Dosimetric Aspects of Medical and other Special Applications of Nuclear Technology

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Abstract

The nuclear technology is widespread in our daily lives with radiation isotopes for medical applications being the most important spin-off. The applications of radiation isotopes range from treatment of cancer, production of better seeds by mutation, increasing the shelf-life of food products leading to food security, to space applications. It is necessary to take proper care to ensure the safety of the public from the harmful effects of radiation, while reaping the benefits of nuclear technology. This necessity has led to a new branch of Physics called "Radiation Dosimetry", wherein Bhabha Atomic Research Centre (BARC) has developed expertise over decades of usages of nuclear technology. BARC is responsible for carrying out country-wide personnel dosimetry all over India and, maintaining and updating the dosimetry data of about 2 lac active radiation workers. Towards this, techniques to synthesize phosphors for dosimetry and related instrumentation are well in place. Additionally, BARC has developed different techniques for dosimetry during medical diagnostics and cancer therapy, and biological and physical techniques of retrospective dosimetry. The latter can be invoked in the situations of accidental radiation exposures such as in nuclear power plant accidents, illegal dumping of radioactive waste and use of Radiological Dispersion Devices. For all mentioned applications, it is important to develop systems and techniques for improved accuracy of the estimated radiation doses. This article attempts to highlight the efforts made by BARC, in the recent few years, to augment the existing dosimetric techniques and to develop new modalities for varied applications.

Keywords: *Dosimetry, cancer therapy, quality assurance, 4D Dynamic Phantom (FDDP), brachytherapy, thermoluminescence (TL), Optically stimulated luminescence (OSL), Dicentric Chromosomal Aberration (DCA), Fluorescent in-situ Hybridization (FISH), Premature Chromosome Condensation, Cosmic ray dosimetry.*

1. Introduction

The last few decades have seen an upsurge in the non-power applications of nuclear technology. It has spread across multiple sectors such as healthcare, food and agriculture, consumer products, industry, scientific research and environment. With the advent of various sophisticated facilities like synchrotron and particle accelerators, and widespread use of radioisotopes for these applications, the associated risk of inadvertent or potential exposures cannot be ruled out. This necessitates the development of accurate techniques and procedures to quantify the energy deposited in a material which is being irradiated or absorbed by humans, termed as Radiation Dosimetry. It attempts to quantitatively relate specific measurements carried out in a radiation field to chemical and/or biological changes produced by radiation. Accurate dosimetry has an important role in the optimization process of various applications where the desired beneficial effect depends on the dose delivered. In addition, dosimetry is essential for compliance with dose limits as stipulated by the standardized procedures or regulatory authorities. The choice of a dosimetry system or technique depends on the specific application. It goes without saying that all dosimetry systems and techniques need to validated and well calibrated against a traceable standard to make it easily comparable with similar available systems.

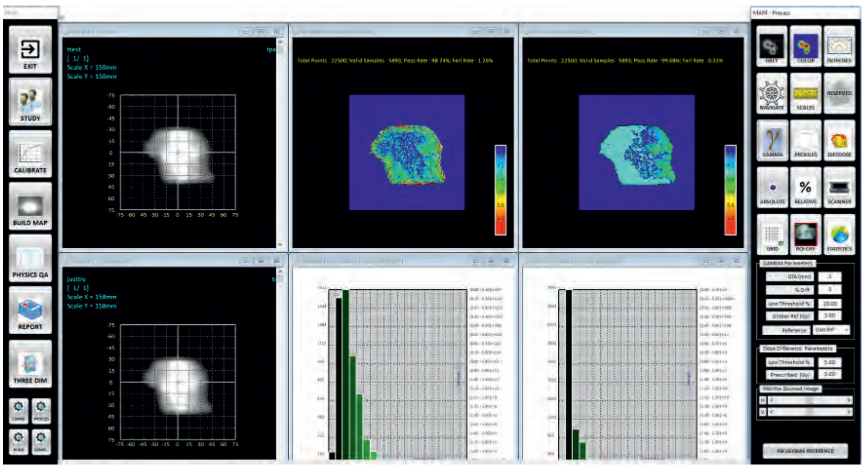
2. Dosimetric aspects in medical diagnostics and therapeutics

Medical professionals use diagnostic techniques such as radiopharmaceutical scans or radioisotopes, and apply radiotherapy treatments using x-rays, radiations from radioactive elements and accelerators which produce radiation. The radiation exposures from these examinations are generally low. In case of therapeutic applications, the delivered doses may be high, but they are justified either by the benefits of accurate diagnosis of possible disease conditions or by benefits of accurate treatment of some disease. It is important to accurately relate the administered amount of radioactivity to the absorbed radiation dose in organ of interest, or tumors, or the whole body. This is achieved by a Quality Assurance program, specifically set up for a given treatment modality. Appropriate dosimetric phantoms are generally used for verifying the dose delivered in radiation therapy. Finally, all dosimetric measurements need to be calibrated against reference standards traceable to international standards. In this direction, the development of in-house standards is an integral part of medical physics activities. These are briefly discussed in the following sections.

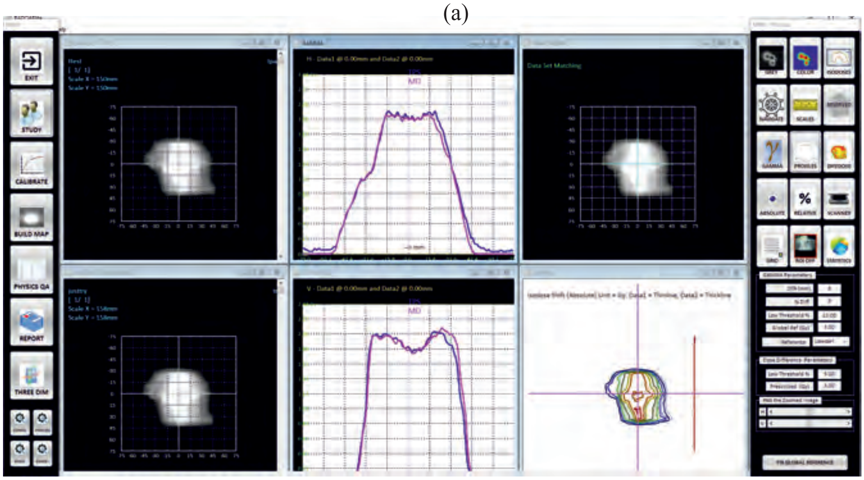
2.1 *Image based dose verification system for accuracy of cancer therapy*

There are several advanced radiotherapy techniques available for treatment of cancer such as Proton therapy, volumetric modulated arc therapy (VMAT), Intensity modulated radiotherapy (IMRT), and image guided radiotherapy (IGRT). The success of treatment highly depends on the use of comprehensive quality assurance (QA) program throughout the chain of the treatment process to verify the dose to be delivered to the cancer patient. This necessitates the implementation of patient specific pre-treatment dose verification.

