Published in final edited form as:

Phys Med Biol. 2011 April 21; 56(8): 2309–2346. doi:10.1088/0031-9155/56/8/001.

AN IMAGE-BASED SKELETAL DOSIMETRY MODEL FOR THE ICRP REFERENCE ADULT MALE – INTERNAL ELECTRON SOURCES

Matthew Hough, MS,

Department of Nuclear & Radiological Engineering, University of Florida, Gainesville, FL USA

Perry Johnson, MS,

Department of Nuclear & Radiological Engineering, University of Florida, Gainesville, FL USA

Didier Rajon, PhD,

Department of Neurosurgery, University of Florida, Gainesville, FL USA

Derek Jokisch, PhD,

Department of Physics and Astronomy, Francis Marion University, Florence, SC

Choonsik Lee, PhD, and

Radiation Epidemiology Branch, National Cancer Institute, Bethesda, MD USA

Wesley Bolch, PhD

Departments of Nuclear & Radiological and Biomedical Engineering, University of Florida, Gainesville, FL USA

Abstract

Target tissues include the active bone marrow, associated with radiogenic leukemia, and total shallow marrow, associated with radiogenic bone cancer. Monoenergetic electron emissions are considered over the energy range 1 keV to 10 MeV for the following sources: bone marrow (active and inactive), trabecular bone (surfaces and volumes), and cortical bone (surfaces and volumes). Specific absorbed fractions are computed according to the MIRD schema, and are given as skeletal-averaged values in the paper with site-specific values reported in both tabular and graphical format in an electronic annex. The distribution of cortical bone and spongiosa at the macroscopic dimensions of the phantom, as well as the distribution of trabecular bone and marrow tissues at the microscopic dimensions of the phantom, are imposed through detailed analyses of whole-body *ex-vivo* CT images (1 mm resolution) and spongiosa-specific *ex-vivo* microCT images (30 μm resolution), respectively, taken from a 40-year male cadaver. The method utilized in this work includes: (1) explicit accounting for changes in marrow self-dose with variations in marrow cellularity, (2) explicit accounting for electron escape from spongiosa, (3) explicit consideration of spongiosa cross-fire from cortical bone, and (4) explicit consideration of the ICRP's change in the surrogate tissue region defining the location of the osteoprogenitor cells (from a 10- μm endosteal layer covering the trabecular and cortical surfaces, to a 50- μm shallow marrow layer covering trabecular and medullary cavity surfaces). Skeletal-averaged values of absorbed fraction in the present model are noted to be very compatible with those weighted by the skeletal tissue distributions found in the ICRP Publication 110 adult male and female voxel phantoms, but are in many cases incompatible with values used in current and widely implemented internal dosimetry software.

Keywords

skeletal dosimetry; bone dosimetry; hematopoietic stem cells; osteoprogenitor cells; reference adult male; electron transport

1. Introduction

The skeleton is perhaps the most difficult of all organ systems to model anatomically in the field of computational dosimetry. The relevant tissues of the bone trabeculae and marrow cavities cannot be imaged directly by clinical *in-vivo* systems such as computed tomography (CT) or magnetic resonance imaging (MR). Consequently, one must rely upon previously developed skeletal dosimetry models in which *ex-vivo* microimages of excised spongiosa (acquired via contact radiography, NMR microscopy, or microCT) are used in radiation transport studies. Until recently, the only complete set of skeletal microstructural data in a format sufficient for radiation transport in the adult skeleton is that generated at the University of Leeds in the late 1960s to mid-1970s. The Leeds group used optical scanning techniques to acquire linear pathlength distributions across the bone trabeculae and marrow cavities of the lumbar vertebrae for several subjects, as well as across several skeletal sites in a 1.7-year child (5 sites), a 9-year child (5 sites), and a 44-year male (7 sites) (Darley, 1972; Beddoe, 1976; Beddoe *et al.*, 1976; Whitwell, 1973; Whitwell and Spiers, 1976). The bone and marrow pathlength distributions for the Leeds 44-year male subject have been used as the basis for electron (and thus beta particle and photon) absorbed fractions embodied in essentially all skeletal dosimetry models published to date. These include (1) MIRD Pamphlet No. 11 for nuclear medicine (Snyder *et al.*, 1975), (2) ICRP Publication 30 for radiation protection (ICRP, 1979), (3) ORNL TM-8381 for photon internal dosimetry (Cristy and Eckerman, 1987), (4) Bouchet *et al* for nuclear medicine (Bouchet *et al.*, 1999; Bouchet *et al.*, 2000), (5) the MIRDose3 code (Eckerman and Stabin, 2000), and (6) the OLINDA/EXM code (Stabin and Siegel, 2003). More recently, cadaver studies by Shah (2004) and Kielar (2009) have used microCT imaging of trabecular spongiosa to assemble skeletal dosimetry models unique to a 64-year adult male and a 66-year adult female.

Of equal importance are estimates of skeletal tissue mass. Unfortunately, complete tissue masses were not reported for the Leeds 44-year male subject, and thus the various skeletal dosimetry models above have had to rely on a variety of patient and/or cadaver studies as summarized in ICRP Publications 70 and 89 (ICRP, 2002, 1995). These studies include those by (1) Mechanik in 1926 (total marrow masses and their relative distribution within the skeleton) (Mechanik, 1926; Woodard and Holodny, 1960), (2) Custer in 1974 (reference marrow cellularities) (Custer, 1974), (3) Trotter and Hixon in 1974 (bone tissue masses) (Trotter and Hixon, 1974), and (4) Beddoe in 1976 (bone trabeculae surface-to-volume ratios for estimating endosteal tissue masses) (Beddoe, 1976). The ICRP reference adult male skeletal model is thus assembled from a wide range of subject populations and measurement techniques. More fundamentally, the anatomical sources for its absorbed fractions are not the same as those from which reference tissue masses are reported.

In this study, we present a comprehensive model for electron internal skeletal dosimetry for the ICRP reference adult male (ICRP, 2002). The effort builds upon previous work in our laboratory on a NURBS-based hybrid computational phantom for the reference adult male by Lee *et al* (2010), methods for skeletal dosimetry applied to the reference newborn by Pafundi *et al* (2009; 2010), and the EGSnrc-based Paired Image Radiation Transport or PIRT code of Shah *et al* (2005). Values of electron absorbed fraction $\phi(r_T \leftarrow r_S)$ are assembled for 32 bone sites, 6 source tissues, and 2 target tissues, the latter being active bone marrow (surrogate tissue for the hematopoietic stem cells) and total shallow marrow¹

(surrogate tissue for the osteoprogenitor cells). In a companion study, values of $\phi(r_T \leftarrow r_S)$ are used to report values of photon fluence-to-dose response functions needed for photon dosimetry of the adult male skeleton (Johnson *et al.*, submitted).

2. Materials and Methods

2.1 Cadaver selection

Candidate cadavers for skeletal model development were reviewed through the State of Florida Anatomical Board located on the University of Florida (UF) campus. Cadaver selection criteria included (1) an age between 20 and 50 years [compatible with a younger reference individual as per section 1.4.2 of ICRP Publication 89 (ICRP, 2002)], (2) a body mass index of between 18.5 and 30 kg m² (recommended range for healthy subjects), and (3) a cause of death that would preclude significant skeletal deterioration. The subject identified was a 40-year male approximately 82 kg in total mass and 170 cm in stature at time of death (BMI of 28.4 kg m²). The subject died of sudden complications associated with cardiopulmonary arrest following myocardial infarction. For comparison, the weight and height of the ICRP 89 reference adult male are 73 kg and 176 cm (ICRP, 2002), respectively, while 50th percentile values for US adult males are 78 kg and 173 cm, respectively (Johnson *et al.*, 2009).

2.2 In-vivo CT imaging

Prior to bone harvesting, the entire cadaver was imaged with a multi-detector CT at a pitch necessary to reconstruct contiguous 1-mm axial slices of the anatomy. These images were acquired on a Siemens Sensation 16 unit within the Department of Radiology at UF Shands Hospital. Image reconstruction was performed with a bone filter at a maximum in-plane pixel resolution of 977 μ m $\times$ 977 μ m. The CT image sets were then transferred to workstations in the UF Advanced Laboratory for Radiation Dosimetry Studies (ALRADS) for image processing and data storage. The *in-vivo* CT images provided data for guidance on subsequent bone harvesting, and served as backups to subsequent *ex-vivo* images acquired post-harvest.

2.3 Bone site collection and ex-vivo CT

Following detailed review of the whole-body *in-vivo* CT images, bone harvesting was conducted. Thirty-eight major skeletal sites were excised from the male cadaver: the cranial cap (2), mandible (1), scapulae (2), clavicles (2), sternum (1), ribs (6), spinal column (1 - including cervical, thoracic, and lumbar vertebrae), pelvis (1 - os coxae and sacrum), and proximal and distal ends of all long bones including humeri (4), radii (4), ulnae (4), femora (4), fibulae (3), and tibiae (3). Due to the presence of a surgical pin, the left distal tibia and fibula were not recovered. The cranial cap included the occipital, left and right parietal, and frontal bones, and was extracted in two left/right halves. Skeletal sites which were unrecovered were the facial bones, hands, feet, patellae, and long bone shafts as needed to permit ash formation during body cremation. Once each skeletal site was excised, it was cleaned of excess tissue, bagged, labeled, and stored frozen until *ex-vivo* CT imaging could be scheduled.

Ex-vivo CT imaging was again conducted using a Siemens Sensation 16 CT scanner at the highest resolution permitted for each sample's field of view (1.0-mm slice thickness with in-plane resolutions ranging from 0.57 mm $\times$ 0.57 mm for the pelvis to 0.11 mm $\times$ 0.11 mm for

¹The term *total shallow marrow* is used to define a tissue region where the osteoprogenitor cells are believed to be located. It is a 50- μ m layer on the trabecular surfaces and along the inner medullary cavity surfaces of all long bones, and it replaces the previously defined 10- μ m trabecular and cortical endosteal layers of ICRP 30.

the clavicles). The *ex-vivo* CT scans provided image data for (1) identifying the location and extent of spongiosa to be sectioned for microCT imaging, and (2) quantifying the fraction of bone volumes associated with spongiosa or cortical bone.

2.4 Bone coring and microCT imaging

Following review of the *ex-vivo* CT images, cores of marrow-intact spongiosa were strategically excised from each harvested bone sample. Core sizes were limited to 35 mm on edge in cross section and 75 mm in length as per the requirements of the scanner bore. All samples were imaged on a μ CT-80 system from Scano Medical AG (Bassersdorf, Switzerland) at a 30 μ m isotropic voxel size. For some bone sites, multiples cores were taken. For example, the cranial cap was sampled three times within its frontal, parietal, and occipital bones. Only the bones of the cadaver's right arm and leg were included in the study, with symmetry assumptions utilized to permit full analysis of proximal and distal ends of all arm and leg bones.

2.5 Image segmentation of spongiosa and cortical bone in ex-vivo CT images

As discussed previously in Brindle et al (2006), gray-scale CT image segmentation of the skeletal tissues into regions of cortical bone and spongiosa is problematic and not readily amenable to automation. Consequently, these regions of each skeletal site were segmented manually using an in-house IDL program *CT-Contours* originally developed and described by Nipper et al (2002). In this program, the CT image data are displayed in a 2D array where the user can create colored overlays, or contours, to manually delineate cortical bone from spongiosa within each skeletal site. An example of the program's user interface is shown in Figure 1 for one axial slice of the os coxae. A count of the fractional number of voxels belonging to either cortical bone or spongiosa regions of the bone site yield the volume fractions cortical bone volume fraction (CBVF) and spongiosa volume fraction (SVF), respectively, which were in turn used to impose these same divisions within the homogeneous bones of the UF adult male hybrid phantom (see section 2.7).

2.6 Image segmentation of marrow and trabecular bone in microCT images

Multiple image processing steps were applied to the microCT images of the spongiosa cores to assess both the marrow volume fraction (MVF) and trabecular bone volume fraction (TBVF) of spongiosa by skeletal site. These steps included (1) extracting a region of interest (ROI) to remove remnants of cortical bone, (2) applying a median filter to increase the signal-to-noise ratio, (3) determining the threshold gray-level value to optimize the location of the bone-marrow interface, and (4) segmenting the ROI into a binary image based upon this threshold value. The thresholding technique used visual inspection of the image gradient magnitude as described in Rajon *et al* (2006).

2.7 Partitioning of ICRP adult male reference tissue masses across skeletal sites

As noted in Lee *et al* (2010), the total volume of homogeneous bone contained within the skeleton of the UF hybrid adult male phantom (UFHADM) was previously matched to within 0.2% of reference values for total marrow (active and inactive), total mineral bone (cortical and trabecular), and miscellaneous skeletal tissues (MST) combined. Cartilage was considered separately and is found within the phantom in either its bone-associated (false ribs and inter-vertebral discs) or non-bone associated forms, the latter being a homogeneous constituent of its residual soft tissues. Teeth were also excluded and tagged separately. The methodology used in the current study for distributing ICRP 89 reference skeletal masses across individual bones of the adult male is outlined in Pafundi *et al* (2009) in their analysis of the UF newborn phantom. Targeted reference masses for the adult male included 3650 g of total marrow (1170 g active and 2480 g inactive), 5500 g of mineral bone (4400 g cortical

and 1100 g trabecular), and 200 g of miscellaneous skeletal tissues (MST). Mass densities of 1.03, 0.98, 1.90, and 1.03 g cm⁻³ were assumed for active marrow, inactive marrow, mineral bone (both cortical and trabecular), and MST, respectively (ICRU, 1992).

The partitioning process involved four steps. First, the total volume of reference MST was proportioned to each bone of the skeleton according to their fractional homogeneous skeletal volume. These volumes and corresponding masses were subsequently divided further across each bone's constituent tissues of marrow (active and inactive) and mineral bone (cortical and trabecular) as determined in the following steps. Second, values of CBVF and SVF (obtained from the *ex-vivo* CT scans) were used to partition values of homogeneous bone volumes into regions of cortical bone and spongiosa, inclusive of their MST contributions. Third, values of MVF and TBVF (obtained from the microCT images), as well as ICRP reference cellularities (ICRP, 1995), were used to further partition spongiosa volumes into regions of trabecular bone, active marrow, and inactive marrow, also inclusive of their MST contributions. As an example, the volumes and masses of active marrow in skeletal site *x* are given as:

$$V_{AM*}^x = \left(V_{HB*}^x \right) (SVF^x) (MVF^x) (CF^x), \quad (1)$$

$$V_{AM}^x = \left(V_{TAM*}^x \right) - (V_{MST} - TAM^x), \quad (2)$$

$$m_{AM*}^x = \left(m_{AM}^x \right) + (m_{MST} - AM^x) = \left[\left(V_{AM}^x \right) (\rho_{AM}) \right] + [(V_{MST} - AM^x) (\rho_{ST})], \quad \text{and} \quad (3)$$

$$m_{AM}^x = \left(V_{AM}^x \right) (\rho_{AM}) \quad (4)$$

where V_{AM*}^x and m_{AM*}^x are the volumes and masses of active marrow inclusive of miscellaneous skeletal tissues (MST), while V_{AM}^x and m_{AM}^x are their equivalent values exclusive of MST. Other parameters in Eqs. 1-4 are defined in the Glossary.

A fourth and final step involved fine manual adjustments to the cadaver-based CBVF and SVF values to better match targets of 5500 g of total mineral bone and 3650 g of total marrow mass, both inclusive of MST. Care was taken to ensure that these modified of CBVF and SVF stayed within a few percent of original values seen in the cadaveric *ex-vivo* CT scans. For example, as the CBVF was decreased slightly, a corresponding increase is seen in SVF, and thus in the volumes assigned to trabecular bone and active / inactive marrow increased in proportion. No explicit attempt was made to individually match ICRP 89 values of trabecular (1100 g) and cortical bone (4400 g), only their combined volume and corresponding mass. Similarly, no explicit attempt was made to individually match ICRP 89 values of active marrow (1170 g) and inactive marrow (2480 g), only their combined volume and corresponding mass. A set of bone-specific tissue masses, following the inclusion of their corresponding MST masses, was assembled for use in reporting skeletal electron specific absorbed fractions.

2.8 Creation of a heterogeneous UFHADM skeleton for electron transport

With volumes of cortical bone and spongiosa now assigned per skeletal site, the next phase of the study involved modeling these separate regions in each of the homogeneous bones of the UFHADM phantom. Initially, each homogeneous bone was opened in the NURBS/PM modeling software *Rhinoceros*TM. The outer bone surface was copied and assigned a new tag

value to represent the outer boundary of its spongiosa region. This new spongiosa surface was then modified using the *Offset Mesh* function of the code to allow its reduction and corresponding enlargement of cortical bone until both targeted volumes were realized in the final model. At each iteration, the *Volume Calculator* tool of *Rhinoceros* was used to confirm desired volumes. Representative examples of the craniofacial bones, thoracic vertebrae, sacrum, and os coxae are shown in the leftmost columns of Figures 2 and 3, respectively, with spongiosa regions tagged orange and cortical bone regions tagged yellow. Additionally, 2D microCT images of spongiosa and their 3D segmented images are shown for each bone site in the central and rightmost columns of Figures 2 and 3, respectively.

