

Quality Assurance in Radiation Dosimetry: Achievements and Trends

A. Introduction

Dosimetry is the science of measuring radiation dosage. The absorbed dose of radiation is measured in a unit called “gray” (Gy). Radiation dosage measurements and ensuring they are as accurate as possible are important if the benefits of the application of nuclear technology in health care are to be harnessed. Radioactive processes and radiation are utilized in many health related technologies, and the requirement for Quality Assurance (QA) and accuracy in dosimetry depends upon the specific needs of the particular applications.

In the case of delivering radiation to a patient as part of a treatment regime, accuracy is vital. The goal of a radiotherapeutic procedure is to deliver the dose required to eradicate a tumour while at the same time minimizing the radiation exposure to healthy tissue. Delivering too much radiation can result in serious complications that could harm the patient’s quality of life. On the other hand, delivering too little radiation to malignant tissue can ultimately result in the death of the patient as a consequence of the disease.

Dosimetry is also an important component in diagnostic medicine. In this case, the primary driver for accuracy is the need to balance the quality of an image with the amount of radiation exposure. By preventing unnecessary repetitions of imaging procedures, the cumulative dose to the patient is minimized, while still providing the information necessary to diagnose and monitor disease.

The use of radiation in hospitals, industry, laboratories and nuclear power plants also necessitates consideration of the potential radiation exposure to workers in the course of carrying out their duties. The level of accuracy required in dosimetry for the measurement of occupational dose is lower than that needed for patient dosimetry; however, traceability of measurements at a defined level of uncertainty is still important. Dosimetry is an essential component of all radiation safety and protection programmes designed to monitor and achieve the safe use of radiation.

There are industrial applications of nuclear technology that require radiation to be delivered at high doses. Some irradiated products may be used directly by consumers, as in the examples of irradiated food or sterilized medical products. Optimisation of irradiation delivery is important as the health and safety of individuals are at risk if the dose delivered to the product is inadequate to achieve the proper effect. Alternatively, if the dose is too high, resources will be wasted resulting in economic consequences. Hence the level of accuracy required in industrial processing dosimetry applications is determined by the economics of the radiation process and the processor’s need to ensure that their product meets health and safety standards.

Requirements for safe and optimal use of radiation vary depending on the dosimetric accuracy required. Developing and implementing an appropriate QA programme will ensure fulfilment of these requirements. The main components of such QA programmes include traceability of radiation measurements through accurate calibration of instrumentation, training of staff, dosimetry audits and the establishment of quality control and radiation safety procedures.

Recent achievements and trends relating to dosimetry and QA of measurement standards, radiotherapy, diagnostic radiology, internal dosimetry, and radiation protection are described in the sections below.

B. Measurement Standards

Reliable measurements are fundamental in dosimetry, and strategies have been developed to provide confidence using the traceability principle. The idea of traceability is that the result of a measurement, no matter where it is made, can be related to a national or international measurement standard, and this relationship is documented. The Bureau International des Poids et Mesures (BIMP) ensures worldwide unification of physical measurements in radiation dosimetry [II-1] with the active participation of national dosimetry laboratories¹ which have their own measurement standards. Reference standards are maintained permanently at the BIPM and are used as a benchmark for comparison of national dosimetry standards [II-2]. This benchmarking has allowed some national laboratories to improve their standards as well as prompted the dosimetry community to strive for improved accuracy. For example, development of primary standards for the absorbed dose to water for high-energy photon and electron beams [II-3 and II-4] in the past few years, and improvements in radiation dosimetry concepts have reduced the uncertainty in the dosimetry of radiotherapy beams. The concept of dosimetry comparisons is now widely accepted and recognized as an important element of QA programmes and also recommended in recent ISO and IEC guides [II-5] and ICRU Report 76 [II-6]. It can also be used as a tool to demonstrate the calibrations and measurement capabilities of national calibration laboratories and to seek accreditation.