Most commonly, patient specific dosimetric QA is performed by two methods: *point dose based dosimetry* and *planar dosimetry*. The ionisation chamber, MOSFETs, diodes and diamond detector based dose verification provides information about agreement only at a particular point. Image based systems provide information about planar dose distribution which helps in deciding the technique to be used for a given cancer patient. It also provides information regarding agreement between the planned and measured dose distributions.



(a)



(b)

Figure 1: Screen shot showing comparison between dose maps from TPS and image based system a) gamma map and Distance to agreement and b) profile map

Considering the importance of planar dose verification approach, an image based dosimetry QA system for advanced radiotherapy has been developed and demonstrated as a cost-effective import substitute with several added features. The system carries out a quantitative and comparative analysis of two data sets. The first data set is a dose map obtained from radiotherapy treatment planning system (TPS). The second is the image of the radiation beam portals acquired during pre-treatment verification delivery, which is subsequently converted into dose map using suitable built-in calibration process, and is further processed and stored in DICOM RT format. This is directly comparable with the corresponding TPS generated dose map file.

This image based QA system also has the capability to reconstruct 3D dose cube from the measured 2D projections, which can be compared with 3D dose distribution generated by the TPS. User interactive features have been provided to modify the input for quantitative and qualitative analysis. The added features include *Physics QA* module for the evaluation of radiation field size, radiation beam uniformity, radiation beam symmetry and radiation beam penumbra.

This dosimetry QA system will be highly useful for clinical medical physicists in evaluating advanced treatment plans to achieve higher level of accuracy and consistency in treatment delivery.

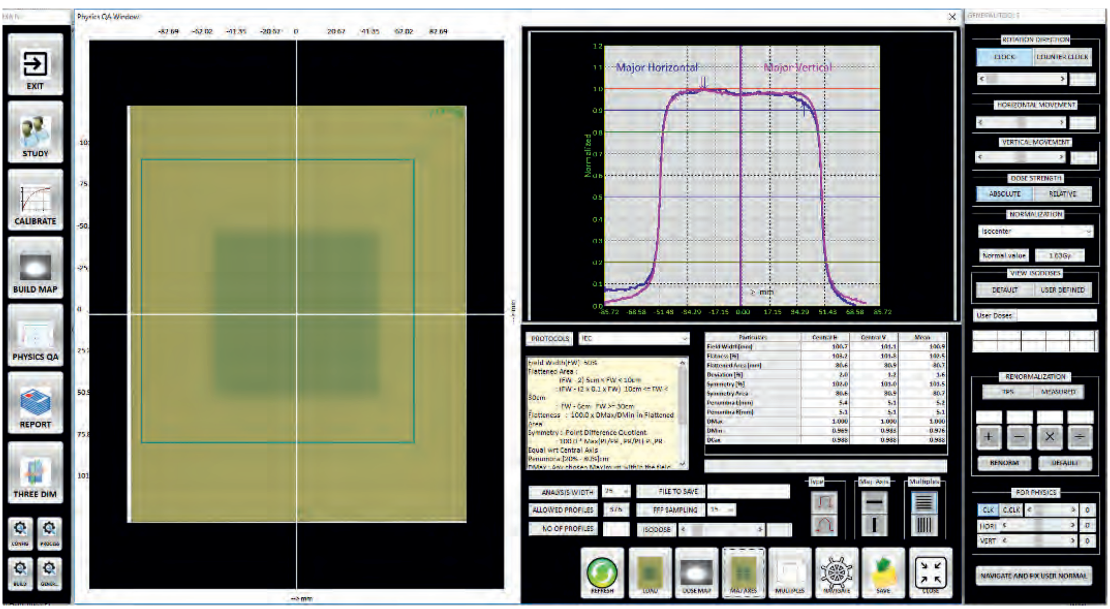


Figure 2: Screen shot showing physics QA features of the image based system.

2.2 Dosimetric phantoms for QA in diagnostics and radiotherapy

4D Dynamic Phantom (FDDP): Four-dimensional radiotherapy (4DRT) is capable of correcting the error in dose delivery under respiratory induced tumour motion, taking into account the temporal changes of anatomy during the imaging, planning and dose delivery. The 4D dynamic phantom (Figure 3(a)) is developed to carry out quality assurance for 4D computed tomography and 4DRT dose delivery system [1]. The phantom body represents average human thorax in shape and size. The lung is represented by a cylinder, which has provision to hold different types of detectors at the planning target volume (PTV) site which represents the tumour.

The 3D motion (up-down, left-right, and front-back) of the PTV can be mimicked through linear, translation and rotational motion of the lung equivalent rod controlled through a graphical user interface (GUI) based control software. There are three different replaceable lung-inserts representing (i) PTV of varying sizes, (ii) PTV with provision to hold miniature ionization chamber, and (iii) PTV to hold radiochromic films (Figure 3(b)).

