A publicly accessible Monte Carlo database for validation purposes in emission tomography

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Abstract. Monte Carlo (MC) methods provide ideal data sets to assess reconstruction and correction techniques in emission tomography (ET). Although several ET-dedicated MC codes are available, their use is hindered by the heavy computation burden required for high statistics simulations as well as by the need to adapt the code to the purpose of the individual user. In this work a publicly accessible database of MC-simulated ET data sets (the MC-ET database) was created and published on an Internet web site (http://www.ibfm.cnr.it/mcet/index.html), in order to provide MC-simulated data ready to be downloaded and used by researchers at different sites with similar evaluation purposes. At present, the MC-ET database provides direct access to MC-simulated raw data of unscattered, scattered and total events: (a) obtained by different MC codes, (b) relative to different radioactive sources, from simple geometrical phantoms to studies of normal and pathological subjects and (c) derived from different SPECT and PET scanners. The main features of the MC-ET data sets are: (a) validation by comparison with measured data, (b) classification according to pre-defined database characteristics, (c) common-use file format and (d) easy and free access and download.

Keywords: Internet databases – Monte Carlo method – Emission tomography – Scatter – Image reconstruction

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Introduction

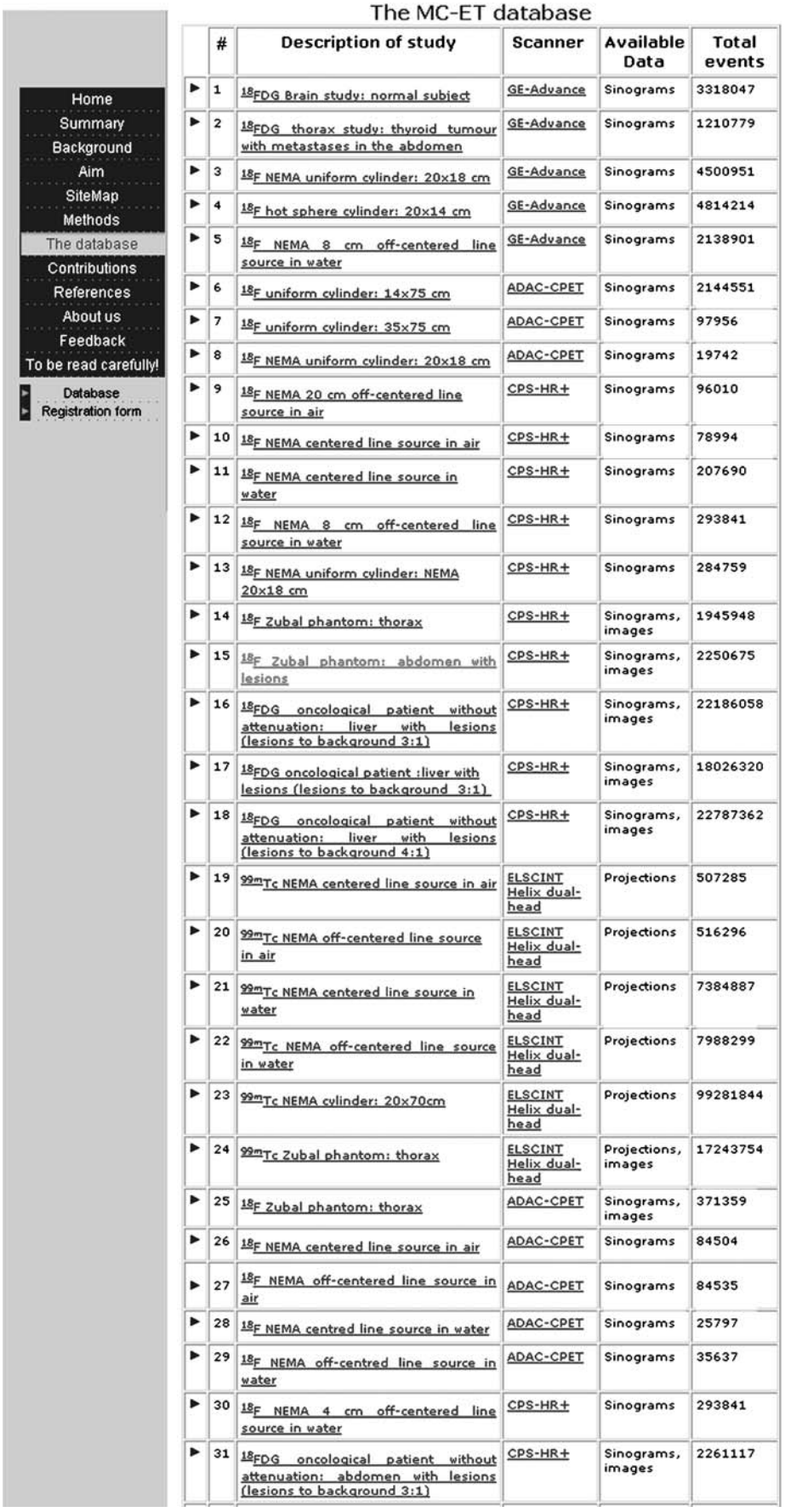
To be ideal for the assessment of reconstruction and correction techniques in single-photon emission computed tomography (SPECT) and positron emission tomography (PET), data sets should fulfil several characteristics: (1) activity and attenuation distributions underlying the observed data should be fully known; (2) activity and attenuation distributions should be representative of clinical situations at different levels of complexity; (3) the data should be fully characterized in terms of true signal, noise components (e.g. scatter) and instrumentation artefacts (e.g. detector malfunctioning); and (4) the data should present realistic statistical properties.