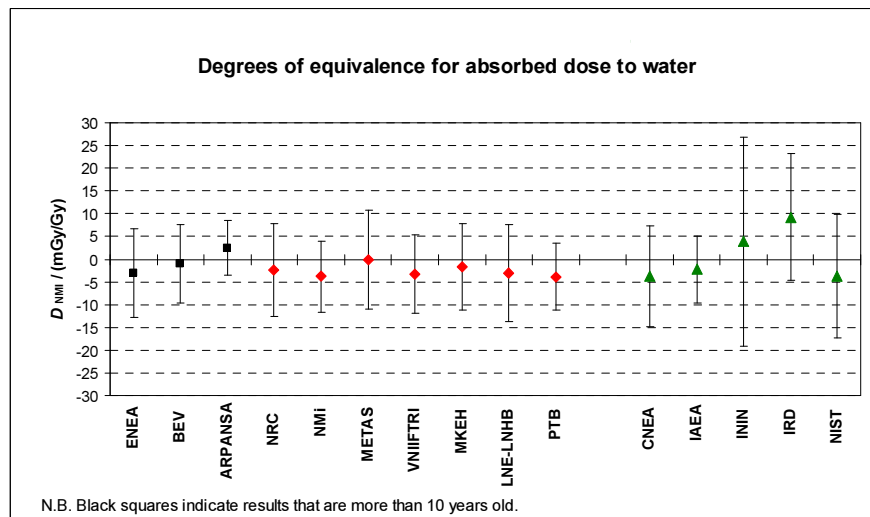


FIG. II-1. This figure, adapted from [II-2], shows an example of an international dosimetry comparison. It depicts the degree of equivalence between national dosimetry standards (X-axis) with respect to the BIPM reference value (Y-axis). The degree of equivalence to the Agency reference dosimetry system is also given.

C. Dosimetry in Radiotherapy

Radiotherapy involves delivering large amounts of radiation to specific targets within the human body. A high degree of accuracy, reliability and reproducibility is necessary for safe and effective radiation treatment of cancer patients. This ensures confidence in both the dose delivered to the tumour, as well

¹ A network of Secondary Standards Dosimetry Laboratories, known as the IAEA/WHO Network of Secondary Standards Dosimetry Laboratories (SSDLs) was established jointly with the WHO in 1976. At present this network includes 80 laboratory Member States in 67 Member States.

as to the nearby healthy organs and tissues, thereby maximizing tumour control and minimizing adverse radiation effects. QA programmes have increasingly important roles as radiotherapy technology becomes more complex. Equipment designs are evolving and more complex treatment techniques are being implemented. For example, conformal radiotherapy is now widely available; this modality enables higher doses to be delivered to the tumour and therefore should increase the cure rates. Intensity modulated radiotherapy (IMRT) is a similar technique, which is built upon conformal radiotherapy but takes the concept further by using a multileaf collimator (MLC) to deliver a series of smaller concisely targeted fields of radiation. For the application of these small fields dosimetry errors can be considerably larger than with conventional beams mostly due to two reasons; (i) the reference conditions recommended by existing dosimetry codes of practice cannot be established in more complex machines and (ii) absorbed dose to water measurements in composite fields are not standardized and reference conditions are not yet defined. To address these problems, an international working group has been established by the Agency in cooperation with the American Association of Physicists in Medicine (AAPM) to develop recommendations for reference dosimetry of small and non-standard fields.²

New technologies, such as IMRT, intensity-modulated arc therapies (IMAT), volumetric intensity modulated arc therapy (VMAT), together with other newer radiation delivery platforms, such as TomoTherapy and CyberKnife, all require complex QA and verification methods for dosimetry. In light of these technologies, new QA devices such as two dimensional (2D)-array detectors, 3D-based detectors, radiochromic film, and thermo luminescent dosimeter (TLD) sheets, are becoming available and the dosimetry verification techniques in radiotherapy are evolving accordingly. Gel dosimetry is also used to verify complex 3D dose distributions; however, it is not yet widely used. In the past few years a new technology has been emerging in some countries with hospital based facilities employing proton and light ion beams for radiotherapy. The advantage of using these radiations is that they allow for greater control of radiation dose distribution, thus enabling higher doses to tumours and lower doses to healthy tissue. Similarly to photon and electron beam treatment, planning of this high precision conformal therapy requires accurate dosimetry and beam calibration in order to ensure exact delivery of the prescribed dose. A major obstacle to establishing such dosimetry stems from the fact that these are different types of radiation, and primary dosimetry standards for proton and light ion beams do not currently exist. Current practice utilizes ionization chambers with cobalt-60 calibration coefficients, recognized as the most practical and reliable reference instrument for dosimetry of proton and light ion beams. The recent report from the International Commission on Radiation Units and Measurements (ICRU) on proton therapy [II-7] has recommended the use of the IAEA TRS 398 [II-4] in practical dosimetry. The ICRU report has also adopted the most recent developments in the field of ionization chamber dosimetry for these beams.