A final step in preparation for radiation transport was to convert each heterogeneous NURBS/PM bone model to its voxelized equivalent. To this end, the in-house MATLAB code *Voxelizer 5* was used with recently implemented speed-up algorithms and additional user-friendly GUI features. The meshing tolerance was set at 10° based upon the study by Lee *et al* (2007) to minimize volumetric errors exceeding 1% across all skeletal sites. Voxel dimensions were selected across the range of 100 to 1000 μm to provide both a reasonable array size for computation, while maintaining voxelized volumes within a few percent of targeted volumes. The guiding parameter for voxel dimensions were the thicknesses of cortical bone which, as shown in Table 1, ranged from 450 μm in the patellae to as much as 4300 μm in the upper humeral shaft.

2.9 Paired Image Radiation Transport in the heterogeneous UFHADM skeleton

In this study, the PIRT model, originally described by Shah *et al* (2005), was employed using both the thresholded microCT images of adult spongiosa, and the voxelized heterogeneous bone models of the UF adult male hybrid phantom. In this study, 10^7 particle histories were run to ensure statistical precision on the electron absorbed fraction to within 1%. Values of absorbed fraction in the energy range of 1 to 10 keV were obtained via logarithmic extrapolation to limiting theoretical values for each unique source-target combination. For example, the absorbed fractions $\phi(AM \leftarrow AM)$, $\phi(TM_{50} \leftarrow TBS)$, and $\phi(AM \leftarrow TBS)$ should approach limiting values of 1.0, 0.5, and $(0.5 \times CF)$ at low energy, considered to be 1 keV in the present study.

Electron absorbed fractions were assembled for two target tissues – active marrow (AM) and total shallow marrow (TM_{50}) (see Glossary). Source tissues included active marrow (AM), inactive marrow (IM), trabecular bone surfaces and volumes (TBS and TBV) and cortical bone surfaces and volumes (CBS and CBV). Cortical bone surfaces were further considered as those of the Haversian canals (CBS_{HC}) and those of the medullary cavities of all long bones (CBS_{MC}). As the microscopic histology of cortical bone is not considered in this study, electron sources on CBS_{HC} are appropriately represented by the CBV source region. For those bone sites with multiple microCT images available, volumetric averaging was applied as described in Pafundi *et al* (2010). Due to the extensive nature of the bone harvesting and microCT imaging effort, very few skeletal sites required an assignment of a surrogate bone for dose assessment. The distal humerus was used to model the microstructure of the hand bones, and the distal femur was used to model the microstructure of the patellae and foot bones. All other skeletal regions of spongiosa were modeled according to their corresponding and unique microCT images.

2.10 Special considerations for shallow marrow targets in the shafts of the long bones

The presence of osteoprogenitor cells within a 50 μm layer of medullary marrow along the shafts of the long bones required separate modeling of electron transport (see Figure 4).² Cortical thicknesses and diameters of medullary marrow at mid-shaft were obtained for each of the six pairs of long bones of the UFHADM phantom. An equivalent cylindrical model of

medullary marrow and surrounding cortical bone were created within the MCNP5 radiation transport code. The target region was assigned as TM_{50} for all six bone sites, with AM as an additional target in the upper halves of the femora and humeri (at ICRP 70 reference cellularity). Source regions included medullary active marrow (MAM), medullary inactive marrow (MIM), cortical bone surfaces (CBS_{MC}), and cortical bone volumes (CBV which also serves as the source region CBS_{HC}).³

3. Results

Bone-specific volumetric data acquired from the UFHADM phantom (homogeneous bone volumes), analysis of CT images of excised cadaveric bone (CBVF, SVF, and MCVF values), and analysis of microCT images of cored cadaveric spongiosa (TBVF and MVF values) are shown in Table 1 under columns 2 to 7, respectively. For the craniofacial bones, ribs, vertebrae, and femoral heads, individual values for each spongiosa sub-region core are given separately. The *shallow marrow volume fraction* (SMVF) is given in column 8 and is defined as the fraction of spongiosa volume occupied by total marrow localized within 50 μm of the bone trabeculae. The corresponding percentage of total marrow that is shallow (within 50 μm of bone surfaces) is given next in column 9. Marrow cellularity at ICRP 70 reference values are given in table column 10 (ICRP, 1995). The total skeletal mass of the phantom is 9355 g, a value only 0.05% different from the idealized value for the ICRP 89 reference adult male (9350 g).

The partition of ICRP 89 reference skeletal tissues by bone site is shown in columns 2 to 5 of Table 2 for active marrow, inactive marrow, trabecular bone, and cortical bone, respectively. Total active marrow is exactly matched to 1170 g, while the UFHADM phantom is within 0.3% of its target of 2480 g of inactive marrow. Total mineral bone is 5514 g or within 0.3% of its reference value. The distribution of mineral bone to its trabecular and cortical components shows an agreement to within 5% for trabecular bone and to within 1% for cortical bone. The overall ratio of TBV to CBV in the UF adult male phantom is thus 21% / 79% trabecular to cortical bone – only slightly different than the rounded average of 20% / 80% assumed by the ICRP.

The central columns of Table 2 give bone-specific tissue masses for AM, IM, TM_{50} , TBV, and CBV *inclusive* of their miscellaneous skeletal tissues. A total mass of 447 g is assigned to total shallow marrow in the UF hybrid adult male phantom, of which only 1.3% is located on the inner surfaces of the long bone shafts. Bone surface areas are given next for trabecular bone, cortical Haversian canals, and cortical medullary surfaces. These estimates are based upon reported volumes of these bone tissues in the phantom, site-dependent S/V ratios for trabecular bone⁴, and the ICRP reference S/V ratio of 30 mm^2/mm^3 for cortical bone. Surface areas for the medullary cavities are taken from the long bone models of the UFHADM phantom. Values of TBS and CBS_{HC} are shown to be 5% lower and 9% higher than reference values (10.5 and 6.5 m^2 , respectively) given in ICRP Publication 89 (ICRP,

²We note that the approach to electron dosimetry in the long bone shafts of the adult differs from that used in the previous study by Pafundi *et al* (2010) for ICRP reference newborn, where all long bones were treated as one single source/target with proximal end, shaft, and distal end together. The justification was that for the smaller bones of newborn arms and legs, electron cross-fire between tissues in the bone shafts and proximal/distal ends could be significant and had to be handled implicitly during PIRT simulations.

³In our previous study by Pafundi *et al* (2009), we defined the marrow contained within the medullary cavities of long-bone shafts as cortical active marrow (CAM) and cortical inactive marrow (CIM). These terms have been replaced in this study by the terms medullary active marrow (MAM) and medullary inactive marrow (MIM). This change attempts to avoid confusion with what is meant by “cortical marrow” in ICRP Publication 67 biokinetic compartmental models – the fluids within the Haversian canals of cortical bone (ICRP 1993).

⁴Values of trabecular surface-to-volume (S/V) ratios were estimated using Cauchy's theorem which states that $S/V = 4/\bar{\ell}_{TB}$ where $\bar{\ell}_{TB}$ is the mean value of the pathlength frequency distribution through the bone trabeculae (see Table 8).

2002). Fractional tissue weights, needed for assessing skeletal averaged absorbed fractions, are given in the final columns of Table 2. It is noted that 85.9% of all cortical surfaces are found across the skeleton along the Haversian canals, while 14.1% are found along the inner cortical boundary of the long bone shafts.

In Table 3, bone-specific elemental compositions and mass densities are given for both spongiosa and medullary marrow regions of the UFHADM phantom. These values are based upon the fractional tissue weights of Table 2, and the reference elemental compositions of active marrow, inactive marrow, mineral bone, and generic soft tissue (for MST) given in Section 13 of ICRP 89 (ICRP, 2002). Homogeneous spongiosa densities range from a low of 1.051 g cm^{-3} for the distal fibulae to a high of 1.492 g cm^{-3} for the craniofacial bones. The densities of medullary marrow in the lower humeri/femora and lower arm/leg bones are 0.981 g cm^{-3} (100% inactive marrow), while they are slightly higher – 0.994 g cm^{-3} – in the upper humeri/femora where the reference cellularity is 25%. The skeletal-average densities for spongiosa, spongiosa plus medullary marrow, and total homogeneous bone in the UFHADM phantom are 1.14, 1.12, and 1.38 g cm^{-3} , respectively. For comparison, the assigned homogeneous bone density of the adult ORNL stylized phantom is 1.4 g cm^{-3} (Cristy and Eckerman, 1987).

A three-part Annex is provided to this study in electronic form. Annex A lists tabular values of electron *specific absorbed fraction* (Φ) for each skeletal site over the energy range of 1 keV to 10 MeV. A representative example is given in Table 4 for the os coxae. Values of $\Phi(AM \leftarrow AM)$ are given as a function of marrow cellularity from 100% to 10%, and then separately at the ICRP 70 marrow cellularity (48%). Cellularity independent values of $\Phi(AM \leftarrow r_S)$ are given next for the source regions IM, TBS, TBV, CBS_{HC}, and CBV. A final set of cellularity-independent values of $\Phi(TM_{50} \leftarrow r_S)$ are given in the last five columns of Table 4 for all potential source tissues.

Annexes B and C give graphical representations of $\phi(AM \leftarrow r_S)$ and $\phi(TM_{50} \leftarrow r_S)$, respectively, for all skeletal sites within the reference adult male. Figures 5A and 5B show representative plots from these two annexes where again we use the os coxae as an example skeletal site. As expected, absorbed fractions converge to source-independent values at high energy for all spongiosa tissue sources, with cortical bone contributions being lower at all energies. It is noted that values of $\phi(AM \leftarrow TBS)$ and $\phi(TM_{50} \leftarrow TBS)$ at the lowest energy considered (1 keV) are 0.24 and 0.5, respectively. The value of 0.24 for $\phi(AM \leftarrow TBS)$ is simply the product of a half-space absorbed fraction (0.5) and the ICRP 70 marrow cellularity (48%). The value of 0.5 for $\phi(TM_{50} \leftarrow TBS)$ is only the former as, by definition, the TM_{50} target is the sum of its two constituent tissues TAM_{50} and TIM_{50} . Consequently, $\phi(TM_{50} \leftarrow TBS)$ is cellularity independent [see similar discussion in Pafundi *et al* (2010)]. Tabular values of the skeletal-averaged absorbed fraction and specific absorbed fraction for the UFHADM phantom are given in Tables 5 and 6, respectively, for all 12 combination of source and target tissues.

4. Discussion

4.1 Comparison of skeletal volume fractions with those of ICRP 70

The skeletal volumetric data from Table 1 represents perhaps the most comprehensive set of values available for construction of a skeletal dosimetry model, both in terms of its mass distribution and by providing 3D images for radiation transport. Nevertheless, limited data exist for validation of the skeletal tissue model of the present study. Table 10 of ICRP Publication 70 (ICRP, 1995), for example, does give data on the partitioning of mineral bone to its cortical and trabecular forms as reported in two studies -Johnson (1964) and Spiers and Beddoe (1983). As shown in columns 2 to 8 of Table 7, excellent agreement between these

studies and the present model is seen for bones of the extremities, as well as for the sacrum and ox coxae. In contrast, Johnson (1964) states that the ratio of cortical to trabecular bone is 1:3 in the vertebrae, while the opposite is seen in the present study. We note that the values from Johnson (1964) are given without citation to earlier studies, and without explanation of the method applied or sample size used. Similarly, Johnson (1964) cites a fairly low percentage of trabecular bone in the skull, scapulae, clavicles, sternum, and ribs – 5 to 6% (offered as “estimates”). Our studies indicate that these bones contain 15 to 20% trabecular bone. In the last four columns of Table 7, we summarize values of MVF and TBVF in the present model, and compare them to values given in Table 15 of ICRP Publication 70 which are in turn taken from Arnold and Wei (1972) for the vertebrae and from Beddoe (1976) for other skeletal sites. In general, the agreement is excellent, giving confidence in the distribution of reference tissues across the skeleton of the UFHADM phantom.

Using techniques previously described by Rajon et al (2003), pathlength distribution were assembled across both the marrow cavities and bone trabeculae for each of the 35 microCT images of the 40-year male cadaver of this study as shown in Table 6. In the craniofacial bones, mean pathlengths across the marrow cavities t_{MC} and bone trabeculae t_{TB} are shown to be consistent for the frontal and parietal bones, with the occipital bone displaying a much more dense structure (smaller cavities and thicker trabeculae). For comparison, we also show mean values reported by Darley (1968) and Beddoe et al (1976) for their 44-year male cadaver. The microstructure of their parietal bone sample is shown to have thicker trabeculae and smaller marrow cavities on average than seen in the corresponding sample of the present study. Values t_{MC} and t_{TB} from the University of Leeds studies in the remaining four skeletal sites are shown to be generally consistent with those reported for the present model.

4.2 Site-specific variations in absorbed fraction in the UF adult male hybrid phantom

Figure 6 shows the bone-specific variations in the electron absorbed fraction for active and inactive marrow sources for AM (Figs. 6A / 6B) and TM_{50} (Figs. 6C/ 6D) target tissues. All values are given at ICRP 70 reference cellularities, and thus their energy-dependent magnitudes are driven both by differences in their trabecular microstructure and marrow fat content. In each plot, skeletal averaged values are shown for comparison (bolded dashed lines). In Figure 6A, $\phi(AM \leftarrow AM)$ is seen to be highest in the ribs and sacrum at energies below and above ~500 keV, respectively. They are lowest for the proximal femora/humeri and craniofacial bones at energies below and above ~200 keV, respectively. Values of $\phi(AM \leftarrow IM)$ in Figure 6B, given for the first time in this study, vary in their maximal values from 0.19 (femoral/humeral shafts at 1.5 MeV) to 0.62 (sternum at 200 keV). For $\phi(AM \leftarrow IM)$, skeletal averaged values are shown to be substantially lower than the individual bone-specific values shown, as roughly 52% of all inactive marrow in the adult male skeleton is localized in skeletal regions with no active marrow present; consequently, their contributions of $\phi(AM \leftarrow IM) = 0$ substantially depress the skeletal average. Values of $\phi(TM_{50} \leftarrow AM)$ and $\phi(TM_{50} \leftarrow IM)$ are shown in Figures 6C and 6D, respectively. For both marrow sources, values of the absorbed fraction to TM_{50} are significantly higher in the craniofacial bones than in any other skeletal region. This finding is reflective of the volumetric data in Table 1 where the shallow marrow is shown to comprise between 34% (frontal/parietal) to 69% (occipital) of total marrow in the plates of the cranium – values much higher than seen in other bone sites (which range from 8.6% in the proximal radii to 18.7% in the femoral head).

Figure 7 show values of the absorbed fraction to AM and TM_{50} targets for electron sources on the surfaces (Figs. 7A / 7C) and in the volumes (Figs. 7B / 7D) of trabecular bone.

Values of $\phi(AM \leftarrow TBS)$ at energies below ~ 100 keV are fairly constant with magnitudes dictated primarily by bone-specific marrow cellularity. Maximal values of $\phi(AM \leftarrow TBS)$ and $\phi(AM \leftarrow TBV)$ are seen at energies between 500 and 800 keV, and are highest in the sternum and sacrum, and lowest in the proximal humeri/femora and craniofacial bones. Skeletal average values for $\phi(AM \leftarrow TBS)$ and $\phi(AM \leftarrow TBV)$ are strongly influenced by their values seen in the craniofacial bones which account for 15.3% of total trabecular surfaces and 29.5% of total trabecular mass. No site-dependence is seen in values of $\phi(TM_{50} \leftarrow TBS)$ below ~ 100 keV as shown in Figure 7C, and only modest variations above that energy. Values of $\phi(TM_{50} \leftarrow TBV)$ shown in Figure 7D are highest in the sternum (maximum at ~ 150 keV) and wrists & hands (given by its surrogate – the distal humerus), and lowest in the craniofacial bones followed by the ribs at energies above 1 MeV.

Site-specific variations in electron absorbed fraction for cortical bone sources are shown in Figure 8. Values of $\phi(AM \leftarrow CBS)$ and $\phi(AM \leftarrow CBV)$ given in Figures 8A and 8B, respectively, are identical across individual skeletal sites, with one exception. For $\phi(AM \leftarrow CBS)$, an additional contribution to active marrow dose is present from electrons emitted along the medullary cavity surfaces of the upper femoral and humeral shafts. This modest contribution to total cortical surfaces (2.3% in upper humeri and 5.0% in upper femora – see Table 2) nevertheless increases the skeletal averaged values of $\phi(AM \leftarrow CBS)$ slightly above those for $\phi(AM \leftarrow CBV)$ (which are essentially zero) at energies below several 100 keV. A similar observance can be made in comparing values of $\phi(TM_{50} \leftarrow CBS)$ in Figure 8C to values of $\phi(TM_{50} \leftarrow CBV)$ in Figure 8D, where the former includes the additional contribution to shallow marrow dose from the cortical surfaces of the medullary cavities – which in this case includes all the long bone shafts of the adult skeleton.

4.3 Comparisons to the skeletal tissue models of the ICRP 110 reference voxel phantoms

In late 2009, the ICRP issued its Publication 110 (ICRP, 2009) defining computational voxel phantoms representing the ICRP Publication 89 (ICRP, 2002) reference adult male and female. In both phantoms, an exercise similar to that outlined in this study (section 2.7) was undertaken to distribute ICRP 89 reference skeletal tissues amongst the various bones of their voxelized skeletons (Zankl *et al.*, 2007). Differences in methodology are noted between this and the present study. First, cartilage was considered a tissue constituent of homogeneous spongiosa in the ICRP voxel phantoms, while it is considered to lie outside the skeletal tissues of the UFHADM phantom. Second, cortical bone was added to the ICRP voxel phantoms through manual retagging of homogeneous skeletal voxels, while it was modeled in the UFHADM as an independent polygon mesh surface whose volume fraction was matched to values seen in bone-specific *ex-vivo* CT images. Third, total masses of active and inactive marrow, as well as cortical and trabecular bone, were independently matched to their corresponding reference values in the ICRP computational phantoms, while in the present study, only total marrow and total mineral bone were correspondingly matched, with CT and microCT imaging data used to guide the distribution of mineral bone into its trabecular and cortical portions. These differences in methodology, as well as the different source anatomies used for phantom construction (e.g., rib cage or skull might be slightly larger in proportion in one phantom than in the other), yield corresponding differences in the percent distribution of skeletal tissues.