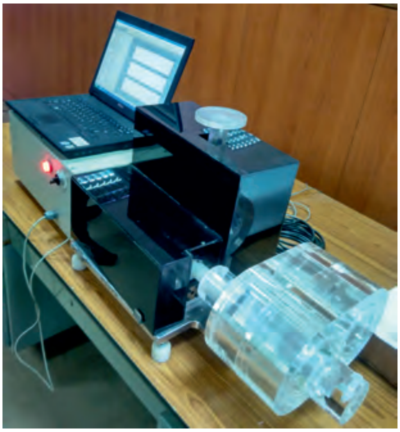


Figure 3(a): 4D dynamic phantom and its control system

Figure 3(b): Replaceable lung-inserts representing PTV

ABS IMRT Phantom: The Acrylonitrile Butadiene Styrene (ABS) phantom is developed as a low-cost tissue equivalent phantom for pre-treatment dose verification in IMRT (Figure 4) [2]. It has provisions for holding ionization chambers, radiographic/radiochromic films, thermoluminescent dosimeters (TLDs), MOSFET and gel dosimeters. Its clinical applicability was tested for the IMRT treatment of prostate cancer in comparison to the commercially available solid water phantoms. The doses calculated with TPS and measured in ABS IMRT phantom and commercial IMRT phantom were found in agreement within ± 2%. Fluence maps and dose distribution of patients generated by the TPS and those measured in ABS IMRT phantom were found comparable, both numerically and spatially. This phantom has been used at a number of radiotherapy centers in the country for 1D, 2D and 3D dosimetry.

Computed Tomography Imaging QA Phantom: Computed Tomography (CT) is an imaging technique which provides sectional images by acquiring multiple projections at closely spaced

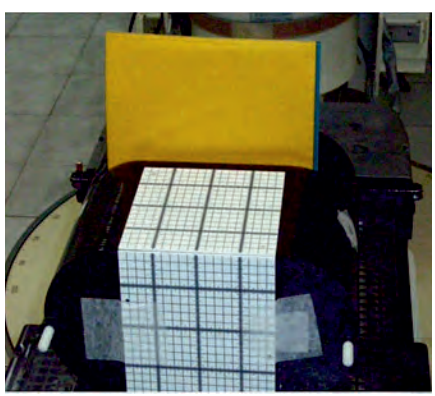


Figure 4: Photograph of ABS IMRT phantom with a dosimetry film placed in transverse plane.

angles which are reconstructed using various back projection algorithms. A comprehensive imaging phantom for performing QA tests of CT scanners was designed and fabricated locally (Figure 5). This phantom, suitable for evaluating the image quality parameters, consists of four cylindrical modules made poly methyl methacrylate (PMMA), each module being 4 cm wide and 20 cm in diameter. The first module is for evaluation of noise and uniformity of the CT imaging system, while the second module is to evaluate CT number linearity. The third module is for evaluation of high contrast resolution and slice thickness, while the fourth evaluates low contrast resolution.

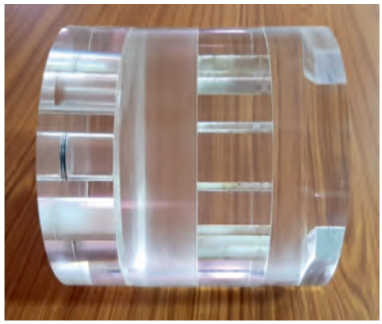


Figure 5: Photograph of the CT imaging QA phantom.

Mammography Phantom (Mammo-DOS): Phantom based measurements in diagnostic radiology, including mammography, are well established for quality assurance (QA)/quality control (QC) procedures involving equipment performance and comparisons of x-ray machines of different models [3]. PMMA is among the most suitable materials for simulation of the breast and hence a PMMA phantom, Mammo-DOS, was developed for imaging and dosimetry QA/QC of mammography systems (Figure 6) [3]. This is an inexpensive, tissue equivalent, TLD slot phantom that can be fabricated easily. It comprises of 10 nearly hemispherical slabs (each of thickness 5 mm) of different radii. The radius of the central slab is 10 cm, radius of other slabs decreases in steps of 5 mm as we go away from the central slab [3]. Every slab has 15 TLD slots, arranged as three slots in a row at five different locations. Its equivalence to commercial mammography phantoms has been established by various comparative studies [3]. Mammo-DOS will be very useful in periodic QA of mammography machines.

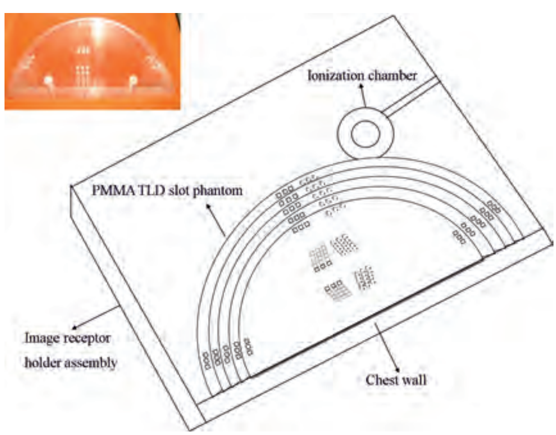


Figure 6: Photograph and schematic drawing of Mammo-DOS (PMMA slot phantom)

2.3 Dosimetric Standards for improved accuracy in diagnostics and radiotherapy

Reference Ionization Chamber for strength determination of brachytherapy sources: A cylindrical graphite ionization chamber of sensitive volume 1002.4 cm^3 is designed and fabricated (Figure 7(a)) for use as a reference ionization chamber [4, 5] to determine the strength of high dose rate (HDR) ^{192}Ir brachytherapy sources in terms of reference air kerma rate (RAKR). The air kerma calibration coefficient, N_K, was estimated for this chamber for the microSelectron HDR old/classic ^{192}Ir brachytherapy source analytically using Burlin general cavity theory and by the Monte Carlo method. In the analytical method, calibration coefficients were calculated for each spectral line of an HDR old/classic ^{192}Ir brachytherapy source and the weighted mean was taken as N_K. The reference air kerma rate (RAKR) was estimated with total photon energy fluence and mass energy absorption coefficients. The value of charge rate in the ionization chamber was simulated with energy deposition rates and N_K was determined. The value estimated by both methods was found to agree within 1.77 % [4].

The experimentally determined RAKR of HDR ^{192}Ir sources (as per the set up shown in Figure 7(b)), using this reference ionization chamber by applying the analytically estimated N_K, was found to be in agreement within 1.43% with RAKR quoted by the vendor. This ionization chamber can be used to calibrate the well type ionization chambers available at the hospitals and will help in enhancing the dose delivery to the patients treated by brachytherapy [4].