One notable method for verifying the dose delivered to patients is by using direct measurements taken while patients are being treated, i.e. in vivo dosimetry (see patient setup in Fig. II-2). In vivo dosimetry provides insight into the accuracy and precision of the treatment delivery, detection of systematic errors and helps in the prevention of radiation accidents. Although such measurements may not prevent a single dose misadministration, they will minimize the possibility of escalating problems across many treatments or patients. Point detectors (1D) used for in vivo dosimetry utilize various solid state detectors (semiconductor diodes, MOSFET, TLD, OSL) and are generally considered useful for patients treated with uniform intensity beams, in particular in radiotherapy centres where

² This included providing training opportunities for about 100 medical physicists, from across the world, educational programmes on the use of these technologies through IAEA workshops and courses organized in collaboration with the International Centre for Theoretical Physics, the American Association of Physicists in Medicine and the European Federation of Organizations for Medical Physics.

on-line electronic verification of treatment set-up parameters (through records and verify systems³) are not available. However, some issues are arising because point detectors are not suitable in non-uniform radiation fields with rapid dose gradients, such as those relevant to IMRT. To verify the IMRT dose delivery, 2D in vivo dosimetry methods are being developed based on the electronic portal imaging device (EPID) attachments for treatment machines. EPID dosimetry is used in advanced academic radiotherapy centres but at this time it is not commercially available. The newest methodology for 3D in vivo dosimetry is under development, based on the reconstruction of the dose distribution from EPID measurements and patient images taken during the treatment using on-board imaging devices.

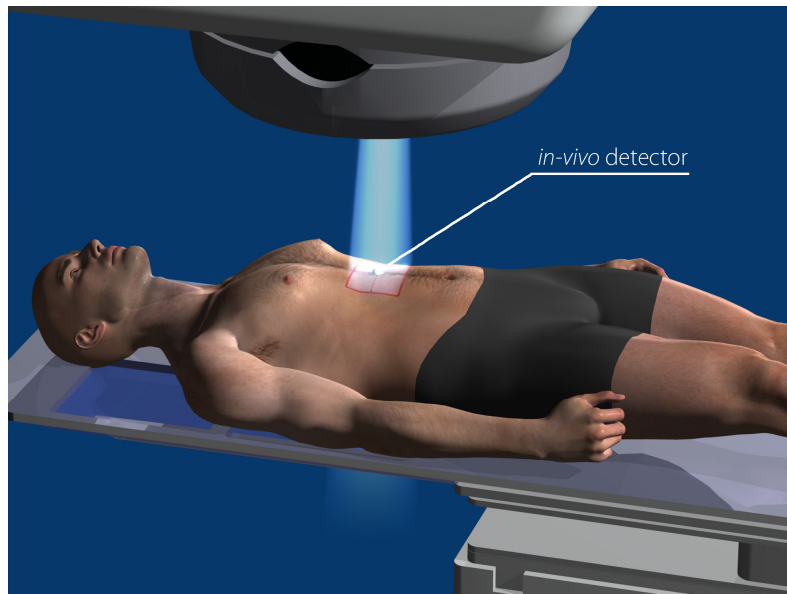


FIG II-2. Set-up for in-vivo dosimetry during cancer patient treatment with a radiation beam. The dose delivered to the tumour during treatment is derived from measurements with a radiation detector placed on a patient's skin during irradiation and compared to the planned dose. (Graphic courtesy of Ewaryst Izewski)

