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Thermoluminescence Dosimetry (TLD) and its Application in Medical Physics

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Abstract. Radiation dosimetry is fundamental in Medical Physics, involving patients and phantom dosimetry. In both cases thermoluminescence dosimetry (TLD) is the most appropriate technique for measuring the absorbed dose. In this paper thermoluminescence phenomenon as well as the use of TLD in radiodiagnosis and radiotherapy for in vivo or in phantom measurements is discussed. Some results of measurements made in radiotherapy and radiodiagnosis using home made LiF:Mg,Cu,P+PTFE TLD are presented.

INTRODUCTION

Radiation dosimetry is fundamental in the applications of the radiation and radioisotopes, especially in Medical Physics. Ionizing radiations most used in diagnosis and radiotherapy are X-rays, gamma radiation and beta particles; however, high-energy electrons, heavy particles and neutrons are used in the major medical centers.

Dosimetry in Medical Physics involves the patients and phantom dosimetry as well as that for the occupationally exposed personnel and the environmental monitoring in hospitals. In the former case, radiation exposures are intentional in order to obtain a direct benefit to the patient's health; then, the radiation field is well defined. Its purpose is to evaluate the risk or the effectiveness of the radiation exposure. In the other cases the aim is to verify the observation of the radiation protection regulation.

This type of measurements are carried out more conveniently by using thermoluminescent dosimeters (TLD), based on the thermoluminescence (TL) phenomenon, which consists in the fact that certain previously irradiated solids emits light when heated at a temperature below its incandescence temperature. This phenomenon is named thermally stimulated radioluminescence; however, for historical reasons(1), it is known as radiothermoluminescence o simply as thermoluminescence (TL).

The general mechanism for explaining the TL phenomenon is as follows: when a crystalline material is irradiated it suffers alterations in its structure due to ionization; during this process electrons are liberated from the crystal lattice generating two

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types of mobile carriers: electrons and holes. Both charge carriers are able to trip along the crystal until be trapped in the crystal defects generating color centers.

Electrons and holes remain trapped until enough energy is supplied for liberating them returning the crystal to its original state before the irradiation. When this occurs, electrons and holes release the excess of energy emitting photons of visible light. If this energy is supplied by heating the crystal, the TL phenomenon is produced(2); this energy is known as activation energy or trap depth.

Until date, there is not a complete theory to explain this phenomenon. However, there are some models trying to explain it by using three main elements: recombination centers, mobile carriers or charge carriers, and traps. In addition, the electronic energy band model is used(3), assuming the existence of energy excited states in the forbidden band. These energy states, having a relatively long lifetime (metastable states), are due to defects in the crystalline lattice of the material and can play the role of traps or recombination centers.

Ionizing radiation can supply the energy for creating the mobile carriers (electrons and holes). The electrons are transferred from the valence band to the conduction band, meanwhile, the holes remain in the valence band when the electrons are transferred to the conduction band.

These charge carriers wander along the crystal lattice until they recombine or they are trapped in metastable states. Later, during the heating, electrons and holes are released from their traps to wander along the crystal until they recombine emitting a visible light photon. Due that the light emission process involves the evacuation of some traps at different energies, the mobile carrier is released at different temperatures giving rise to a glow curve which is characteristic of the material and can exhibit one or more peaks.

The importance of this phenomenon for radiation dosimetry is due to the fact that the amount of light emitted is proportional to the dose absorbed by the irradiated material(3).

The number of radiative recombinations in a TL material is proportional to the number of trapped ions, consequently to the number of electron-hole pairs created by ionization. Finally, the emitted luminescence is proportional to the absorbed dose. Besides, it has been demonstrated that the amplitude or the area under one peak, at a constant heating rate, is proportional to the total number of ions captured in the traps. So, the area under the glow curve is representative of the luminous energy released. This property is used by the most of the TL readers in which the measurements are made based on the total emission of one or more glow peaks. This fact makes possible that TL material can be used as dosimeters in the range in which their TL response is linear as a function of dose.

