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INDIVIDUALIZED ADJUSTMENTS TO REFERENCE PHANTOM INTERNAL ORGAN DOSIMETRY – SCALING FACTORS GIVEN KNOWLEDGE OF PATIENT EXTERNAL ANATOMY

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Abstract

Internal radiation dose estimates for diagnostic nuclear medicine procedures are typically calculated for a reference individual. Resultantly, there is uncertainty when determining the organ doses to patients who are not at 50th percentile on either height or weight. This study aims to better personalize internal radiation dose estimates for individual patients by modifying the dose estimates calculated for reference individuals based on easily obtainable morphometric characteristics of the patient. Phantoms of different sitting heights and waist circumferences were constructed based on computational reference phantoms for the newborn, 10-year-old, and adult. Monoenergetic photons and electrons were then simulated separately at 15 energies. Photon and electron specific absorbed fractions (SAFs) were computed for the newly constructed non-reference phantoms and compared to SAFs previously generated for the age-matched reference phantoms. Differences in SAFs were correlated to changes in sitting height and waist circumference to develop scaling factors that could be applied to reference SAFs as morphometry corrections. A further set of arbitrary non-reference phantoms were then constructed and used in validation studies for the SAF scaling factors. Both photon and electron dose scaling methods were found to increase average accuracy when sitting height was used as the scaling parameter (~11%). Photon waist circumference-based scaling factors showed modest increases in average accuracy (~7%) for underweight individuals, but not for overweight individuals. Electron waist circumference-based scaling factors did not show increases in average accuracy. When sitting height and waist circumference scaling factors were combined, modest average gains in accuracy were observed for photons (~6%), but not for electrons. Both photon and electron absorbed doses are more reliably scaled using scaling factors computed in this study. They can be effectively scaled using sitting height alone as patient-specific morphometric parameter.

Keywords

Nuclear medicine dosimetry; patient-specific dose scaling; specific absorbed fraction; dose sensitivity

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1. Introduction

Estimates of internal organ dose in diagnostic nuclear medicine typically employ data obtained using computational phantoms of reference individuals. Individual patients, however, may exhibit heights and weights that are far from their 50th percentile values (ICRP, 2002), and thus adjustments are needed for improved dose accuracy. Our research group has thus explored two approaches to the adjustment of organ radionuclide S values (radiation absorbed dose delivered to a target tissue per radioactive decay in the source tissue) computed in a reference phantom to increase internal dose patient-specificity. In our first approach, knowledge of patient's internal anatomy is assumed, in particular organ masses (for adjustments to organ self-dose) and inter-organ separation distances (for adjustments to organ cross-dose) (Wayson, 2012). Given these patient-specific parameters, specific absorbed fraction (SAF – the fraction of radiation energy emitted from a source tissue that is imparted per unit mass to a target tissue) scaling factors are provided as needed for re-computing radionuclide S values in an internal dosimetry software package.

Another approach to tailoring reference phantom dose estimates to specific individual patients is to scale SAF values, and thus S values, based on known and clinically accessible exterior patient body morphometry. Internal anatomy varies substantially with variations in patient stature (de la Grandmaison *et al.*, 2001). While some changes, such as obesity in a similar height individual, are known to cause small changes in internal dose estimates due to subcutaneous fat deposits (which contribute the most to weight gain) (Clark *et al.*, 2010), other variations such as patients of different torso sizes or same-weight individuals with different sized waist circumferences could have impacts on internal dose estimates. For these individuals, dose tailoring could be of benefit to provide more accurate estimates of organ dose. A systematic method is presented in this study in which variations in sitting height, waist circumference, or both are incorporated within the University of Florida series of hybrid computational phantoms. Monte Carlo-based radiation transport methods are used to simulate the interactions of photons and electrons within the body, and specific absorbed fractions are used as the measure by which dose variations are evaluated.

2. Materials and Methods

In 2009, the University of Florida (UF) Advanced Laboratory for Radiation Dosimetry Studies (ALRADs) developed its first phantom library that addressed a range of patient morphometries representing the recent United States population (Johnson *et al.*, 2009). Primary target parameters were defined as standing height, sitting height, and total body mass, and secondary target parameters were defined as waist, buttocks, arm, and thigh circumferences. A set of 50 adult phantoms (25 males and 25 females) were created with each of these parameters derived from the National Health and Nutrition Examination Surveys (NHANES) conducted by the National Center for Health Statistics of the CDC (Johnson *et al.*, 2009). This library of phantoms could be utilized to perform dosimetry on “patient-dependent” phantoms rather than reference phantoms. If measures of a patient's standing height, sitting height, weight, and various circumferences were available, a closely matched phantom could be selected from the library for dosimetry analysis. Presumably, the

patient-dependent phantom would yield more accurate dose estimates than provided by use of a reference phantoms (which represent the average individual).

Despite the advantage of a library of computational phantoms, performing Monte Carlo radiation transport simulations for every phantom in a large library is currently impractical due to computational processing times. Instead of performing time-consuming simulations for every phantom in a large library or for individual patients with a full complement of segmented organs, this study attempted to develop patient-specific scaling factors based on easily measureable morphometric characteristics such as sitting height, body circumference, and body weight. These scaling relationships would be applied to organ dose estimates from a set of reference phantoms for which the detailed simulations were already completed.

2.1 Sitting Height-Based Dose Scaling

2.1.1 Scaling Factors—While organ sizes have been shown to correlate fairly well with standing height (de la Grandmaison *et al.*, 2001), sitting height was isolated as a metric by which reference internal organ doses could be scaled. The size of important internal organs correlate more closely with changes in the trunk size rather than with changes in leg length, as variations in standing height are heavily influenced by variations in leg length. Because the chest cavity expands or contracts with increases or decreases in sitting height relative to the sitting height of the reference phantoms from which the library of patient-dependent phantoms was derived, it was expected that radiation absorbed doses to tissues of interest would be influenced by the change in position and size of organs within the torso. Consequently, a computational study was designed to attempt to derive a correlation between changes in radiation dose from internal emitters and changes in sitting height.

To develop the library of scaling factors, two phantoms of shorter stature and two phantoms of taller stature were created for each of three UF reference phantoms – the UF newborn male hybrid phantom (UFH00M), the UF 10-year-old male hybrid phantom (UFH10M), and the UF adult male hybrid phantom (UFHADM) – giving us a total of 12 scaled phantoms for the study [the UF hybrid computational phantoms are described in Lee *et al.* (2010)]. Sitting heights were chosen to span a large range of values so that dose dependencies could be effectively observed and modeled. All tissues except those located in the legs of the phantoms were scaled in three dimensions, consistent with the methodology described in Johnson *et al.* (2009), to achieve these different statures. The UFH00M phantoms created for the sitting height study are shown in Figure 1. Phantom morphometric measurements are given in Table 1, and voxel resolutions and total matrix sizes used in the radiation transport simulations using MCNPX v2.6 are given in Table 2.