Monte Carlo (MC) methods have been extensively used in emission tomography (ET) to generate data which satisfy the above requirements. Although several ET-dedicated MC codes are now freely available [1–6], and some of them include time optimization strategies [1, 3, 4, 6], the major drawback of MC methods remains the heavy computation burden required to perform high statistics simulations as well as the time required for a new MC user to gain experience in the use of MC-based software.

The aim of this work was to generate a collection of data sets ideal with respect to the assessment of correction and reconstruction techniques in ET and to make them freely and easily available to the scientific community. This goal was accomplished by creating a publicly accessible, Internet-published database of MC-simulated data for both SPECT and PET (MC-ET), presenting all the ideal characteristics mentioned above. The experiments comply with the current laws of the countries in which they were performed inclusive of ethics approval.

Materials and methods

A variety of SPECT and PET data sets were MC simulated, to generate data suitable to the investigation of physical problems underlying SPECT and PET. The simulated data were validated, e.g. [3, 5, 7–9], classified, stored and organized in a database according to predefined criteria. In order to make the data sets freely available, the database was published on a publicly accessible Internet web site.



The MC-ET database

	#	Description of study	Scanner	Available Data	Total events
▶	1	^{18}FDG Brain study: normal subject	GE-Advance	Sinograms	3318047
▶	2	^{18}FDG thorax study: thyroid tumour with metastases in the abdomen	GE-Advance	Sinograms	1210779
▶	3	^{18}F NEMA uniform cylinder: 20x18 cm	GE-Advance	Sinograms	4500951
▶	4	^{18}F hot sphere cylinder: 20x14 cm	GE-Advance	Sinograms	4814214
▶	5	^{18}F NEMA 8 cm off-centered line source in water	GE-Advance	Sinograms	2138901
▶	6	^{18}F uniform cylinder: 14x75 cm	ADAC-CPET	Sinograms	2144551
▶	7	^{18}F uniform cylinder: 35x75 cm	ADAC-CPET	Sinograms	97956
▶	8	^{18}F NEMA uniform cylinder: 20x18 cm	ADAC-CPET	Sinograms	19742
▶	9	^{18}F NEMA 20 cm off-centered line source in air	CPS-HR+	Sinograms	96010
▶	10	^{18}F NEMA centered line source in air	CPS-HR+	Sinograms	78994
▶	11	^{18}F NEMA centered line source in water	CPS-HR+	Sinograms	207690
▶	12	^{18}F NEMA 8 cm off-centered line source in water	CPS-HR+	Sinograms	293841
▶	13	^{18}F NEMA uniform cylinder: NEMA 20x18 cm	CPS-HR+	Sinograms	284759
▶	14	^{18}F Zubal phantom: thorax	CPS-HR+	Sinograms, images	1945948
▶	15	^{18}F Zubal phantom: abdomen with lesions	CPS-HR+	Sinograms, images	2250675
▶	16	^{18}FDG oncological patient without attenuation: liver with lesions (lesions to background 3:1)	CPS-HR+	Sinograms, images	22186058
▶	17	^{18}FDG oncological patient :liver with lesions (lesions to background 3:1)	CPS-HR+	Sinograms, images	18026320
▶	18	^{18}FDG oncological patient without attenuation: liver with lesions (lesions to background 4:1)	CPS-HR+	Sinograms, images	22787362
▶	19	^{99m}Tc NEMA centered line source in air	ELSCINT Helix dual-head	Projections	507285
▶	20	^{99m}Tc NEMA off-centered line source in air	ELSCINT Helix dual-head	Projections	516296
▶	21	^{99m}Tc NEMA centered line source in water	ELSCINT Helix dual-head	Projections	7384887
▶	22	^{99m}Tc NEMA off-centered line source in water	ELSCINT Helix dual-head	Projections	7988299
▶	23	^{99m}Tc NEMA cylinder: 20x70cm	ELSCINT Helix dual-head	Projections	99281844
▶	24	^{99m}Tc Zubal phantom: thorax	ELSCINT Helix dual-head	Projections, images	17243754
▶	25	^{18}F Zubal phantom: thorax	ADAC-CPET	Sinograms, images	371359
▶	26	^{18}F NEMA centered line source in air	ADAC-CPET	Sinograms	84504
▶	27	^{18}F NEMA off-centered line source in air	ADAC-CPET	Sinograms	84535
▶	28	^{18}F NEMA centred line source in water	ADAC-CPET	Sinograms	25797
▶	29	^{18}F NEMA off-centred line source in water	ADAC-CPET	Sinograms	35637
▶	30	^{18}F NEMA 4 cm off-centered line source in water	CPS-HR+	Sinograms	293841
▶	31	^{18}FDG oncological patient without attenuation: abdomen with lesions (lesions to background 3:1)	CPS-HR+	Sinograms, images	2261117

Fig. 1. The MC-ET database (the first 31 data sets) as presented on the MC-ET web site

