Recent achievements in external radiation dosimetry

Antonio Delgado

CIEMAT, Radiation Dosimetry Unit, Avda. Complutense 22, 28040 Madrid, Spain
antonio.delgado@ciemat.es

Abstract.
Some of the more relevant recent achievements and developments in the field of external radiation dosimetry are reviewed in this presentation. Among them, topics related to personal dosimetry, as the relative role of active and passive methods and the features of some recently proposed new methods. Electronic personal dosemeters and Optically Stimulated Luminescence, OSL, have already accredited their adequacy for practical work, their features and performance are compared with more conventional methods as TLD. The special situation of personal dosimetry for the protection of the staff in complex interventional radiology procedures, is also commented. Underestimations as well as overestimations of the effective dose are to be avoided without a clear solution for the moment respect to the number and position of the personal dosimeters. Some recent recently results published related to single and double dosimetry are discussed. The situation of neutron dosimetry, both area and personal, is reviewed following the recently published results obtained by a European research consortium (Evidos). While the situation of area dosimetry is more or less comfortable, personal methods still present drawbacks and limitations particularly with respect to the energy dependence of response. The impact of computational methods for practically every area of dosimetry is another topic included in this Key Note that finishes with some reference to the new 2007 ICRP recommendations regarding the dosimetry system.

Introduction

The dosimetry of external radiation is in general a mature discipline after many decades of continuous development. Actually, the measurement needs of a rather extended range of applications are well covered, permitting an adequate control of the doses to people, radiation workers in particular and the environment.

Along the years new necessities have emerged associated to new uses of radiations in medicine, research, and industry, creating new challenges to dosimetry. Among others space exploration, new accelerator technologies broadening the range of particles or ions for cancer treatments, or the general requirements for a more precise and accurate dosimetry even in more conventional applications, are some of the activities marking the development of the dosimetry methods and techniques.

Since the last IRPA congress in Madrid, four years ago, it is possible to identify some working lines deserving to be highlighted. Of the various possibilities, a few have been selected for comments in this Key Note by mere personal and subjective criteria, no doubt other choices would be equally possible. Alternative methods for individual dosimetry including electronic personal dosimeters for photons, neutron dosimetry, personal dosimetry for medical radiology workers, computational methods in dosimetry, are the selected topics to be commented. In addition, some comments on the radioprotection dosimetry system with reference to the new 2007 ICRP recommendations will be included. No changes are proposed with respect to quantities and units and the dual system including protection and operational quantities is maintained. Nevertheless, it is to be noted the emphasis made in the 2007 recommendations respect to the limitations in the use of the system. These limitations will be briefly commented in this Note.

Alternative methods for individual dosimetry

Thermoluminescence dosimetry, a passive method, is still by far the more often employed method for personal dosimetry. As it is known, in the last decade electronic, active, personal dosimeters were developed and promoted as a more convenient alternative to passive dosimetry, mainly due to their ability to assess individual doses caused by specific operations, thus giving useful information for the optimization of the working procedures. This is an advantageous feature over passive dosimetry that, on the contrary, can only give the integrated dose over the exposure interval or the average dose rate.

Initially electronic dosimeters were in many cases presented as an alternative to passive dosimetry that potentially will replace it. Nowadays after more than ten years of use the real situation is that both methods peacefully coexist. Each one with its characteristics more or less convenient/inconvenient depending on the type of application considered, so it is possible to appreciate some kind of specialization, with passive detectors employed as the baseline system and electronic detectors employed in situations were doses are more likely to occur. Nevertheless, there are services that have moved to electronic personal dosimetry fully. The situation respect to the legal authorisation of electronic dosimeters for individual dosimetry varies from country to country and is not going to be commented here in detail, although it seems that more and more countries are accepting them, as is the case of the UK, France or Germany for example.

The technology for electronics dosimeters and their dosimetric performance are nowadays rather mature as demonstrated by very recent overview studies (1) and also by the results of some intercomparison exercises (2). Table I reproduced from reference 1, presents a comparison of some technical characteristics of APDs and TLDs respect to the requirements of the IEC 61526.

Table 1. Technical characteristics of APDs and TLDs for beta, gamma and neutron personal dosemeters compared with IEC 61526 requirements.