Uniform monoenergetic photon and electron sources were separately simulated in the brain, liver, lungs, and spleen as source tissues to assess scaling dependencies on source tissue. A whole-body active marrow (AM) source was simulated based on the active marrow mass distributions of the relevant reference phantoms (e.g., the tallest scaled UFHADM-based scaled phantom was assigned an active marrow distribution of the UFHADM reference phantom). Target tissues simulated in Wayson *et al.* (2012) were simulated in this study. Fifteen monoenergetic photon and electron energies were simulated, and each energy selected was assigned a particle history value taking into account the loss in statistical

certainty with decreasing radiation energy. All photons and electrons generated during transport were tracked, and total energy deposition in each target tissue was recorded.

Scaling factors were calculated as the ratio of the energy-dependent, source tissue-dependent, and target tissue-dependent SAF of the newly constructed non-reference phantom at a non-reference sitting height to the SAF of the reference phantom for the same energy/source/target combination. This approach is reflected in Equation 1 where the non-reference sitting height refers to those of the newly constructed non-reference phantoms. A library of dose scaling factors (ratios of SAF values) was created based on the individual reference phantom and sitting height.

$$f(r_T \leftarrow r_S, E_i, H_{non-ref}, H_{ref}) = \frac{\Phi(r_T \leftarrow r_S, E_i, H_{non-ref})}{\Phi(r_T \leftarrow r_S, E_i, H_{ref})} \quad (1)$$

where $\Phi(r_T \leftarrow r_S, E_i, H_{non-ref})$ is the SAF for source tissue r_S irradiating target tissue r_T at radiation energy E_i for the newly constructed non-reference phantom of sitting height $H_{non-ref}$. $\Phi(r_T \leftarrow r_S, E_i, H_{ref})$ is the same measure for the reference phantom with sitting height H_{ref} and $f(r_T \leftarrow r_S, E_i, H_{non-ref}, H_{ref})$ is the dose scaling factor as defined above.

If a dose assessment was performed for an individual patient, the sitting height of the patient would be measured¹, and the appropriate scaling factor would be interpolated from the dataset developed through simulations and Equation 1. Equation 2 would be used to scale the reference SAFs for the individual patient.

$$\Phi(r_T \leftarrow r_S, E_i, H) = \Phi(r_T \leftarrow r_S, E_i, H_{ref}) \cdot f(r_T \leftarrow r_S, E_i, H, H_{ref}) \quad (2)$$

where H is the sitting height of the individual patient. S values can be scaled by incorporating the scaled SAFs. Direct S value scaling is impractical as each SAF scales differently according to its dependent variables.

2.1.2 Validation Studies—Dose scaling based on anthropometric characteristics was the goal of the morphometry-based dosimetric sensitivity study, so ultimately the results would be applied to the UF reference hybrid phantom monoenergetic SAFs. To verify the efficacy of this method, a series of validation studies were performed, and the general process was as follows:

1. Create a unique non-reference computational phantom as a scaled version of an existing reference phantom (in this case the UF series of hybrid phantoms).
2. Simulate a radionuclide spectrum in a source tissue within the unique non-reference phantom using MCNPX v2.6 and determine the radionuclide S value to all target tissues. This is the test phantom.

¹The distance from the vertex of the head to the supporting surface on which a person is *sitting* erect.

3. Calculate estimated S values by scaling existing monoenergetic SAFs that were available for the reference phantom (used to create the test phantom in Step 1) using Equation 2 based on spectrum information for the test radionuclide.
4. Compare the explicitly simulated non-reference S values to the scaled reference S values.

Scaling the reference SAFs should yield more accurate estimates of radionuclide S values for a non-reference phantom than radionuclide S values for the reference phantom. If this is the case, the dosimetric sensitivity studies will improve dose estimates for individual dosimetry.

Conditions of the sitting height dose variation study were such that dose variations were valid for uniform three-dimensional scaling of the torso of the UF hybrid phantoms with no additional weight adjustments. Three non-reference phantoms were scaled from the reference UFH00M, UFH10M, and UFHADM phantoms (one scaled phantom per reference phantom), and uniform photon and electron sources were separately simulated within the liver of each phantom. The ^{131}I photon spectrum and ^{90}Y beta spectrum were selected, and the radiation energies and yields were obtained from ICRP Publication 107 (ICRP, 2008).

Dose scaling techniques derived from the sitting height dose sensitivity study were applied to the relevant reference phantom (e.g., scaling techniques were applied to the UFHADM reference phantom to estimate dose for the scaled version of the UFHADM reference phantom) SAFs given in Wayson (2012) at each radiation energy and combined to yield the photon component of the ^{131}I radionuclide S value and the beta component of the ^{90}Y radionuclide S value. Scaling techniques were unique to each reference phantom since it was not assumed that internal doses would scale independent of the reference phantom. These scaled results were compared to the explicitly simulated radionuclide S values obtained for the three non-reference phantoms through simulation in MCNPX v2.6 to determine the efficacy of dose scaling based on sitting height. All emission energies of ^{131}I and ^{90}Y were included, and ten million particle histories were simulated. All photons and electrons generated during transport were tracked, and total energy deposition in each target tissue was recorded. Target tissues with greater than 10% uncertainty in the direct simulations were excluded from comparison.

The physical characteristics of the sitting height-based validation phantoms were as follows:

1. UFH00M-based non-reference phantom with a sitting height of 31.2 cm and a weight of 2.7 kg.
2. UFH10M-based non-reference phantom with a sitting height of 68.2 cm and a weight of 25.2 kg.
3. UFHADM-based non-reference phantom with a sitting height of 96.0 cm and a weight of 79.6 kg.

2.2 Weight-based Dose Scaling

2.2.1 Scaling Factors—Previous studies have shown that radiation absorbed doses do not heavily depend on increases in subcutaneous fat (Clark *et al.*, 2010), but dose dependencies for underweight individuals have not been examined. It would be expected that internal doses would not change much with increases in subcutaneous fat because the internal structure of the patient remains fairly unchanged in these cases. Only the absorbed dose to subcutaneous fat itself and structures exterior to the subcutaneous fat would be expected to change. However, when underweight individuals were modeled in the UF patient-dependent computational phantom library, some were scaled in two dimensions to match the waist and buttocks circumferences (Johnson *et al.*, 2009). According to the autopsy study of de la Grandmaison *et al.*, which demonstrated correlated changes in organ size with changes in anthropometric characteristics, the two-dimensional scaling technique created reasonably accurate organ sizes (Johnson *et al.*, 2009). However, individual variability is unavoidable, and a range of organ sizes was noted. As a result of two-dimensional scaling for underweight individuals, organ volumes decrease, and the separation between the organs decreases. Dose variation for underweight individuals was therefore expected, and a dosimetric sensitivity study was created similar to that for variations in sitting height (Section 2.1.1).

Two underweight phantoms and one overweight phantom were created using the UFH00M, UFH10M, and UFHADM phantoms as the reference phantoms for a total of 9 scaled phantoms. Weights were chosen to span a large range of values so that dose dependencies could be effectively observed and modeled. The underweight phantoms were created by decreasing the arm, thigh, waist, and buttocks circumferences through two-dimensional scaling in the transverse plane. The overweight phantom was created by increasing the arm, thigh, waist, and buttocks circumferences in addition to adding subcutaneous fat elsewhere in the body. NURBS/PM models of the UFH00M phantoms created for the weight study are in Figure 2. Phantom morphometric measurements are in Table 3, and voxel resolutions and total matrix sizes used for the radiation transport simulations using MCNPX v2.6 are in Table 4.