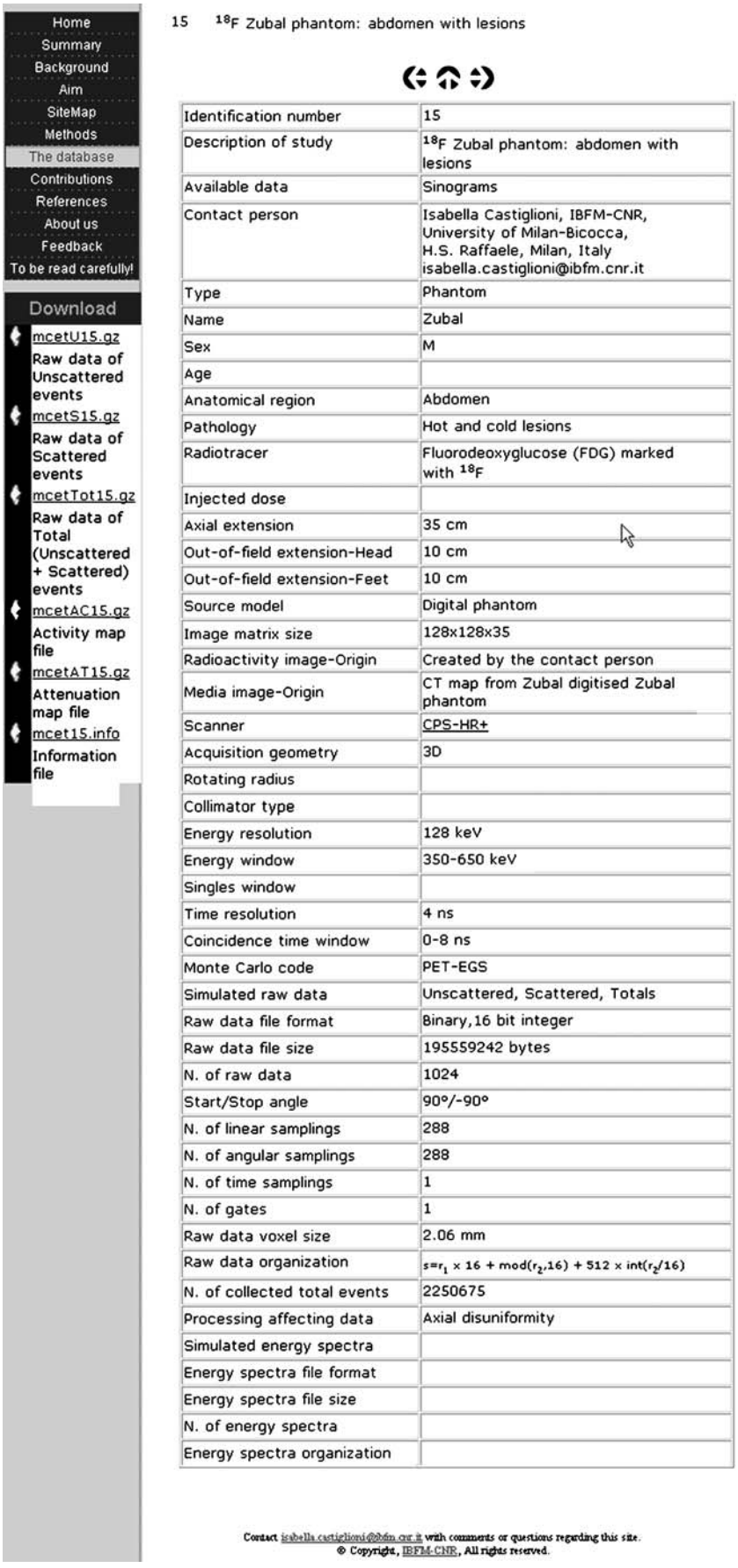


Fig. 2. Characteristics of a representative MC-ET data set (data set #15) as presented on the MC-ET web site

MC simulations

The codes SimSET [3] and PET-EGS [5] were used to simulate the physical processes of the transport and interaction of radiation in matter, from a given radioactive source to the SPECT and PET detection systems. Inputs to the two MC codes were: (a) a description of the source object, in terms of both radioactivity distribution and propagating medium, (b) a description of the geometrical and physical characteristics of the scanner and (c) a description of an "acquisition" protocol. Outputs of the MC codes were "raw data", defined as projections for SPECT and sinograms for PET of unscattered, scattered, random (for PET only) and total (unscattered + scattered + random) events. Non-uniformity response of the detectors was not simulated in either SPECT or PET; thus data normalization was not necessary. PET simulated data were affected by axial sensitivity variation, which required compensation.