Figure 7(a): Photograph of the cylindrical graphite reference ionization chamber

Figure 7(b): Experimental set-up for determination of Reference Air Kerma Rate

Primary Standards for air kerma measurement for low energy synchrotron radiation and diagnostic x-ray beams: For the low and medium energy x-ray beams, the free-air ionization chamber (FAIC) is considered as the primary standard for the determination of air-kerma. Since the walls of the chamber do not influence the measurement of charge, the response of FAIC is energy independent.

Synchrotron radiation (SR, up to 25 keV) has the potential to override the limitations of insufficient spatial resolution, contrast and quantitative scaling as observed with conventional imaging methods, owing to its very high intensity beam and broad energy spectra. The SR source is available from INDUS-II high energy accelerator at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. A dedicated beamline [Beamline-4 (BL-4)] has been provided at INDUS-II offering facilities for both the conventional as well as advanced x-ray imaging experiments.

The SR beams as well as low kV diagnostic x-ray beams (up to 125 kV) used in the radiology departments of hospitals are needed to be standardized in terms of air-kerma. To fulfill this national requirement, a parallel-plate type FAIC has been developed as air kerma primary standard for SR [6] as well as diagnostic x-rays beams (Figure 8). This is an energy independent instrument which requires sufficiently large size for the air cavity and is larger than the range of secondary electron in air. The parallel-plate FAIC has a gap of 3 cm and 8.5 cm respectively between the high voltage electrode and the collecting electrode in order to avoid the loss of charged particle equilibrium. This FAIC can also be used to standardize the Beamline-4 (BL-4) at INDUS-II [6].

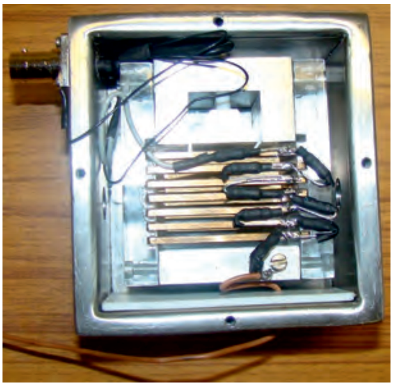


Figure 8 (a): Photograph of the parallel-plate type Free Air Ionization Chamber

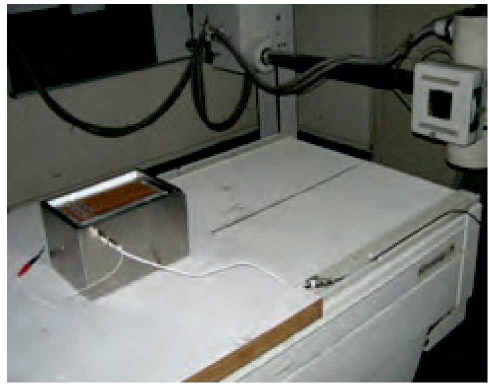


Figure 8(b): Experimental set-up for determination of air-kerma from diagnostic x-rays beam using FAIC.

2.4 Evaluation of radioprotective garments used in Radiology

X-ray imaging is an effective diagnostic tool, poses radiation hazards to the healthcare workers as well as patients if radiation protection practices are not followed. During the operation of x-ray machines, the professionals are recommended the use of radioprotective garments to minimize personal exposures. These protective garments are received from the manufacturers/suppliers for testing their adequacy for providing protection to the user. A dedicated x-ray laboratory consisting of quality controlled radiography x-ray machine (Figure 9 (a)) and test gadgets/tools are used for testing and evaluation of various samples received. The types of radio-protective garments tested include lead and lead-free aprons, thyroid collars,

Figure 9 (a): Experimental set-up showing medical diagnostic x-ray machine and the apron to be tested for its lead equivalence.

vests, skirts, gonad shields, gloves, head caps, lead glass, slabs and sheets (Figure 9 (b)). At times, these products are also used by the patient's comforter and for covering the vital body parts of the paediatric patient to minimize radiation risk to the critical organs.

A product having lead equivalence of 0.50 mm is able to provide approximately 95 % x-ray attenuation at 100 kV x-ray energy. Almost all personal radiation protective products used in radiology have lead equivalence in the range of 0.25 mm to 0.50 mm which provides x-ray attenuation in the range of 85 to 95% at 100 kV x-ray beam energy. Testing of these products is carried out to demonstrate the conformity of the radiation shielding effectiveness to the requirements stipulated by the international standard (IEC 61331-1).

Figure 9 (b): Radio-protective garments tested at x-ray laboratory of RPAD (Courtesy: M/s UniRay medical LLP, Navi Mumbai; M/s Horizon Healthcare Solutions, New Delhi; M/s Kiran Medical Systems, Thane).

3. Photo-neutron Dosimetry in Medical Linacs

In a medical linear accelerator (LINAC), electrons are accelerated to high energies and photons are generated in order to kill the malignant tumors, thereby treating the cancer. The energetic particles (energy ~ 10 MeV and above) striking the surrounding materials of the LINAC head of the accelerator, create neutrons due to various nuclear interactions [7].

During commissioning of high energy medical LINACs, the levels of photo-neutron is surveyed at different locations by the supplier. The quantification of infield neutron dose under various beam parameters are however are not carried out considering that it is within the specific limit with respect to photon dose. To study this, photo-neutron dose equivalents were estimated for various beam parameters used in therapy (10 MV and 15 MV photon beams and 9-22 MeV of electron beams) in collaboration with Tata Memorial Hospital and Advanced Centre for Treatment, Research and Education in Cancer (ACTREC), Kharghar, Navi Mumbai [7]. Plastic nuclear track detector (CR-39) and neutron sensitive thermoluminescecnt dosimeters were used for measurement of fast and lower energy neutron dose equivalent.

Figure 10 shows that neutron dose equivalent per unit photon dose due to fast neutron decreases with depth, whereas thermal neutron dose increases with depth, although the total neutron fluence increases with depth (2-3 cm). It implies that the normal tissues existing at different depths below and above tumor site may receive enough neutron dose [7]. Photo-neutron dose equivalent at a distance of 75 cm from the tumour is about 33% and can contribute significant neutron dose up to about 38 mSv to healthy tissue outside the treatment field [7, 8].