Uniform monoenergetic photon and electron sources were simulated in the brain, liver, lungs, and spleen as source tissues to assess scaling dependencies on source tissue. A whole-body active marrow source was simulated based on the active marrow mass distributions of the relevant reference phantom (e.g., thinnest scaled UFHADM-based phantom was assigned a marrow distribution of the UFHADM reference phantom). Target tissues simulated in Wayson *et al.* (2012) were simulated in this weight-based study. Fifteen monoenergetic photon and electron energies were simulated, and each energy selected was assigned a particle history value accounting for the loss in statistical certainty with decreasing radiation energy. All photons and electrons generated during transport were tracked, and total energy deposition in each target tissue was recorded. Target tissues with >10% uncertainty in the direct simulations were excluded from comparison.

Scaling factors were calculated in the same way as for sitting height as shown in Equation 3, Waist circumference instead of weight was selected as the scaling parameter since waist circumference correlates more closely with body habitus.

$$f(r_T \leftarrow r_S, E_i, WC_{non-ref}, WC_{ref}) = \frac{\Phi(r_T \leftarrow r_S, E_i, WC_{non-ref})}{\Phi(r_T \leftarrow r_S, E_i, WC_{ref})} \quad (3)$$

where $\Phi(r_T \leftarrow r_S, E_i, WC_{non-ref})$ is the SAF for source tissue r_S irradiating target tissue r_T at radiation energy E_i for the newly constructed non-reference phantom with waist circumference $WC_{non-ref}$, $\Phi(r_T \leftarrow r_S, E_i, WC_{ref})$ is the same measure for the reference phantom with waist circumference WC_{ref} , and $f(r_T \leftarrow r_S, E_i, WC_{non-ref}, WC_{ref})$ is the dose scaling factor as defined above.

If a dose assessment was performed for an individual patient, the waist circumference of the patient would be measured, and the appropriate scaling factor would be interpolated from the dataset developed through simulations and Equation 3. Equation 4 would be used to scale the reference SAFs for the individual patient.

$$\Phi(r_T \leftarrow r_S, E_i, WC) = \Phi(r_T \leftarrow r_S, E_i, WC_{ref}) \cdot f(r_T \leftarrow r_S, E_i, WC, WC_{ref}) \quad (4)$$

where WC is the waist circumference of the individual patient.

2.2.2 Validation Studies—Several phantoms of varying weight were simulated with uniform photon (^{131}I spectrum) and electron (^{90}Y beta spectrum) sources in the liver of each phantom. Three adult male phantoms from a previously developed patient-dependent phantom library (Johnson *et al.*, 2009) were selected for validation – 10th, 75th, and 90th percentile by weight at the 50th percentile by height, indicated as m5010, m5075, and m5090, respectively. Two additional phantoms were created for comparison purposes – one based on the UFH00M phantom and one based on the UFH10M phantom. One scaled phantom was created for each reference phantom, holding the height constant and varying the weight. The weight for the UFH00M phantom was decreased, and the weight for the UFH10M phantom was increased to assess dose scaling performance for both underweight and overweight individuals.

Scaling factors developed in the weight dose variation study were applied to reference monoenergetic SAFs (Wayson, 2012) for the relevant age-specific reference phantom to estimate the photon component of the radionuclide S value for ^{131}I and the beta component of the radionuclide S value for ^{90}Y . These results were compared to the explicitly simulated radionuclide S values found using MCNPX v2.6 for each of the non-reference weight-varying phantoms. Target tissues with greater than 10% uncertainty in the direct simulations were excluded from comparison.

The physical characteristics of the weight-based validation phantoms were as follows:

1. UFH00M-based non-reference phantom with a sitting height of 34.0 cm, a weight of 3.1 kg, and a waist circumference of 35.0 cm.
2. UFH10M-based non-reference phantom with a sitting height of 75.6 cm, a weight of 38.3 kg, and a waist circumference of 83.6 cm.
3. The three UFHADM-based non-reference phantoms (m5010, m5075, and m5090) are described in Johnson et al. (Johnson *et al.*, 2009).

2.3 Combined Sitting Height- and Weight-based Dose Scaling

2.3.1 Scaling Factors—Scaling factors taking into account both non-reference sitting height and waist circumference were next derived as a multiplication of the individual sitting height and waist circumference-based scaling factors as shown in Equation 5.

$$f(r_T \leftarrow r_S, E_i, H_{non-ref}, H_{ref}, WC_{non-ref}, WC_{ref}) = \frac{\Phi(r_T \leftarrow r_S, E_i, H_{non-ref})}{\Phi(r_T \leftarrow r_S, E_i, H_{ref})} \cdot \frac{\Phi(r_T \leftarrow r_S, E_i, WC_{non-ref})}{\Phi(r_T \leftarrow r_S, E_i, WC_{ref})} \quad (5)$$

where $f(r_T \leftarrow r_S, E_i, H_{non-ref}, H_{ref}, WC_{non-ref}, WC_{ref})$ is the combined dose scaling factor based upon input parameters as defined previously. If a dose assessment was performed for an individual patient, the sitting height, and waist circumference of the patient would be measured, and the appropriate scaling factor would be interpolated from the datasets developed through simulations to compute the final combined scaling factor in Equation 5. The scaling factor would then be applied to the relevant reference SAF. After all SAFs are corrected, the final scaled S value would be computed.

2.3.2 Validation Studies—A similar method used to validate the sitting height- and weight-based scaling factors was used to validate the combination of the sitting height and weight scaling factors. The key difference for analyzing a combinatorial approach to dose scaling is that phantoms at both non-50th percentile height and non-50th percentile weight were used. The library of patient-dependent phantoms based on the UFHADM reference phantom described in (Johnson *et al.*, 2009) was used. Two additional phantoms were created for comparison purposes – one based on the UFH00M phantom and one based on the UFH10M phantom. One scaled phantom was created for each reference phantom, varying both the height and weight. Height was increased, and weight was decreased for the UFH00M phantom. Height was decreased, and weight was increased for the UFH10M phantom.

Radionuclide S values for ¹³¹I and ⁹⁰Y were calculated for phantoms of various weights at non-50th percentile heights by applying scaling factors derived from the sitting height and weight dose variation studies to the UFHADM reference monoenergetic SAFs (Wayson, 2012). These results were compared to the explicitly simulated radionuclide S values found using MCNPX v2.6. Target tissues with greater than 10% uncertainty in the direct simulations were excluded from comparison.

Photons and electrons were simulated in the liver of these phantoms with the ^{131}I photon spectrum and ^{90}Y beta spectrum using MCNPX v2.6. Scaling methods derived in the height and weight dose variation studies were combined and applied to reference UFH00M and UFH10M monoenergetic SAFs (Wayson, 2012) to calculate the photon and electron components of the radionuclide S values for ^{131}I and ^{90}Y , respectively, for the non-reference phantoms. These results were compared to the explicitly simulated radionuclide S values found using MCNPX v2.6. The physical characteristics of the combined height and weight validation phantoms were as follows:

1. UFH00M-based non-reference phantom with a sitting height of 37.1 cm, a weight of 3.7 kg, and a waist circumference of 36.6 cm.
2. UFH10M-based non-reference phantom with a sitting height of 68.4 cm, a weight of 29.1 kg, and a waist circumference of 75.3 cm.
3. The three UFHADM-based non-reference phantoms (m5010, m5075, and m5090) are described in Johnson et al. (Johnson *et al.*, 2009).