As shown previously, Table 2 gives fractional tissue weights for all skeletal tissues among the bones of the UFHADM phantom. We have constructed similar tables of fractional tissue weights for the ICRP 110 adult male phantom (Table 9) and the ICRP 110 adult female phantom (Table 10). In cases where bone regions are given in condensed form for the ICRP phantoms (e.g., tibiae, fibulae, and patella together), their individual masses are estimated here using relative bone volumes as seen in the UFHADM phantom. The fractional tissue

weights of Tables 9 and 10 were subsequently used to derive skeletal-averaged absorbed fractions unique to the ICRP voxel phantoms but based upon bone-specific absorbed fractions developed in this study (see section 4.4 below).

One important update to ICRP 110 is indicated in Tables 9 and 10 – the estimated mass of TM_{50} and its skeletal distribution. Estimates of TM_{50} mass given in Table 4.2 of ICRP 110 are 544 g and 407 g, respectively, for the reference adult male and adult female (ICRP, 2010). These masses were based on preliminary microCT imaging data of spongiosa cores taken from a 66-year male cadaver as reported in Bolch *et al* (2007). In Tables 9 and from column 8 of Table 1 (percent marrow that is shallow). Such an approach revises downward our estimates of total shallow marrow from 544 g to 452 g in the ICRP adult male and from 407 g to 333 g in the ICRP adult female. The two bone sites with the highest percentage of shallow marrow are shown to be the cranium and the os coxae. In the UFHADM phantom, these two bone sites comprise 11.8% and 17.4% of all shallow marrow, respectively (Table 2). Corresponding values are 17.4% and 11.4% in the ICRP adult male, and 18.2% and 11.9% in the ICRP adult female (ICRP, 2009).

4.4 Comparisons of skeletal averaged absorbed fractions for marrow sources

In Figures 9A to 9D, graphical comparisons of skeletal-averaged absorbed fractions for marrow electron sources are shown as given by (1) the present model for the UFHADM phantom, (2) the ICRP 110 adult male and female phantoms, and (3) the pathlength-based infinite spongiosa transport (IST) model of Stabin and Siegel (2003). As seen in Figure 9A, good agreement is seen for $\phi_{skel}(AM \leftarrow AM)$ across all models out to an energy of ~400 keV, after which the IST model increasingly overestimates energy deposition to active marrow due to a lack of consideration for electron escape from spongiosa. A similar divergence in model results was seen in the reference newborn skeleton, but beginning at a much lower energy of 10 keV (Pafundin *et al.* 2010). Values of $\phi_{skel}(AM \leftarrow AM)$ for the ICRP phantoms are only slightly higher than those of the UFHADM phantom in the energy range of 60 to 1000 keV. As seen in Figure 9B, the IST model does not consider electron sources inactive marrow. The present model gives slightly higher values of $\phi_{skel}(AM \leftarrow IM)$ than for the two ICRP voxel phantoms with peak differences of 10% and 6% at 150 keV for the ICRP male and female phantoms, respectively.

For targets relevant to bone cancer risk, higher values of $\phi_{skel}(TM_{50} \leftarrow AM)$ are shown in Figure 8C for the present model over values of $\phi_{skel}(TBE_{10} \leftarrow AM)$ given in the IST model which are reflective of the change in target thickness from 10 to 50 μm . The dip and subsequent rise in $\phi_{skel}(TM_{50} \leftarrow AM)$ for the present model occurs as electrons lose energy to surrounding bone trabeculae, yet eventually enter those trabeculae with sufficient energy to penetrate them fully and irradiate shallow marrow on their opposite side. A similar pattern is seen for inactive marrow sources under Figure 9D. Values of $\phi_{skel}(TM_{50} \leftarrow IM)$ are shown to be very consistent between the present and ICRP tissue models.

4.5 Comparisons of skeletal averaged absorbed fractions for trabecular bone sources

Skeletal-averaged absorbed fractions for electron sources in trabecular bone are shown in Figure 10. In Figure 10A, values of $\phi_{skel}(AM \leftarrow TBS)$ for the present model begin at 0.16 at low energy (product of a half-space value of 0.5 and a skeletal-averaged cellularity of 0.32 [or $1170 / (1170 + 2480)$]). In contrast, values of $\phi_{skel}(AM \leftarrow TBS)$ under the IST model report a value of 0.213 at 1 keV inferring a skeletal-averaged marrow cellularity of 0.426 – a value not supported by ICRP reference marrow masses. Under the present model, values of $\phi_{skel}(AM \leftarrow TBS)$ begin to increase at ~100 keV and peak at ~400 keV due to electron traversal of the bone trabeculae (irradiating active marrow on the opposite side), after which they decline owing to spongiosa escape. In contrast, values of $\phi_{skel}(AM \leftarrow TBS)$ in the IST

model continue to climb and plateau at just under 0.3. For electrons born uniformly within the trabecular volumes, the curves of Figure 10B show a divergence of the present and IST models at energies as low as 40 keV.

Values of $\varphi_{skel}(TM_{50} \leftarrow TBS)$ are uniformly higher under the present model than values of $\varphi_{skel}(TBE_{10} \leftarrow TBS)$ under the IST model as shown in Figure 10C. At energies above 1 MeV, the present model shows values of $\varphi_{skel}(TM_{50} \leftarrow TBS)$ that continue to decline with increasing electron escape. In Figure 10D, all models show a peak in the value of the absorbed fraction from TBV sources at between 150 and 200 keV, but they are significantly lower in magnitude under the IST model, again owing primarily to the change in target thickness.

4.6 Comparisons of skeletal averaged absorbed fractions for cortical bone sources

Skeletal-averaged absorbed fractions for electron sources in cortical bone are shown in Figure 11. Plots of $\varphi_{skel}(AM \leftarrow CBS)$ and $\varphi_{skel}(AM \leftarrow CBV)$ are shown in Figures 11A and 11B, respectively, where under the present model, a peak contribution of 0.05 is seen at just under 2 MeV. Good agreement is seen between the present and ICRP models, with the ICRP female model being somewhat closer to that of the UFHADM phantom. In the energy range below several hundred keV, values of $\varphi_{skel}(AM \leftarrow CBV)$ are shown to be higher (~ 0.01) than corresponding values of $\varphi_{skel}(AM \leftarrow CBS)$, where additional dose to active marrow is seen in the upper halves of the humeri and femora for electron sources along their interior medullary shafts. As noted in both figures, the IST model did not consider electron cross-fire from cortical bone to the spongiosa tissues.

Values of $\varphi_{skel}(TM_{50} \leftarrow CBS)$ are shown in Figure 11C in which the present model yields a value of ~ 0.07 at energies below 100 keV and lower values thereafter. For comparison, values of $\varphi_{skel}(CBE_{10} \leftarrow CBS)$ are shown from the IST model of Stabin & Siegel (2003) where *CBE10* represents the target tissue cortical endosteum as defined under ICRP Publications 26 and 30, and is a 10- μ m layer along the walls of the Haversian canals of cortical bone. Similarly, values of $\varphi_{skel}(TM_{50} \leftarrow CBV)$ from the present study and $\varphi_{skel}(CBE_{10} \leftarrow CBV)$ from the Stabin and Siegel model are shown in Figure 11D. While $\varphi_{skel}(CBE_{10} \leftarrow CBV)$ rises from zero to a plateau of ~ 0.02 at 300 keV, corresponding values of $\varphi_{skel}(TM_{50} \leftarrow CBV)$ increase over a higher energy range (starting at ~ 100 keV) to a peak value of ~ 0.03 at 3.3 MeV, where they decline thereafter.

4.7 Comparisons of skeletal radionuclide S values to those of Stabin & Siegel (2003)

A final comparison may be made between the current adult male skeletal model and that given in Stabin and Siegel (2003) through calculations of skeletal-averaged S values for various source-target tissue combinations. The following three bone-seeking radionuclides were selected based upon their importance in environmental risk assessments, and their varying beta particle energy spectra: ^{90}Sr ($\beta = 196$ keV; $\beta_{\text{max}} = 546$ keV), ^{89}Sr ($\beta = 585$ keV; $\beta_{\text{max}} = 1500$ keV), and ^{90}Y ($\beta = 933$ keV; $\beta_{\text{max}} = 2800$ keV). Radionuclide S values were calculated according to Equation 4A of Bolch et al (2009) given the beta-particle energy distribution of Eckerman and Endo (2008). For the present model, skeletal averaged SAF values from Table 8 were used, while for the 2003 Stabin & Siegel model, skeletal-averaged SAF values were calculated as the ratio of their skeletal averaged absorbed

fractions and corresponding ICRP 89 reference masses.⁵ The resulting S values for both models are given in Table 11.

For S values relevant to the assessment of hematopoietic stem cell dose, source and target tissues are equivalent between the two models, with the exception of the assigned total marrow mass (1170 g versus 1205 g). Consequently, at a minimum we would expect S value differences of a factor of 1.03. As shown in the upper half of Table 11 for active marrow targets, S value ratios range from a low of 1.05 (AM sources of ⁹⁰Sr and ⁸⁹Sr) to a high of 1.47 (TBV sources of ⁸⁹Sr and ⁹⁰Y).

For radiation targets relevant to dose assessment to the osteoprogenitor cells for sources in spongiosa, S value ratios range from a low of 1.19 (⁸⁹Sr and ⁹⁰Y sources in TBV) to a high of 1.49 (⁸⁹Sr and ⁹⁰Y sources in AM). Substantially higher discrepancies are noted for cortical bone surface sources (S value ratios of ~13) and somewhat less so for cortical bone volume sources (S value ratios of between 5 and 6.6). Again, these larger discrepancies are driven primarily by the ICRP decision to exclude cortical bone as a relevant target tissue for radiation dose assessment. Consequently, only electron cross-fire to spongiosa will result in irradiation of the osteoprogenitor cells for localized radioactivity in cortical bone.

5. Conclusions

A comprehensive model for electron transport in the skeletal tissues of the ICRP 89 reference adult male is presented. The model explicitly accounts for the volume distribution cortical bone and spongiosa by skeletal site, as seen in *ex-vivo* CT images derived from a 40-year male cadaver, as well as the distribution of trabecular bone and marrow tissues within spongiosa regions of this same individual seen in *ex-vivo* microCT images. The resulting tissue model was used to create a truly heterogeneous skeletal model for the UF hybrid adult male phantom at both its macroscopic and microscopic dimensions. Radiostrontium and radioyttrium S-values to active marrow are noted to be lower under the present model for marrow and trabecular bone sources – by factors of 1.1 to 1.5 – in comparison to those based upon previously published data. S-values for these radionuclides to surrogate tissues defining the osteoprogenitor cells are shown to be lower by factors of 1.2 to 1.5 for trabecular bone sources under the present model, while significant reductions in osteoprogenitor cell dose (up to a factor of 13) are noted for cortical bone activity, as these cells are no longer thought to reside with the cortical osteons. Skeletal-averaged values of absorbed fraction in the present model are noted to be very compatible with those weighted for the ICRP Publication 110 adult male and female voxel phantoms, but are in many cases incompatible with values given by the model of Stabin and Siegel (2003). Current efforts are being devoted to the completion of a complimentary model for the adult reference female and other members of the ICRP reference series.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This research was supported in part by grants R01 CA116743 and R01 CA96441 with the National Cancer Institute, and by grant DE-FG07-06ID14773 with the US Department of Energy. The research of Matthew Hough (first

⁵In the ICRP 89 reference adult male, target masses include 1170 g of active marrow, 106 g of trabecular endosteum, and 71 g of cortical endosteum. The latter two estimates are based upon reference masses of trabecular and cortical bone (1100 g and 4400 g, respectively), corresponding S/V ratios (180 and 30 cm² / cm³, respectively), thickness of endosteum under the previous ICRP assumption (10 μm), mass density of adult mineral bone (1.92 g / cm³), and mass density of endosteum (1.03 g / cm³).

author) was supported by the US Department of Energy Health Physics Fellowship program, sponsored by DOE's Office of Nuclear Engineering, Science, and Technology.

References

- Arnold, JS.; Wei, CT. Radiobiology of plutonium. Stover, BJ.; Jee, WS., editors. J. W. Press; Salt Lake City, Utah: 1972. p. 333-352.
- Beddoe, AH. The microstructure of mammalian bone in relation to the dosimetry of bone-seeking radionuclides. Department of Medical Physics. University of Leeds; Leeds, UK: 1976. p. 165
- Beddoe AH, Darley PJ, Spiers FW. Measurements of trabecular bone structure in man. *Phys. Med. Biol.* 1976; 21:589-607. [PubMed: 972924]
- Bolch WE, Eckerman KF, Sgouros G, Thomas SR. MIRD Pamphlet No. 21 – A generalized schema for radiopharmaceutical dosimetry: Standardization of nomenclature. *J Nucl Med.* 2009; 50:477–484. [PubMed: 19258258]
- Bolch WE, Shah AP, Watchman CJ, Jokisch DW, Patton PW, Rajon DA, Zankl M, Petoussi-Henss N, Eckerman KF. Skeletal absorbed fractions for electrons in the adult male: Considerations of a revised 50-microm definition of the bone endosteum. *Radiat Prot Dosimetry.* 2007; 127:169–173. [PubMed: 17556345]
- Bouchet LG, Bolch WE, Howell RW, Rao DV. S values for radionuclides localized within the skeleton *J. Nucl. Med.* 41 189-212. 2000
- Bouchet LG, Jokisch DW, Bolch WE. A three-dimensional transport model for determining absorbed fractions of energy for electrons in trabecular bone. *J. Nucl. Med.* 1999; 40:1947–1966. [PubMed: 10565793]
- Brindle J, Trindade A, Pichardo J, Myers S, Shah A, Bolch W. CT volumetry of the skeletal tissues. *Med Phys.* 2006; 33:3796–3803. [PubMed: 17089844]
- Cristy, M.; Eckerman, KF. Specific absorbed fractions of energy at various ages from internal photon sources. Oak Ridge National Laboratory; Oak Ridge, TN: 1987.
- Custer, R. An atlas of the blood and bone marrow. W.B. Saunders; Philadelphia, PA: 1974.
- Darley, PJ. Measurement of linear path length distributions in bone and bone marrow using a scanning technique.. In: Booz, J.; Ebert, HG., editors. Symposium on Microdosimetry. Ispra, Italy: 1968. p. 509-526. EAEC Report EUR 3747
- Darley, PJ. Department of Medical Physics. University of Leeds; Leeds, UK: 1972. An investigation of the structure of trabecular bone in relation to the radiation dosimetry of bone-seeking radionuclides.; p. 231
- Eckerman, KF.; Endo, A. MIRD: Radionuclide Data and Decay Schemes. The Society of Nuclear Medicine; Reston, VA: 2008.
- Eckerman KF, Stabin MG. Electron absorbed fractions and dose conversion factors for marrow and bone by skeletal regions. *Health Phys.* 2000; 78:199–214. [PubMed: 10647986]
- ICRP. Limits for intakes of radionuclides by workers. International Commission on Radiological Protection; Oxford, UK: 1979.
- ICRP. ICRP Publication 67: Age-dependent doses to members of the public from intake of radionuclides: Part 2 - ingestion dose coefficients. *Ann ICRP.* 1993; 23:1–167.
- ICRP. Publication 70: Basic anatomical and physiological data for use in radiological protection: the skeleton. *Ann ICRP.* 1995; 25:1–180.
- ICRP. ICRP Publication 89: Basic anatomical and physiological data for use in radiological protection - reference values. *Ann ICRP.* 2002; 32:1–277.
- ICRP. ICRP Publication 110: Adult reference computational phantoms. *Ann ICRP.* 2009; 39:1–165.
- ICRP. ICRP Publication 110: Adult reference computational phantoms. *Ann ICRP.* 2010; 39:1–165.
- ICRU. ICRU Report 46: Photon, electron, proton and neutron interaction data for body tissues. International Commission on Radiation Units and Measurements; Bethesda, MD: 1992.
- Johnson L. Frost HM. Morphologic Analysis in Pathology. 1964:543–654.
- Johnson P, Bahadori A, Eckerman KF, Lee C, Bolch WE. Response functions for computing absorbed dose to skeletal tissues from photon irradiation - an update. *Phys Med Biol.* submitted.