Characteristic	IEC 61526 requirement	Typical values for APD	Typical values for TLDs
Size	<250 cm^3	100 cm^3 (31/31)	15 cm^3
Mass	<200 g	80 g (31/31)	50 g
Mechanical resistance	±10%, 1.5 m hard-tiled surface	Some APDs do not pass the test (~26/31)	No problem
Environmental immunity	±10%, 100 V m^{-1} at 100 kHz – 500 MHz and 1 V m^{-1} at 500 MHz – 1 GHz	Old APDs used to have problems (~28/31)	No problem
Effective range of Measurement	1 µSv – 1 Sv	1 µSv–10 Sv (25/31)	10 µSv – 1 Sv
Photon radiation fields (33 keV–2 MeV)	Dose equivalent, ±15%	(50 keV – 2 MeV) (11/31)	33 keV – 2 MeV
Beta radiation fields ($^{90}Sr/^{90}Y$, ^{204}Tl)	Dose equivalent, ±15%	(4/31)	$^{90}Sr/^{90}Y$ (90%) ^{204}Tl (70%)
Neutron radiation fields	-35 to +122% (100 keV – 15 MeV -35 to 200% (0.025 eV – 100 keV)	Only fulfilled in limited energy regions [10]	-50 to +100% in workplaces with field-dependent correction factors

In parentheses, the number of APDs that comply with the requirements are indicated

In general the performance of APDs for photon radiation are comparable or even better than TLDs respect to the lower dose limit, reported to be of the order of 1µSv, in comparison to the 10µSv estimated in Table I for TLDs. It is my impression that some high sensitivity TLDs can also be able to measure such low doses if it were necessary. The response of APDs at lower energies is not completely satisfactory. The situation for beta (extremity dosimetry) and neutron radiation fields is not good and both TLDs and APDs present problems, although those of APDs seem to be more important and difficult to solve.

Mechanical resistance is one of the less convenient features of APDs, cost is another not favourable point as APDs are more expensive than TLD systems, although considerations have to be made not only to initial costs, but also to running costs and durability and replacement costs that can be different for both systems. A point that seems to be not well resolved, important for dosimetric reliability, is in connection with calibration and testing procedures that apparently are far from to be well harmonised for APDs. This is one of the conclusions of an also recent study developed in the EURADOS Action on harmonisation of individual monitoring for external radiation in Europe (3).

The main advantage of APDs over PPDs resides in their capability to provide direct dose readings and in the possibility of alarm features. Both characteristics are very convenient as they favour the analysis of the working and safety conditions in situations or activities where doses are incurred, optimizing protection measures and eventually reducing the doses to the workers. Thus, APDs are more directly applicable for the implementation of ALARA principle in specific or punctual situations than passive dosimeters giving only the integrated dose.

In addition to technical aspects, practical aspects are also of consideration to determine, in the specific circumstances of a personal dosimetry service, which kind of technology, or better, in what proportion both technologies should be employed. An experience shared by many personal dosimetry services is that a substantial proportion of the controlled workers have a dose history

composed of nil or very low doses above background. So there is little or nothing to optimize from the point of view or radiation safety in their working places and so little or nothing would be gained using APDs for these workers. In situations where significant doses were not improbable APDs can be justified, and also as an investigation dosimeter in support of passive dosimetry if doses above the established investigation limits have been detected. This is just the way in which we are using TLDs and APDs in CIEMAT, TLD as a base method, APDs when investigation is required. This is so because for the moment only the TLD system is authorised for official dosimetry, nevertheless we do not foresee problems to achieve a similar authorisation also for our APDs.

Hence, the actual situation regarding APDs and PPDs can be presented not as two competing technologies disputing the field of personal dosimetry but instead collaborating for a better control of the doses of radiation workers.

OSL

It is clear that passive dosimetry still has a good role to play in personal dosimetry, and the fact is that new passive methods are proposed from time to time, among them one that has reached practical feasibility is the Optically Stimulated Luminescence Dosimetry (OSLD). Still recently a world wide dosimetry service (Luxel, Landauer) started to offer personal dosimetry services using OSL and Al_2O_3 detectors. Personal dosimeters and OSLD readers are also available commercially. The marketing of OSLD systems present them as the personal dosimetry method for the 21st century.

