At the present state of the art, the accuracy of activity determination by means of whole-body and partial-body counters is no longer determined by errors in counting statistics, but by the bias caused by calibration. This is true in particular of low-energy photon emitters, such as Pb-210, U-235, Th-234 (daughter product of U-238), and Am-241. In addition, these nuclides in general show a very inhomogeneous distribution in the body (bone surface, lung, lymph nodes, liver, kidneys). These problems cannot be solved completely even by the most advanced physical phantoms, as these phantoms always represent one standard distribution only.

The Karlsruhe Research Center has a whole-body counter for measurements of photon emitters in the energy range between 100 and 3000 keV, and two partial-body counters for measuring photon emitters in the energy range between 15 and 200 keV. The whole-body counter is made up of four NaI(Tl) scintillation detectors with a crystal diameter of 20 cm and a crystal thickness of 10 cm. The partial-body counters, on the other hand, use large-area phoswich detectors or smaller HPGe detectors. The phoswich detectors each consist of a thin NaI(Tl) scintillation crystal for detection of low-energy photon radiation, and a comparatively thick CsI(Tl) scintillation crystal acting as an anti-Compton shield to reduce the background of the NaI(Tl) crystal. In partial-body counting, the phoswich detectors are in direct contact with the body and are moved as close as possible to the organ under study. Figure 1 shows the example of a detector arrangement in lung counting. As a result of anti-Compton discrimination, the phoswich detectors have a relatively high sensitivity specifically to low-energy photon emitters. However, their energy resolution is relatively bad, which may give rise to major problems in the presence of spurious emitters, such as Cs-137. For this reason, another partial-body counter with special HPGe sandwich detectors was developed at the Research Center. These detectors constitute a solid-state analog of phoswich detectors in which a planar HPGe crystal assumes the role of the NaI(Tl) crystal, and a coaxial HPGe detector assumes the function of the CsI(Tl) crystal. Four such detectors are used in the Karlsruhe HPGe partial-body counter (Fig. 2).

Four different physical phantoms are available for calibration of the partial-body counters. Figure 3 shows the example of a disassembled trunk phantom used at the Research Center. The models of organs in this phantom each contain a matrix of holes into which radioactive standard sources can be introduced to simulate almost any nuclide deposition. Both partial body counters are regularly calibrated with this trunk phantom and with a comparable torso phantom. Nevertheless, inconsistent results are frequently encountered in practice when (a) the proportions of the body of the subject do not match those of the phantom, and
(b) the nuclide distributions and the organs of the subject do not correspond to those in the phantom.

One solution to this problem is offered by the voxel phantoms recently introduced into internal dosimetry. These voxel phantoms allow mathematical simulations of photon transport from a source organ to a target organ in the body, and have proved to work excellently in the calculation of dose coefficients for internal dosimetry. The voxel phantoms also allow photon transport from a source organ within the body to a detector outside the body to be simulated, thus basically permitting the efficiency of this detector to be calculated for the radiation emitted by the nuclide deposition. This mathematical calibration of whole-body and partial-body counters has the decisive advantage of allowing voxel phantoms, unlike physical phantoms, to be matched easily to the individual body proportions and activity distributions of the subject.

**Mathematical Simulation of a Subject**

**Basic Dataset**

The “MEET-Man” dataset of the Institute of Biomedical Engineering of the University of Karlsruhe is used to simulate the subject [1]. Originally, this dataset was designed to simulate physics processes in the body, especially electromagnetic, elastomechanical and thermal processes.

The basis of this MEET-Man is the Visible-Man dataset produced in 1994 within the framework of the Visible Human project run by the National Library of Medicine (NLM), Bethesda, Maryland, USA [2, 3]. The Visible-Man dataset is composed of tomograms of a male body generated by computerized tomography (CT), nuclear magnetic resonance tomography (NMR), and thin-film color photography. The man was 180 cm tall and weighed 92 kg. The tomograms were processed by the Institute for Biomedical Engineering. Geometric errors and errors in color were corrected, missing or useless tomographic slices were interpolated in a special process (image warping). Then the images were segmented. In this case, each three-dimensional element was assigned precisely one out of 28 characteristic tissue and organ numbers, respectively. Figure 4 shows a picture of the structures of the MEET-Man.