To ensure quality care, it is generally recognized that there is a continual need for national and international comparisons and audit programmes for radiotherapy dosimetry such as those conducted by the IAEA/WHO [II-8], Radiological Physics Centre (RPC) in USA [II-9] and other national and international organizations [II-10]. TLD auditing programmes have significantly improved the compliance rate among participating radiotherapy centres with regard to dosimetric accuracy. Other current dosimetry auditing programmes used for the verification of treatment planning and dose delivery, including those developed by the Agency [II-11] and RPC [II-12], are based on solid (anthropomorphic and semi-anthropomorphic) phantoms because of the multidimensional dosimetric aspects necessary in these techniques. They are used for a variety of dosimetric situations, including dose measurements in advanced conformal radiotherapy techniques and IMRT. The experience gained in external audits for complex techniques, such as IMRT, has shown that careful attention must still be given to basic aspects of dosimetry.

³ Records and Verify (R&V) systems are interfaced with linear accelerators and are used to verify treatment parameters.

D. Dosimetry in X-ray Diagnostic Radiology

Radiology is an area of medicine which has witnessed significant technologic developments in recent years including the advancement of new imaging techniques such as digital radiology, interventional radiology and computed tomography (CT) in order to improve and enhance patient care. However, while these developments have undoubtedly conferred benefits to a large number of patients, they have also raised concerns for the quality and safety of practices because the use of radiation for medical diagnostic examinations is a significant source of man-made radiation exposure. Therefore, the impact of these technical developments has to be quantified through measurement with the use of appropriate and internationally recognized dosimetry protocols and standards.

Diagnostic dosimetry measurements vary from the use of simple dose indicators used to provide information on the general magnitude of the radiation dose delivered to a patient, to more detailed and complex estimations of the dose, including estimations of the dose to particular organs for typical patient models. Dose indicators play a pivotal role in the control of patient dose as they allow trends to be identified and prompt corrective action on a local level through the use of optimization processes. Accurate determination of organ-based radiation dosimetry provides useful information regarding biologically relevant radiation tissue damage and aids in the statistical estimation of risks to the population. Population risks are particularly important for low to medium dose usage of radiation as this comprises the majority of examinations performed in diagnostic radiology. Research is therefore being actively conducted on the development of methodologies for more accurate patient specific models and organ specific dosimetry. This work is most active and notable in computed tomography and interventional radiology, where considerable patient exposure can occur.

Standardization of dosimetry and calibration protocols is clearly central to the effectiveness of dosimetric measurement necessary in diagnostic radiology. This has recently been addressed in publications by the International Commission on Radiation Units and Measurement (ICRU Report 74) [II-13] and a code of practice by the IAEA (TRS457) [II-14]. These complementary documents set out standards for the measurement of the diverse range of dosimetric quantities necessary to tackle the challenges of the rapidly changing and expanding environment of diagnostic radiology. Many laboratories have commenced development of a standardized set of reference beam qualities and some countries have started providing calibration services to hospitals.

Dosimetry audits and comparison are not fully developed in this field. More work is needed by the international community to set-up external dosimetry audits and comparisons to reach the same level as in radiotherapy dosimetry.

E. Internal Dosimetry

In nuclear medicine imaging, patients are injected with radiopharmaceuticals and then imaged with radiation detecting cameras. Distribution of isotopes in the body presents the need for internal dosimetry, which currently is most often based on standard reference tables published in medical internal radiation dose (MIRD) pamphlets. These tables give the average absorbed dose to the main human organs for any specified amount of injected radioactivity. The tables were calculated in computationally intensive simulations for a reference man (with an average weight, height and radioactivity distribution). The tables also provide a rough estimate of the dose distribution for all commonly used radiopharmaceuticals in nuclear medicine. This method for calculating radiation dose can be used as an estimate of the resulting organ doses for most diagnostic procedures.

