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Radiation protection and dosimetry issues in the medical applications of ionizing radiation

Pedro Vaz*

Instituto Superior Técnico, Campus Tecnológico e Nuclear, Unidade de Protecção e Segurança Radiológica, Estrada Nacional 10, km 139.7, 2695-066 Bobadela LRS, Portugal

HIGHLIGHTS

- The robustness and shortcomings of the system of radiation protection are discussed.
- Pediatric exposures to ionizing radiation are identified as a major cause of concern.
- Routine sub-mSv (below 1 mSv) CT exams are at reach during this decade.
- Significant progress in the justification of medical exams is mandatory.
- The future relies on computational dosimetry, using MC simulations and voxel phantoms.

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ABSTRACT

The technological advances that occurred during the last few decades paved the way to the dissemination of CT-based procedures in radiology, to an increasing number of procedures in interventional radiology and cardiology as well as to new techniques and hybrid modalities in nuclear medicine and in radiotherapy. These technological advances encompass the exposure of patients and medical staff to unprecedentedly high dose values that are a cause for concern due to the potential detrimental effects of ionizing radiation to the human health. As a consequence, new issues and challenges in radiological protection and dosimetry in the medical applications of ionizing radiation have emerged.

The scientific knowledge of the radiosensitivity of individuals as a function of age, gender and other factors has also contributed to raising the awareness of scientists, medical staff, regulators, decision makers and other stakeholders (including the patients and the public) for the need to correctly and accurately assess the radiation induced long-term health effects after medical exposure. Pediatric exposures and their late effects became a cause of great concern.

The scientific communities of experts involved in the study of the biological effects of ionizing radiation have made a strong case about the need to undertake low dose radiation research and the International System of Radiological Protection is being challenged to address and incorporate issues such as the individual sensitivities, the shape of dose–response relationship and tissue sensitivity for cancer and non-cancer effects.

Some of the answers to the radiation protection and dosimetry issues and challenges in the medical applications of ionizing radiation lie in computational studies using Monte Carlo or hybrid methods to model and simulate particle transport in the organs and tissues of the human body. The development of sophisticated Monte Carlo computer programs and voxel phantoms paves the way to an accurate dosimetric assessment of the medical applications of ionizing radiation.

In this paper, the aforementioned topics will be reviewed. The current status and the future trends in the implementation of the justification and optimization principles, pillars of the International System of Radiological Protection, in the medical applications of ionizing radiation will be discussed. Prospective views will be provided on the future of the system of radiological protection and on dosimetry issues in the medical applications of ionizing radiation.

* Tel.: +351 219946291.
E-mail address: pedrovaz@ctn.ist.utl.pt

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1. Introduction

During the last 15 years, the radiological protection of the patient emerged as of paramount importance in view of the dissemination of the use of computer tomography (CT) in practically all medical specialities and of the increasing utilization of interventional procedures. Of particular relevance are the pediatric exposures resulting from the growing prescription of CT procedures to newborns, children and adolescents and the awareness that such younger individuals feature a much higher radiosensitivity than those of adults and have their life spans over several decades after exposure, enough time to allow late manifestation of cancer effects.

General consensus exists about the outstanding progress that has been achieved during the last decade, on the implementation of the principle of optimization of protection, one of the three pillars of the International System of Radiological Protection. The IAEA International Action Plan (IAEA, 2002) approved shortly after the Malaga Conference (IAEA, 2001) has been instrumental in promoting the radiological protection of the patient and the need for dose reduction in the medical exposures to ionizing radiation. Such dose reduction has been achieved with the active involvement of several stakeholders, including the equipment manufacturers, namely the CT manufacturers who have developed sophisticated systems such as Tube Current Modulation and Automatic Exposure Control and incorporated them into the equipment for routine clinical use. Significant progress and technological advancements at the level of the detectors, electronics and software were also implemented.

In recent years, an awareness emerged about the risks associated to the exposure of medical staff and their critical organs such as the lens of the eye, the thyroid and the extremities, in interventional procedures (radiology, cardiology, orthopedy, gastroenterology, urology, coronary angiography, etc.). This awareness and the epidemiological evidence, during the last few years, about the late manifestation of non-cancer effects associated to the protracted or chronic exposures to ionizing radiation, led the ICRP to review the dose limits to the lens of the eye in 2011 (ICRP statement, 2011) and to draw the attention of the radiological protection community to, amongst others, the cerebrovascular effects associated to absorbed dose values significantly smaller than traditionally assumed.