Then, the readout of a TL material is very simple and direct. In a relatively short time (a few seconds or minutes), the material must be heated from an initial temperature in the range of 50 to 100°C until approximately 300°C measuring quantitatively the light emitted, commonly using a photomultiplier tube.

TL dosimeters exhibit certain characteristics, which make appropriate for using them for in vivo or in phantom dosimetry. One of the most important characteristics of TLDs is their small size which allows to be adhered to the patient without causing it discomfort or interfering with its movement. Furthermore, it is not very probable that TLDs produce an image on the radiographic film that could provoke interference whit some useful diagnosis information.

These advantages contrast with the use of ionization chambers, which commonly are greater than TLDs and require a permanent connection to an electronic system. Consequently, it is difficult to be adhered to the patients limiting severely the movement of the patient and causing great interference with the radiographies.

Other characteristics of TLDs, which make appropriate for dosimetry are the following:

1) Good tissue equivalence
2) Low fading
3) High sensitivity
4) Good precision and accuracy
5) Good stability under standard environmental conditions (temperature and humidity)

Due that radiodiagnosis and radiotherapy use diverse types of radiation and several dose levels, different characteristics for the TLDs are required to be used either in radiodiagnosis or radiotherapy(4).

RADIODIAGNOSIS

The doses applied to patients undergoing radiodiagnosis are not very controlled as in radiotherapy because the result of a radiological examination does not depend on the dose as much as a therapeutic exposition.

In radiology, the pertinence of an exposure is determined by the quality of the image and rarely a strict control of the exposition is required because it is more important the benefit obtained by improving the diagnosis that the radiation risks.

However, clear evidence exists, in practice that the doses received by patients submitted to the same type of radiological examination vary very much from one patient to another. In addition, medical radiology contributes very much to the collective dose of the population.

Optimization of the radiodiagnosis requires the evaluation of the effectiveness of the diagnosis as well as the measurements of the absorbed dose of the patients. So, it is necessary to have criteria for establishing the image quality required to make the diagnosis sure and to determine the dose to the patient.

Dosimetry must be directed to:

a) Establish that the doses received by the patients are in accordance with the optimal performance of the equipment (as a part of the quality control program)
b) Compare the doses among different equipments and techniques for optimizing the design and performance of new equipment.
c) Estimate the risk to the patient.

The most appropriate TLD to be used in radiodiagnosis must have the following characteristics(4):

1) Available in the appropriate physical form
2) Tissue equivalent

3) Low fading
4) Accuracy (± 10% from 100 μGy to 1 Gy)

RADIOTHERAPY

The successful application of the ionizing radiations in therapy requires to give high doses within a well defined volume in order to kill all the malignant cells injuring as less as possible the surrounding tissues. To get this objective it is necessary to know the doses received by radiosensitive organs as well as by tumors into the patient.

Often it is not possible to measure the dose at an organ or tumor directly due the obvious obstacles for introducing dosimeters into the patient. In this case the dose can be calculated taking into account the appropriate models of the anatomy of the patient anatomy as well as the radiation field parameters from measurements on the skin of the patient.

It is essential that the dose imparted is very much accurate, because inadequate tumor regressions have been observed when the dose is 5% below the prescribed dose; meanwhile, if the dose exceeds the prescribed value, an unacceptable injury to the normal tissues can occur.

The modern treatment methods used in radiotherapy are computerized; then, the depth dose data for different geometries of the radiation field and for given equipment as well as the anatomic data of the patient, are stored in the computer memory. However, even using these sophisticated treatment plans, the possibility of error is not excluded.

It is important to verify these theoretical treatment plans by making direct measurements of the dose. Fortunately, the fractionated nature of the most of the radiotherapeutic exposures, which administrate the doses daily along several weeks, allows us to verify *in vivo,* the dose administrated during the treatment and consequently its rectification, if it is necessary.

The small size of the DTLs is an advantage even greater in radiotherapy than in radiodiagnosis, due that in the former one there is the possibility of placing the dosimeters within the patient either intracavitary or in implants.