Data sets covering a variety of situations, with respect to both scanners and source objects, were MC simulated. Two SPECT scanners (Helix dual-head SPECT camera, Elscint Industries; Prism 3000, PICKER Industries) and three PET scanners in the three-dimensional acquisition geometry (Advance BGO scanner, GE Medical Systems; HR+ BGO scanner, CPS Innovations; CPET NaI scanner, ADAC Laboratories) were considered. Phantom and patient studies were simulated:

- SPECT simulations: ^{99m}Tc simple geometrical phantoms (lines, spheres, cylinders) and anthropomorphic phantoms (Zubal-derived phantoms [10]), described by segmented images of radioactivity and attenuation distributions; ^{123}I real patient studies described by unsegmented images of radioactivity distributions (patient emission images) and by segmented images of attenuation distributions (derived from patient transmission images, co-registered with the emission studies)
- PET simulations: ^{18}F simple geometrical phantoms (lines, spheres, cylinders) described by analytical functions; anthropomorphic phantoms (Zubal-derived phantoms [10]); real patient studies described by unsegmented images of radioactivity distributions (patient emission images) and by segmented images of attenuation distributions (derived from patient transmission images, co-registered with the emission studies)

Data validation, classification, data set organization and storing

Simulated data were systematically validated by comparing the MC-simulated raw data of total events with experimentally measured raw data [5, 7–9].

Data were classified in a database (Fig. 1) according to predefined characteristics (Fig. 2). These corresponded to the main fields in the database and referred to the input source object, the scanner, the MC code and the output data.

Data were organized as data sets consisting of SPECT and PET raw data of unscattered, scattered and total events. Data were saved in an integer 16-bit binary format, compressed with gzip and stored in separate files, namely mcetU*.gz for unscattered events, mcetS*.gz for scattered events and mcetTot*.gz for all events, where * is a number identifying the data set. The data set characteristics were written in an ASCII text file, mcet*.info. Additional data can be downloaded: attenuation (mcetAT*.gz) and activity (mcetAC*.gz) distribution files.

Data from the database can be easily converted into any format by using the information regarding the "raw data organization" (Fig. 2).

Internet publication of the database

The database was published on an Internet web site using a software tool (NET Object Fusion 4.0) allowing easy and free download of the data.

Results

The MC-ET database

The MC-ET database is published as an interactive database on the Internet web site http://www.ibfm.cnr.it/mcet/index.html. Data can be easily downloaded directly from the web site, after registering as an MC-ET user. An overview of the contents of the MC-ET database is presented in Fig. 1. A representative data set for PET (#15) is presented in Fig. 3, showing raw data of unscattered, scattered and total (unscattered + scattered) events.

Fifty-four data sets (less than 4 Mbytes per data set after compression) have been included so far, 17 for SPECT and 37 for PET. Twenty data sets correspond to simple phantoms (lines, spheres, cylinders), while five correspond to anthropomorphic phantoms and 29 were obtained from real patient data. Cerebral, thoracic and abdominal regions were considered.

Example of use of the MC-ET data sets

To show the potential of the MC-ET data sets for the assessment of correction and reconstruction methods, a representative example of their possible use is reported for data set #15 in a study of lesion detection. Figure 4 shows a

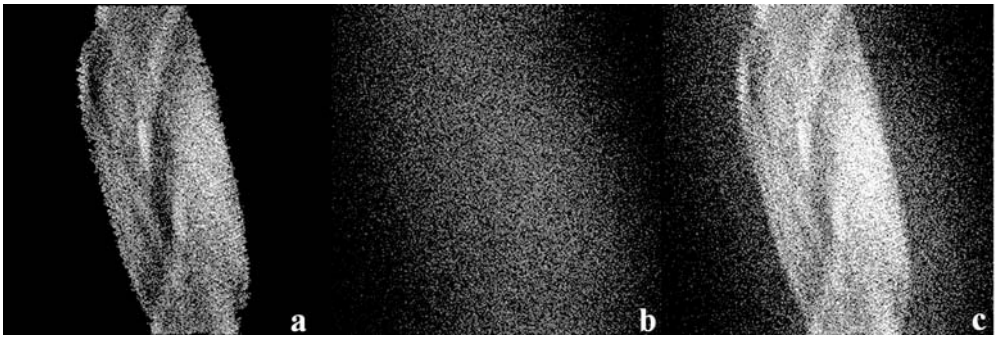


Fig. 3. A representative sinogram of a PET brain study (data set #15). MC-simulated unscattered (**a**), scattered (**b**) and total (**c**) events

