STUK Radiation and Nuclear Safety Authority

The Monte Carlo method

Monte Carlo calculation of x-radiation transport is based on stochastic mathematical simulation of the interactions between photons and matter. The simulation has been formulated in PCXMC in a standard manner (for a review and general references on Monte Carlo techniques see, e.g., Andreo 1991). Photons are emitted (in a fictitious mathematical sense) from an isotropic point source into the solid angle specified by the focal distance and the x-ray field dimensions, and followed while they interact with the phantom according to the probability distributions of the physical processes that they may undergo: photo-electric absorption, coherent (Rayleigh) scattering or incoherent (Compton) scattering. Other interactions are not considered in PCXMC, because the maximum photon energy is limited to 150 keV.

The range of secondary electrons in soft tissue is only a fraction of a millimetre, and the energy of the secondary electrons is approximated to be absorbed at the site of the photon interaction (except in calculating the bone marrow dose, see below). A large number of individual photon histories are generated, and estimates of the mean values of the energy depositions in the various organs of the phantom are used for calculating the dose in these organs.

Pseudo random numbers are generated by a multiplicative linear congruential generator, MLCG(16807, 2^{31}-1) (Vattulainen et al. 1993), and used for sampling the initial photon direction, distance between interactions, type of interacting atom, type of interaction, scattering angle and energy. In fact, to improve precision, the photons are constrained so as not to be absorbed by the photo-electric interaction; instead, photo-electric absorption has been treated by associating a 'weight' to the photons. This weight, w, represents the expected proportion of photons that would have survived absorption in the preceding interactions, and is reduced in each interaction according to the probability of absorption (p). At each interaction, an energy deposition of wpE+w(1-p)DE (E is the photon energy before the interaction and DE the energy loss in the scattering interaction) is made to the organ where the interaction occurs, and the photon weight is reduced to $w_{new} = w_{old}$ (1-p). Each photon is followed until it exits the phantom without hitting it again, its energy falls to below 2 keV (in which case it is forced to be absorbed), or until its weight is reduced to less than 0.003. In the last case, the photon is subjected to a game of Russian roulette: it is discarded by a probability of 0.75, but if it survives its weight is multiplied by a factor of four.

The cross sections for the photo-electric interaction, coherent scattering and incoherent scattering have been taken from Storm and Israel (1970) and the atomic form factors and incoherent scattering functions from Hubbell et al. (1975).

The bones of the mathematical phantoms are modelled as a homogeneous mixture of mineral bone, active bone marrow, and other organic constituents of the skeleton. The overall composition of the skeleton is approximated as being constant over all bones in the body and over all phantoms representing patients of various ages (see Table 3), but the amount of active bone marrow is varied from one part of the skeleton to another and is different for phantoms representing different ages (Cristy 1980). In reality, active bone marrow is located in small cavities in the trabecular bone, and this must be taken into account when calculating the dose to the active bone marrow.

The Monte Carlo method used here calculates the kerma in both components of the skeleton, the active bone marrow and the rest of skeletal material, by dividing the absorbed energy in the whole skeleton into two parts, applying the method of Rosenstein (1976). Here, however, the actual energy spectrum at the interaction site was used instead of the incident photon spectrum used by Rosenstein. The influence of the small cavity size on the dose in the active bone marrow is considered by applying a photon energy dependent kerma-to-dose conversion factor (Kerr and Eckerman 1985), which increases the active bone marrow dose by a few percent when compared to the kerma. The size of the bone marrow cavities may vary depending on the age or the anatomical part of the skeleton (Kerr and Eckerman 1985), but this has not been taken into account here. The absorption of energy in the other parts of the skeleton has been reduced by the same amount as it has been increased for the active bone marrow.

PCXMC calculates the organ doses for monochromatic photons of 10, 20 ... 150 keV energy (or up to less than the maximum 150 keV, if the user so specifies) in ten different batches of each energy value. The final estimate of the absorption at each energy value is obtained as the average of these batches, and the statistical error is estimated from their standard deviation. The doses and their statistical errors for a practical x-ray spectrum of interest are calculated afterwards by another module included in the program. The same Monte Carlo data can, therefore, be used for calculating doses for any spectrum of interest; the calculation is fast because it does not involve any further Monte Carlo simulation.

The x-ray spectra are calculated according to the theory of Birch and Marshal (1979) and specified in terms of the x-ray tube voltage (kV), the angle of the tungsten target of the x-ray tube, and filtration. In the present version of the program, the user can simultaneously define two filters of arbitrary atomic number and thickness. The filter data are, for practical reasons, from the compiled x-ray interaction data of McMaster et al. (1969). Air kerma is calculated from photon fluence data using the conversion coefficients in ICRU (1992b).

It should be noted that the accuracy of both the dose estimate and its statistical error depend on the number of interactions in the organ. This number may be low even for a large number of photon histories if the dose in the organ is low or the organ small. It should also be noted that when the number of interactions is low, which is indicated by a high value of the statistical error, the estimate has a skewed non-normal distribution and the actual statistical errors may be higher than expected on the basis of the standard deviation.