- Johnson P, Whalen S, Wayson M, Juneja B, Lee C, Bolch W. Hybrid patientdependent phantoms covering statistical distributions of body morphometry in the US adult and pediatric population. *Proc IEEE*. 2009; 97:2060–2075.
- Kielar, KN. Nuclear & Radiological Engineering. University of Florida; Gainesville, FL: 2009. Bone marrow dosimetry via microCT imaging and stem cell spatial mapping..
- Lee C, Lodwick D, Hasenauer D, Williams JL, Lee C, Bolch WE. Hybrid computational phantoms of the male and female newborn patient: NURBS-based whole-body models. *Phys Med Biol*. 2007; 52:3309–3333. [PubMed: 17664546]
- Lee C, Lodwick D, Hurtado J, Pafundi D, Williams JL, Bolch WE. The UF family of reference hybrid phantoms for computational radiation dosimetry. *Phys Med Biol*. 2010; 55:339–363. [PubMed: 20019401]
- Mechanik N. Studies of the weight of bone marrow in man *Zeitschrift fur die. Gest. Anatomy*. 1926; 79:58–99.
- Nipper JC, Williams JL, Bolch WE. Creation of two tomographic voxel models of paediatric patients in the first year of life. *Phys Med Biol*. 2002; 47:3143–3164. [PubMed: 12361215]
- Pafundi D, Lee C, Watchman C, Bourke V, Aris J, Shagina N, Harrison J, Fell T, Bolch W. An image-based skeletal tissue model for the ICRP reference newborn. *Phys Med Biol*. 2009; 54:4497–4531. [PubMed: 19556686]
- Pafundi D, Rajon D, Jokisch D, Lee C, Bolch W. An image-based skeletal dosimetry model for the ICRP reference newborn--internal electron sources. *Phys Med Biol*. 2010; 55:1785–1814. [PubMed: 20208096]
- Rajon D, Pichardo J, Brindle J, Kielar K, Jokisch D, Patton P, Bolch W. Image segmentation of trabecular spongiosa by visual inspection of the gradient magnitude. *Phys Med Biol*. 2006; 51:4447–4467. [PubMed: 16953037]
- Rajon DA, Shah AP, Watchman CJ, Brindle JA, Bolch WE. A hyperboloid representation of the bone-marrow interface within 3D NMR images of trabecular bone: Applications to skeletal dosimetry. *Phys Med Biol*. 2003; 48:1721–1740. [PubMed: 12870579]
- Shah, A. Department of Biomedical Engineering. University of Florida; Gainesville, FL: 2004. Reference skeletal dosimetry model for an adult male radionuclide therapy patient based on 3D imaging and paired-image radiation transport.; p. 488
- Shah AP, Bolch WE, Rajon DA, Patton PW, Jokisch DW. A paired-image radiation transport model for skeletal dosimetry. *J Nucl Med*. 2005; 46:344–353. [PubMed: 15695796]
- Snyder, WS.; Ford, MR.; Warner, GG.; Watson, SB. MIRD Pamphlet No. 11: S, absorbed dose per unit cumulated activity for selected radionuclides and organs. Society of Nuclear Medicine; New York, NY: 1975.
- Spiers FW, Beddoe AH. Sites of incidence of osteosarcoma in the long bones of man and the beagle. *Health Phys*. 1983; 44:49–64. [PubMed: 6575001]
- Stabin MG, Siegel JA. Physical models and dose factors for use in internal dose assessment. *Health Phys*. 2003; 85:294–310. [PubMed: 12938720]
- Trotter M, Hixon B. Sequential changes in weight, density, and percentage ash weight of human skeletons from an early fetal period through old age. *Anat. Rec*. 1974; 179:1–18. [PubMed: 4821360]
- Whitwell, JR. Department of Medical Physics. University of Leeds; Leeds, UK: 1973. Theoretical investigations of energy loss by ionizing particles in bone.; p. 268
- Whitwell JR, Spiers FW. Calculated beta-ray dose factors for trabecular bone. *Phys. Med. Biol*. 1976; 21:16–38. [PubMed: 1257296]
- Woodard H, Holodny E. A summary of the data of Mechanik on the distribution of human bone marrow. *Phys. Med. Biol*. 1960; 5:57–59. [PubMed: 13786520]
- Zankl M, Eckerman KF, Bolch WE. Voxel-based models representing the male and female ICRP reference adult--the skeleton. *Radiat Prot Dosimetry*. 2007; 127:174–186. [PubMed: 17545663]

Figure 1.

Graphical user interface of the IDL-based contouring program. An *ex-vivo* CT image of the os coxae is overlaid with tag values to distinguish volumes of soft tissue (green), cortical bone (blue), and spongiosa (red).

Figure 2.
Graphical illustration of the input images to the PIRT model of skeletal electron transport for the craniofacial bones and thoracic vertebrae of the UF adult male hybrid phantom.

Figure 3.
Graphical illustration of the input images to the PIRT model of skeletal electron transport for the sacrum and os coxae of the UF adult male hybrid phantom.

Figure 4. Graphical illustration of the spatial location of shallow marrow within both the trabecular spongiosa regions of the femoral head and neck, as well as long the inner cortical surfaces of the medullary cavity of the diaphysis (shaft).

Figure 5. Plot of electron absorbed fractions in the os coxae to (A) active marrow and (B) total shallow marrow targets as a function of electron energies and source tissue as given in Annex B and C, respectively.

Figure 6.

Variations in bone-specific values of the electron absorbed fraction to active marrow (A, B) and total shallow marrow (C,D) for active and inactive marrow sources, respectively. Dashed line indicates the skeletal averaged values for these source-target combinations. Note – the list of bones given in the legend for Figure 5D has been truncated for spacing reasons.

Figure 7.

Variations in bone-specific values of the electron absorbed fraction to active marrow and total shallow marrow targets for (A, B) trabecular bone surfaces and (C,D) trabecular bone volume sources, respectively. Dashed line indicates the skeletal averaged values for these source-target combinations.

Figure 8. Variations in bone-specific values of the electron absorbed fraction to active marrow and total shallow marrow targets for (A, B) cortical bone surfaces and (C,D) cortical bone volume sources, respectively. Dashed line indicates the skeletal averaged values for these source-target combinations.

Figure 9.

Comparisons of skeletal-averaged electron absorbed fractions to active marrow and to total shallow marrow for (A, B) active marrow and (C, D) inactive marrow sources, respectively. Compared are the results of the present study, those of the ICRP 110 reference phantoms, and those of the model of Stabin & Siegel (2003).

Figure 10.

Comparisons of skeletal-averaged electron absorbed fractions to active marrow and to total shallow marrow for (A, B) trabecular bone surface and (C, D) trabecular bone volume sources, respectively. Compared are the results of the present study, those of the ICRP 110 reference phantoms, and those of the model of Stabin & Siegel (2003).

Figure 11.

Comparisons of skeletal-averaged electron absorbed fractions to active marrow and to total shallow marrow for (A, B) cortical bone surface and (C, D) cortical bone volume sources, respectively. Compared are the results of the present study, those of the ICRP 110 reference phantoms, and those of the model of Stabin & Siegel (2003).

Table 1

Macroscopic and microscopic volume fractions within the skeleton of the UF adult male hybrid phantom.

Skeletal Site	Homogeneous Bone Volume (cm^3)	Homogeneous Bone Volume Fractions			Spongiosa Volume Fractions			TM ₅₀ (% MV)	ICRP 70 Cellularity	CB Thickness (mm)
		Cortical Bone	Spongiosa	Med Cavity	Trab Bone	Marrow	Shallow Marrow			
Craniofacial Bones	997.89	0.67	0.33	0.00						3.11
<i>Frontal / Facial</i>	249.47				0.445	0.555	0.192	34.5%	38%	
<i>Parietal</i>	449.05				0.394	0.606	0.211	34.8%	38%	
<i>Occipital</i>	299.37				0.912	0.088	0.061	68.7%	38%	
Mandible	48.49	0.40	0.60	0.00	0.089	0.911	0.078	8.6%	38%	1.25
Scapulae	488.91	0.35	0.65	0.00	0.153	0.847	0.100	11.8%	38%	1.68
Clavicles	68.60	0.40	0.60	0.00	0.116	0.884	0.080	9.0%	33%	1.83
Sternum	65.38	0.30	0.70	0.00	0.082	0.918	0.099	10.8%	70%	1.22
Ribs	310.80									0.77
<i>Upper</i>	85.66	0.40	0.60	0.00	0.103	0.897	0.072	8.1%	70%	
<i>Middle</i>	135.25	0.40	0.60	0.00	0.142	0.858	0.109	12.7%	70%	
<i>Lower</i>	89.89	0.40	0.60	0.00	0.101	0.899	0.109	12.2%	70%	
Cervical Vertebrae	96.67									1.07
<i>C3 (C1 - C3)</i>	42.43	0.35	0.65	0.00	0.159	0.841	0.155	18.5%	70%	
<i>C6 (C4 - C7)</i>	54.24	0.35	0.65	0.00	0.194	0.806	0.140	17.3%	70%	
Thoracic Vertebrae	309.42									0.94
<i>T3 (T1 - T4)</i>	81.18	0.25	0.75	0.00	0.132	0.868	0.111	12.8%	70%	
<i>T6 (T5 - T8)</i>	98.15	0.25	0.75	0.00	0.042	0.959	0.056	5.8%	70%	
<i>T11 (T9 - T12)</i>	130.09	0.25	0.75	0.00	0.111	0.889	0.106	12.0%	70%	
Lumbar Vertebrae	292.68									0.97
<i>L2 (L1 - L3)</i>	169.47	0.20	0.80	0.00	0.114	0.887	0.112	12.7%	70%	
<i>L4 (L4 - L5)</i>	123.21	0.20	0.80	0.00	0.091	0.909	0.091	10.0%	70%	
Sacrum	197.17	0.25	0.75	0.00	0.118	0.882	0.111	12.6%	70%	1.46
Os coxae	923.96	0.25	0.75	0.00	0.100	0.901	0.112	12.4%	48%	1.77
Humeri, Proximal	180.80	0.15	0.85	0.00	0.096	0.904	0.080	8.8%	25%	1.36
Humeri, Upper Shaft	91.44	0.65		0.35	0.000	1.000			25%	4.30
Humeri, Lower Shaft	81.37	0.65		0.35	0.000	1.000			0%	3.90

Skeletal Site	Homogeneous Bone Volume (cm^3)	Homogeneous Bone Volume Fractions			Spongiosa Volume Fractions			TM ₅₀ (% MV)	ICRP 70 Cellularity	CB Thickness (mm)
		Cortical Bone	Spongiosa	Med Cavity	Trab Bone	Marrow	Shallow Marrow			
Humeri, Distal	110.65	0.30	0.70		0.151	0.849	0.127	14.9%	0%	1.52
Radii, Proximal	18.03	0.30	0.70		0.089	0.911	0.063	6.9%	0%	1.18
Radii, Upper Shaft	28.09	0.75		0.25	0.000	1.000			0%	3.17
Radii, Lower Shaft	28.09	0.75		0.25	0.000	1.000			0%	3.17
Radii, Distal	32.59	0.30	0.70		0.116	0.884	0.107	12.1%	0%	1.48
Ulnae, Proximal	59.97	0.30	0.70		0.161	0.839	0.112	13.4%	0%	1.60
Ulnae, Upper Shaft	34.30	0.75		0.25	0.000	1.000			0%	3.47
Ulnae, Lower Shaft	34.30	0.75		0.25	0.000	1.000			0%	3.47
Ulnae, Distal	11.29	0.25	0.75		0.139	0.861	0.133	15.5%	0%	0.80
Wrists and Hands	141.62	0.65	0.35		0.151	0.849	0.127	14.9%	0%	2.10
Femora, Proximal	260.72									0.85
Head	92.77	0.05	0.95		0.229	0.771	0.144	18.7%	25%	
Neck	167.89	0.10	0.90		0.103	0.897	0.112	12.5%	25%	
Femora, Upper Shaft	194.87	0.35		0.65	0.000	1.000			25%	2.40
Femora, Lower Shaft	148.19	0.35		0.65	0.000	1.000			0%	2.80
Femora, Distal	303.72	0.10	0.90		0.146	0.854	0.118	13.9%	0%	0.94
Patellae	246.65	0.10	0.90		0.146	0.854	0.118	13.9%	0%	0.45
Tibiae, Proximal	113.79	0.10	0.90		0.115	0.885	0.108	12.2%	0%	0.88
Tibiae, Upper Shaft	113.79	0.35		0.65	0.000	1.000			0%	2.23
Tibiae, Lower Shaft	90.75	0.35		0.65	0.000	1.000			0%	2.23
Tibiae, Distal	22.86	0.15	0.85		0.125	0.875	0.111	12.7%	0%	1.02
Fibulae, Proximal	19.87	0.20	0.80		0.078	0.922	0.079	8.6%	0%	0.83
Fibulae, Upper Shaft	19.87	0.70		0.30	0.000	1.000			0%	1.92
Fibulae, Lower Shaft	22.15	0.70		0.30	0.000	1.000			0%	1.92
Fibulae, Distal	35.59	0.30	0.70		0.147	0.853	0.128	15.0%	0%	1.09
Ankles and Feet	508.46	0.30	0.70		0.146	0.854	0.118	13.9%	0%	1.52
Total Skeleton (cm^3)	6753.78									
Total Skeletal Mass (g)	9355									

Note - based on average homogeneous bone density of 1.385 g cm^{-3}

Skeletal Site	Homogeneous Bone Volume (cm^3)	Homogeneous Bone Volume Fractions			Spongiosa Volume Fractions			TM ₅₀ (% MV)	ICRP 70 Cellularity	CB Thickness (mm)
		Cortical Bone	Spongiosa	Med Cavity	Trab Bone	Marrow	Shallow Marrow			
ICRP 89 Mass (g)	9350	Note - ICRP 89 total skeletal mass (10,500 g) less that of cartilage (1100 g) and teeth (50 g)								
Ratio	1.00									

Table 2

Skeletal tissue masses and their fractional distribution within the skeleton of UF adult male hybrid phantom.

Skeletal Site	Tissue Masses exclusive of MST (g)					Tissue Masses inclusive of MST (g)					Surface Areas (m ²)			Fractional Tissue Weights						
	AM	IM	TBV	CBV	AM	IM	TM ₅₀	TBV	CBV	TBS	CBS _{HC}	CBS _{MC}	f _{AM}	f _{IM}	f _{TM50}	f _{TBV}	f _{CBV}	f _{TBS}	f _{CBS-HC}	f _{CBS-MC}
Craniofacial Bones	54.84	85.13	341.48	1233.79	56.46	87.78	52.96	346.96	1253.59	1.573	2.006		0.0469	0.0345	0.1184	0.2947	0.2833	0.1583	0.2435	
Mandible	10.08	15.65	4.76	35.79	10.38	16.13	2.27	4.83	36.36	0.051	0.058		0.0086	0.0063	0.0051	0.0041	0.0082	0.0051	0.0071	
Scapulae	102.34	158.86	89.67	315.78	105.37	163.81	31.65	91.11	320.84	0.769	0.513		0.0874	0.0643	0.0708	0.0774	0.0725	0.0774	0.0623	
Clavicles	12.02	23.21	8.78	50.64	12.37	23.94	3.28	8.92	51.45	0.071	0.082		0.0103	0.0094	0.0073	0.0076	0.0116	0.0072	0.0100	
Sternum	29.42	12.00	6.92	36.20	30.29	12.37	4.61	7.03	36.78	0.092	0.059		0.0251	0.0049	0.0103	0.0060	0.0083	0.0092	0.0071	
Ribs	115.00	46.89	41.06	229.41	118.41	48.35	18.70	41.72	233.09	0.407	0.373		0.0983	0.0190	0.0418	0.0354	0.0527	0.0410	0.0453	
Cervical Vertebrae	36.14	14.74	20.72	62.44	37.21	15.20	9.34	21.05	63.44	0.201	0.102		0.0309	0.0060	0.0209	0.0179	0.0143	0.0202	0.0123	
Thoracic Vertebrae	147.17	60.01	40.42	142.75	151.53	61.88	21.58	41.07	145.04	0.446	0.232		0.1258	0.0243	0.0483	0.0349	0.0328	0.0449	0.0282	
Lumbar Vertebrae	146.92	59.91	44.91	108.02	151.27	61.77	24.56	45.63	109.75	0.473	0.176		0.1255	0.0242	0.0549	0.0388	0.0248	0.0476	0.0213	
Sacrum	91.36	37.25	32.15	90.96	94.06	38.41	16.68	32.66	92.42	0.307	0.148		0.0781	0.0151	0.0373	0.0277	0.0209	0.0309	0.0179	
Os coxae	299.65	308.86	127.24	426.26	308.52	318.47	77.74	129.28	433.10	1.467	0.693		0.2561	0.1250	0.1738	0.1098	0.0979	0.1477	0.0841	
Humeri, Proximal	34.75	99.18	27.23	50.05	35.77	102.26	12.13	27.66	50.85	0.255	0.081		0.0297	0.0401	0.0271	0.0235	0.0115	0.0257	0.0099	
Humeri, Upper Shaft	8.00	22.85	0.00	109.68	8.24	23.56	0.46	0.00	111.44	0.000	0.178	0.186	0.0068	0.0092	0.0010	0.0000	0.0252	0.0000	0.0216	0.0226
Humeri, Lower Shaft	0.00	27.11	0.00	97.60	0.00	27.95	0.45	0.00	99.17	0.000	0.159		0.0000	0.0110	0.0010	0.0000	0.0224	0.0000	0.0193	
Humeri, Distal	0.00	62.57	21.63	61.26	0.00	64.52	9.63	21.97	62.24	0.207	0.100		0.0000	0.0253	0.0215	0.0187	0.0141	0.0208	0.0121	
RadII, Proximal	0.00	10.95	2.06	9.98	0.00	11.29	0.78	2.10	10.14	0.016	0.016		0.0000	0.0044	0.0017	0.0018	0.0023	0.0016	0.0020	
RadII, Shaft	0.00	13.37	0.00	77.75	0.00	13.78	0.39	0.00	79.00	0.000	0.126	0.081	0.0000	0.0054	0.0009	0.0000	0.0179	0.0000	0.0153	0.0098
RadII, Distal	0.00	19.20	4.88	18.04	0.00	19.79	2.39	4.96	18.33	0.053	0.029		0.0000	0.0078	0.0053	0.0042	0.0041	0.0054	0.0036	
Ulnae, Proximal	0.00	33.52	12.48	33.20	0.00	34.56	4.62	12.68	33.73	0.103	0.054		0.0000	0.0136	0.0103	0.0108	0.0076	0.0103	0.0066	
Ulnae, Shaft	0.00	16.32	0.00	94.94	0.00	16.83	0.43	0.00	96.47	0.000	0.154	0.089	0.0000	0.0066	0.0010	0.0000	0.0218	0.0000	0.0187	0.0108
Ulnae, Distal	0.00	6.94	2.17	5.21	0.00	7.16	1.11	2.21	5.29	0.024	0.008		0.0000	0.0028	0.0025	0.0019	0.0012	0.0025	0.0010	
Wrists and Hands	0.00	40.04	13.84	169.87	0.00	41.29	6.16	14.06	172.60	0.132	0.276		0.0000	0.0162	0.0138	0.0119	0.0390	0.0133	0.0335	
Femora, Proximal	50.87	145.22	66.09	39.54	52.38	149.73	29.40	67.15	40.18	0.609	0.064		0.0435	0.0588	0.0657	0.0570	0.0091	0.0613	0.0078	
Femora, Upper Shaft	31.68	90.42	0.00	125.86	32.62	93.24	1.02	0.00	127.88	0.000	0.205	0.410	0.0271	0.0366	0.0023	0.0000	0.0289	0.0000	0.0248	0.0498
Femora, Lower Shaft	0.00	91.68	0.00	95.71	0.00	94.54	1.00	0.00	97.25	0.000	0.156		0.0000	0.0371	0.0022	0.0000	0.0220	0.0000	0.0189	
Femora, Distal	0.00	222.14	73.75	56.05	0.00	229.05	31.70	74.93	56.95	0.739	0.091		0.0000	0.0899	0.0709	0.0636	0.0129	0.0744	0.0111	