TLD, or more appropriately TSLD, Thermally Stimulated Luminescence Dosimetry, and OSLD, Optically Stimulated Luminescence Dosimetry are sister techniques. Similar trapping, detrapping and radiative recombination processes of the charge carriers liberated by exposure to ionizing radiation in the solid material forming the dosimeter, are the base or the fundament of the method. The difference is in the way the detrapping and subsequent recombination is stimulated, thermally in the case of TLSD and optically in the case of OSLD. OSLD is thus a fully optical method and apparently this is the origin of the reported advantages over TSLD. Reproducible heating is complicate to achieve and in addition can induce structural changes in the materials leading to sensitivity changes, causing unwanted irreproducibility in the dose response.
A relatively recent debate (2003) on the advantages and disadvantages of OSL and TLD has been published in Radiation Protection Dosimetry (4). The summary of the debate indicates that TLD has been established for many decades as a successful dosimetric method and that "it is difficult to imagine how any new technique could easily supplant it." It is also suggested that OSL should not be considered as an entirely new technique, but "an evolution of the well established technology that may be considered superior in some aspects."

A comparison of the reported characteristics, from a practical point of view, does not seem to reveal a definite superiority of OSL over TLD. OSL is applied to personal dosimetry using a single material Al_2O_3:C, and higher sensitivity than TLD is reported, but there are many different TL materials for dosimetry and some of them, the so called hypersensitive materials, as LiF:Mg,Cu,P can be equally sensitive. In any case, material sensitivity is not a problem for TL personal dosimetry in the usual one month exposure intervals. At the same time, LiF based TL dosimeters because of their intrinsically good tissue equivalence have a rather good energy dependence. Al_2O_3:C, on the contrary, has a poor energy dependence. This problem can be corrected, but at the price of worsening the low energy cut-off and also the angle dependence of the dosimeter response.

OSL is a non destructive method, as only a small fraction of the trapped charges is freed by the stimulation light, so the OSL dosimeter can be re-read many times, up to 15 times has been reported (4). TLD is considered a destructive method, as readout implies heating up to relatively

high temperatures emptying all the traps lying within that temperature interval. Nevertheless, in this point it should be remembered, that as was convincingly demonstrated (5), dose re-estimation is also possible for some TL materials, as LiF.Mg,Ti, using UV-phototransferred thermoluminescence (PTTL). Certainly PTTL is a more complicated process than the simple repetition of the OSL measurement process. As far as I know PTTL dose re-estimation has never been implemented in practice, probably because the real and practical interest of this possibility is not very high.

OSL is an all-optical process, heating is not required as in TL. Heating has some critical aspects complicating reproducibility. Practical problems as thermal contacts or the difficulty to keep clean the dosimeters, and more importantly intrinsic problems as thermal quenching of the radiative emission efficiency or sensitivity changes induced during heating by modification of the traps distribution. For TLD stability of response can only be achieved if all the stages of the thermal readout and annealing are reproducibly applied. OSL, not requiring heating, avoids all this sort of problems. Hence, it is plausible to assume that stability of response can more easily be achieved by OSL than by TLD. It would be interesting to compare both methods in the exigent conditions of environmental dosimetry, involving long exposure intervals, up to three months and high ambient temperatures, up to 40ºC, or even higher temperatures taht can be reached during environmental exposures. The incidence of fading/sensitivity changes for the two methods deserves to be studied. Up to now and as far as I know this study has not been conducted yet.

In summary, OSL is a splendid new possibility increasing the range of options for personal dosimetry. OSL seems to offer somewhat improved characteristics over TLD, a robust and well proven method accredited by many decades of successful use. Both solid state based dosimetry methods will probably in the future share the market of passive or integrating dosimeters for personal and environmental dosimetry.

Personal dosimetry in interventional radiology

Interventional radiology procedures may involve significant doses to the medical staff applying them in close proximity to the patients. Conventional personal dosimetry procedures based in the readings of a single dosimeter exposed on the front of the torso and measuring Hp(10), cannot be directly applied as the conditions in which Hp(10) can be assumed to be a reliable estimation of the limiting quantity effective dose, E, are not fulfilled. Exposures in X-rays radiology are not uniform and in addition workers usually wear protective clothing, lead aprons and other protective devices as thyroid collars, rendering more complex the decision on where on the body the personal dose has to be measured and what value should be registered, as it is clear that the direct measurement of a personal dosimeter cannot be taken as a reliable estimation of E and that correction factors should be applied.