The radiation safety of patients in radiotherapy treatments was another topic that gained additional importance in view of the incidents and accidents that occurred in several countries.

Last but not the least, the need to gain further scientific insight into the risk versus dose relationship for low dose radiation exposures and to better understand the risks associated to protracted exposures, exploring novel approaches in radiobiology and molecular biology and involving communities of experts such as toxicologists, epidemiologists, geneticians, etc., in addition to the communities of experts already involved was emphasized by means of international collaborative efforts (MELODI, 2013) and scientific projects.

Despite the aforementioned advances in the promotion and implementation of the optimization principle, it is felt that major efforts have to be devoted to the implementation of the principle of justification, another pillar of the International System of Radiological Protection. Discussion of this issue will be provided in a later section, after a short description of the International System of Radiological Protection in the next section, a review of the medical exposures' dosimetric data and trends and of radiological protection and safety issues associated to CT and interventional procedures.

Last but not the least, a succinct discussion of the computational dose assessment in the medical examinations and procedures in order to characterize the radiation exposures of the medical staff and the patient, will be presented. Such computational dosimetric assessment can be achieved by performing Monte Carlo simulations and biokinetic models calculations, in both cases using reference (based on reference individuals) or patient-tailored (using patient imaging data) voxel phantoms.

2. The International System of Radiological Protection

The current system of radiological protection is an outstanding framework which uses the best available scientific knowledge and incorporates state-of-the-art scientific methodologies for the assessment of the risk associated to the exposures of individuals and the environment to ionizing radiation, trying to avoid undue exposures. It uses dose as a surrogate of risk and is based on the linear non-threshold (LNT) hypothesis. It incorporates radiation weighting factors and gender and age average tissue weighting factors that lead to the assessment of the effective dose, a dosimetric quantity that has proven to be very useful for regulatory purposes and for prospective dosimetric studies.

However, as the scientific knowledge and the associated risk perception evolve, experts naturally discuss and question the robustness of the system and its adequacy for the protection of individuals to the biologically detrimental aspects of ionizing radiation (HLEG, 2009). The adequacy of the LNT hypothesis for low dose radiation doses is a recurrent and longstanding question that should be addressed in the future.

In recent years attention has shifted from the traditional topics (namely cancer effects) to emerging topics such as the individual sensitivity and individual variability in cancer risk as a function of age, gender, lifestyle, genetics and other factors, the non-cancer effects induced by ionizing radiation and the shape of the dose–response curve for cancer. Fig. 1 extracted from reference HLEG (2009), depicts the issues currently addressed by the International System of Radiological Protection (boxes on the top part of the figure) and issues that must be addressed in the future system.

The underlying questions about the International System of Radiological Protection are associated to the level of under- or over-protection it provides and the associated consequences. New major findings associated to the risks of exposures to low dose and to protracted radiation exposures should translate into major developments of the system of radiological protection to address topics such as the medical exposures to ionizing radiation (namely in diagnostic) and exposures to radon, amongst several other topics.

3. Medical exposures: a hard look at the data

The table in Fig. 2, extracted from UNSCEAR (2008) displays the time evolution through two decades, from 1988 to 2008, of the number of medical radiological procedures and the effective dose per capita, worldwide. As is clearly seen, the number of radiological procedures more than doubled whilst the annual effective dose per inhabitant almost doubled.

Similar but more pronounced trends can be seen in the report NCRP-160 (NCRP, 2009) for the USA, that pinpoints a significant increase of the population exposure to ionizing radiation due to the medical applications of ionizing radiation, namely CT, nuclear medicine, and interventional procedures. In the USA the number of prescribed CT scans grew by approximately 10% per annum from the 1990s until the middle of the last decade. Data is also available for several countries (Bfs, 2010) pinpointing the major role played by the increasing frequency of CT exams in the significant increase of the mean effective dose per inhabitant.