**Individual Matching of the Dataset**

Matching the MEET-Man to the individual proportions of a subject’s body can be achieved by linear extension and compression, respectively, of the voxels or by non-linear morphing. Linear extension is a congruent transformation in which the structures of the phantom are extended or compressed in the three directions in space, x, y, and z, with the fixed extension factors, \( f_x \), \( f_y \), and \( f_z \). In this way, the dimensions of all structures of the phantom change in the same way. In morphing, however, the structures
are extended and compressed, respectively, in different ways, thus causing the shape of the phantom or of individual structures of the phantom to change. Matching is achieved on the basis of a surface model of the subject. To generate a surface model of this kind, the RAMSIS (Computer-assisted Anthropological Mathematical System for Subject Simulation) process developed at the Munich Technical University [4, 5] can be used. However, a comparatively simple surface scan can also be carried out by means of a laser scan. Figure 5 shows the example of a surface model of a subject produced with a laser scanner of the Munich Technical University [6].

**Linear Matching**

When the proportions of the body of a subject differ only slightly from those of the basic dataset, linear matching is possible. In this case, first the voxel representations of the MEET-Man organs are transformed into the surface envelope of the subject. This transformation is achieved by means of the KisMo code developed at the Research Center [7]. The voxel organs are positioned in such a way that their centers of mass are in the anatomically correct positions. Afterwards, the voxel organs are extended and compressed, respectively, in the three directions in space, x, y, and z, until their shapes correspond to the criteria contained in a three-dimensional anatomical atlas. Figure 6 shows the organs (brain, lung, stomach, liver, spleen, kidneys) of the MEET-Man dataset implemented into the surface model of a subject in this way.

**Non-linear Matching**

In non-linear matching, surface representations of the organs of the phantom are produced in a first step by means of the KisMo code. They are construed interactively with check points and derivation vectors by means of form surfaces, with tomograms of MEET-Man serving as models. First of all, the organ to be modeled is identified in the tomograms, a design level is selected, and the contours of the object in the tomograms are generated by interactive placing and erasing of check points. The contours of the object must not be construed for all tomograms, as final linear interpolation will automatically generate missing contours and produce the 3D object surface. Four check points each with the associated derivation vectors constitute a so-called patch with the associated interpolation points calculated by means of a spline function. Figure 7 shows the example of a surface representation of the left lung of the MEET-Man dataset, with the patches being shown in red and the check points being shown in yellow.

In a second step, the surfaces are now modified by clicking and moving the check points in such a way that the organs assume the desired shape and the desired volume. Also ultrasonic images may be used for orientation. Movement is in any plane in the surface model of a subject; the person is identical with the subject in Fig. 7, but the surface is represented as a wire frame for better clarity.
three-dimensional space and is indicated by the code simultaneously both in a perspective view and in the xy, xz, and yz planes.

In the third and last step, voxel representations are generated again from the surface representations. For this purpose, a circumscribing block is construed around the respective surface area and filled with voxels of the desired size. Next, each voxel will be checked with respect to whether it will be used or not, i.e. whether it lies within or outside the surface area.

It is assumed that the surfaces are closed, simply connected, and free from double points in the mathematical sense. This is generally assured for the surfaces generated by KisMo.

The MEET-Man phantom matched to the test person serves as a basis for simulating photon transport from a specific organ or tissue of the phantom to a specific detector of the whole-body or partial-body counter. Simulation is carried out by means of the Visual Monte Carlo Code (VMC) [8]. First, a random number generator is used to select a voxel of the respective organ or tissue from which a photon is emitted at the given energy. Then a random value is determined for the angle of emission, and the next interaction of the photon in the respective direction in space is determined by means of the corresponding cross sections. If this interaction is a photo effect, the photon is fully absorbed at this point. If it is a Compton effect or pair production effect, the random number generator is employed to determine the starting parameters of the scattered photon and those of the annihilation quanta, respectively, produced after pair production. This simulation is continued until the photons generated in the interactions are absorbed by the photo effect or leave a given volume. After simulation of a sufficiently large number of processes, the number of those photons is determined which reach the detector without being scattered and are absorbed there by the photo effect. Relating this number to the total number of photons emitted yields the efficiency of the re-
pective detector for nuclide deposition in the respective organ or tissue. For illustration, Figure 8 shows the simulation of photon transport by the VMC code for a deposition of Am-241 in the skeleton of a voxel phantom. The short violet lines indicate the directions of photon emission. The green circles (mainly in the center and around the feet) stand for interactions of the photons with air molecules, while the yellow circles in the detector symbolize absorption events due to the photo effect.

Experience so far has shown this method to produce a sufficiently accurate simulation of photon transport from any nuclide deposition in the body to any detector of a whole-body or partial-body counter. However, the method is unable to simulate subsequent processes in the detector and in the downstream electronics. These processes can be determined experimentally in a simple way. On the basis of those experiments, empirical correction factors can be derived to take into account electronic effects and can be implemented in the simulation program. This is the subject of further studies.

Literature