It is not completely clear where to place the dosimeter or even if a single dosimeter is sufficient (6). The dose readings of an unshielded dosimeter placed above the lead apron will lead to an important overestimation of E, while if the dosimeter is place under the apron then E would be underestimated as not all regions and organs of the body are shielded in the same extent as the under apron dosimeter. Depending on the energy and irradiation geometry overestimations as high as a factor 60 for unshielded dosimeters or underestimations of factor up to 7 for shielded dosimeters have been reported. If underestimations cannot be accepted because of the inadequate protection they signify, excessive overestimations are also undesirable as then, as indicated in (6), there is the risk that the dose limits were falsely reached, and the workers unnecessarily separated form doing their job, with negative consequences for the workers and for the efficiency and the economy of the health services.

As a very recent overview study (7) conducted by EURADOS within the EU countries has shown there is not consensus, nor harmonisation on the dosimetric procedures employed for the

interventional radiology workers. Single dosimeters can be employed either above or below apron, using a range of different correction factors or algorithms depending on the X-ray procedure. Double dosimetry, combining the readings of dosimeters placed below and above the apron are perhaps gaining acceptance and in fact is the procedure recommended by ICRP in publication 85 (8) and by NCRP in report No 122 (9). A number of algorithms for double dosimetry have been published, up to 14 are reviewed in (7).

Monte Carlo (MC) codes and mathematical anthropomorphic phantoms have been employed for the development of algorithms both for single and double dosimetry and for a variety of interventional procedures. The simulation of the patient and doctor permitted to obtain reliable values for E caused by scattered radiation. These values can be compared with also simulated Hp(10) values estimated at different positions on the body and above or under shielding. Experimental studies using TL detectors in different organ positions in anthropomorphic Rando Alderson phantoms were also conducted permitting to compare E values deduced from organ doses with determinations of Hp(10) on different positions on the phantom surface. Both MC based calculations and TLD measurements were the approaches employed to derive dose algorithms and to estimate their performance for the calculation of sufficiently representative E values.

Intensive effort has been devoted to the dosimetry of workers in interventional radiology with many papers published in the past recent years. Despite of it, there is not agreement on a particular approach, and some authors even question the advantages or the superiority of double dosimetry over single dosimetry (10) as it seems possible by using appropriate algorithms to obtain comparable E values. There are other evidences indicating that single dosimetry algorithms are more prone to produce, in some cases, underestimations of E than double dosimetry, so recommending the use of double dosimetry and the associated algorithms (10).

In what there is good agreement is in the necessity of further work, experimental and computational, particularly for some more critical procedures in interventional radiology to try to get more reliable methods of estimating representative values for E.

Neutron Dosimetry

Neutron dosimetry is a permanently open field of research because of its intrinsic complexity. Neutrons interact with tissue through different processes for the different energy ranges, presenting different radiobiological efficiency with energy. This leads to a strong dependence with energy of the conversion coefficients from fluence to personal or ambient dose equivalent, dependence that up to now none of the various neutron dosimetry systems can reproduce satisfactorily. In addition, the usually broad range of neutron energies present in practical situations, where neutrons are always mixed with an important photon radiation component, is another source of complications. The situation is that there are, particularly for personal dosimeters, important response variations for different neutron spectra, so a precise dosimetry requires some knowledge of the neutron field to be measured in order to introduce field specific correction factors or alternatively to use calibrations as close as possible to the real fields to be measured. Another approach is to develop dosimetry systems with some spectrometric capabilities able to automatically correct for the response variation.

Recently the results of the European Union research project EVIDOS were published (11, 12). The project main objective was to perform a comprehensive evaluation of the different personal and area dosimetry methods in the mixed neutron-photon field characteristics of workplaces in the nuclear industry (reactors, transport casks and fuel reprocessing fields). As none of the actual dosimeters can provide correct results in all neutron field the project devoted especial attention to the development of fluence to dose equivalent conversion factors for different specific workplaces as a function of energy spectra and directional dependence. In addition,

attention was given to the development of reference methods for the determination of the personal dose equivalent.

Figure 1 presents some data reported by the EVIDOS project (13). The response of different neutron personal dosimeters is presented for four different types of neutron fields, namely a simulated workplace (CANEL), reactor fields, transport casks fields and at a fuel reprocessing facility. The response of eleven dosimeters is presented including commercial devices and also new prototypes: HpSLAB, and PTB DOS 2002. Electronic, Bubble, PADC and TLDs were included in test. The reference value was obtained from measurements using novel methods of directional spectrometry in each of the workplaces.