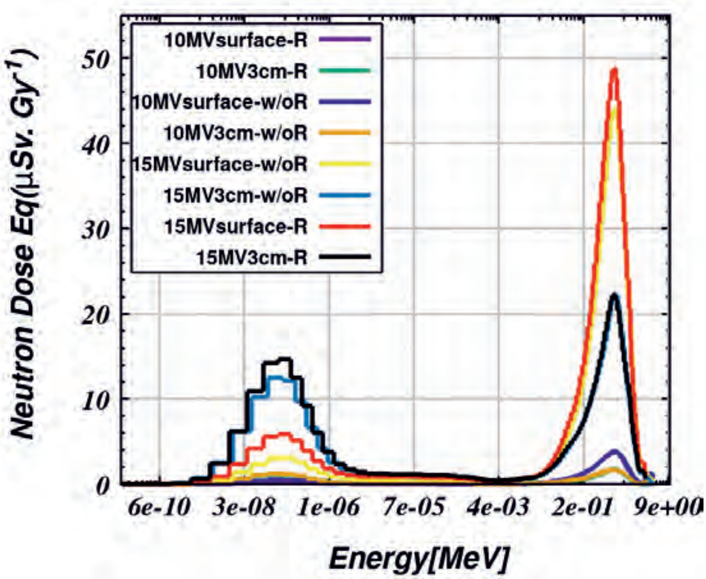


Figure 10: Variation of neutron dose equivalent for 10 and 15 MV photon beams with and without room at the patient plane and at 3 cm depth of the phantom (representing patient)

4. Dosimetric applications of Luminescence materials and techniques

In India, the dosimetry of occupational radiation workers is routinely carried out using passive methods employing Thermoluminescence (TL) technique as it is efficient and cost effective. TL is the emission of light (generally in visible range) during heating of an insulator/semiconductor material that was previously exposed to ionizing radiation. In TL, the heat energy acts as stimulation, while in the Optically Stimulated Luminescence (OSL) technique, the stimulation is carried out with light energy (generally blue or green). Since no heating is involved, OSL technique has some advantages over TL technique like faster readout, possibility of using any polymer as a binding material, multiple readout etc. The emitted light in both the techniques is a function (linear response is preferred) of dose which forms the basis of dosimetry.

4.1 Synthesis of Luminescence Materials

The materials which emit light after excitation by various sources like ionizing radiation, electrons, photons etc., are called as luminescence materials. These are synthesized by various techniques like solid state diffusion, chemical precipitation followed by sintering, sol-gel, single crystal growth etc. In the recent years, several sensitive OSL phosphors have been synthesized in BARC. Al_2O_3:C (Alumina), a standard OSL phosphor used worldwide for radiation dosimetry, was synthesized on a large scale using the melt processing technique. This method is protected under the US patent [9]. The OSL sensitivity and other properties of this phosphor are at par with the commercially available Al_2O_3:C (Landauer Inc.). $LiMgPO_4$:Tb,B is another OSL phosphor which is synthesized by solid state diffusion technique [10]. It has a sensitivity of about 5 times that of Al_2O_3:C with dose linearity up to 1 kGy. $LiCaAlF_6$:Eu,Y is also synthesized with OSL sensitivity of about 20 times that of Al_2O_3:C and minimum detectable dose of about 0.5 µGy [11].

4.2 Applications of Synthesized TL/OSL Materials

Clinical Dosimetry: Diagnostic radiology (e.g. X-ray exposure in mammography, dentistry and general health screening) and radiotherapy (cancer treatment) are the two areas of clinical dosimetry wherein accurate dosimetry is required for effective treatment outcomes. The primary requirement of a TL/OSL material to be used for clinical dosimetry is its tissue equivalency. High sensitivity is desirable so that the sizes of the dosimeters can be kept as small as possible for *in vivo* measurements. Moreover, since the doses involved can be quite high in radiotherapy, a linear dose response over a wide dose range is advantageous. OSL technique also offers 2D dose mapping and online measurement of dose/dose rates during radiotherapy with the help of optical fibres (Figure 11). Considering these requirements, $LiCaAlF_6$:Eu,Y, developed in-house, is a suitable candidate for its application in clinical dosimetry for online measurements of dose/dose rates, as it also exhibits radioluminescence phenomenon.

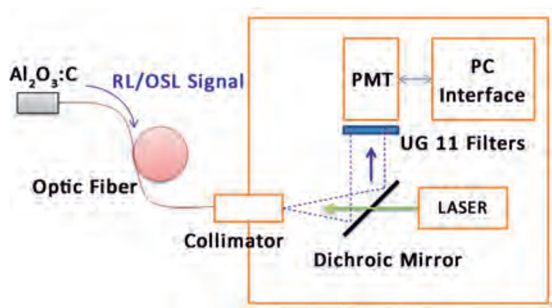


Figure 11: Schematic diagram of optical fibre based OSL set up

Retrospective Dosimetry: Retrospective dosimetry is the method by which dose can be estimated in the absence of conventional dosimeters such as film badge, TLD, OSLDs. This can happen in scenarios of accidental radiation exposures in case of nuclear power plants accidents, illegal dumping of radioactive waste and terrorist attacks with Radiological Dispersion Devices (RDD). This dosimetry technique uses fortuitous materials for dose evaluation to members of the public and is a useful tool for rapid triage of individuals needing medical attention. TL technique had been used for dose evaluation in Chernobyl, the Techa River (Russia), Hiroshima and Nagasaki (Japan) and the Nevada Test site (USA) accidents. Quartz, which is ubiquitous in soil and building materials, common salt, common medicinal tablets etc. have been studied and protocols are developed to measure dose using these materials in the retrospective dosimetry laboratory of RP&AD.

Environmental Monitoring: TLDs are very often deployed in places near nuclear installations for monitoring pre-operational levels (background levels) as well as levels above the natural background, which can be linked with the operation of these facilities. Since exposure levels in the environment are low, long exposure times are required, and thus, long-term stability of the signal becomes vital. However, if the dosimeters are highly sensitive, the exposure time can be reduced. Highly sensitive OSL material like Al_2O_3:C (Figure 12) and $LiCaAlF_6$:Eu,Y are relevant for this application. Portable, compact, battery operated TL/OSL reader systems can be installed at various places and used for environmental monitoring (Figure 13).