Skeletal Site	Tissue Masses exclusive of MST (g)				Tissue Masses inclusive of MST (g)				Surface Areas (m ²)			Fractional Tissue Weights																			
	AM	IM	TBV	CBV	AM	IM	TM ₅₀	TBV	CBV	TBS	CBS _{HC}	CBS _{MC}	f _{AM}	f _{IM}	f _{TM50}	f _{TBV}	f _{CBV}	f _{TBS}	f _{CBS-HC}	f _{CBS-MC}											
Patellae	0.00	26.03	8.64	6.57	0.00	26.84	3.71	8.78	6.67	0.600	0.011		0.0000	0.0105	0.0083	0.0075	0.0015	0.0604	0.0013												
Tibiae, Proximal	0.00	186.91	47.27	45.52	0.00	192.72	23.57	48.03	46.25	0.238	0.074		0.0000	0.0756	0.0527	0.0408	0.0105	0.0239	0.0090												
Tibiae, Shaft	0.00	140.80	0.00	146.99	0.00	145.18	1.49	0.00	149.35	0.000	0.239	0.305	0.0000	0.0570	0.0033	0.0000	0.0338	0.0000	0.0290	0.0370											
Tibiae, Distal	0.00	64.01	17.73	25.63	0.00	66.00	8.35	18.01	26.05	0.045	0.042		0.0000	0.0259	0.0187	0.0153	0.0059	0.0045	0.0051												
Fibulae, Proximal	0.00	16.05	2.63	8.44	0.00	16.55	1.41	2.67	8.57	0.027	0.014		0.0000	0.0065	0.0032	0.0023	0.0019	0.0027	0.0017												
Fibulae, Shaft	0.00	11.35	0.00	51.33	0.00	11.70	0.42	0.00	52.16	0.000	0.083	0.087	0.0000	0.0046	0.0009	0.0000	0.0118	0.0000	0.0101	0.0106											
Fibulae, Distal	0.00	12.59	4.21	12.26	0.00	12.98	1.94	4.28	12.46	0.067	0.020		0.0000	0.0051	0.0043	0.0036	0.0028	0.0067	0.0024												
Ankles and Feet	0.00	289.25	96.03	281.49	0.00	298.25	41.27	97.57	286.01	0.962	0.458		0.0000	0.1171	0.0923	0.0829	0.0646	0.0968	0.0555												
Totals	1170	2471	1159	4355	1205	2548	447	1177	4425	9.9	7.1	1.2	1.000	1.000	1.000	1.000	1.000	1.000	0.859	0.141											
ICRP 89 Values	Total Skeletal Mass																														
					9355																										
	1170				2480				1100				4400				ICRP 89 Value				9350				10.5				6.5		
Ratio	1.00		1.00		1.05		0.99				Ratio		1.00		0.95		1.09														

Table 3
Elemental composition and density for the spongiosa and medullary cavities of the UFADM phantom.

Skeletal Site (<i>Spongiosa / Medullary Cavity</i>)														Element							Density (<i>g/cm³</i>)							
														H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Fe			
Craniofacial Bones														5.81	27.41	3.47	41.04	0.24	0.16	6.65	0.25	0.00	0.00	14.95	0.01	1.492		
Mandible														9.94	48.59	2.15	34.06	0.13	0.09	1.56	0.17	0.01	0.01	3.26	0.03	1.077		
Scapulae														9.20	44.81	2.39	35.30	0.15	0.11	2.47	0.18	0.01	0.01	5.35	0.03	1.134		
Clavicles														9.65	47.85	2.15	33.78	0.14	0.09	1.95	0.17	0.01	0.01	4.17	0.03	1.099		
Sternum														9.77	42.99	2.84	39.41	0.13	0.15	1.47	0.19	0.01	0.01	2.99	0.06	1.086		
Ribs														9.35	41.15	2.93	39.77	0.14	0.15	2.01	0.20	0.01	0.01	4.23	0.06	1.118		
Cervical Vertebrae														8.73	38.45	3.07	40.31	0.16	0.15	2.80	0.21	0.01	0.01	6.06	0.05	1.169		
Thoracic Vertebrae														9.62	42.36	2.87	39.53	0.13	0.15	1.65	0.20	0.01	0.01	3.41	0.06	1.097		
Lumbar Vertebrae														9.52	41.89	2.89	39.62	0.13	0.15	1.79	0.20	0.01	0.01	3.73	0.06	1.105		
Sacrum														9.36	41.22	2.93	39.76	0.14	0.15	1.99	0.20	0.01	0.01	4.19	0.06	1.117		
Os coxae														9.73	46.09	2.41	35.95	0.13	0.11	1.72	0.18	0.01	0.01	3.62	0.04	1.091		
Humeri, Proximal														9.95	50.56	1.90	32.00	0.13	0.07	1.67	0.16	0.01	0.01	3.53	0.02	1.078		
Humeri, Upper Shaft (MC)														11.22	57.45	1.44	29.44	0.10	0.05	0.13	0.13	0.01	0.01	0.00	0.03	0.994		
Humeri, Lower Shaft (MC)														11.47	63.23	0.76	24.22	0.10	0.00	0.10	0.11	0.01	0.01	0.00	0.00	0.981		
Humeri, Distal														9.47	51.27	1.63	29.43	0.15	0.05	2.45	0.16	0.01	0.01	5.38	0.00	1.117		
Radii, Proximal														10.24	55.86	1.30	27.43	0.13	0.03	1.55	0.14	0.01	0.01	3.31	0.00	1.061		
Radii, Shaft (MC)														11.47	63.23	0.76	24.22	0.10	0.00	0.10	0.11	0.01	0.01	0.00	0.00	0.981		
Radii, Distal														9.90	53.80	1.44	28.33	0.14	0.04	1.96	0.14	0.01	0.01	4.24	0.00	1.085		
Ulnae, Proximal														9.36	50.59	1.68	29.73	0.15	0.05	2.59	0.16	0.01	0.01	5.68	0.00	1.125		
Ulnae, Shaft														11.47	63.23	0.76	24.22	0.10	0.00	0.10	0.11	0.01	0.01	0.00	0.00	0.981		
Ulnae, Distal (MC)														9.62	52.13	1.57	29.06	0.15	0.05	2.28	0.15	0.01	0.01	4.99	0.00	1.106		
Wrists and Hands														9.47	51.27	1.63	29.43	0.15	0.05	2.45	0.16	0.01	0.01	5.38	0.00	1.117		
Femora, Proximal														9.32	47.15	2.12	33.26	0.15	0.09	2.43	0.17	0.01	0.01	5.28	0.02	1.126		
Femora, Upper Shaft (MC)														11.22	57.45	1.44	29.44	0.10	0.05	0.13	0.13	0.01	0.01	0.00	0.03	0.994		
Femora, Lower Shaft (MC)														11.47	63.23	0.76	24.22	0.10	0.00	0.10	0.11	0.01	0.01	0.00	0.00	0.981		
Femora, Distal														9.53	51.62	1.60	29.28	0.15	0.05	2.38	0.15	0.01	0.01	5.22	0.00	1.112		
Patellae														9.53	51.62	1.60	29.28	0.15	0.05	2.38	0.15	0.01	0.01	5.22	0.00	1.112		

Skeletal Site (<i>Spongiosa / Medullary Cavity</i>)													Density (<i>g/cm³</i>)
	H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Fe	
Tibiae, Proximal	9.90	53.84	1.44	28.31	0.14	0.04	1.95	0.14	0.01	0.01	4.22	0.00	1.085
Tibiae, Shaft (MC)	11.47	63.23	0.76	24.22	0.10	0.00	0.10	0.11	0.01	0.01	0.00	0.00	0.981
Tibiae, Distal	9.78	53.14	1.49	28.62	0.14	0.04	2.09	0.15	0.01	0.01	4.54	0.00	1.093
Fibulae, Proximal	10.38	56.68	1.24	27.08	0.13	0.03	1.39	0.13	0.01	0.01	2.94	0.00	1.051
Fibulae, Shaft (MC)	11.47	63.23	0.76	24.22	0.10	0.00	0.10	0.11	0.01	0.01	0.00	0.00	0.981
Fibulae, Distal	9.52	51.56	1.61	29.31	0.15	0.05	2.40	0.15	0.01	0.01	5.24	0.00	1.113
Ankles and Feet	9.53	51.62	1.60	29.28	0.15	0.05	2.38	0.15	0.01	0.01	5.22	0.00	1.112
Whole Skeleton (<i>SP only</i>)	9.14	45.00	2.34	34.89	0.15	0.10	2.57	0.18	0.01	0.01	5.58	0.03	1.139
Whole Skeleton (<i>SP + MC</i>)	9.36	46.54	2.22	34.05	0.15	0.09	2.34	0.18	0.01	0.01	5.05	0.02	1.122
Whole Skeleton (<i>SP + MC + CB</i>)	6.64	32.17	3.14	39.11	0.22	0.14	5.65	0.23	0.00	0.00	12.67	0.01	1.385

Table 4

Table of electron *specific absorbed fractions* for the os coxae of the reference adult male (taken from Annex A).

Energy (MeV)	Os Coxae - Adult Male										Os Coxae - Adult Male										Os Coxae - Adult Male									
	$\Phi(AM \leftarrow AM)$ as a function of cellularity (g^{-1})										$\Phi(AM \leftarrow r_d)$ (g^{-1})										$\Phi(TM_{50} \leftarrow r_s)$ (g^{-1})									
	Cellularity										Source Tissue r_s										Source Tissue r_s									
	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	48% (ICRP 70)	IM	TBS	TBV	CBS _{HC} or CBV	AM	IM	TBS	TBV	CBS _{HC} or CBV										
0.0010	1.56E-03	1.73E-03	1.94E-03	2.22E-03	2.59E-03	3.11E-03	3.89E-03	5.19E-03	7.78E-03	1.56E-02	3.24E-03	9.72E-07	7.78E-04	1.62E-07	3.24E-09	1.60E-03	1.60E-03	6.43E-03	1.67E-06	5.40E-09										
0.0015	1.56E-03	1.73E-03	1.94E-03	2.22E-03	2.59E-03	3.10E-03	3.88E-03	5.17E-03	7.74E-03	1.55E-02	3.23E-03	1.93E-06	7.87E-04	3.29E-07	6.70E-09	1.57E-03	1.57E-03	6.50E-03	3.27E-06	1.05E-08										
0.0020	1.56E-03	1.73E-03	1.94E-03	2.22E-03	2.58E-03	3.10E-03	3.87E-03	5.15E-03	7.72E-03	1.54E-02	3.23E-03	3.13E-06	7.94E-04	5.45E-07	1.12E-08	1.54E-03	1.54E-03	6.55E-03	5.25E-06	1.68E-08										
0.0030	1.56E-03	1.73E-03	1.94E-03	2.21E-03	2.58E-03	3.09E-03	3.85E-03	5.13E-03	7.69E-03	1.53E-02	3.22E-03	6.21E-06	8.03E-04	1.11E-06	2.32E-08	1.52E-03	1.52E-03	6.62E-03	1.03E-05	3.25E-08										
0.0040	1.55E-03	1.72E-03	1.94E-03	2.21E-03	2.57E-03	3.08E-03	3.84E-03	5.12E-03	7.66E-03	1.53E-02	3.21E-03	1.01E-05	8.10E-04	1.83E-06	3.89E-08	1.49E-03	1.49E-03	6.67E-03	1.65E-05	5.20E-08										
0.0050	1.55E-03	1.72E-03	1.94E-03	2.21E-03	2.57E-03	3.08E-03	3.84E-03	5.11E-03	7.64E-03	1.53E-02	3.20E-03	1.47E-05	8.15E-04	2.71E-06	5.80E-08	1.48E-03	1.48E-03	6.71E-03	2.38E-05	7.48E-08										
0.0060	1.55E-03	1.72E-03	1.93E-03	2.21E-03	2.57E-03	3.07E-03	3.83E-03	5.10E-03	7.63E-03	1.52E-02	3.20E-03	2.00E-05	8.19E-04	3.73E-06	8.04E-08	1.47E-03	1.47E-03	6.74E-03	3.22E-05	1.01E-07										
0.0080	1.55E-03	1.72E-03	1.93E-03	2.20E-03	2.56E-03	3.07E-03	3.82E-03	5.08E-03	7.60E-03	1.52E-02	3.19E-03	3.25E-05	8.26E-04	6.17E-06	1.35E-07	1.45E-03	1.45E-03	6.79E-03	5.18E-05	1.61E-07										
0.010	1.55E-03	1.72E-03	1.93E-03	2.20E-03	2.56E-03	3.06E-03	3.82E-03	5.07E-03	7.59E-03	1.51E-02	3.19E-03	4.74E-05	8.32E-04	9.11E-06	2.01E-07	1.43E-03	1.43E-03	6.83E-03	7.49E-05	2.32E-07										
0.015	1.55E-03	1.71E-03	1.92E-03	2.18E-03	2.52E-03	3.01E-03	3.74E-03	4.95E-03	7.38E-03	1.47E-02	3.13E-03	9.61E-05	8.32E-04	1.85E-05	4.15E-07	1.42E-03	1.42E-03	6.79E-03	1.51E-04	4.50E-07										
0.020	1.55E-03	1.71E-03	1.90E-03	2.15E-03	2.48E-03	2.95E-03	3.64E-03	4.81E-03	7.13E-03	1.41E-02	3.06E-03	1.59E-04	8.33E-04	3.03E-05	6.95E-07	1.40E-03	1.40E-03	6.74E-03	2.47E-04	7.20E-07										
0.030	1.54E-03	1.68E-03	1.85E-03	2.07E-03	2.37E-03	2.78E-03	3.40E-03	4.43E-03	6.49E-03	1.27E-02	2.88E-03	3.15E-04	8.32E-04	6.07E-05	1.44E-06	1.35E-03	1.35E-03	6.59E-03	4.89E-04	1.40E-06										
0.040	1.54E-03	1.65E-03	1.80E-03	1.99E-03	2.24E-03	2.59E-03	3.12E-03	3.99E-03	5.75E-03	1.10E-02	2.68E-03	4.97E-04	8.31E-04	9.87E-05	2.41E-06	1.31E-03	1.31E-03	6.39E-03	7.82E-04	2.23E-06										
0.050	1.53E-03	1.62E-03	1.74E-03	1.90E-03	2.10E-03	2.39E-03	2.82E-03	3.53E-03	4.96E-03	9.24E-03	2.46E-03	6.89E-04	8.28E-04	1.43E-04	3.59E-06	1.25E-03	1.25E-03	6.14E-03	1.11E-03	3.21E-06										
0.060	1.52E-03	1.59E-03	1.69E-03	1.81E-03	1.97E-03	2.19E-03	2.52E-03	3.08E-03	4.20E-03	7.54E-03	2.24E-03	8.74E-04	8.28E-04	1.90E-04	4.72E-06	1.19E-03	1.19E-03	5.89E-03	1.44E-03	4.03E-06										
0.080	1.50E-03	1.54E-03	1.60E-03	1.66E-03	1.75E-03	1.87E-03	2.05E-03	2.36E-03	2.97E-03	4.78E-03	1.90E-03	1.16E-03	8.24E-04	2.87E-04	7.73E-06	1.09E-03	1.09E-03	5.02E-03	1.98E-03	6.61E-06										
0.10	1.48E-03	1.51E-03	1.54E-03	1.58E-03	1.63E-03	1.71E-03	1.82E-03	2.00E-03	2.37E-03	3.44E-03	1.73E-03	1.28E-03	8.37E-04	3.88E-04	1.12E-05	1.03E-03	1.03E-03	4.13E-03	2.28E-03	9.10E-06										
0.15	1.43E-03	1.44E-03	1.46E-03	1.48E-03	1.50E-03	1.54E-03	1.60E-03	1.68E-03	1.85E-03	2.34E-03	1.55E-03	1.35E-03	9.18E-04	6.46E-04	2.12E-05	1.01E-03	1.01E-03	2.93E-03	2.39E-03	1.78E-05										
0.20	1.38E-03	1.39E-03	1.40E-03	1.41E-03	1.43E-03	1.46E-03	1.49E-03	1.54E-03	1.65E-03	1.96E-03	1.46E-03	1.34E-03	1.02E-03	8.64E-04	3.19E-05	1.05E-03	1.05E-03	2.38E-03	2.13E-03	2.67E-05										
0.30	1.33E-03	1.33E-03	1.34E-03	1.35E-03	1.36E-03	1.38E-03	1.40E-03	1.42E-03	1.48E-03	1.65E-03	1.38E-03	1.31E-03	1.16E-03	1.09E-03	5.36E-05	1.12E-03	1.12E-03	1.78E-03	1.64E-03	4.66E-05										
0.40	1.30E-03	1.31E-03	1.31E-03	1.32E-03	1.33E-03	1.34E-03	1.35E-03	1.37E-03	1.41E-03	1.53E-03	1.34E-03	1.30E-03	1.20E-03	1.15E-03	7.29E-05	1.14E-03	1.14E-03	1.55E-03	1.46E-03	6.51E-05										
0.50	1.28E-03	1.29E-03	1.29E-03	1.30E-03	1.31E-03	1.31E-03	1.32E-03	1.34E-03	1.38E-03	1.46E-03	1.31E-03	1.28E-03	1.21E-03	1.17E-03	9.62E-05	1.14E-03	1.14E-03	1.45E-03	1.38E-03	8.53E-05										
0.60	1.27E-03	1.27E-03	1.28E-03	1.28E-03	1.29E-03	1.29E-03	1.30E-03	1.32E-03	1.35E-03	1.40E-03	1.30E-03	1.27E-03	1.20E-03	1.18E-03	1.20E-04	1.13E-03	1.13E-03	1.39E-03	1.33E-03	1.05E-04										
0.80	1.24E-03	1.24E-03	1.24E-03	1.25E-03	1.26E-03	1.26E-03	1.27E-03	1.28E-03	1.29E-03	1.35E-03	1.26E-03	1.25E-03	1.19E-03	1.17E-03	1.70E-04	1.12E-03	1.12E-03	1.30E-03	1.26E-03	1.54E-04										
1.0	1.21E-03	1.21E-03	1.22E-03	1.22E-03	1.23E-03	1.23E-03	1.23E-03	1.24E-03	1.26E-03	1.30E-03	1.23E-03	1.22E-03	1.17E-03	1.16E-03	2.14E-04	1.10E-03	1.10E-03	1.24E-03	1.21E-03	1.98E-04										
1.5	1.14E-03	1.15E-03	1.15E-03	1.16E-03	1.16E-03	1.16E-03	1.17E-03	1.17E-03	1.18E-03	1.20E-03	1.16E-03	1.15E-03	1.12E-03	1.11E-03	3.06E-04	1.04E-03	1.04E-03	1.14E-03	1.12E-03	2.86E-04										
2.0	1.08E-03	1.08E-03	1.08E-03	1.08E-03	1.08E-03	1.09E-03	1.10E-03	1.10E-03	1.12E-03	1.13E-03	1.09E-03	1.09E-03	1.06E-03	1.05E-03	3.45E-04	9.85E-04	9.85E-04	1.06E-03	1.04E-03	3.19E-04										
3.0	9.56E-04	9.59E-04	9.63E-04	9.66E-04	9.69E-04	9.75E-04	9.84E-04	9.85E-04	9.85E-04	1.00E-03	9.77E-04	9.66E-04	9.54E-04	9.47E-04	3.75E-04	8.86E-04	8.86E-04	9.44E-04	9.30E-04	3.43E-04										
4.0	8.57E-04	8.59E-04	8.61E-04	8.62E-04	8.63E-04	8.68E-04	8.74E-04	8.74E-04	8.75E-04	8.85E-04	8.69E-04	8.58E-04	8.46E-04	8.44E-04	3.73E-04	7.90E-04	7.90E-04	8.23E-04	8.23E-04	3.47E-04										