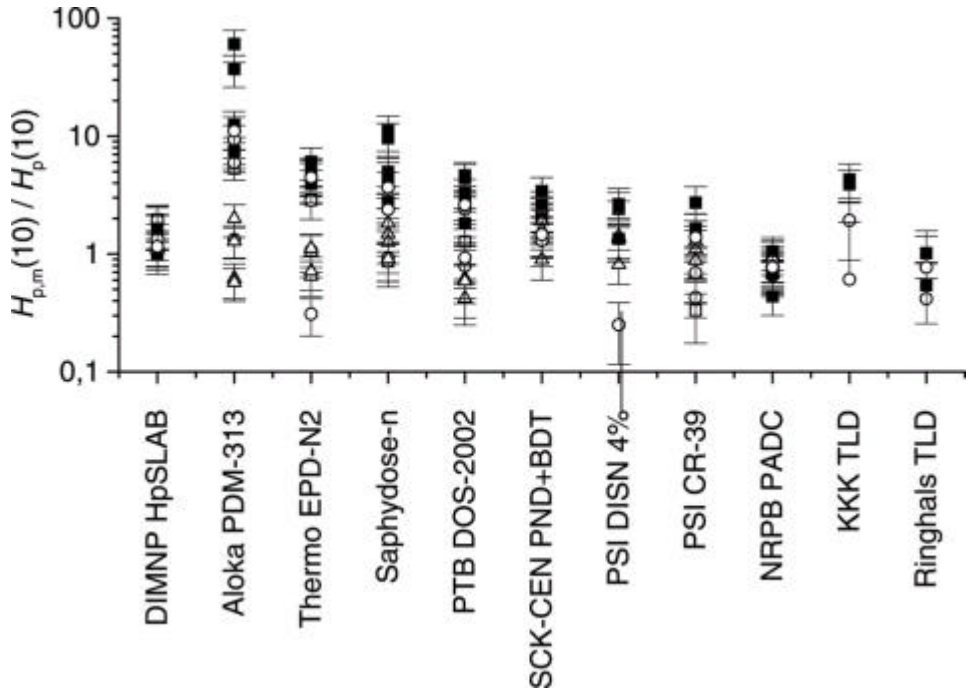

FIG. 1. Response of different personal dosemeters in the simulated workplace field CANEL (?), the reactor fields (¦), the fields at transport casks (?) and the fields at the fuel facility Belgonucleaire (?)

The spread of responses for the different workplaces is high. The lowest variation, a factor 2 or 3, is obtained for the superheated drop and the PADC detectors, and the highest for a particular electronic detector with two order of magnitude variation among the different workplaces. For the rest of the electronic dosemeters tested, response varies by a factor of ten or so. In general the response values observed in reactor fields are higher than those found at casks and reprocessing neutron fields. Therefore, an immediate conclusion is that the situation can be improved by the use of field, or workplace, dependent correction factors, or by the use of realistic calibration fields depending on the characteristics of the workplace to be measured.

Some other conclusions can be obtained from the EVIDOS project. In general the performance of neutron electronic personal dosemeters is not found to be superior to passive methods, except perhaps for the higher sensitivity they present allowing the measurement of comparatively lower doses: a minimum measurable dose of 20µSv with a statistical uncertainty of 10% in reactor fields has been reported (12). Another interesting result is the promising good performance of the HpSLAB device, a superheated drop detector placed a 10mm depth inside a slab phantom. It promises to be a good reference instrument for Hp(10). At present such reference instrument for personal dose equivalent does not exist.

The spread of responses is not so important for area monitors (12). These instruments provide in general with a moderate overestimation the quantities Hp(10) and E, lying most of the cases ranging between a 0,5 and 1,5. (instrument readings divided by the adopted reference value).

Neutron dosimetry, particularly personal dosimeters, still requires improvement. New designs are frequently proposed some of them with promising preliminary results as reported by the EVIDOS project. For this development it is important to count with reference values for H*(10) and Hp(10), this seems to be possible by the use of new methods of directional spectrometry.

Computational Dosimetry.

Computational methods are playing a progressively more important role in practically every area of radiation dosimetry, external, as well as internal. Monte Carlo methods together with mathematical phantoms simulating rather precisely the human body permit to calculate dose distributions in organs and tissues in an ample range of irradiation geometries and for different radiation fields. In addition the simulation of detector responses is also of great help for the development of new dosimeters and to characterize the response in terms of physical, operational or limiting quantities.