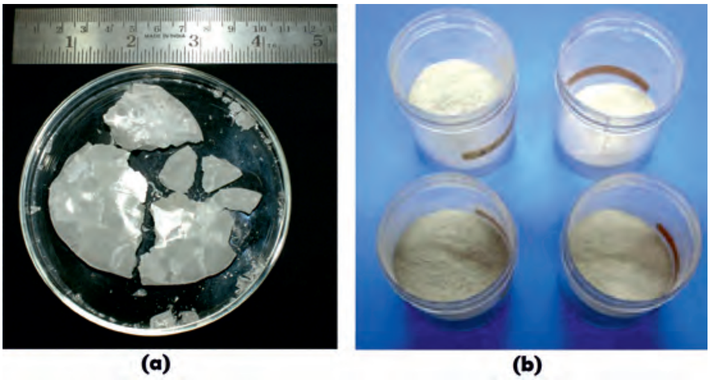


Figure 12: Carbon doped alumina in a) molten lump and b) powder

Figure 13: Battery Operated Portable TL Reader

Food Irradiation Dosimetry: Food irradiation is the treatment of food by ionizing radiation (gamma irradiation, electron beam and bremsstrahlung X-rays) carried out for food preservation by inhibition of sprouting of some vegetables (e.g. potatoes, onions, garlic etc.), postponing of ripening of some fruits (e.g. bananas, mangoes, papayas etc.), parasite and insect disinfestations [12]. It is also an effective technique for the control of food-borne diseases, retardation of spoilage and sterilization of food products [12]. For example, about 30 Gy is sufficient for inhibition of sprouting of onions and potatoes, about 800 Gy is required to kill the seed weevil in mangoes and about a few kilo Gray of dose is required for treating dry species and seafood. TL/OSL based dosimeters can serve as an alternate to the existing chemical and film based dosimeters used for assessment of doses. $LiMgPO_4$:Tb, B phosphor (LMP), developed in RP&AD, BARC has got advantages of simple synthesis technique, cost effective with readily available raw material and is amenable to large-scale production. A field trial using this phosphor was successfully carried out at KRUSHAK facility, Lasalgaon, Nashik, Maharashtra, for Onion and mango irradiation [12].

5. Biological Dosimetry

In scenarios such as suspected occupational excessive exposures, radiological incidents and malicious incidents involving radioactivity, where no physical information about the extent of exposure is available, biological dosimetry is the technique to estimate the dose received by exposed individuals by analysis of the whole blood sample collected from the individual. This method estimates the absorbed radiation dose using a biological response in an exposed individual. Various biological indicators are being used to measure, ascertain and confirm the radiation exposure. All these indicators have their own strengths and shortcomings and no single indicator is available which can satisfy all the requirements. Nevertheless, combinations or selections of various biodosimetry procedures can address most of the complex conditions of radiation exposure [13]. Often it becomes necessary to adapt multi-parametric approach to estimate exposure levels. A number of standard methods (based on cytogenetic changes on exposure to ionizing radiation) recommended by IAEA have been established at Radiological Physics and Advisory Division to facilitate biodosimetric evaluations and the expertise was well utilized in several small-scale radiation accidents including radiological incident at Mayapuri, New Delhi.

5.1 Dicentric Chromosomal Aberration (DCA) assay

This assay exhibits very good radiation specificity and is hence considered as the gold standard assay. It is based on identification of dicentrics, which are chromosomes with two centromeres created due to breaks and exchanges between different chromosomes. It has a minimum detectable limit of about 100 mSv and is applicable for estimation when doses are in the range of 0.1 to 4 Gy. For dose estimation, blood sample from individual with suspected exposure is collected and cultured for 48-52 h. The chromosomes are visualized under a microscope and the frequency of dicentrics is assessed and associated dose is obtained from standard calibration curve. Highly trained persons are required to detect and score dicentrics.

5.2 Micronucleus (MN) Assay

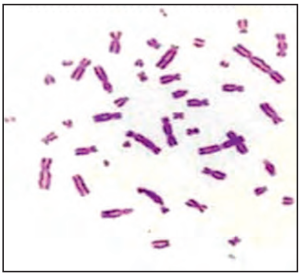
Micronuclei are small nuclei containing mostly fragmented chromosomes arising due to radiation exposure, however, non-specifically, thereby leading to a higher uncertainty compared to DCA. Dose estimation can be done in the range of 0.25 - 4 Gy. However, scoring can be done by untrained personnel too, in case large number of samples need to be scored for triage purpose [14].

5.3 Fluorescent in-situ Hybridization (FISH)

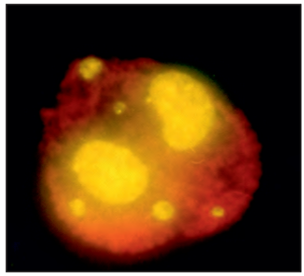
This is a tool by which specific region or whole chromosome can be fluorescently painted. Whole chromosome painting of two or more chromosomes is performed which allows identification of chromosomal translocations. Reciprocal translocations are most suitable markers for *retrospective dosimetry* of past exposure, including *cumulative exposure* over a long period of time. The method is also being used for bone marrow dose estimation of thyroid cancer patients receiving radiotherapy of active Iodine. ***Pseudo Pelger-Huet Anomaly*** is another marker being studied in Thyroid Cancer Patients. PHA is a morphological anomaly in neutrophil nuclei caused by mutation in bone marrow cells. Frequency of cells with PHA is associated with radiation dose. With multi-color FISH (*mFISH*), it is now possible to paint all the chromosomes together in 23 different colors allowing inter-chromosomal exchanges in whole genome. *mBAND* is another similar advanced method in which regions of a chromosome are painted in different colors so that any rearrangement within it can be identified. These intra-chromosomal rearrangements are signature of high LET radiation.