3. Results

3.1 Sitting Height

3.1.1 Dose Dependencies—The sitting heights of three reference phantoms, the UFH00M, UFH10M, and UFHADM phantoms, were systematically adjusted, consistent with methods outlined in Johnson et al. (2009), and simulated with both monoenergetic photons and electrons uniformly distributed throughout the active marrow, brain, lungs, liver, and spleen of those phantoms. Absorbed dose in the form of the SAF was calculated for all source-target-energy combinations.

An excerpt of the results for the 500 keV and 4 MeV photon simulations in the liver of the UFH00M-based phantoms are shown in Figure 3, and an excerpt of the results for the 500 keV and 4 MeV electrons simulations in the liver of the UFH00M-based phantoms are given in Figure 4. These graphs show the extent to which the monoenergetic SAFs change as a function of sitting height of the UFH00M-based phantoms. An overall gradual decrease in SAF is observed across almost all target tissues for both photons and electrons. Increasing organ-to-organ separations and organ sizes with increases in sitting height both contribute to the overall decrease in SAFs. Target tissues with increasing SAFs as a function of sitting height were assumed to display poorer statistical uncertainties, and this was found to be the case. Some of the target tissues in the 500 keV electron simulations had poor statistical uncertainties and were therefore not useful in developing dose scaling factors.

Figure 5 shows whole-body dose for uniform 4 MeV photon and electron sources in the liver of all phantoms in the sitting height dose variation study. The whole-body SAF appears to be log-linearly decreasing with increases in sitting height for both photons and electrons. Another feature of interest is the dependence of the whole-body SAF on the reference phantom. The plots demonstrate that one could not simply scale absorbed doses according to relative sitting height because the anthropometric structure of each phantom age is different. For any dose scaling to occur, the reference phantom must first be specified. Next, a sitting

height measurement could be taken and compared to the sitting height of the selected reference phantom. Actual sitting height-based scaling methodologies are discussed later.

3.1.2 Validation Studies—Uniform ^{131}I photon and ^{90}Y electron sources were simulated in the liver of a UFH00M-based phantom with decreasing sitting height, a UFH10M-based phantom with decreasing sitting height, and a UFHADM-based phantom with increasing sitting height. Radionuclide S values were predicted for all target tissues by applying dose scaling factors to each target tissue according to the sitting height of the scaled phantom and the reference phantom upon which the scaled phantom was based. The predicted S values were then compared to those obtained through direct simulation.

Different levels of scaling factors were available to scale reference SAFs. The scaling factor for a particular source-target combination could be used, and this would be the finest level of scaling detail possible. In this case, each source-target-energy combination has its own scaling factor. One alternative is to use the scaling factor calculated as the average across all source tissues for the target tissue of interest. This would be the target-average scaling factor. A global average scaling factor calculated as the average scaling factor across all source-target combinations could also be used. S values determined using the global average and target-average dose scaling factors were compared to S values determined using dose scaling factors that were calculated from the active marrow, brain, liver, lungs, and spleen source tissue simulations.

Complete results for the ^{131}I study for the UFH00M-based phantom are shown in Table 5. The same analysis was done for ^{90}Y , but only the summarized results are shown later. Summarized results for the ^{131}I and ^{90}Y studies for all phantoms are given in Tables 6 and 7, respectively. Target tissues with greater than 10% uncertainty in the direct simulations were excluded from comparison because the predictive quality of the scaling factors cannot be assessed when the standard values themselves have larger uncertainties.

It was found that fairly significant increases in accuracy could be attained when using dose scaling factors based on sitting height for both photons and electrons. The gains in accuracy for the UFH00M- and UFH10M-based phantoms were on the order of 15% while the gains in accuracy for the UFHADM-based phantom were on the order of 5% for both photons and electrons. Problems arise for electron dose scaling since electrons do not penetrate as deeply as photons into tissue. As a result, surface-to-surface distances between organ pairs can cause dose scaling factors to vary widely between phantoms of differing sitting heights. For example, the thyroid and salivary glands of the reference phantom may be oriented such that primary electrons emitted from the thyroid reach the salivary glands but may not reach that target organ in a non-reference phantom, leading to orders of magnitude differences in target dose. Dose scaling factors cannot always accurately predict these anatomical changes in source/target tissues.

3.2 Weight

3.2.1 Dose Dependencies—The weights of the same three reference phantoms used for the sitting height dose sensitivity study – the UFH00M, UFH10M, and UFHADM phantoms – were systematically adjusted, consistent with methods outlined in Johnson *et al.* (2009),

and monoenergetic photons and electrons were simulated as uniformly distributed throughout the active marrow, brain, lungs, liver, and spleen of the weight-adjusted phantoms. SAFs were calculated for all source-target-energy combinations.

An excerpt of the results for the 500 keV and 4 MeV photon simulations in the liver of the UFH00M-based weight-scaled phantoms are in Figure 6, and an excerpt of the results for the 500 keV and 4 MeV electrons simulations in the liver of the UFH00M-based weight-scaled phantoms are in Figure 7. These graphs show changes in monoenergetic SAFs as a function of waist circumference of the UFH00M-based phantoms.

An overall gradual decrease in SAF is observed across most target tissues for both photons and electrons for the underweight phantoms. However, no appreciable decrease in organ doses is observed for the severely overweight phantom, as predicted previously by Clark *et al.* (2010). Decreasing organ-to-organ separations and organ sizes in the underweight phantoms explains the increase in dose with decreases in waist circumference. Overweight patients will generally not show dramatic changes in absorbed dose because the internal structure is similar to that of the reference phantom. Only adipose tissue is added to the outer contour of the phantom to model overweight patients, causing only limited increases in photon backscatter. Poor statistical uncertainties were implicated for target tissues displaying increasing SAFs as a function of waist circumference.

Figure 8 shows whole-body dose for uniform 4 MeV photon and electron sources in the liver of all phantoms in the weight dose variation study. The whole-body SAF appears to be log-linearly decreasing with increases in waist circumference for both photons and electrons for each reference phantom. Like the sitting height study, absorbed dose trends appear to depend on the reference phantom.

3.2.2 Validation Studies—Uniform ^{131}I photon and ^{90}Y electron sources were simulated in the liver of a UFH00M-based phantom with decreased weight/waist circumference, a UFH10M-based phantom with increased weight/waist circumference, and a series of UFHADM-based phantoms with increased and decreased weight/waist circumference. Radionuclide S values were predicted for all target tissues by applying dose scaling factors to each target tissue according to the waist circumference of the scaled phantom and the reference phantom upon which the scaled phantom was based. The predicted S values were then compared to those obtained through direct simulation. S values determined using overall average and target-average dose scaling factors were compared to S values determined using dose scaling factors that were calculated from the active marrow, brain, liver, lungs, and spleen simulations. Summarized results for the ^{131}I and ^{90}Y studies for all phantoms are in Tables 8 and 9, respectively.

It was found that increases in accuracy (average of 7% using target-average scaling) could be attained when using dose scaling factors based on waist circumference when simulating photons for underweight phantoms, but no significant gains were seen for overweight phantoms. This was expected because overweight phantoms are constructed by simply adding adipose tissue around the body, but no significant changes in internal anatomy are made.