The impetus for more accurate and patient-specific dosimetry comes mainly from an increased availability and use of therapeutic radiopharmaceuticals [II-15]. Such treatments deliver high doses of radiation to specific targets, with the intent of providing a curative or palliative effect however the

resulting radiation dose absorbed by both the target and healthy organs is several orders of magnitude higher than what is received from a diagnostic scan. The demand for more accurate and possibly patient specific internal dosimetry has grown accordingly. This demand is partially being met by developments in the methodology by which the patient-specific dose is calculated, and also by computer-based tools available for the implementation of the improved methods. Dedicated software packages exist to aid in patient-specific dosimetry calculations.

The tools for calculating absorbed doses have become more sophisticated, covering the whole spectrum from estimating the whole-body dose to evaluating the specific radiation energy deposited in single cells. These important tools are however partially based upon assumptions and depend on user calculation and input of the true radioactivity distribution for individual patients in order to perform accurate dose calculations. Accurate quantification of the radioactivity distribution within the patient is thus essential for internal dosimetry (see Fig. II-3). Methods to track the radioactivity distribution in patients over time can include measurement with an external probe; measuring the amount of radioactivity in blood samples; and also includes efforts to quantitate the images from gamma-camera scans [II-17]. All these methods are currently being refined with the involvement of the Agency.

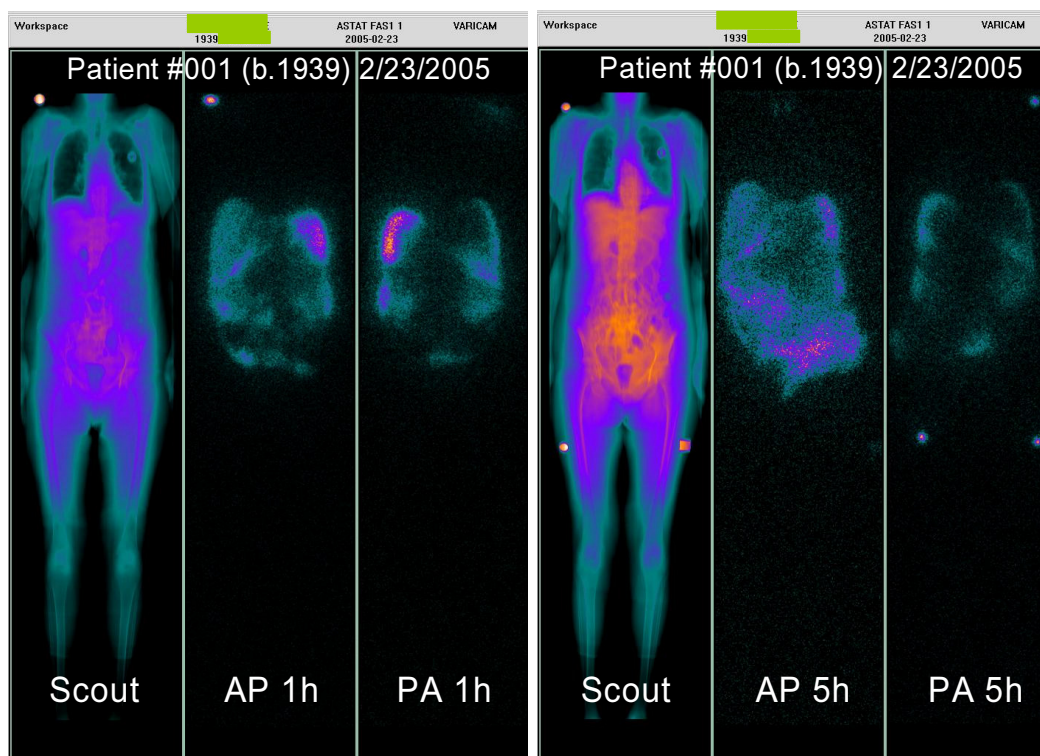


FIG. II-3. X-ray and gamma-camera images of a patient with ovarian cancer being experimentally treated with the alpha-particle emitter astatine-211 labelled to a molecule that targets the cancer cells. In addition to alpha-particles, astatine-211 also emits photons that can be detected by a gamma-camera. The left 3 panels show the distribution 1 hour after the radiopharmaceutical was infused into the peritoneal cavity. The far left X-ray image was acquired simultaneously with the gamma-camera images of the front (AP) and the back (PA) of the patient. The right 3 panels show the distribution 5 hours after the infusion. When combined and analyzed, these images provide information on the radiation absorbed dose to tumour and critical healthy tissue. The information is used to predict the therapeutic and toxic effects of this treatment (courtesy of University of Gothenburg, Sweden).