The TLD most appropriate for radiotherapy(4) must have the following characteristics:

a) Available in the appropriate physical form
b) Tissue equivalent
c) Low fading
d) Accuracy (± 3% from 10 mGy to 10 Gy)

Good tissue equivalence at energies below 100 keV is relevant only in superficial radiotherapy due that, in this case, x-rays in the range of 10-50 keV are used, although high-energy electrons can be used too.

Commonly, in radiotherapy it is required an accuracy level greater than in radiodiagnosis, but at dose levels very much higher. So, a very high sensitivity is not required. Lithium fluoride, because of its dosimetric characteristics and its tissue and air equivalence, is one of the most appropriate TL to be used in medical applications of ionizing radiation$^{(5)}$.

Dosimetry can be carried out directly on the patient or in phantom; the former is accomplished placing the dosimeters, in the sites of interest for the physician, either on the skin and/or into the patient. Meanwhile, the phantom dosimetry is effectuated in order to know the dose distribution when it is not possible to insert the dosimeters into the patient. In this case, the patient is simulated by means of a deposit filled with water or by a dummy made of wax/paraffin or any other tissue equivalent material.

Phantom measurements$^{(6)}$ are carried out, in order to simulate the treatment for diverse individuals, placing the dosimeters at different depths given by the interest points in the patient. This method is used for determining depth dose percentages, for which it is necessary to generate the corresponding isodose curves inside a phantom. In order to obtain the dose distribution in the patient, it is necessary to use a number of analytical expressions and to do many calculations. For this reason it is convenient to use automated methods for processing the data obtained from the measurements.

"In vivo" dosimetry is performed placing the dosimeters in the points of interest on the patient, either to measure the entrance or exit dose, the effectiveness of the protections at points distant from the radiation field such as gonads in young patients affected by breast cancer. This information is valuable because it is possible to use it for modifying the treatment plan or for controlling its quality.

Other type of *"in vivo"* applications are the intracavitary measurements, such as the rectum dosimetry in the case of intrauterine implants; due that if the implant is not made in the appropriate form, the dose at the rectum could be raised at levels such that can produce rectitis $^{(6)}$.

Our working group has performed measurements in radiodiagnosis as well as in radiotherapy using LiF:Mg,Cu,P+PTFE TLDs developed in Mexico for the group itself. In all cases dosimeters were readout using a TL analyzer Harshaw model 4000 coupled to a PC. The TL signal is digitized by means of two channels of an *interface RC232C* at a heating rate of de 10°C/s and an acquire time of 30s. The light emitted was integrated in the temperature range of 100 to 240°C. All readings were made under nitrogen atmosphere. After readout, the TLDs were submitted to an annealing at 240°C during 10 seconds in order to be reused. Previously to use the dosimeters were annealed and cooling down to room temperature.

Some of the research works of our group, in which TLDs were applied in Medical Physics, are the following:

UROGRAPHY AND HISTEROSALPINGOGRAPHY

Effective dose in gonads, mammas and thyroid of patients submitted to urography and histerosalpingography studies was estimated by measuring the dose using TLDs; meanwhile, the dose at eyes, thyroid, hands and total body was measured for the physician.

To measure the patient dose two TLDs were placed at the right as well as at the left-hand side on gonads, mammas and thyroid. To measure the dose for the radiologist dosimeters were placed on eyes, thyroid and hands; meanwhile, to measure total body dose, the dosimeters were placed under the leaded apron. After each examination, the dosimeters were stored in a lead box and then read out at the next day.

Results show that doses received by patients are similar to those reported in the literature(6). In the case of the radiologist, the dose is lower than the limits established for occupationally exposure personal.

