MONTE CARLO TECHNIQUES IN DIAGNOSTIC AND THERAPEUTIC NUCLEAR MEDICINE

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Monte Carlo techniques have become one of the most popular tools in different areas of medical radiation physics following the development and subsequent implementation of powerful computing systems for clinical use. In particular, they have been extensively applied to simulate processes involving random behaviour and to quantify physical parameters that are difficult or even impossible to calculate analytically or to determine by experimental measurements. The use of the Monte Carlo method to simulate radiation transport turned out to be the most accurate means of predicting absorbed dose distributions and other quantities of interest in the radiation treatment of cancer patients using either external or radionuclide radiotherapy. The same trend has occurred for the estimation of the absorbed dose in diagnostic procedures using radionuclides.

There is broad consensus in accepting that the earliest Monte Carlo calculations in medical radiation physics were made in the area of nuclear medicine, where the technique was used for dosimetry modelling and computations. Formalism and data based on Monte Carlo calculations, developed by the Medical Internal Radiation Dose (MIRD) committee of the Society of Nuclear Medicine, were published in a series of supplements to the *Journal of Nuclear Medicine,* the first one being released in 1968. Some of these pamphlets made extensive use of Monte Carlo calculations to derive specific absorbed fractions for electron and photon sources uniformly distributed in organs of mathematical phantoms. Interest in Monte Carlo-based dose calculations with β-emitters has been revived with the application of radiolabelled monoclonal antibodies to radioimmunotherapy. As a consequence of this generalized use, many questions are being raised primarily about the need and potential of Monte Carlo techniques, but also about how accurate it really is, what would it take to apply it clinically and make it available widely to the medical physics community at large.

The application of Monte Carlo techniques in medical physics is an ever lasting enthusiastic topic and an area of considerable research interest. Monte Carlo modelling has contributed to a better understanding of the physics of radiation transport in medical physics. As an example, the large number of applications of the Monte Carlo method attests to its usefulness as a research tool in different areas of nuclear medicine imaging including detector modelling and systems design, image reconstruction and correction techniques, internal dosimetry and pharmacokinetic modelling. In particular, Monte Carlo simulation is a gold standard for the simulation of nuclear medicine imaging systems and is an indispensable research tool to develop and evaluate dose planning algorithms.

Recent developments in nuclear medicine instrumentation including high-resolution SPECT/PET scanners and multimodality imagers as well as applications in patient-specific dosimetry are ideal for Monte Carlo modelling techniques because of the stochastic nature of radiation emission, transport and detection processes. Factors, which have contributed to the wider use, include improved models of radiation transport processes, the practicality of application with the development of acceleration schemes and the improved speed of computers as well as the availability of multiple-processor parallel processing systems.

Modelling of imaging and other medical applications is best done with phantom models that match the gross parameters of an individual patient. Recent three- and four-dimensional computer phantoms seek a compromise between ease of use, flexibility and accurate modelling of populations of patient anatomies, and attenuation and scatter properties and biodistributions of radiopharmaceuticals in the patients. Current developments are aimed at computer phantoms that are flexible while providing accurate modelling of patients. Modelling of the nuclear medicine imaging process has been improved by more accurate simulation of the physics and instrumentation involved in the process. Monte Carlo software packages, especially those developed specifically for nuclear medicine and with different performance characteristics, have been found useful in the modelling work. A major limitation has been the long simulation time required by the intensive computations. With advances of computer technologies and implementation techniques, we are able to model interactions of radiation within the patient and characteristics of the imaging system with much improved accuracy in an increasingly shorter computational time. The combination of realistic computer phantoms and accurate models of the imaging process allows simulation of nuclear medicine data that are ever closer to actual patient data. Simulation techniques will find an increasingly important role in the future of nuclear medicine in light of further development of realistic computer phantoms, accurate modelling of projection data and computer hardware. However, cautions must be taken to avoid errors in the simulation process and verification via comparison with experimental and patient data is essential.

This paper presents derivation and methodological basis for this approach and critically reviews their areas of application in medical radiation physics with special emphasis on nuclear medical imaging and dosimetry. Basic aspects of nuclear medicine instrumentation and quantitative image reconstruction and analysis are reviewed, followed by the presentation of potential applications of Monte Carlo techniques in different areas of nuclear imaging such as detector modelling and systems design, image reconstruction and correction techniques, internal dosimetry and pharmacokinetic modelling. An overview of existing simulation programs is provided and illustrated with examples of some useful features of such sophisticated tools in connection with common computing facilities and more powerful multiple-processor parallel processing systems. Current and future trends in the field are also discussed.

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