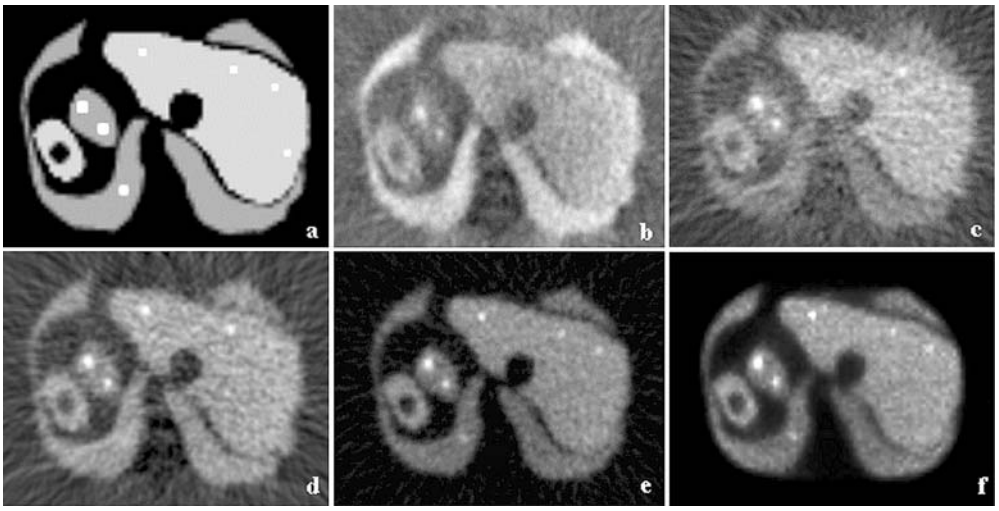


Fig. 4. PET Zubal-derived phantom study (data set #15). **a** Simulated activity map; **b** reconstructed image (SS rebinning + FBP) without attenuation or scatter correction; **c** reconstructed images (SS rebinning + FBP) with attenuation correction but without scatter correction; **d** reconstructed images (SS rebinning + FBP) with attenuation and scatter corrections; **e** reconstructed images (SS rebinning + FBP) without attenuation and scatter simulation (propagation in air); **f** reconstructed images (fully 3D OSEM) without attenuation and scatter simulation (propagation in air)

representative slice from the Zubal-derived phantom reproducing the conditions of a pathological PET study with neoplastic lesions. Lesions of different sizes and lesion/background radioactivity concentration ratios were artificially added on the radioactivity map derived from the Zubal abdominal phantom according to [11] (Fig. 4a). Images 4b–f show the same slice reconstructed (analytic and iterative algorithms) from the MC sinograms published on the database and processed using different approaches (scatter and attenuation free, scatter and attenuation affected, scatter and attenuation corrected). Figure 4 demonstrates that the MC-ET database is suitable for the independent assessment of the effects of physical phenomena (e.g. scatter and attenuation) and processing methods (e.g. correction and reconstruction methods) on image quality and lesion detection. Works making use of MC-ET data sets have already been published, e.g. [5, 7–9].

Discussion

The aim of this work was to make freely and easily available to the scientific community data sets for ET that are ideal with respect to validation of correction and reconstruction techniques. These data sets were obtained by MC methods, taking advantage of their capability to produce realistic ET data and to differentiate between signal and noise components, and providing a gold standard activity map for evaluation.

MC-simulated data sets were organized in an Internet-published database with the following main features: (a) the collection of SPECT and PET data sets covers a large variety of situations with respect to scanners and source objects; (b) data sets in the database have been validated by comparison with measured data, thus warranting the accuracy of simulations; (c) classification of the data sets according to the database fields allows easy choice and access; (d) a common file format is adopted to store data sets, allowing easy and direct use of the data.

The MC-ET database will be enriched in the future with other data sets. We plan to open the database to contributions from other MC users so that it might become a source of data for researchers at different sites with similar evaluation purposes.

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