Os Coxae - Adult Male																				
$\Phi(AM \leftarrow AM)$ as a function of cellularity (g^{-I})																				
Cellularity																				
Os Coxae - Adult Male																				
$\Phi(AM \leftarrow r_S)(g^{-I})$																				
Source Tissue r_S																				
Os Coxae - Adult Male																				
$\Phi(TM_{50} \leftarrow r_S)(g^{-I})$																				
Source Tissue r_S																				
Energy (MeV)	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	48% (ICRP 70)	IM	TBS	TBV	CBS _{HC} or CBV	AM	IM	TBS	TBV	CBS _{HC} or CBV
5.0	7.69E-04	7.68E-04	7.66E-04	7.71E-04	7.78E-04	7.77E-04	7.74E-04	7.76E-04	7.80E-04	7.88E-04	7.76E-04	7.65E-04	7.66E-04	7.58E-04	3.66E-04	7.06E-04	7.06E-04	7.44E-04	7.44E-04	3.40E-04
6.0	6.89E-04	6.90E-04	6.91E-04	6.91E-04	6.91E-04	6.93E-04	6.96E-04	6.95E-04	6.95E-04	7.07E-04	6.93E-04	6.96E-04	6.89E-04	6.83E-04	3.42E-04	6.29E-04	6.29E-04	6.67E-04	6.67E-04	3.19E-04
8.0	5.65E-04	5.67E-04	5.70E-04	5.70E-04	5.71E-04	5.70E-04	5.67E-04	5.68E-04	5.68E-04	5.79E-04	5.69E-04	5.71E-04	5.63E-04	5.59E-04	2.94E-04	5.18E-04	5.18E-04	5.43E-04	5.43E-04	2.74E-04
10.0	4.75E-04	4.77E-04	4.79E-04	4.80E-04	4.80E-04	4.79E-04	4.78E-04	4.79E-04	4.80E-04	4.83E-04	4.79E-04	4.76E-04	4.72E-04	4.76E-04	2.52E-04	4.37E-04	4.37E-04	4.55E-04	4.55E-04	2.34E-04

Table 5

Skeletal-averaged electron *absorbed fractions* for the uf adult male hybrid phantom based upon pirt simulations.

Energy (MeV)	$\phi(\text{AM} \leftarrow \text{AM})$	$\phi(\text{AM} \leftarrow \text{IM})$	$\phi(\text{AM} \leftarrow \text{TBS})$	$\phi(\text{AM} \leftarrow \text{TBV})$	$\phi(\text{AM} \leftarrow \text{CBS})$	$\phi(\text{AM} \leftarrow \text{CBV})$	$\phi(\text{TM}_{50} \leftarrow \text{AM})$	$\phi(\text{TM}_{50} \leftarrow \text{IM})$	$\phi(\text{TM}_{50} \leftarrow \text{TBS})$	$\phi(\text{TM}_{50} \leftarrow \text{TBV})$	$\phi(\text{TM}_{50} \leftarrow \text{CBS})$	$\phi(\text{TM}_{50} \leftarrow \text{CBV})$
0.0010	1.00E+00	1.23E-04	1.61E-01	2.56E-05	8.93E-03	8.62E-07	1.26E-01	1.15E-01	5.00E-01	9.87E-05	7.03E-02	6.85E-07
0.0015	9.97E-01	2.43E-04	1.63E-01	5.11E-05	8.98E-03	1.72E-06	1.25E-01	1.15E-01	5.06E-01	1.90E-04	7.00E-02	1.31E-06
0.0020	9.96E-01	3.93E-04	1.64E-01	8.34E-05	9.02E-03	2.80E-06	1.24E-01	1.15E-01	5.10E-01	3.03E-04	6.98E-02	2.08E-06
0.0030	9.93E-01	7.77E-04	1.66E-01	1.67E-04	9.06E-03	5.58E-06	1.23E-01	1.15E-01	5.15E-01	5.85E-04	6.95E-02	4.01E-06
0.0040	9.91E-01	1.26E-03	1.68E-01	2.73E-04	9.10E-03	9.12E-06	1.22E-01	1.15E-01	5.20E-01	9.33E-04	6.93E-02	6.38E-06
0.0050	9.90E-01	1.83E-03	1.69E-01	4.00E-04	9.13E-03	1.34E-05	1.22E-01	1.15E-01	5.23E-01	1.34E-03	6.92E-02	9.17E-06
0.0060	9.89E-01	2.49E-03	1.70E-01	5.46E-04	9.15E-03	1.83E-05	1.22E-01	1.15E-01	5.25E-01	1.81E-03	6.90E-02	1.23E-05
0.0080	9.87E-01	4.05E-03	1.71E-01	8.95E-04	9.19E-03	2.99E-05	1.21E-01	1.15E-01	5.30E-01	2.89E-03	6.88E-02	1.97E-05
0.010	9.85E-01	5.90E-03	1.72E-01	1.31E-03	9.24E-03	4.39E-05	1.21E-01	1.15E-01	5.33E-01	4.16E-03	6.87E-02	2.84E-05
0.015	9.70E-01	1.20E-02	1.72E-01	2.64E-03	9.32E-03	8.79E-05	1.19E-01	1.14E-01	5.30E-01	8.27E-03	6.70E-02	5.53E-05
0.020	9.51E-01	1.97E-02	1.72E-01	4.31E-03	9.40E-03	1.46E-04	1.18E-01	1.13E-01	5.25E-01	1.34E-02	6.55E-02	8.89E-05
0.030	9.02E-01	3.88E-02	1.71E-01	8.61E-03	9.58E-03	2.94E-04	1.14E-01	1.09E-01	5.13E-01	2.63E-02	6.77E-02	1.74E-04
0.040	8.46E-01	6.12E-02	1.70E-01	1.39E-02	9.77E-03	4.82E-04	1.10E-01	1.04E-01	4.97E-01	4.17E-02	7.04E-02	2.80E-04
0.050	7.86E-01	8.46E-02	1.69E-01	1.99E-02	9.99E-03	7.10E-04	1.05E-01	9.98E-02	4.79E-01	5.90E-02	7.22E-02	4.06E-04
0.060	7.27E-01	1.07E-01	1.68E-01	2.65E-02	1.03E-02	9.64E-04	9.95E-02	9.47E-02	4.58E-01	7.69E-02	7.24E-02	5.45E-04
0.080	6.32E-01	1.43E-01	1.65E-01	4.05E-02	1.08E-02	1.54E-03	9.03E-02	8.61E-02	3.90E-01	1.07E-01	6.25E-02	8.51E-04
0.10	5.82E-01	1.58E-01	1.65E-01	5.53E-02	1.14E-02	2.23E-03	8.48E-02	8.09E-02	3.21E-01	1.25E-01	5.08E-02	1.17E-03
0.15	5.27E-01	1.65E-01	1.74E-01	9.15E-02	1.32E-02	4.17E-03	8.01E-02	7.67E-02	2.28E-01	1.38E-01	3.30E-02	1.99E-03
0.20	4.97E-01	1.64E-01	1.87E-01	1.24E-01	1.51E-02	6.31E-03	8.11E-02	7.74E-02	1.86E-01	1.33E-01	2.48E-02	2.87E-03
0.30	4.63E-01	1.60E-01	2.06E-01	1.59E-01	1.88E-02	1.07E-02	8.43E-02	8.07E-02	1.45E-01	1.16E-01	1.81E-02	4.89E-03
0.40	4.45E-01	1.59E-01	2.10E-01	1.71E-01	2.25E-02	1.50E-02	8.48E-02	8.12E-02	1.30E-01	1.08E-01	1.58E-02	6.88E-03
0.50	4.33E-01	1.56E-01	2.10E-01	1.74E-01	2.62E-02	1.94E-02	8.42E-02	8.09E-02	1.22E-01	1.04E-01	1.53E-02	8.90E-03
0.60	4.23E-01	1.54E-01	2.08E-01	1.74E-01	2.97E-02	2.35E-02	8.31E-02	8.03E-02	1.17E-01	1.01E-01	1.54E-02	1.08E-02
0.80	4.04E-01	1.49E-01	2.03E-01	1.72E-01	3.59E-02	3.09E-02	8.07E-02	7.90E-02	1.09E-01	9.66E-02	1.66E-02	1.46E-02
1.0	3.87E-01	1.44E-01	1.96E-01	1.67E-01	4.07E-02	3.67E-02	7.78E-02	7.73E-02	1.03E-01	9.24E-02	1.79E-02	1.77E-02
1.5	3.51E-01	1.33E-01	1.80E-01	1.55E-01	4.76E-02	4.53E-02	7.11E-02	7.33E-02	9.30E-02	8.42E-02	2.07E-02	2.34E-02
2.0	3.19E-01	1.23E-01	1.65E-01	1.42E-01	4.98E-02	4.82E-02	6.52E-02	6.94E-02	8.53E-02	7.71E-02	2.21E-02	2.68E-02
3.0	2.70E-01	1.06E-01	1.41E-01	1.22E-01	4.82E-02	4.74E-02	5.56E-02	6.24E-02	7.38E-02	6.68E-02	2.24E-02	2.88E-02
4.0	2.31E-01	9.19E-02	1.21E-01	1.05E-01	4.47E-02	4.44E-02	4.78E-02	5.60E-02	6.48E-02	5.83E-02	2.18E-02	2.87E-02

Energy (MeV)	$\phi(\Delta M \leftarrow \Delta M)$	$\phi(\Delta M \leftarrow IM)$	$\phi(\Delta M \leftarrow TBS)$	$\phi(\Delta M \leftarrow TBV)$	$\phi(\Delta M \leftarrow CBS)$	$\phi(\Delta M \leftarrow CBV)$	$\phi(TM_{50} \leftarrow \Delta M)$	$\phi(TM_{50} \leftarrow IM)$	$\phi(TM_{50} \leftarrow TBS)$	$\phi(TM_{50} \leftarrow TBV)$	$\phi(TM_{50} \leftarrow CBS)$	$\phi(TM_{50} \leftarrow CBV)$
5.0	2.00E-01	8.06E-02	1.07E-01	9.16E-02	4.05E-02	4.06E-02	4.17E-02	5.09E-02	5.81E-02	5.19E-02	2.06E-02	2.72E-02
6.0	1.76E-01	7.17E-02	9.40E-02	8.07E-02	3.65E-02	3.69E-02	3.68E-02	4.63E-02	5.23E-02	4.66E-02	1.93E-02	2.55E-02
8.0	1.40E-01	5.75E-02	7.53E-02	6.46E-02	2.98E-02	3.05E-02	2.95E-02	3.91E-02	4.35E-02	3.88E-02	1.71E-02	2.23E-02
10.0	1.15E-01	4.73E-02	6.20E-02	5.35E-02	2.49E-02	2.56E-02	2.43E-02	3.36E-02	3.70E-02	3.28E-02	1.53E-02	1.98E-02

Table 6
Skeletal-averaged electron *specific absorbed fractions* (g^{-1}) for the UF adult male hybrid phantom based upon PIRT simulations.