5.4 G0-Premature Chromosome Condensation (G0-PCC)

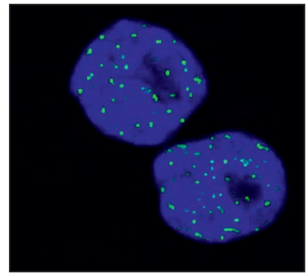
In this method, lymphocytes isolated from blood are fused to mitotic cells. Factors in the mitotic cells lead to premature chromosome condensation in resting phase (G0-Phase) lymphocytes without requiring 48 h of culture. Hence, dose estimation is rapid with results available within the same day after blood collection [15, 16]. It has a detection range of 0.3-20 Gy. It is most suitable method for *high dose accidental exposures* and dosimetry of *non-uniform exposur*e where conventional gold standard method does not work.



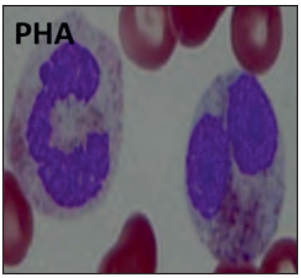
Dicentric Gold Standard assay in Metaphase



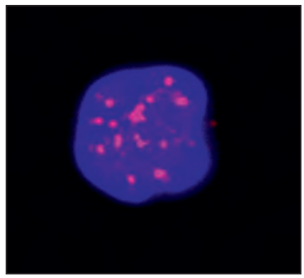
Micronucleus Assay in Bi-nucleated Lymphocytes



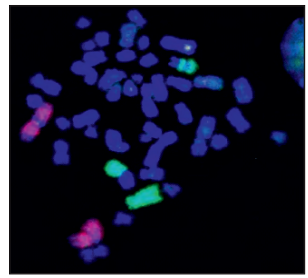
Gamma H2AX foci Assay in Lymphocytes



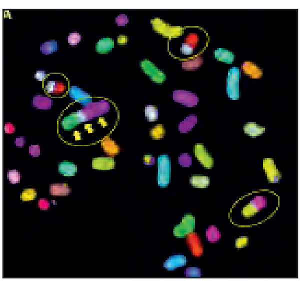
Pseudo Pelger Huet Anomaly assay in Neutrophils



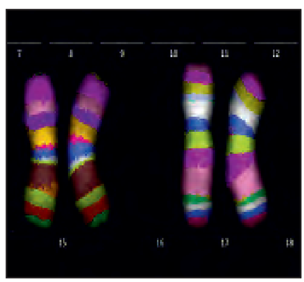
ATM/53BP1 Foci Assay in Lymphocytes



Whole chromosome painting FISH in Metaphase chromosomes 1&2

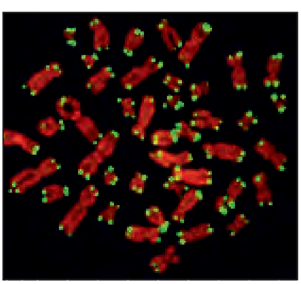


Multicolor FISH in Metaphase Chromosomes

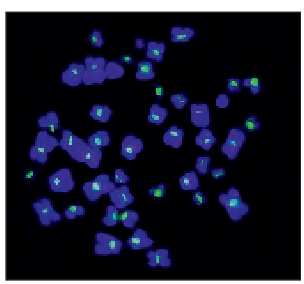


mBAND FISH in Metaphase chromosomes 1 & 2

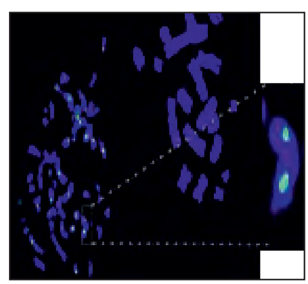
mBAND FISH in G0-Phase Chromosomes



Telomere Staining in Metaphase Chromosomes



Centromere FISH staining in metaphase Chromosomes



Centromere FISH in G0-Phase Chromosomes (Dicentric enlarged)

Figure 14: Microscopic images showing various biodosimetric techniques

5.5 GammaH2AX, 53BP1, ATM Foci assay

These are proteomic markers which appear inside cells in response to DNA damage induced by radiation. These markers appear within hours after exposure and then gradually decay during next 24 to 48 h as the repair is completed. The method is useful for triage of a large number of samples as scanning and scoring of foci is automated and requires a very small number of cells to be analyzed. However, due to decay of signal, it requires blood collection within limited time window after exposure. These markers make a great application for dosimetry of planned exposures planned clinical radiation exposure.

The Biodosimetry lab has established state of the art facilities with high throughput capabilities and developed a team of skilled manpower. The research studies being addressed include complexities in nature of radiation accidents such as non-uniform exposures, protracted exposures with varying dose rates, chronic exposure, life-style type confounding factors and retrospective or follow up assessments. The lab has also trained many national institutes to establish a national network of accredited laboratories. Medical applications of the developed techniques are also being explored.

6. Radiation Dosimetry at Antarctica

Antarctica is protected under the Antarctic Treaty, as a natural reserve dedicated to peace and science and is the world's largest natural laboratory, devoid of anthropogenic radiation. After the establishment of Indian station Bharati, Antarctica in 2012, BARC has participated in four expeditions (35^{th} to 38^{th}) conducted by National Centre for Antarctic and Polar Research (NCPOR), Goa. Radiological Physics and Advisory Division (RP&AD) BARC has conceived and executed the project with the objectives of radiation dosimetry of cosmic rays and terrestrial background, measurement of terrestrial radioactivity in soil, rock, water and snow samples and continuous measurement of gamma and neutron dose rate by installing on-line instruments inside Bharati station.