For radiation protection, the possibility of estimating the effective or the organ equivalent dose, the non measurable protection or limiting quantities, is a major advance. It is possible to obtain reliable values for E and H starting from a field characterization in terms of the type of radiation, the energy and directional distributions, and the fluence or absorbed dose values in a well defined point, i.e. starting from robust and well defined physical quantities. Good examples of such calculations are the previously commented activities of interventional radiology and also neutron dosimetry, where E, the operational quantities and also the detectors response can be obtained by computational dosimetry methods.

Patient dosimetry is also benefited from computational methods, permitting to calculate accurate dose distributions and also the contribution of scattered radiation. Among many others, a good example is the estimation of the contribution of photoneutrons in radiotehrapy treatments with high energy photons (14). The simulation of the treatment unit, using patient anthropomorphic mathematical phantoms in combination with measurements in physical phantoms in well characterised photon beams, permitted to calculate neutron and photon organ doses and the effective dose, E. For a prostate treatment with a total tumor dose of 70 Gy, the total effective dose, due to scattered radiation, photons and neutrons, was estimated as 1 Gy, of which only 16% is due to neutrons. According to the risk factors actually accepted, this means a total risk increase to develop a secondary tumor of 5%, of which 0.65% is due to photoneutrons (15).

Computational methods are also helping the development of more fundamental areas of dosimetry as micro and nanodosimetry. The energy deposition events in tissue volumes of nanometric dimensions can be simulated for different radiations, permitting to obtain interesting results on the track structures, the ionization density, and the associated specific energy distributions for different radiations. These research lines can help to improve the understanding of the mechanisms leading to the different biological effectiveness of radiations and even to the variation of this effectiveness as certain radiation types traverse the human body, heavy ions for example. More accurate radiation weighting factors for nuclides with complex decay schemes or emitting low energy Auger X-rays can be calculated using Monte Carlo codes. These calculations are the only possibility for some internal radionuclides bound to cellular structures. The Proceedings of the last Microdosimetry Symposium (16) includes many papers dealing with computational methods applied to microdosimetry.

2007 ICRP Recommendations

In the main text but more specifically in the scientific ANNEX B of the 2007 ICRP recommendations (17), the radioprotection dosimetry system is revised. Apart from justified and punctual changes in the values for some of the weighting factors, for neutron and proton radiations and for tissues, the structure of the dosimetry system remains unaltered. It includes body related protection quantities, the equivalent dose and the effective dose, and in addition operational quantities intended for monitoring purposes and providing with generally convenient estimations of the not directly measurable (but calculable) protection quantities.

Emphasis is given in the Recommendations to the limitations for the application of effective dose. Effective dose was defined, and is being satisfactorily employed, only for regulatory purposes, to demonstrate compliance with dose limits and for dose record. It is not considered appropriate, see section B.5.8 Application of Effective Dose, in (16), for the assessment of causation of cancer, assessment of tissue reactions (deterministic effects), or for the assessment of doses associated to medical treatments. In addition, effective dose is not considered adequate for the retrospective assessment of occupational doses where "a limit or constraint" could have been exceeded, instead it is considered more appropriate to make "specific individual estimates of dose and risk".

In spite of the real success of the actual dosimetry system, it seems that it is only valid for trivial doses not requiring any investigation. The thought comes if for such doses the really complex dual system is fully justified or if other simpler approaches can be at least imagined.