However, no appreciable gains in accuracy was seen for electron dosimetry for overweight or underweight phantoms when scaling based on waist circumference was performed. An overall average gain in accuracy of only 2% (using target-average scaling) was found.

3.3 Combined Sitting Height and Weight Validation Studies

In this final study, dose scaling using both sitting height and waist circumference were tested. Uniform ^{131}I photon and ^{90}Y electron sources were simulated in the liver of a UFH00M-based phantom with increased sitting height and decreased weight/waist circumference, a UFH10M-based phantom with decreased sitting height and increased weight/waist circumference, and a series of UFHADM-based phantoms with various combinations of increased and decreased sitting height and weight/waist circumference. Radionuclide S values were predicted for all target tissues by applying two dose scaling factors to each target tissue according to the sitting height and waist circumference of the scaled phantom and the reference phantom upon which the scaled phantom was based.

The predicted S values were then compared to those obtained through direct simulation. S values determined using overall average and target-average dose scaling factors were compared to S values determined using dose scaling factors that were calculated from the active marrow, brain, liver, lungs, and spleen simulations. Summarized results for the ^{131}I and ^{90}Y studies for all phantoms are in Tables 10 and 11, respectively.

It was found that increases in accuracy could be attained when using dose scaling factors based on the combination of sitting height and waist circumference for photons. The gains in accuracy for the UFH00M-based phantom were on the order of 5% for target-average scaling, and gains for the UFH10M-based phantoms were on the order of 15% for target-average scaling. Gains in accuracy for the UFHADM-based phantom set varied between almost no gains in accuracy to about 22%. The greatest gains in accuracy for the photon simulations were seen for the shorter, underweight phantoms. The three largest target-average scaling factor-based gains in accuracy were 11%, 15%, 22%, and these belonged to the m5010 phantom (50th percentile by height and 10th percentile by weight), the scaled UFH10M phantom (decreased height and increased waist circumference), and the m1010 patient-dependent phantom (10th percentile by height and 10th percentile by weight), respectively.

In contrast, dose scaling factors proved to be largely unhelpful in predicting non-reference doses across all phantoms for the electron simulations. Percentage point gains varied widely across all target tissues, but most phantoms did not show appreciable increases in dose prediction accuracy. This is probably due to the complexity of collisional versus radiative electron dose. Orders of magnitude variations in electron dose occur depending on the patient's unique body morphometry, which renders predictions of internal electron dose subject to very large uncertainties.

3.4 Dose Scaling Factors

Sitting height-based and waist circumference-based internal dose scaling factors were computed for the UFH00M, UFH10M, and UFHADM reference phantoms. Target-average dose scaling was found to be the most accurate for each validation study, and so target

tissue-specific scaling factors were first calculated for each source-target-energy combination. Final scaling factors were averaged over all source tissues for each target tissue. Several pre-processing conditions were set before the scaling factors were calculated – (1) any SAF with uncertainty greater than 10% was set to zero, (2) both reference and non-reference SAFs were required to be greater than zero (after interpolation) for a unique scaling factor to be computed, and (3) if either the reference or non-reference SAF was zero, the scaling factor was set to the average of all other target-average scaling factors, essentially replacing a nonexistent scaling factor with a value from the globally averaged trend.

An excerpt of the photon dosimetry sitting height-based results for the shortest UFHADM-based phantom is given in Table 12. Expected trends in dose scaling factors are observed. Absorbed doses are expected to increase in general for the shortest phantom, resulting in scaling factors greater than unity, and all scaling factors in Table 12 are indeed greater than unity. Alternatively, the tallest phantom was expected to have scaling factors less than unity, and this was also seen in the results (not shown). In both cases, the scaling factors tended to flatten out at energies greater than or equal to 50 keV while they tended to shift away from unity at lower energies, increasing for the shortest phantom and decreasing for the tallest phantom. Absorbed dose scales more dramatically with changes in body morphometry at lower initial radiation energies due to the less penetrating nature of the radiation of interest. Similar tables were generated for both sitting height-based and waist circumference-based photon dosimetry for the UFH00M-based, UFH10M-based and UFHADM-based phantom series.

Scaling factors for UFH00F-based and UFH10F-based non-reference phantoms were implicit because the internal structure of the UFH00F and UFH10F reference phantoms is almost identical to that of the UFH00M and UFH10M phantoms, respectively, aside from gender-specific organs. Gender-specific organs were assigned the energy-dependent globally averaged scaling factors.

However, no implicit data was available for the UFH01MF, UFH05MF, UFH15M, UFH15F, or UFHADDF reference phantoms. Scaling factors for these phantoms were interpolated between the existing datasets based on sitting height and waist-circumference ratios. In these cases, scaling factors were calculated by interpolating between scaling factors of the UFH00M-based, UFH10M-based, and UFHADM-based phantoms according to the sitting height and waist circumference of the phantom of interest. Interpolated scaling factors could only be computed if a sitting height and waist circumference ratio was assigned to each virtual phantom in the non-reference series. Essentially, a set of virtual phantoms were created for the UFH01MF, UFH05MF, UFH15M, UFH15F, and UFHADDF reference phantoms with sitting height and weight adjustments similar to those used for the UFH00M, UFH10M, and UFHADM phantoms.

Sitting height and waist circumference ratios were used to determine the sitting heights and waist circumferences of the virtual phantoms. For example, if a non-reference UFH00M-based sitting height phantom had a sitting height that was 20% greater than the reference phantom, a virtual UFH01MF-based phantom with a 20% greater sitting height was defined. The sitting height and waist circumference ratios of the UFH00M-based phantoms were

assigned to the virtual UFH01MF-based phantoms. The sitting height and waist circumference ratios of the UFH10M-based phantoms were assigned to the virtual UFH05MF-based phantoms. Similarly, the sitting height and waist circumference ratios of the UFHADM-based phantoms were assigned to the virtual UFH15M-, UFH15F-, and UFHADDF-based phantoms.

This approach was considered reasonable given the trends observed in both Figures 5 and 8. Absorbed dose scaled more dramatically with changes in sitting height for the UFH00M-based phantoms than for the UFHADM-based phantoms, and the UFH10M-based phantoms had somewhat intermediate dosimetric sensitivity. Therefore, it is not unreasonable to assume that dosimetric sensitivity for the UFH01MF and UFH05MF phantoms would fall between the trends seen for the UFH00M-based and UFH10M-based phantoms or that dosimetric sensitivity for the UFH15M, UFH15F, and UFHADDF would fall between trends seen for the UFH10M-based and UFHADM-based phantoms.

4. Discussion

Increases in accuracy were observed for each dosimetric sensitivity study – sitting height, waist circumference, and a combined evaluation. However, when averaged across all target tissues for a particular phantom, some scenarios demonstrated much better overall predictive accuracy than others. Some scenarios ultimately showed no increases in predictive accuracy, and scaling factors in those scenarios should not be used.

Dose scaling based on sitting height was by far the most valuable method as gains in accuracy of ~10% were observed for both photon and electron sources. Waist circumference-based scaling did not consistently yield greater accuracy for either photons or electrons, only in the most underweight individuals. This is because internal anatomy (organ size and separation) is fairly independent of patient size for overweight individuals as much of the fat deposits are subcutaneous. In several cases, either no gain in accuracy or a decrease in accuracy was seen. The combined approach demonstrated modest gains in accuracy for photons, but no gains in accuracy for electrons.