6.1 Cosmic ray dosimetry

Figure 15 (A & B) show the Photographs of Bharati Station at Antarctica and the radiation monitoring laboratory set up by BARC inside Bharati station. Under the cosmic ray dosimetry programme, radiation levels due to cosmic rays and terrestrial radioactivity both inside and outside Bharati station were measured by REM counters and Tissue equivalent proportional counter (TEPC) Indian Environmental Radiation Monitor (IERMON) and RADEYE G gamma survey meter. Continuous measurement of radiation level inside Bharati station is being

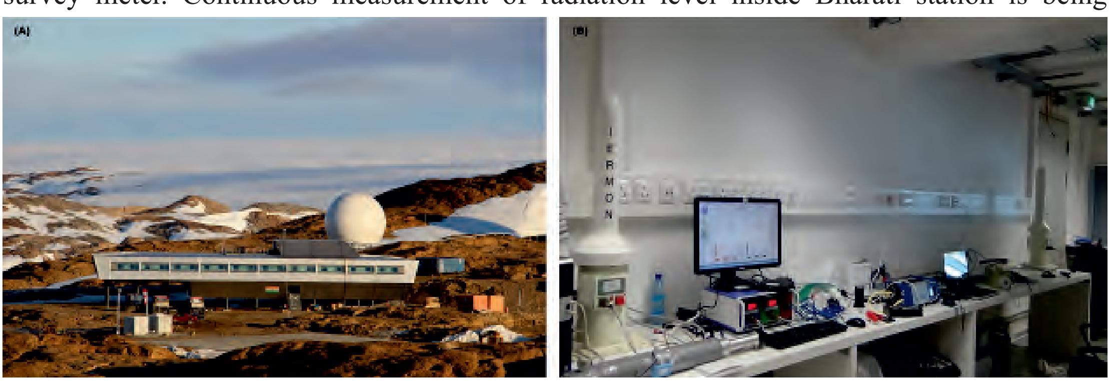


Figure 15: Photograph of (A) Bharati station (B) Radiation monitoring laboratory at Bharati station

continued using online monitoring system with the help of NCPOR and Indian Institute of Geomagnetism (IIG). Results of measurements indicate that the gamma and neutron dose rate varies between 100-160 nGy/h (10-16 R/h) and 10-22 nSv/h, respectively [18].

6.2 Measurement of terrestrial natural radioactivity

Measurement of terrestrial activity such as ^{238}U, ^{232}Th and ^{40}K were carried out in soil, rock in and around Bharati station, Antarctica. In addition to this, measurement of radioactivity concentration of ^{3}H (Tritium) and Uranium in lake water and snow samples collected from different locations around Bharati was also carried out. (Figure 16 shows the bar diagram of radioactivity concentration of all the three natural radionuclides present in soil samples collected from different islands around Bharati station along with world and Indian average values. The radioactivity concentration of ^{232}Th and ^{40}K in the soil around Bharati station are higher by a factor of about 5 and 2 with respect to world average and is attribute for higher gamma radiation level in that region [17]. Concentration of radioactivity of ^{3}H (Tritium) and Uranium in lake water and snow samples were found to well within the recommended limit of WHO for water.

Figure 17 depicts the involvement of various components of natural radiation to the total dose equivalent using a pie chart [18]. Bakshi et al. reported that the total dose equivalent received by the members of the Indian Antarctica Expedition can be up to 1.90 mSv during six months [18]. This value (1.90 mSv) is substantially large as compared to half yearly global average background radiation (0.44 mSv) (terrestrial: 0.24 mSv and cosmic: 0.20 mSv) [18]. It is however noted that all the activities depicted in Figure 17 may not be carried out by single expedition member. The total dose equivalent received by an individual during his/her stay including air travel will therefore be much lower than 1.90 mSv during summer [18].

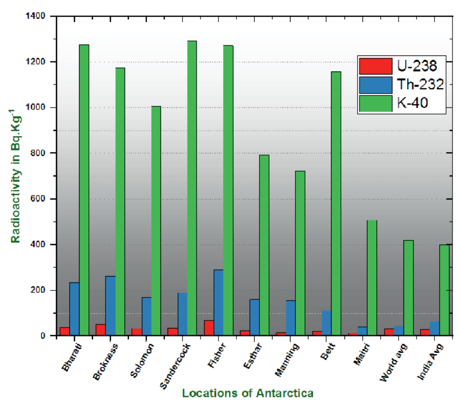


Figure 16: Radioactivity concentration (Bq/kg) in soil in different Islands around Bharati along with India and World average

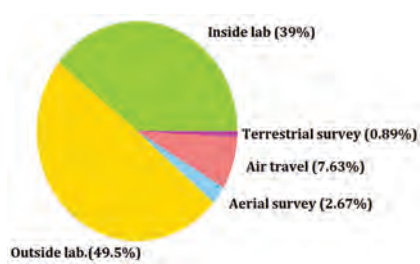


Figure 17: Contribution of dose due to different components of natural radiation to expedition members

7. Direct Economic Gains

Radiological Physics and Advisory Division (RP&AD) of BARC is responsible for carrying out country-wide personnel dosimetry of about 2 lakh active radiation workers all over India. Currently $CaSO_4$:Dy based TLDs are used as personnel dosimeters. Direct revenue generated through personnel monitoring service for medical and industrial applications of radiation is about Rs. 110-120 lakhs per annum. RP&AD also provides free personnel monitoring service to all personnel at BARC facilities, which otherwise would have incurred a cost of about Rs. 50-60 lakhs per annum. Due to the various advantages offered by OSL technique, concerted efforts are on to replace TLD with OSLD based personnel monitoring system with about same investment and similar cost of processing per OSLD badge. Currently, dosimeters used in food irradiation dosimetry in various irradiation facilities are imported. Once the OSL based dosimeter and related instrumentation systems are developed and put into practice, the cost towards import of these dosimeters will be eliminated.

RP&AD also conducts testing and certification of protective accessories (Protective aprons, gonad shields, protective goggles, gloves, protective research samples, etc.) used in diagnostic radiology and the total revenue generated per annum is about Rs. 1.5 lakhs. This activity has high societal impact and hence these testing are conducted at nominal rate. Development of phantoms and their application in medical applications will also generate a revenue of about Rs. 10 lakhs per annum.

8. Conclusion

With a wide variety of applications of radiation in our daily lives, it is of utmost importance to assess accurately the radiation doses for these applications. Most of the times, the effects expected in humans or materials being studied are dose dependent. Any deviations in the doses delivered could have severe implications in terms of the damages caused. Also, it is necessary to follow the strict guidelines and radiation protection principles to ensure that the regulatory compliance is met for all operations. This is imperative to derive maximum benefits from radiation applications.

Contributors from RP&AD, BARC

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