COMPUTED TOMOGRAPHY

Due that it is not possible to measure directly the dose distribution in a patient submitted to computed tomography examinations, it is necessary to use the computed tomography dose index (CTDI) measured in air. The CTDI is a useful tool to describe the absorbed dose in computed tomography(7). To get this objective a cylindrical phantom is used placing the dosimeters in its central axis. The dose profile obtained by this technique provides information about the collimation of the CT as web as the scattered radiation which affects the dose received by the patient:

Previously to obtain the CTDI, it was necessary to determine the radiation beam quality by measuring the half value layer (HVL) in a type of material; in this case aluminum. These measurements were performed using a dosimetric arrangement consisting on TLDS surrounded by aluminum 1100 layers, in order to obtain the same irradiation conditions among the different scanners studied. The HVL was taken equal to 5.5 mm aluminum for 120 kV.

The CTDI for thorax examinations in the CT scanners of the Mexican Republic was determined by obtaining first the dose profile which was measured placing the TLDs spaced 5 mm among them at the central axis of a polimetil metacrilate (PMMA) phantom of 30 cm width and 15 cm thickness.

Results obtained show that the computed tomography scanners at the center of the country provide the lowest effective dose which is similar to that reported by the U. K. National Radiological Protection Board for chest examinations(8).

BRACHYTHERAPY

Brachytherapy using low dose rate ^{137}Cs sources (<1 Gy h^{-1})(9) is used in most of the cases for the cervical-uterine cancer treatment. Protocols for dose prescription in any case are based on the knowledge of the physical characteristics of the radiation source as well as on the geometry of the dispensers according to the anatomy of the patient. A limiting factor in the brachytherapy treatments is the radiation absorbed dose that could be received by the rectum and bladder. The intracavitary implantation, as that used in low dose rate brachytherapy treatment planning, using the Manchester system, is based on sources, which are considered fixed; i.e. it is assumed that the arrangement of the sources does not change during the treatment.

However, the experience has shown that the sources can be displaced respect to their original position owing to the patient movements during treatment. In turn, this could change the dose previously prescribed in the point of interest as well as in the surrounding tissues. The prescribed doses vary in the range from 25 to 40 Gy originating long application times of about 30 to 55 hours. This very long irradiation time provokes patient movements during the treatment and then, as a consequence, displacements of the sources and large variations in the absorbed doses. These variations may be so important that a dose re-calculation can be needed. Furthermore, some damage can be given to the surrounding organs.

In this case the absorbed dose in rectum and bladder of the patients submitted to low dose rate ^{137}Cs brachytherapy treatments using the Manchester system were measured using TLDs.

Brachytherapy treatments were carried out at 11 women from 45 to 70 years old, affected by cervical-uterine cancers. The ^{137}Cs sources were introduced using the Fletcher-Suit inserters, by placing into an intrauterine sounder two or three sources with activities between 1388 and 1850 MBq. Besides, in each colpostate were placed one source of 2313 MBq. Using these sources arrangements dose rates in the range from 0.55 to 1.11 Gy/h were obtained in the A points of Manchester. The doses originally prescribed were in the range from 25 to 40 Gy, performing the treatments for periods in the range of 23 to 45 hours.

To make "in vivo" measurements in the bladder, TLD's were placed into a Foley sounder; meanwhile to make measurements of the absorbed dose in rectum, the TLD's were placed into a Nelaton sounder. Due to the very long-time treatments, it was initially planned to make measurements for periods of one hour, at the beginning and at the end of the treatment. However, it was noted that the presence of the dosimeters during this period was annoying for the patient. For this reason it was decided to make measurements for periods of only 20 minutes at the beginning and during 20 minutes before the end of the treatment. All the experimental arrangements of the TLD's into the patients were the same along the measurements. In order to check the position of both sources and TLD's, radioscopy examinations were taken at the beginning and at the end of each treatment.

These results confirm that the dose in bladder at the beginning of the treatment is higher than that in the rectum. This is an indication that the dose prescribed originally is being conducted correctly to the treatment of the cancer in question. However, as the treatment time is elapsed, the position of the sources is displaced considerably from their original position due to the movement of the patient. This provokes finally that the rectum receives the higher dose (until six times that initially prescribed dose) causing possibly irreversible damages to the patient. For this reason it is strongly recommended that the arrangements of the sources must be checked twice.

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