As the methods and tools for more precise internal dosimetry are developed, it is important that medical physicists and other health professionals are continuously updated and trained so that the shortage of professionals with adequate skills in internal dosimetry does not lead to an unnecessary delay in the clinical use of novel and promising therapeutic radiopharmaceuticals.

Workers in different nuclear applications are potentially occupationally exposed due to intakes of radionuclides while working with unsealed sources of radiation. From the source activity measured the intake of radionuclide is assessed and the committed effective dose is calculated. New detection methods, metabolic and dosimetric models are currently under development to better represent the transfer of radionuclides and exposure process in the human body.

F. Dosimetry in Radiation Protection

Radiation protection is an essential infrastructure element in the use of radiation-based technologies in medicine, industry, agriculture, space exploitation, education and research. Radiation protection measurements require a dependable level of accuracy as they can have serious implications and can significantly influence practices. This is particularly true for applications related to health and safety of individuals and the public. Radiation fields can be very complex, depending on the practice and type of radiation involved. The wide range of ionizing radiation applications requires a wide range of instruments for characterizing various radiations and their intensities.

External dosimetry is necessary for workplaces where there is medical or industrial use of ionizing radiation. This primarily involves using detectors and dosimeters for measurement of photons, neutrons and beta radiation for area monitoring and personal dosimetry. More traditional personal film dosimetry systems are being gradually replaced by solid state detectors thermoluminescence (TL), radiophotoluminescence dosimeters (RPL,) and optically stimulated luminescence (OSL) and electronic dosimeters. Rapid development of medical applications of radiation, mainly interventional radiology, requires new approaches in monitoring medical staff. Comparisons of dosimetry systems for monitoring of occupational doses have been organized by the EU and the Agency. These types of exercises are widely accepted as an efficient tool for harmonization of dosimetry approaches and quality assurance of services provided to end users. Radiation protection also faces challenges in addressing problems associated with radiation produced by high energy accelerators, nuclear power installations, and radiation received on aircraft or during space missions, and requires the use of a broad range of techniques for measurement of photons, electrons, neutrons, protons and other charged particles as well as techniques in computational dosimetry. Behaviour of many dosimetry systems in such radiations is still not very well known. Assurance of quality of measurements is achieved through joint benchmark exercises organized in facilities that can provide these types of radiations. Complex workplace radiation fields have been established at the European Organization for Nuclear Research (CERN) [II-16] and other high energy accelerator facilities, in nuclear installations, neutron calibration facilities and also in some radiotherapy facilities worldwide. Extensive research in this area is still required.

Another concern in radiation protection is environmental dosimetry. Environmental dosimetry is a field which aims to describe the distribution of natural and artificial radiation sources in the environment and assess the resultant doses to the general public and other species. It involves various active (ionization chambers, proportional and Geiger Mueller counters, and spectrometers) and passive (TLD, OSL) dosimetry techniques used to assess short-time and long-time variations of radiation levels. Environmental dosimetry systems are linked to national networks thus providing continuous monitoring and early warning of nuclear accidents with local or transboundary implications. While the environmental dosimeters are calibrated at the laboratory, once used in the field they may lose traceability due to differences in radiation fields encountered during calibration and in the environment. Field comparisons play an important role during quality assurance of environmental measurements. The natural environmental radiation stations and underground testing laboratories,

developed in the frame of the EU research programme, have been successfully used for testing various dosimetry and national network systems.

G. Conclusion

Technologies which utilize radiation have shown enormous potential benefits for society. These benefits are best realized when proper knowledge of radiation dosimetry is incorporated into the science and application of the different technologies. While working modalities differ in the fields relevant to radiation dosimetry, efforts are continually being made across the board to improve their accuracy. Strategies for measurements are applied worldwide to create common international standards and comparison platforms, which play an important role in QA programmes.