According to the percentage point gains in accuracy for both photon and electron dose scaling, our study recommends that only sitting height-based scaling factors should be utilized for both photon and electron components of internal dose. Photon and electron internal dose scaling seems plausible based on the validation simulations that were performed for the sitting height-only scaling. Up to an overall average of about 17% gain in accuracy was observed with greater gains in accuracy seen at the organ level. Changes in dose seem to be dominated by changes in sitting height rather than changes in waist circumference.

No strong source tissue dependence was observed, indicating that an average dose trend across source tissues are adequate to predict dose behavior of the various target tissues. Resultantly, it is proposed that target-average photon and electron dose scaling factors should be used to calculate non-reference doses based on sitting height alone. It would be

beneficial to use average values so that no one source tissue must be selected as the source tissue upon which all dose scaling is based.

It is acknowledged that patient-specific validation studies were not performed in addition to those performed based on modified reference phantoms. Uncertainty in patient-specific dose estimates is due in large part to anatomical mismatch between a simulation phantom and the patient. By validating the scaling approach in this work with modified reference phantoms, the anatomical mismatch uncertainty was eliminated, allowing us to focus on dose scaling effectiveness. The scaling validation in this work demonstrated the feasibility of scaling reference doses rather than completing extensive simulations for a large library of modified reference phantoms as reported by Geyer et al. (2014). Future work could assess the accuracy of scaled internal dose estimates as compared to patient-specific simulations.

5. Conclusions

When patient-specific information on organ volumes is not available, reference phantom SAF (and subsequently radionuclide S value) scaling may still be applied given anthropometric measurements of the patient. To this end, dosimetric sensitivity for internal emitters was investigated for dependence on in-clinic measurable morphometric characteristics such as sitting height and waist circumference. If a patient underwent a diagnostic nuclear medicine procedure, hospital staff could easily measure the sitting height and waist circumference of the patient and enter this information into a software program that would incorporate the scaling methodology results of this study. Radiation dose estimates based on reference values would be scaled to attempt to more closely model internal organ doses of the individual patient. Reference phantom dose estimates are intended to represent an average individual, but dosimetry for a specific patient is almost always quite different.

This study attempted to predict the difference between reference and non-reference radiation internal organ dose based on the differences between the sitting height and waist circumference of the reference phantom and non-reference individual. It was shown that both patient-specific photon and electron absorbed doses could be better estimated by using sitting height as the single parameter by which internal dose is scaled from reference values. Final absorbed dose estimates for patients will likely be more accurately computed using the scaling techniques developed in this study, and this is one step in the direction of more patient-specific dose estimates in diagnostic nuclear medicine.

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Figure 1.
Sample set of NURBS/PM phantoms created for the internal dosimetric sitting height sensitivity study. UFH00M phantoms shown at standing heights of 39.0 cm, 43.4 cm, 47.4 cm (ICRP-reference), 51.7 cm, and 55.9 cm.

Figure 2.
Sample set of NURBS/PM phantoms created for the internal dosimetric weight sensitivity study. UFH00M phantoms shown at weights of 1.6 kg, 2.2 kg, 3.5 kg (ICRP-reference), and 5.2 kg.

Figure 3. Variations in SAF with changes in sitting height for uniform (A) 500 keV and (B) 4 MeV photon sources in the liver of the UFH00M-based phantoms for a limited number of target tissues.

Figure 4. Variations in SAF with changes in sitting height for uniform (A) 500 keV and (B) 4 MeV electron sources in the liver of the UFH00M-based phantoms for a limited number of target tissues.

Figure 5. Variations in whole-body SAF with changes in sitting height for uniform 4 MeV (A) photon and (B) electron sources in the liver of the UFH00M-, UFH10M-, and UFHADM-based phantoms.

Figure 6. Variations in SAF with changes in waist circumference for uniform (A) 500 keV and (B) 4 MeV photon sources in the liver of the UFH00M-based phantoms for a limited number of target tissues.

Figure 7. Variations in SAF with changes in waist circumference for uniform (A) 500 keV and (B) 4 MeV electron sources in the liver of the UFH00M-based phantoms for a limited number of target tissues.

Figure 8. Variations in whole-body SAF with changes in waist circumference for uniform 4 MeV (A) photon and (B) electron sources in the liver of the UFH00M-, UFH10M-, and UFHADM-based phantoms.

Morphometric measurements for the phantoms created (along with the reference phantom measurements) to assess dosimetric sensitivity as a function of sitting height.

Table 1

Phantom	Mass (kg)	Standing Height (cm)	Sitting Height (cm)	Arm Circum. (cm)	Thigh Circum. (cm)	Waist Circum. (cm)	Buttocks Circum. (cm)
UFH00M							
Shortest	1.3	39.0	25.4	9.4	16.5	27.8	27.0
Short	2.4	43.4	29.7	11.6	16.4	32.4	31.6
Reference	3.5	47.4	33.9	13.7	17.0	37.0	36.0
Tall	4.5	51.7	38.2	15.7	16.7	41.7	40.5
Tallest	6.1	55.9	42.3	17.4	16.8	46.3	44.9
UFH10M							
Shortest	17.7	121.3	56.9	15.0	31.3	53.3	54.1
Short	23.8	130.4	66.1	17.5	31.0	62.4	62.6
Reference	32.4	139.9	75.5	19.9	31.2	71.0	71.8
Tall	42.3	149.2	85.4	22.3	31.2	79.9	80.7
Tallest	55.4	158.2	95.2	24.9	31.4	88.7	89.8
UFHADM							
Shortest	40.4	151.7	70.6	19.9	41.7	73.4	72.9
Short	53.5	162.8	81.7	22.9	42.2	85.6	83.4
Reference	73.1	174.9	92.9	26.2	41.7	97.8	94.0
Tall	94.0	185.9	104.9	29.7	42.2	110.1	107.0
Tallest	122.8	198.2	117.8	32.8	41.7	122.4	114.2

Table 2

Voxel resolutions and total matrix sizes for the phantoms created (along with the reference phantom specifications) to assess dosimetric sensitivity as a function of sitting height.

Phantom	Voxel Resolution (cm)			Number of Voxels			Matrix Size ($\times 10^6$)
	Width	Depth	Height	Width	Depth	Height	
UFH00M							
Shortest	0.0663	0.0663	0.0663	350	189	593	39.23
Short	0.0663	0.0663	0.0663	350	202	656	46.38
Reference	0.0663	0.0663	0.0663	350	215	720	54.18
Tall	0.0663	0.0663	0.0663	350	228	784	62.56
Tallest	0.0663	0.0663	0.0663	353	242	847	72.36
UFH10M							
Shortest	0.0990	0.0990	0.0990	322	201	503	32.56
Short	0.0990	0.0990	0.0990	374	211	542	42.77
Reference	0.0990	0.0990	0.0990	428	226	580	56.10
Tall	0.0990	0.0990	0.0990	480	248	619	73.69
Tallest	0.0990	0.0990	0.0990	533	275	658	96.45
UFHADM							
Shortest	0.1579	0.1579	0.2207	272	181	690	33.97
Short	0.1579	0.1579	0.2207	317	184	743	43.34
Reference	0.1579	0.1579	0.2207	362	195	796	56.19
Tall	0.1579	0.1579	0.2207	406	206	849	71.01
Tallest	0.1579	0.1579	0.2207	451	220	902	89.50

Table 3

Morphometric measurements for the phantoms created (along with the reference phantom measurements) to assess dosimetric sensitivity as a function of weight.