Energy (MeV)	$\Phi(\text{AM} \leftarrow \text{AM})$	$\Phi(\text{AM} \leftarrow \text{IM})$	$\Phi(\text{AM} \leftarrow \text{TBS})$	$\Phi(\text{AM} \leftarrow \text{TBV})$	$\Phi(\text{AM} \leftarrow \text{CBS})$	$\Phi(\text{AM} \leftarrow \text{CBV})$	$\Phi(\text{TM}_{50} \leftarrow \text{AM})$	$\Phi(\text{TM}_{50} \leftarrow \text{IM})$	$\Phi(\text{TM}_{50} \leftarrow \text{TBS})$	$\Phi(\text{TM}_{50} \leftarrow \text{TBV})$	$\Phi(\text{TM}_{50} \leftarrow \text{CBS})$	$\Phi(\text{TM}_{50} \leftarrow \text{CBV})$
0.0010	8.30E-04	1.02E-07	1.34E-04	2.12E-08	7.42E-06	7.16E-10	2.81E-04	2.58E-04	1.12E-03	2.21E-07	1.57E-04	1.53E-09
0.0015	8.28E-04	2.01E-07	1.35E-04	4.24E-08	7.46E-06	1.42E-09	2.79E-04	2.57E-04	1.13E-03	4.25E-07	1.57E-04	2.93E-09
0.0020	8.26E-04	3.26E-07	1.36E-04	6.93E-08	7.48E-06	2.32E-09	2.77E-04	2.57E-04	1.14E-03	6.77E-07	1.56E-04	4.66E-09
0.0030	8.24E-04	6.45E-07	1.38E-04	1.38E-07	7.52E-06	4.63E-09	2.75E-04	2.57E-04	1.15E-03	1.31E-06	1.55E-04	8.96E-09
0.0040	8.23E-04	1.05E-06	1.39E-04	2.26E-07	7.55E-06	7.57E-09	2.74E-04	2.57E-04	1.16E-03	2.09E-06	1.55E-04	1.43E-08
0.0050	8.21E-04	1.52E-06	1.40E-04	3.32E-07	7.58E-06	1.11E-08	2.73E-04	2.57E-04	1.17E-03	3.00E-06	1.55E-04	2.05E-08
0.0060	8.20E-04	2.07E-06	1.41E-04	4.54E-07	7.59E-06	1.52E-08	2.72E-04	2.57E-04	1.17E-03	4.04E-06	1.54E-04	2.76E-08
0.0080	8.19E-04	3.36E-06	1.42E-04	7.43E-07	7.63E-06	2.48E-08	2.71E-04	2.57E-04	1.18E-03	6.45E-06	1.54E-04	4.41E-08
0.010	8.18E-04	4.89E-06	1.43E-04	1.09E-06	7.66E-06	3.64E-08	2.70E-04	2.57E-04	1.19E-03	9.29E-06	1.54E-04	6.36E-08
0.015	8.05E-04	9.94E-06	1.43E-04	2.19E-06	7.73E-06	7.29E-08	2.67E-04	2.55E-04	1.18E-03	1.85E-05	1.50E-04	1.24E-07
0.020	7.89E-04	1.63E-05	1.43E-04	3.58E-06	7.81E-06	1.21E-07	2.64E-04	2.52E-04	1.17E-03	3.00E-05	1.47E-04	1.99E-07
0.030	7.49E-04	3.22E-05	1.42E-04	7.15E-06	7.95E-06	2.44E-07	2.55E-04	2.43E-04	1.15E-03	5.88E-05	1.51E-04	3.89E-07
0.040	7.02E-04	5.08E-05	1.41E-04	1.15E-05	8.11E-06	4.00E-07	2.45E-04	2.33E-04	1.11E-03	9.33E-05	1.57E-04	6.27E-07
0.050	6.52E-04	7.02E-05	1.40E-04	1.65E-05	8.30E-06	5.89E-07	2.34E-04	2.23E-04	1.07E-03	1.32E-04	1.61E-04	9.09E-07
0.060	6.03E-04	8.91E-05	1.39E-04	2.20E-05	8.52E-06	8.00E-07	2.22E-04	2.12E-04	1.03E-03	1.72E-04	1.62E-04	1.22E-06
0.080	5.24E-04	1.18E-04	1.37E-04	3.36E-05	8.98E-06	1.28E-06	2.02E-04	1.92E-04	8.73E-04	2.40E-04	1.40E-04	1.90E-06
0.10	4.83E-04	1.31E-04	1.37E-04	4.59E-05	9.49E-06	1.85E-06	1.90E-04	1.81E-04	7.19E-04	2.80E-04	1.14E-04	2.61E-06
0.15	4.37E-04	1.37E-04	1.44E-04	7.59E-05	1.09E-05	3.46E-06	1.79E-04	1.71E-04	5.10E-04	3.09E-04	7.39E-05	4.46E-06
0.20	4.12E-04	1.36E-04	1.56E-04	1.03E-04	1.25E-05	5.24E-06	1.81E-04	1.73E-04	4.16E-04	2.97E-04	5.54E-05	6.41E-06
0.30	3.84E-04	1.33E-04	1.71E-04	1.32E-04	1.56E-05	8.87E-06	1.89E-04	1.80E-04	3.25E-04	2.59E-04	4.05E-05	1.09E-05
0.40	3.69E-04	1.32E-04	1.75E-04	1.42E-04	1.87E-05	1.25E-05	1.90E-04	1.82E-04	2.91E-04	2.43E-04	3.54E-05	1.54E-05
0.50	3.59E-04	1.29E-04	1.74E-04	1.44E-04	2.17E-05	1.61E-05	1.88E-04	1.81E-04	2.74E-04	2.33E-04	3.42E-05	1.99E-05
0.60	3.51E-04	1.28E-04	1.73E-04	1.45E-04	2.46E-05	1.95E-05	1.86E-04	1.79E-04	2.61E-04	2.26E-04	3.45E-05	2.42E-05
0.80	3.36E-04	1.24E-04	1.69E-04	1.43E-04	2.98E-05	2.56E-05	1.80E-04	1.77E-04	2.44E-04	2.16E-04	3.70E-05	3.26E-05
1.0	3.22E-04	1.20E-04	1.63E-04	1.39E-04	3.38E-05	3.04E-05	1.74E-04	1.73E-04	2.31E-04	2.07E-04	4.00E-05	3.97E-05
1.5	2.91E-04	1.11E-04	1.49E-04	1.28E-04	3.95E-05	3.76E-05	1.59E-04	1.64E-04	2.08E-04	1.88E-04	4.63E-05	5.24E-05
2.0	2.65E-04	1.02E-04	1.37E-04	1.18E-04	4.13E-05	4.00E-05	1.46E-04	1.55E-04	1.91E-04	1.72E-04	4.95E-05	5.99E-05
3.0	2.24E-04	8.81E-05	1.17E-04	1.01E-04	4.00E-05	3.93E-05	1.24E-04	1.39E-04	1.65E-04	1.49E-04	5.01E-05	6.45E-05

Energy (MeV)	$\Phi(\text{AM} \leftarrow \text{AM})$	$\Phi(\text{AM} \leftarrow \text{IM})$	$\Phi(\text{AM} \leftarrow \text{TBS})$	$\Phi(\text{AM} \leftarrow \text{TBV})$	$\Phi(\text{AM} \leftarrow \text{CBS})$	$\Phi(\text{AM} \leftarrow \text{CBV})$	$\Phi(\text{TM}_{50} \leftarrow \text{AM})$	$\Phi(\text{TM}_{50} \leftarrow \text{IM})$	$\Phi(\text{TM}_{50} \leftarrow \text{TBS})$	$\Phi(\text{TM}_{50} \leftarrow \text{TBV})$	$\Phi(\text{TM}_{50} \leftarrow \text{CBS})$	$\Phi(\text{TM}_{50} \leftarrow \text{CBV})$
4.0	1.91E-04	7.63E-05	1.01E-04	8.68E-05	3.71E-05	3.68E-05	1.07E-04	1.25E-04	1.45E-04	1.30E-04	4.88E-05	6.41E-05
5.0	1.66E-04	6.69E-05	8.85E-05	7.60E-05	3.36E-05	3.37E-05	9.33E-05	1.14E-04	1.30E-04	1.16E-04	4.61E-05	6.09E-05
6.0	1.46E-04	5.95E-05	7.80E-05	6.69E-05	3.03E-05	3.06E-05	8.23E-05	1.04E-04	1.17E-04	1.04E-04	4.32E-05	5.69E-05
8.0	1.16E-04	4.77E-05	6.25E-05	5.36E-05	2.48E-05	2.53E-05	6.59E-05	8.75E-05	9.73E-05	8.67E-05	3.83E-05	4.99E-05
10.0	9.56E-05	3.93E-05	5.15E-05	4.44E-05	2.07E-05	2.13E-05	5.43E-05	7.51E-05	8.28E-05	7.35E-05	3.42E-05	4.42E-05

Table 7

Distribution of mineral bone by skeletal site, and the distribution of spongiosa tissues, within the UFHADDM phantom with comparisons to values cited in ICRP Publication 70.

Skeletal Site	Distribution of mineral bone				Distribution of spongiosa tissues			
	Present Model		Johnson (1964)		S&B (1983)		Present Model	
	%CB	%TB	%CB	%TB	%CB	%TB	%BM	%TB
Craniofacial Bones	78	22	95	5			44	56
Mandible	88	12	95	5			91	9
Scapulae	78	22	94	6			85	15
Clavicles	85	15	94	6			88	12
Sternum	84	16	94	6			92	8
Ribs	85	15	94	6			88	12
Cervical Vertebrae	75	25	24	76			82	18
Thoracic Vertebrae	78	22	24	76			91	9
Lumbar Vertebrae	71	29	34	66			90	10
Sacrum	74	26	75	25			88	12
Os coxae	77	23	81	19			90	10
Humeri	87	13	80	20	90	10		
RadII	94	6	84	16	87	13		
Ulnae	90	10	87	13	87	13		
Wrist and Hands	92	8	95	5				
Femora	69	31	67	33	77	23	85	15
Patellae	43	57						
Tibiae	77	23	74	26	83	17		
Fibulae	91	9	95	5	89	11		
Ankles and Feet	75	25	95	5				

Table 8

Mean pathlengths through marrow cavities and bone trabeculae of the 40-year male cadaver of the present study, and those for the 44-year male cadaver of the Beddoe et al. (1977).

Skeletal Site	<i>Mean Pathlengths (μm)</i>			
	Present Model		Beddoe et al (1976)	
	<i>Cavity</i>	<i>Trabeculae</i>	<i>Cavity</i>	<i>Trabeculae</i>
Craniofacial Bones				
<i>Frontal</i>	500	392		
<i>Parietal</i>	516	326	389	511
<i>Occipital</i>	154	746		
Mandible	1430	205		
Scapulae	1162	253		
Clavicles	1148	268		
Sternum	1551	164		
Ribs			1706	265
<i>Upper</i>	1344	192		
<i>Middle</i>	1126	221		
<i>Lower</i>	1146	247		
Cervical Vertebrae				
<i>C3 (C1 - C3)</i>	864	189		
<i>C6 (C4 - C7)</i>	913	254		
Thoracic Vertebrae				
<i>T3 (T1 - T4)</i>	1232	221		
<i>T6 (T5 - T8)</i>	1913	154		
<i>T11 (T9 - T12)</i>	1376	195		
Lumbar Vertebrae				
<i>L2 (L1 - L3)</i>	861	214	1172	235
<i>L4 (L4 - L5)</i>	1714	192		
Sacrum	1458	227		
Os coxae	1381	187	907	253
Humeri, Proximal	1660	231		
Humeri, Distal	1170	226		
Radii, Proximal	1172	281		
Radii, Distal	1344	198		
Ulnae, Proximal	1253	263		
Ulnae, Distal	1032	193		
Wrists & Hands	1170	226		
Femora, Proximal			1418	267
<i>Head</i>	910	283		
<i>Neck</i>	1509	192		
Femora, Distal	1171	216		

Skeletal Site	<i>Mean Pathlengths (μm)</i>			
	Present Model		Beddoe et al (1976)	
	<i>Cavity</i>	<i>Trabeculae</i>	<i>Cavity</i>	<i>Trabeculae</i>
Patellae	1171	216		
Tibiae, Proximal	1409	198		
Tibiae, Distal	1344	215		
Fibulae, Proximal	1699	187		
Fibulae, Distal	1118	219		
Ankles & Feet	1171	216		

Table 9
Skeletal tissue masses and their fractional distribution within the skeleton of ICRP 110 adult male phantom.

Skeletal Site	Marrow			Tissue Masses (g)				Surface Areas (m ²)			Fractional Tissue Weights								
	(cm3)	TM ₅₀	Cellularity	AM	IM	TM ₅₀	TBV	CBV	TBS	CBS _{HC}	CBS _{MC}	f _{AM}	f _{IM}	f _{TM50}	f _{TBV}	f _{CBV}	f _{TBS}	f _{CBS-HC}	f _{CBS-MC}
Craniofacial Bones	227.2	34.7%	38%	88.89	138.08	78.78	109.25	562.94	1.024	0.880		0.0760	0.0557	0.1744	0.0993	0.1279	0.0993	0.1099	
Mandible	23.9	8.6%	38%	9.37	14.50	2.05	24.38	76.03	0.229	0.119		0.0080	0.0058	0.0045	0.0222	0.0173	0.0222	0.0148	
Scapulae	83.7	11.8%	38%	32.75	50.86	9.84	52.99	221.18	0.497	0.346		0.0280	0.0205	0.0218	0.0482	0.0503	0.0482	0.0432	
Clavicles	27.6	9.0%	33%	9.37	18.13	2.49	12.48	47.81	0.117	0.075		0.0080	0.0073	0.0055	0.0113	0.0109	0.0113	0.0093	
Sternum	50.3	10.8%	70%	36.26	14.80	5.52	2.50	9.98	0.023	0.016		0.0310	0.0060	0.0122	0.0023	0.0023	0.0023	0.0019	
Ribs	261.7	11.2%	70%	188.70	76.93	29.87	124.03	365.18	1.163	0.571		0.1613	0.0310	0.0661	0.1128	0.0830	0.1128	0.0713	
Cervical Vertebrae	63.3	17.8%	70%	45.63	18.62	11.46	4.61	102.91	0.043	0.161		0.0390	0.0075	0.0254	0.0042	0.0234	0.0042	0.0201	
Thoracic Vertebrae	261.7	10.1%	70%	188.70	76.93	26.88	33.98	286.66	0.319	0.448		0.1613	0.0310	0.0595	0.0309	0.0651	0.0309	0.0560	
Lumbar Vertebrae	199.6	11.5%	70%	143.89	58.70	23.36	48.58	186.24	0.455	0.291		0.1230	0.0237	0.0517	0.0442	0.0423	0.0442	0.0364	
Sacrum	160.7	12.6%	70%	115.88	47.24	20.55	5.18	109.25	0.049	0.171		0.0990	0.0190	0.0455	0.0047	0.0248	0.0047	0.0213	
Os coxae	415.0	12.4%	48%	205.18	211.48	51.70	129.02	398.59	1.210	0.623		0.1754	0.0853	0.1144	0.1173	0.0906	0.1173	0.0778	
Humeri, Proxima	84.9	8.8%	25%	21.85	62.45	7.41	55.87	42.41	0.524	0.066		0.0187	0.0252	0.0164	0.0508	0.0096	0.0508	0.0083	
Humeri, Upper Shaft	19.6	0.8%	25%	5.03	14.39	0.15	0.00	92.95	0.000	0.145	0.181	0.0043	0.0058	0.0003	0.0000	0.0211	0.0000	0.0182	0.0226
Humeri, Lower Shaft	22.5	0.8%	0%	0.00	22.07	0.17	0.00	78.68	0.000	0.123		0.0000	0.0089	0.0004	0.0000	0.0179	0.0000	0.0154	
Humeri, Distal	52.0	14.9%	0%	0.00	50.94	7.61	11.71	49.38	0.110	0.077		0.0000	0.0205	0.0168	0.0106	0.0112	0.0106	0.0096	
Radii, Proxima	14.7	6.9%	0%	0.00	14.39	1.00	3.39	11.30	0.032	0.018		0.0000	0.0058	0.0022	0.0031	0.0026	0.0031	0.0022	
Radii, Shaft	17.9	2.9%	0%	0.00	17.57	0.50	0.00	88.03	0.000	0.138	0.079	0.0000	0.0071	0.0011	0.0000	0.0200	0.0000	0.0172	0.0098
Radii, Distal	25.7	12.1%	0%	0.00	25.23	3.05	8.03	20.43	0.075	0.032		0.0000	0.0102	0.0068	0.0073	0.0046	0.0073	0.0040	
Ulnae, Proxima	45.0	13.4%	0%	0.00	44.05	5.89	20.53	37.59	0.192	0.059		0.0000	0.0178	0.0130	0.0187	0.0085	0.0187	0.0073	
Ulnae, Shaft	21.9	2.6%	0%	0.00	21.45	0.57	0.00	107.49	0.000	0.168	0.087	0.0000	0.0086	0.0013	0.0000	0.0244	0.0000	0.0210	0.0108
Ulnae, Distal	9.3	15.5%	0%	0.00	9.12	1.41	3.57	5.90	0.033	0.009		0.0000	0.0037	0.0031	0.0032	0.0013	0.0032	0.0012	
Wrists and Hands	85.4	14.9%	0%	0.00	83.69	12.51	27.26	179.71	0.256	0.281		0.0000	0.0337	0.0277	0.0248	0.0408	0.0248	0.0351	
Femora, Proxima	187.6	14.6%	25%	48.28	137.88	27.11	95.42	62.56	0.895	0.098		0.0413	0.0556	0.0600	0.0868	0.0142	0.0868	0.0122	
Femora, Upper Shaft	116.8	0.5%	25%	30.10	85.85	0.54	0.00	199.13	0.000	0.311	0.398	0.0257	0.0346	0.0012	0.0000	0.0453	0.0000	0.0389	0.0498
Femora, Lower Shaft	102.5	0.5%	0%	0.00	100.49	0.47	0.00	185.51	0.000	0.290		0.0000	0.0405	0.0010	0.0000	0.0422	0.0000	0.0362	
Femora, Distal	248.5	13.9%	0%	0.00	243.49	33.74	85.63	108.63	0.803	0.170		0.0000	0.0982	0.0747	0.0778	0.0247	0.0778	0.0212	

Skeletal Site	Marrow				Tissue Masses (g)				Surface Areas (m ²)				Fractional Tissue Weights									
	Marrow (cm ³)	TM ₅₀ (% MV)	Cellularity	AM	IM	TM ₅₀	TBV	CBV	TBS	CBS _{HC}	CBS _{MC}	f _{AM}	f _{IM}	f _{TM50}	f _{TBV}	f _{CBV}	f _{TBS}	f _{CBS-HC}		f _{CBS-MC}		
Patellae	30.0	13.9%	0%	0.00	29.35	4.07	15.30	11.76	0.143	0.018		0.0000	0.0118	0.0090	0.0139	0.0027	0.0139	0.0023				
Tibiae, Proxima	215.1	12.2%	0%	0.00	210.77	25.81	83.68	81.49	0.784	0.127		0.0000	0.0850	0.0571	0.0761	0.0185	0.0761	0.0159				
Tibiae, Shaft	162.0	1.1%	0%	0.00	158.77	1.75	0.00	263.16	0.000	0.411	0.296	0.0000	0.0640	0.0039	0.0000	0.0598	0.0000	0.0514	0.0370			
Tibiae, Distal	73.7	12.7%	0%	0.00	72.18	9.15	31.38	45.89	0.294	0.072		0.0000	0.0291	0.0203	0.0285	0.0104	0.0285	0.0090				
Fibulae, Proxima	18.5	8.6%	0%	0.00	18.10	1.55	4.66	15.11	0.044	0.024		0.0000	0.0073	0.0034	0.0042	0.0034	0.0042	0.0030				
Fibulae, Shaft	13.1	3.7%	0%	0.00	12.80	0.47	0.00	91.91	0.000	0.144	0.085	0.0000	0.0052	0.0010	0.0000	0.0209	0.0000	0.0179	0.0106			
Fibulae, Distal	14.5	15.0%	0%	0.00	14.19	2.13	7.45	21.95	0.070	0.034		0.0000	0.0057	0.0047	0.0068	0.0050	0.0068	0.0043				
Ankles and Feet	310.8	13.9%	0%	0.00	304.58	42.21	99.07	232.51	0.929	0.363		0.0000	0.1228	0.0934	0.0901	0.0528	0.0901	0.0454				
Totals				1170	2480	452	1100	4400	10.3	6.9	1.1	1.000	1.000	1.000	1.000	1.000	1.000	0.859	0.141			
ICRP 89 Values		Total Skeletal Mass																				
		ICRP 89 Value																				
Ratio		Ratio																				

Table 10

Skeletal tissue masses and their fractional distribution within the skeleton of ICRP 110 adult female phantom.