Radiotherapy is an example of an active field which relies heavily on these QA programmes to ensure that patients are receiving the most effective and safe treatments for their cancers. Advancements are being made in X-ray diagnostic radiology but dosimetry audits and comparison procedures have yet to be implemented routinely. In nuclear medicine, pharmaceutical effects determine distributions of radioisotopes, and thus dose, within a patient. Work is currently being done to provide better patient specific, and organ specific dosimetry, which in turn, will aid in drug development and in the provision of better patient management. Non-medical and industrial exposures to radiation are also of great interest, and require accurate measurement tools and methodologies to monitor work places and public environments. As technology continues to grow, so do the efforts to assure safety, quality, and accuracy, in radiation related fields. Progress is being made through development of appropriate dosimetry, utilizing QA programmes, audits, new tools, and new ideas.

REFERENCES

- [II-1] BUREAU INTERNATIONAL DES POIDS ET MESURES, "The International System of Units (SI)", BIPM, F-92312 Sevres Cedex (1998).
- [II-2] ROSS, C.K., et al., Final report of the SIM 60Co absorbed-dose-to-water comparison SIM.RI(I)-K4, Metrologia **45** (2008) Tech. Suppl., 06011.
- [II-3] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Dosimetry of High-Energy Photon Beams based on Standards of Absorbed Dose to Water, ICRU Report 64, Bethesda, MD (2000).
- [II-4] INTERNATIONAL ATOMIC ENERGY AGENCY, Absorbed Dose Determination in External Beam Radiotherapy, Technical Reports Series No. **398**, IAEA, Vienna (2000).
- [II-5] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025: 2005, ISO, Geneva (2005).
- [II-6] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Measurement Quality Assurance for Ionizing Radiation Dosimetry, ICRU Report 76, Journal of the ICRU, Vol. 6, No. 2 (2006).
- [II-7] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Prescribing, Recording, and Reporting Proton-Beam Therapy, ICRU Report 78, Journal of the ICRU, Vol. 7, No. 2 (2007).
- [II-8] IZEWSKA, J. and ANDREO, P., The IAEA/WHO TLD postal programme for radiotherapy hospitals. Radioth. Oncol. **54** (2000) 65-72.

- [II-9] AGUIRRE, J.F., et al., Thermoluminescence Dosimetry as a Tool for the Remote Verification of Output for Radiotherapy Beams: 25 Years of Experience, Proc. Int. Symp. Standards and Codes of Practice in Med. Rad. Dosim, IAEA-CN-96/82, Vienna, IAEA, (2002) 191-199
- [II-10] IZEWSKA, J., SVENSSON, H., IBBOTT, G., Worldwide quality assurance networks for radiotherapy Dosimetry, Proc. Int. Symp. Standards and Codes of Practise in Med. Rad. Dosim, IAEA-CN-96/76, Vienna, IAEA (2002) 139-156.
- [II-11] GERSHKEVITSH, E., et al., Dosimetric verification of radiotherapy treatment planning systems: Results of IAEA pilot study, Radiotherapy and Oncology, 2008 (in press).
- [II-12] IBBOTT, G., et al., An anthropomorphic head and neck phantom for the evaluation of intensity modulated radiation therapy, Proc. Int. Symp. Standards and Codes of Practice in Med. Rad. Dosim, IAEA-CN-96/85P, Vienna: IAEA (2002) 209-220.
- [II-13] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Patient Dosimetry for X Rays used in Medical Imaging, ICRU Report 74, Bethesda, MD (2007).
- [II-14] INTERNATIONAL ATOMIC ENERGY AGENCY, Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water, Technical Reports Series No. 457, IAEA, Vienna, (2007).
- [II-15] OYEN, W.J., et al., Targeted therapy in nuclear medicine-current status and future prospects, Ann Oncol. **18** 11 (2007) 1782-92.
- [II-16] EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH, Complex Workplace Radiation Fields at European High-Energy Accelerators and Thermonuclear Fusion Facilities (Silari, M., ed.), CERN 2006-007, CERN, Geneva (2006).