References

1. Ginjaume, M., Bolognese-Milsztajn, T., Luszik-Bhadra, M., Vanhavere, F., Wahl, W. and Weeks, A. Overview of Active Personal Dosemeters for Individual Monitoring in the European Union. Radiat. Prot. Dosim. 125, 261-266 (2007).
2. Butterweck, G., Zimmerli, H.P. and Wernli, C. Comparison Test of Electronic Personal Dosemeters. Radiat. Prot. Dosim. 96, 109-112 (2001).
3. Kamenopoulou, V., van Dijk, J.W.E., Ambrosi, P., Bolognese-Milsztajn, T., Castellani, C:M., Falk, R., Fantuzzi, E., Figel, M., Garcia Alves, J., Ginjaume, M., Janzekovic, H., Kluszcynski, D., López, M.A. , Luszik-Bhadra, M., Olko, P., Stadtmann, H., Vanhavere, F., Vartiainen, E., Wahl, W., Weeks, A. and Wernli, C. Aspects of Harmonisation of Individual Monitoring for External Radiation in Europe: Conclusions of a Eurados Action. Radiat. Prot. Dosim. 118, 139-143 (2006).
4. McKeever, S.W.S. and Moscovitch, M. Topics under Debate: On the Advantages and Disadvantages of Optically Stimulated Luminescence Dosimetry and Thermoluminescence Dosimetry. Radiat. Prot. Dosim. 104, 263-270 (2003).
5. Delgado, A., Gomez Ros, J.M., Muñiz, J.L. and Portillo, J.C. Application of Glow Curve Análisis methods to improve TLD-100 Dose Reassessment Performance. Health Phys. 62 (3), 228-238 (1992).
6. Schultz, F.W. and Zoetelief, J. Estimating Effective Dose for a Cardiac Catheterisation Procedure with Single and Double Personal Dosemeters. Rdait. Prot. Dosim. 118, 196-204 (2006).
7. Overview of Double Dosimetry Procedures for the Determination of the Effective Dose to the Interventional Radiology Staff. Radiat. Prot. Dosim. 129, 333-339 (2008).
8. International Commission on Radiological Protection: Avoidance of Radiation Injuries from Medical Interventional Procedures. ICRP Publication 85. Ann. ICRP 30(2) (2000).
9. National Council on Radiation Protection and Measurements. Use of Personal Monitors to Estimate Effective Dose Equivalent to Workers for external exposure to Low-LET Radiation. NCRP Report No 122 (1995).

10. Schultz, F.W. and Zoetelief, J. Dosemeter Readings and Effective Dose to the Cardiologist with Protective Clothing in a Simulated Interventional Procedure. Radiat. Prot. Dosim. 129, 311-315 (2008).
11. D'Errico, F., Bartlett, D., Bolognese- Milsztajn, Boschung, M., Coeck, M., Curzio, G., Fiechtner, A., Kyllönen, J.E., Lacoste, V., Lindborg, L., Luszik-Bhadra, M., Reginatto, M., Schuhmaker, H., Tanner, R. and Vanhavere, F. Evaluation of Individual Dosimetry in Mixed Neutron and Photon Radiation Fields (EVIDOS). Part I: Scope and Methods of the Project. Radiat. Prot. Dosim. 125, 275-280 (2007).
12. Schuhmaker, H., Bartlett, D., Bolognese- Milsztajn, Boschung, M., Coeck, M., Curzio, G., D'Errico, F., Fiechtner, A., Kyllönen, J.E., Lacoste, V., Lindborg, L., Luszik-Bhadra, M., Reginatto, M., Tanner, R. and Vanhavere, F. Evaluation of Individual Dosimetry in Mixed Neutron and Photon Radiation Fields (EVIDOS). Part II: Conclusions and Recommendations. Radiat. Prot. Dosim. 125, 281-284 (2007).
13. L., Luszik-Bhadra, M., Bolognese- Milsztajn, Boschung, M., Coeck, M., Curzio, Derdau, D., D'Errico, F., Fiechtner, A., Kyllönen, J.E., Lacoste, V., Lievens, B., Lindborg, Lovefors Daun, A., Reginatto, M., Schuhmaker, H., Tanner, R. and Vanhavere, F. Summary of Personal Neutron Dosemeters Results Obtained Within the EVIDOS Project. Radiat. Prot. Dosim. 125, 293-299 (2007).
14. Becker, J., Brunckhorst, E. and Schmidt, R. Photoneutron Production of a Siemens Primus Linear Accelerator Studied by Monte Carlo Methods and a Paired Magnesium and Boron Coated Magnesium Ionization Chamber System. Phys. Med. Biol. 52, 6375-6387 (2007).
15. Vanhavere, F., Huyskens, D., Struelens, L. Peripheral Neutron and Gamma Doses in Radiotherapy with an 18 MV Linear Accelerator. Radiat. Prot. Dosim. 110, 607-612 (2004).
16. Microdosimetry. Proceedings of the 14th International Symposium on Microdosimetry. Radiat. Prot. Dosim. Special Issue, vol 122 1-4 (2006).
17. International Commission on Radiological Protection: Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, Ann. ICRP 37(2-4) (2008).