140	0.91	1.82	3.65	7.30	14.59

All data were acquired with rotation speed of 0.8 s per rotation and a 1.5:1 pitch. All data were acquired with 160 mA and linearly scaled for the various tube current values represented in the table. This linear assumption was tested and shown to be appropriate to within 4% which is considered acceptable for this investigation.

*All data were acquired with tube voltage of 120 kVp, rotation speed of 0.8 s, and pitch of 1.5:1. All data were acquired with 160 mA and linearly scaled for the various tube currents shown here.