Phantom	Mass (kg)	Standing Height (cm)	Sitting Height (cm)	Arm Circum. (cm)	Thigh Circum. (cm)	Waist Circum. (cm)	Buttocks Circum. (cm)
UFH00M							
Lightest	1.6	47.5	33.8	10.2	11.9	25.2	24.3
Light	2.2	47.5	33.9	11.8	13.6	29.5	28.2
Reference	3.5	47.4	33.9	13.7	17.0	37.0	36.0
Heavy	5.2	47.8	36.0	15.1	22.8	48.7	47.9
UFH10M							
Lightest	16.4	139.7	75.3	11.8	19.8	52.6	52.5
Light	22.3	140.4	75.6	13.8	23.1	60.7	60.9
Reference	32.4	139.9	75.5	19.9	31.2	71.0	71.8
Heavy	53.6	139.9	76.3	30.8	42.5	92.7	94.9
UFHADM							
Lightest	36.1	175.1	94.0	18.4	27.9	69.6	67.0
Light	49.1	175.7	93.7	21.0	32.3	81.2	77.8
Reference	73.1	174.9	92.9	26.2	41.7	97.8	94.0
Heavy	124.9	175.1	94.4	41.8	62.9	127.0	126.8

Voxel resolutions and total matrix sizes for the phantoms created (along with the reference phantom specifications) to assess dosimetric sensitivity as a function of weight.

Table 4

Phantom	Voxel Resolution (cm)			Number of Voxels			Matrix Size ($\times 10^6$)
	Width	Depth	Height	Width	Depth	Height	
UFH00M							
Lightest	0.0663	0.0663	0.0663	264	160	720	30.41
Light	0.0663	0.0663	0.0663	306	185	720	40.76
Reference	0.0663	0.0663	0.0663	350	215	720	54.18
Heavy	0.0663	0.0663	0.0663	350	242	720	60.98
UFH10M							
Lightest	0.0990	0.0990	0.0990	316	171	580	31.34
Light	0.0990	0.0990	0.0990	368	198	580	42.26
Reference	0.0990	0.0990	0.0990	428	226	580	56.10
Heavy	0.0990	0.0990	0.0990	452	289	580	75.76
UFHADM							
Lightest	0.1579	0.1579	0.2207	268	145	796	30.93
Light	0.1579	0.1579	0.2207	312	169	795	41.92
Reference	0.1579	0.1579	0.2207	362	195	796	56.19
Heavy	0.1579	0.1579	0.2207	386	245	796	75.28

Table 5

Percentage point gain in accuracy over reference values using different dose scaling factors based on sitting height for the UFH00M-based phantom for ^{131}I photons (e.g., “Brain” indicates that scaling factors based on the brain source were used).

Target tissue	Overall average (%)	Target-average (%)	Active marrow (%)	Brain (%)	Liver (%)	Lungs (%)	Spleen (%)
Whole body	14	15	14	15	15	15	15
Adipose	15	14	14	14	14	14	14
Left adrenal	15	15	15	13	16	16	16
Right adrenal	11	8	10	2	10	10	9
Brain	14	19	17	16	16	19	16
Rest of body	15	12	13	12	12	13	11
Bronchi	15	18	17	16	17	15	17
Right colon wall	13	9	11	-1	12	11	10
Esophagus	13	10	13	5	12	12	10
Eye balls	15	9	12	13	10	8	2
Gall bladder wall	11	13	10	2	11	10	9
Heart wall	15	12	12	8	13	13	13
Left kidney cortex	15	14	13	14	14	14	14
Right kidney cortex	14	14	13	14	14	14	14
Left kidney medulla	15	14	13	14	14	14	14
Right kidney medulla	12	11	10	11	12	11	11
Left kidney pelvis	14	13	12	13	14	13	13
Right kidney pelvis	15	16	16	15	15	15	15
ET2 oral cavity layer	12	11	10	11	11	11	11
Liver	13	10	11	4	12	12	11
Left lung	15	13	13	9	13	14	14
Right lung	14	11	12	8	12	13	12
Oral mucosa	14	11	11	13	11	11	10
Pancreas	14	9	11	1	11	11	13
Right sigmoid wall	15	14	14	2	16	15	15
Salivary glands	15	12	12	13	10	12	11
Small intestine wall	13	8	11	-1	12	10	11

Target tissue	Overall average (%)	Target-average (%)	Active marrow (%)	Brain (%)	Liver (%)	Lungs (%)	Spleen (%)
Skin	15	13	13	12	14	14	14
Spinal cord	13	10	11	8	10	11	9
Spleen	13	10	12	3	11	12	12
Stomach wall	12	9	11	2	11	10	11
Thymus	15	13	14	10	13	14	12
Thyroid	11	6	7	4	5	8	7
Tongue	6	2	3	3	2	3	1
Trachea	14	17	17	18	15	16	17
Urinary bladder wall	14	14	12	5	15	15	12
Left colon wall	15	13	15	3	16	14	16
Muscle	15	11	12	12	11	11	11
Cartilage	15	14	15	13	14	14	14
Cortical bone volume	12	11	12	9	10	10	12
Prostate	15	13	14	-54	11	-34	15

Table 6

Average percentage point gain in accuracy over reference values using different dose scaling factors based on sitting height for all the non-reference phantoms used for the sitting height dose scaling validation study for ^{131}I photons.

Non-reference phantom	Overall average (%)	Target-average (%)	Active marrow (%)	Brain (%)	Liver (%)	Lungs (%)	Spleen (%)
Scaled UFH00M	14	12	12	7	12	11	12
Scaled UFH10M	15	16	18	7	18	17	17
Scaled UFHADM	5	5	4	3	5	4	5
Average	11	11	11	6	12	11	11

Table 7

Average percentage point gain in accuracy over reference values using different dose scaling factors based on sitting height for all the non-reference phantoms used for the sitting height dose scaling validation study for ^{90}Y beta particles.

Non-reference phantom	Overall average (%)	Target-average (%)	Active marrow (%)	Brain (%)	Liver (%)	Lungs (%)	Spleen (%)
Scaled UFH00M	15	13	2	11	16	11	9
Scaled UFH10M	16	17	7	16	22	14	15
Scaled UFHADMI	5	7	5	6	6	-4	4
Average	12	12	5	11	15	7	9

Table 8

Average percentage point gain in accuracy over reference values using different dose scaling factors based on waist circumference for all the non-reference phantoms used for the weight dose scaling validation study for ¹³¹I photons. The patient-dependent naming convention is [gender][height percentile][weight percentile] (e.g., m5090 is a 50th percentile height, 90th percentile weight male).