Skeletal Site	Marrow			Tissue Masses (g)						Surface Areas (m ²)			Fractional Tissue Weights							
	(cm3)	TM ₅₀	Cellularity	AM	IM	TM ₅₀	TBV	CBV	TBS	CBS _{HC}	CBS _{MC}	f _{AM}	f _{IM}	f _{TM50}	f _{TBV}	f _{CBV}	f _{TBS}	f _{CBS-HC}	f _{CBS-MC}	
Craniofacial Bones	174.8	34.7%	38%	68.39	106.23	60.61	160.51	403.58	1.505	0.631		0.0761	0.0590	0.1822	0.2003	0.1261	0.2003	0.1084		
Mandible	18.4	8.6%	38%	7.21	11.17	1.58	10.75	44.93	0.101	0.070		0.0080	0.0062	0.0047	0.0134	0.0140	0.0134	0.0121		
Scapulae	64.4	11.8%	38%	25.24	39.10	7.57	21.50	120.38	0.202	0.188		0.0281	0.0217	0.0228	0.0268	0.0376	0.0268	0.0323		
Clavicles	21.2	9.0%	33%	7.21	13.92	1.91	12.86	32.45	0.121	0.051		0.0080	0.0077	0.0057	0.0161	0.0101	0.0161	0.0087		
Sternum	38.7	10.8%	70%	27.91	11.37	4.25	5.38	1.73	0.050	0.003		0.0310	0.0063	0.0128	0.0067	0.0005	0.0067	0.0005		
Ribs	201	11.2%	70%	144.92	59.09	22.94	36.48	162.82	0.342	0.254		0.1612	0.0328	0.0689	0.0455	0.0509	0.0455	0.0437		
Cervical Vertebrae	48.7	17.8%	70%	35.12	14.31	8.81	15.55	70.85	0.146	0.111		0.0391	0.0079	0.0265	0.0194	0.0221	0.0194	0.0190		
Thoracic Vertebrae	201	10.1%	70%	144.92	59.09	20.64	32.06	203.71	0.301	0.318		0.1612	0.0328	0.0620	0.0400	0.0637	0.0400	0.0547		
Lumbar Vertebrae	153.6	11.5%	70%	110.73	45.18	17.98	69.70	154.56	0.653	0.242		0.1231	0.0251	0.0540	0.0870	0.0483	0.0870	0.0415		
Sacrum	123.6	12.6%	70%	89.10	36.36	15.80	9.98	0.00	0.094	0.000		0.0991	0.0202	0.0475	0.0125	0.0000	0.0125	0.0000		
Os coxae	318.6	12.4%	48%	157.49	162.39	39.69	82.94	259.78	0.778	0.406		0.1751	0.0902	0.1193	0.1035	0.0812	0.1035	0.0698		
Humeri, Proximal	65.3	8.8%	25%	16.83	48.03	5.70	34.37	35.31	0.322	0.055		0.0187	0.0267	0.0171	0.0429	0.0110	0.0429	0.0095		
Humeri, Upper Shaft	15.1	0.8%	25%	3.88	11.06	0.12	0.00	77.39	0.000	0.121	0.131	0.0043	0.0061	0.0003	0.0000	0.0242	0.0000	0.0208	0.0226	
Humeri, Lower Shaft	17.0	0.8%	0%	0.00	16.62	0.13	0.00	62.76	0.000	0.098		0.0000	0.0092	0.0004	0.0000	0.0196	0.0000	0.0169		
Humeri, Distal	39.1	14.9%	0%	0.00	38.36	5.73	12.10	39.39	0.113	0.062		0.0000	0.0213	0.0172	0.0151	0.0123	0.0151	0.0106		
Radii, Proximal	10.4	6.9%	0%	0.00	10.16	0.70	2.02	6.48	0.019	0.010		0.0000	0.0056	0.0021	0.0025	0.0020	0.0025	0.0017		
Radii, Shaft	12.7	2.9%	0%	0.00	12.41	0.35	0.00	50.44	0.000	0.079	0.057	0.0000	0.0069	0.0011	0.0000	0.0158	0.0000	0.0135	0.0098	
Radii, Distal	18.2	12.1%	0%	0.00	17.82	2.16	4.77	11.70	0.045	0.018		0.0000	0.0099	0.0065	0.0060	0.0037	0.0060	0.0031		
Ulnae, Proximal	31.7	13.4%	0%	0.00	31.11	4.16	12.21	21.54	0.114	0.034		0.0000	0.0173	0.0125	0.0152	0.0067	0.0152	0.0058		
Ulnae, Shaft	15.5	2.6%	0%	0.00	15.15	0.40	0.00	61.59	0.000	0.096	0.063	0.0000	0.0084	0.0012	0.0000	0.0193	0.0000	0.0165	0.0108	
Ulnae, Distal	6.6	15.5%	0%	0.00	6.44	1.00	2.12	3.38	0.020	0.005		0.0000	0.0036	0.0030	0.0027	0.0011	0.0027	0.0009		
Wrists and Hands	48.4	14.9%	0%	0.00	47.43	7.09	16.70	104.06	0.157	0.163		0.0000	0.0263	0.0213	0.0208	0.0325	0.0208	0.0279		
Femora, Proximal	144.3	14.6%	25%	37.12	106.05	20.85	21.31	59.21	0.200	0.093		0.0413	0.0589	0.0627	0.0266	0.0185	0.0266	0.0159		
Femora, Upper Shaft	89.8	0.5%	25%	23.14	66.04	0.42	0.00	188.47	0.000	0.294	0.290	0.0257	0.0367	0.0013	0.0000	0.0589	0.0000	0.0506	0.0498	
Femora, Lower Shaft	50.5	0.5%	0%	0.00	49.44	0.23	0.00	146.64	0.000	0.229		0.0000	0.0275	0.0007	0.0000	0.0458	0.0000	0.0394		
Femora, Distal	122.2	13.9%	0%	0.00	119.80	16.60	40.32	85.87	0.378	0.134		0.0000	0.0665	0.0499	0.0503	0.0268	0.0503	0.0231		

Skeletal Site	Tissue Masses (g)				Surface Areas (m ²)				Fractional Tissue Weights														
	Marrow		TM ₅₀		Cellularity		AM	IM	TM ₅₀	TBV	CBV	TBS	CBS _{HC}	CBS _{MC}	f _{AM}	f _{IM}	f _{TM50}	f _{TBV}	f _{CBV}	f _{TBS}	f _{CBS-HC}	f _{CBS-MC}	
	(cm ³)	(% MV)																					
Patellae	27.3	13.9%	0%	0.00	26.72	3.70	14.51	13.70				0.136	0.021		0.0000	0.0148	0.0111	0.0181	0.0043	0.0181	0.0037		
Tibiae, Proximal	195.8	12.2%	0%	0.00	191.88	23.50	79.39	94.92				0.744	0.148		0.0000	0.1066	0.0706	0.0991	0.0297	0.0991	0.0255		
Tibiae, Shaft	147.5	1.1%	0%	0.00	144.55	1.59	0.00	306.53				0.000	0.479	0.215	0.0000	0.0803	0.0048	0.0000	0.0958	0.0000	0.0823	0.0370	
Tibiae, Distal	67.1	12.7%	0%	0.00	65.71	8.33	29.77	53.46				0.279	0.084		0.0000	0.0365	0.0250	0.0372	0.0167	0.0372	0.0144		
Fibulae, Proximal	16.8	8.6%	0%	0.00	16.48	1.41	4.42	17.59				0.041	0.027		0.0000	0.0092	0.0042	0.0055	0.0055	0.0055	0.0047		
Fibulae, Shaft	11.9	3.7%	0%	0.00	11.65	0.43	0.00	107.05				0.000	0.167	0.062	0.0000	0.0065	0.0013	0.0000	0.0335	0.0000	0.0288	0.0106	
Fibulae, Distal	13.2	15.0%	0%	0.00	12.92	1.94	7.07	25.57				0.066	0.040		0.0000	0.0072	0.0058	0.0088	0.0080	0.0088	0.0069		
Ankles and Feet	179.8	13.9%	0%	0.00	176.20	24.42	62.40	171.84				0.585	0.269		0.0000	0.0979	0.0734	0.0779	0.0537	0.0779	0.0462		
Totals				899	1800	333	801	3200				7.5	5.0	0.8	1.000	1.000	1.000	1.000	1.000	1.000	0.859	0.141	
ICRP 89 Values		Total Skeletal Mass										6700											
		ICRP 89 Value										6700											
Ratio		Ratio										1.00											

D values (in units of mGy per MBq-s) for Sr-90, Sr-89, and Y-90 calculated for various skeletal source regions in the skeleton of the ICRP reference adult male based upon skeletal-averaged specific absorbed fractions from either the present study (PIRT model) or that given in Stabin and Niggel (2003).

S Value - PIRT		S Value - S&S 2003		Sr-90 (196 keV / 546 keV)		Sr-89 (585 keV / 1500 keV)		Y-90 (933 keV / 2280 keV)	
(mGy/MBq-s)	PIRT	S Value - S&S 2003		Present Study	S&S 2003	Ratio	Present Study	S&S 2003	Ratio
Targets - Surrogate Tissues for the HSC									
S (AM $\leftarrow$ AM)			S (AM $\leftarrow$ AM)	1.35E-05	1.41E-05	1.05	8.21E-06	8.66E-06	1.05
S (AM $\leftarrow$ TBS)			S (AM $\leftarrow$ TBS)	5.41E-06	7.24E-06	1.34	3.57E-06	4.86E-06	1.36
S (AM $\leftarrow$ TBV)			S (AM $\leftarrow$ TBV)	3.75E-06	5.46E-06	1.45	2.70E-06	3.97E-06	1.47
S (AM $\leftarrow$ CBS)			S (AM $\leftarrow$ CBS)	4.95E-07	0	0	3.66E-07	0	0
S (AM $\leftarrow$ CBV)			S (AM $\leftarrow$ CBV)	4.95E-07	0	0	3.66E-07	0	0
Targets - Surrogate Tissues for the OPC									
S (TM ₅₀ $\leftarrow$ AM)			S (TBE $\leftarrow$ AM)	6.26E-06	9.22E-06	1.47	4.00E-06	5.94E-06	1.49
S (TM ₅₀ $\leftarrow$ TBS)			S (TBE $\leftarrow$ TBS)	1.35E-05	1.94E-05	1.44	7.33E-06	1.00E-05	1.37
S (TM ₅₀ $\leftarrow$ TBV)			S (TBE $\leftarrow$ TBV)	8.68E-06	1.05E-05	1.21	5.35E-06	6.40E-06	1.19
S (TM ₅₀ $\leftarrow$ CBS)			S (CBE $\leftarrow$ CBS)	1.81E-06	2.36E-05	13.03	9.51E-07	1.24E-05	13.00
S (TM ₅₀ $\leftarrow$ CBV)			S (CBE $\leftarrow$ CBV)	1.81E-06	9.05E-06	4.99	9.51E-07	6.11E-06	6.42

Glossary

Tissue Region / Model Parameter	Symbol	Histological Description / Parameter Definitions
<u>Marrow Tissues in Spongiosa</u>		
Miscellaneous skeletal tissues	MST	As per ICRP Publication 89, MST includes blood vessels and periosteum, but excludes periarticular tissues and blood.
Trabecular active marrow	TAM and TAM*	Hematopoietically active (or red) bone marrow within spongiosa.
Trabecular inactive marrow	TIM and TIM*	Hematopoietically inactive (or yellow) bone marrow within spongiosa. Generally considered as marrow adipocytes.
Trabecular shallow active marrow	TAM ₅₀ and TAM ₅₀ *	Active marrow localized within 50 μ m of the bone trabeculae surfaces in spongiosa.
Trabecular shallow inactive marrow	TIM ₅₀ and TIM ₅₀ *	Inactive marrow localized within 50 μ m of the bone trabeculae surfaces in spongiosa. Generally considered as marrow adipocytes.
<u>Marrow Tissues in Long Bone Shafts</u>		
Medullary active marrow	MAM and MAM*	Hematopoietically active (or red) bone marrow within the medullary cavities of long bones.
Medullary inactive marrow	MIM and MIM*	Hematopoietically inactive (or yellow) bone marrow within the medullary cavities of long bones.
Medullary shallow active marrow	MAM ₅₀ and MAM ₅₀ *	Active marrow localized within 50 μ m of the inner cortical surface of the medullary cavities of long bones.
Medullary shallow inactive marrow	MIM ₅₀ and MIM ₅₀ *	Inactive marrow localized within 50 μ m of the inner cortical surface of the medullary cavities of long bones.
<u>Marrow Tissues in both Spongiosa + Long Bone Shafts</u>		
Total marrow	TM and TM*	All bone marrow [active and inactive]. $TM = TAM + TIM + MAM + MIM$.
Total shallow marrow [also called endosteum]	TM ₅₀ and TM ₅₀ *	All bone marrow [active and inactive] within 50 μ m of the bone surfaces. $TM_{50} = TAM_{50} + TIM_{50} + MAM_{50} + MIM_{50}$
Active Marrow	AM and AM*	Hematopoietically active (or red) bone marrow. $AM = TAM + MAM$.
Inactive Marrow	IM and IM*	Hematopoietically inactive (or yellow) bone marrow. Generally considered as marrow adipocytes. $IM = TIM + MIM$.
<u>Bone Tissues and Regions</u>		
Trabecular bone	TB and TB*	Bone trabeculae
Cortical bone	CB and CB*	Cortex of all skeletal sites, and outer tissues of the shafts of the long bones
Mineral bone	MB and MB*	Total tissues of both trabecular and cortical bone. $MB = TB + CB$.
Homogeneous bone	HB and HB*	Homogeneous mixture of mineral bone [cortical and trabecular], marrow [active and inactive], and miscellaneous skeletal tissues.
Spongiosa	SP and SP*	Homogeneous mixture of trabecular bone, total marrow, and miscellaneous skeletal tissues exclusive of the long bone shafts.
Trabecular bone volumes and surfaces	TBV and TBS	Volumes and surfaces of the bone trabeculae in regions of spongiosa
Cortical bone volumes and surfaces	CBV, CBS _{IC} , CBS _{MC}	Volumes and surfaces within cortical bone. Two cortical surfaces exist - along on Haversian canals and along the medullary cavities.
<u>Volume Fractions - Homogeneous Bone</u>		

Tissue Region / Model Parameter	Symbol	Histological Description / Parameter Definitions
Cortical bone volume fraction	CBVF	Fraction of homogeneous bone volume occupied by cortical bone.
Spongiosa volume fraction	SVF	Fraction of homogeneous bone volume occupied by spongiosa.
Medullary cavity volume fraction	MCVF	Fraction of homogeneous bone volume occupied by the medullary cavity (long bones only).
<i>Volume Fractions - Spongiosa</i>		
Trabecular bone volume fraction	TBVF	Fraction of spongiosa volume occupied by bone trabeculae.
Marrow volume fraction	MVF	Fraction of spongiosa volume occupied by bone marrow (active and inactive).
Shallow marrow volume fraction	SMVF	Fraction of spongiosa volume occupied by bone marrow within 50 μ m of the bone surfaces.
Cellularity factor	CF	Fraction of marrow space occupied by active (red) bone marrow. $CF = 1 - [\text{Marrow Fat Fraction}]$
<i>Volume Fractions - Long Bone Shafts</i>		
Shallow marrow volume fraction - shaft	SMVF _{shaft}	Fraction of medullary marrow volume located 50 μ m from inner surface of cortical bone in the long bone shafts
<i>Volume Fractions - Mineral Bone</i>		
Trabecular bone fraction	TB _{fraction}	Ratio of trabecular bone volume to total mineral bone volume. $TB_{\text{fraction}} + CB_{\text{fraction}} = 1.0$
Cortical bone fraction	CB _{fraction}	Ratio of cortical bone volume to total mineral bone volume

Note 1: Starred acronyms imply the inclusion of miscellaneous skeletal tissues. Non-starred acronyms imply the exclusion of miscellaneous skeletal tissues.

Note 2: Values of CBVF and SVF in this study are given individually for the proximal and distal ends of long bones, as well as their shafts.

Note 3: This glossary updates that previously given in Pafundi et al (2009)