Non-reference phantom	Overall average (%)	Target-average (%)	Active marrow (%)	Brain (%)	Liver (%)	Lungs (%)	Spleen (%)
Scaled UFH00M	1	2	2	-2	2	1	2
Scaled UFH10M	0	0	0	-4	0	0	-1
m5090	-1	0	-1	-6	0	-3	1
m5075	0	0	0	0	0	-1	0
m5010	6	12	12	2	13	11	12
Overweight average	0	0	0	-3	0	-1	0
Underweight average	4	7	7	0	8	6	7
Overall average	1	3	3	-2	3	2	3

Table 9

Average percentage point gain in accuracy over reference values using different dose scaling factors based on waist circumference for all the non-reference phantoms used for the sitting height dose scaling validation study for ^{90}Y beta particles. The patient-dependent naming convention is [gender][height percentile][weight percentile] (e.g., m5090 is a 50th percentile height, 90th percentile weight male).

Non-reference phantom	Overall average (%)	Target-average (%)	Active marrow (%)	Brain (%)	Liver (%)	Lungs (%)	Spleen (%)
Scaled UFH00M	7	-7	-1	1	-19	-17	-17
Scaled UFH10M	0	0	-1	-1	1	-1	-2
m5090	-1	4	-3	0	0	-13	0
m5075	0	2	-1	0	0	6	0
m5010	1	10	-7	-1	-3	-64	-1
Overweight average	-1	2	-2	0	0	-3	-1
Underweight average	4	1	-4	0	-11	-40	-9
Overall average	1	2	-3	0	-4	-18	-4

Table 10

Average percentage point gain in accuracy over reference values using different dose scaling factors based on both sitting height and waist circumference for all non-reference phantoms used for the sitting height dose scaling validation study for ^{131}I photons. The patient-dependent naming convention is [gender][height percentile][weight percentile] (e.g., m5090 is a 50th percentile height, 90th percentile weight male).

Non-reference phantom	Overall average (%)	Target-average (%)	Active marrow (%)	Brain (%)	Liver (%)	Lungs (%)	Spleen (%)
Scaled UFH00M	4	5	5	2	2	6	6
Scaled UFH10M	13	15	15	5	5	17	15
m9090	-2	3	3	1	1	2	4
m9050	4	5	5	3	3	5	5
m7590	-2	0	-1	-4	0	-3	2
m7550	1	1	1	1	0	-1	0
m7525	1	4	4	-5	3	2	4
m7510	1	8	7	-4	10	9	8
m5090	-2	1	-1	-3	0	-1	1
m5075	0	0	0	1	0	0	0
m5010	5	11	11	0	13	12	11
m2575	4	5	4	1	5	5	5
m2550	2	-2	0	-8	1	-4	1
m1050	8	6	8	1	7	4	8
m1010	22	22	21	17	20	19	18
Overweight average	2	4	3	0	4	3	5
Underweight average	7	10	10	2	10	10	9
Tall average	1	4	3	-1	4	2	4
Short average	10	9	10	3	10	8	10
Overall average	4	6	5	1	6	4	6

Average percentage point gain in accuracy over reference values using different dose scaling factors based on sitting height and waist circumference for all the non-reference phantoms used for the sitting height dose scaling validation study for ^{90}Y beta particles. The patient-dependent naming convention is [gender][height percentile][weight percentile] (e.g., m5090 is a 50th percentile height, 90th percentile weight male).

Table 11

Non-reference phantom	Overall average (%)	Target-average (%)	Active marrow (%)	Brain (%)	Liver (%)	Lungs (%)	Spleen (%)
Scaled UFH00M	0	-3	-3	-2	-8	-5	-5
Scaled UFH10M	16	19	5	18	24	16	16
m9090	3	-4	-1	3	4	-46	4
m9050	6	5	4	7	7	-4	7
m7590	0	-5	-2	0	1	-35	0
m7550	-1	-3	-3	1	0	-17	0
m7525	0	-4	-8	1	4	-43	3
m7510	6	0	-5	3	9	-68	8
m5090	0	-5	-2	-1	1	-28	0
m5075	0	-2	-1	0	0	-8	0
m5010	9	4	-4	5	12	-41	11
m2575	3	-2	-1	-2	5	-23	4
m2550	-14	-26	-31	-15	-4	-107	-5
m1050	-2	-12	-18	-3	6	-83	4
m1010	1	-13	-46	12	19	-215	15
Overweight average	4	0	0	3	6	-21	4
Underweight average	3	-3	-13	4	7	-74	6
Tall average	2	-2	-3	2	2	-31	2
Short average	1	-7	-18	2	10	-83	7
Overall average	2	-3	-8	2	5	-47	4

Table 12

Photon internal dosimetry scaling factors (excerpt) for the shortest UFHADM-based phantom of the sitting height dosimetric sensitivity study.

Target Tissue	Photon Energy (MeV)									
	0.010	0.020	0.050	0.080	0.100	0.500	1.000	4.000		
Whole body	1.774	1.760	1.520	1.402	1.380	1.426	1.429	1.397		
Brain	23.589	5.217	3.924	2.872	2.704	2.365	2.248	2.016		
Left breast	23.598	6.801	2.622	2.122	2.029	2.243	2.184	1.933		
Right colon wall	23.171	4.959	3.546	3.447	3.177	2.491	2.360	2.088		
Esophagus	23.503	4.004	2.624	2.135	2.009	1.995	1.987	1.927		
Heart wall	7.157	4.558	3.285	2.459	2.295	2.097	2.053	1.917		
Kidney cortex	26.014	5.102	3.910	3.162	2.850	2.356	2.220	2.029		
Kidney medulla	23.598	5.489	3.014	3.296	2.952	2.406	2.212	2.032		
Kidney pelvis	23.598	5.785	3.056	2.495	2.369	2.435	2.304	1.955		
Eye lens	23.598	5.445	2.629	2.139	2.069	2.035	1.999	1.909		
Liver	5.121	4.415	3.185	2.433	2.293	2.148	2.088	1.958		
Left lung	8.925	6.572	2.625	2.172	2.132	2.045	2.018	1.921		
Pancreas	23.756	5.232	4.687	3.451	3.050	2.397	2.291	2.013		
Right sigmoid wall	23.598	5.616	4.448	3.246	2.967	3.132	2.748	2.157		
Salivary glands	24.676	7.040	3.202	2.461	2.290	2.156	2.104	1.939		
Small intestine wall	23.110	6.684	4.429	3.604	3.266	2.591	2.383	2.088		
Skin	24.218	4.863	1.885	1.672	1.637	1.605	1.578	1.515		
Spinal cord	23.586	5.740	2.207	1.912	1.841	1.905	1.919	1.868		
Spleen	10.680	4.668	3.400	2.693	2.492	2.191	2.125	1.948		
Stomach wall	184.590	6.300	4.175	2.982	2.706	2.318	2.232	2.005		
Thyroid	23.598	7.013	3.607	2.672	2.453	2.159	2.086	1.879		
Trachea	23.598	5.358	3.017	2.300	2.148	2.071	2.033	1.916		
Urinary bladder wall	23.598	5.601	5.081	3.543	3.248	2.577	2.824	2.284		
Left colon wall	23.598	7.432	3.395	3.356	3.366	2.483	2.390	2.100		
Muscle	2.353	1.983	1.524	1.385	1.354	1.381	1.383	1.356		
Testes	23.598	5.813	4.732	3.354	3.694	2.872	2.604	2.159		