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THERMOLUMINESCENT DETECTORS APPLIED IN INDIVIDUAL MONITORING OF RADIATION WORKERS IN EUROPE—A REVIEW BASED ON THE EURADOS QUESTIONNAIRE

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Among the activities of EURADOS Working Group 2 formed by experts from several European countries is the harmonisation of individual monitoring as part of radiation protection of occupationally exposed persons. Here, we provide information about thermoluminescent detectors (TLDs) applied by the European dosimetric services and the dosimetric characteristics of dosemeters in which these detectors are applied. Among 91 services from 29 countries which responded to the EURADOS questionnaire, 61 apply dosemeters with TLDs for the determination of personal dose equivalent $H_p(10)$ for photons and beta radiation, and 16 services use TLDs for neutron albedo dosemeters. Those most frequently used are standard lithium fluoride TLDs (mainly TLD-100, TLD-700, Polish MTS-N and MTS-7, Russian DTG-4), high-sensitive lithium fluoride (GR-200, MCP-N) and lithium borate TLDs. Some services use calcium sulphate and calcium fluoride detectors. For neutron dosimetry, most services apply pairs of LiF:Mg,Ti TLDs with ^{6}Li and ^{7}Li. The characteristics (energy response) of individual dosemeters are mainly related to the energy response of the detectors and filters applied. The construction of filters in dosemeters applied for measurements of $H_p(10)$ and their energy response are also reviewed.

INTRODUCTION

In the 1960s and 1970s individual dosimetry techniques based on thermoluminescent detectors (TLDs) were intensively developed in many European countries and frequently implemented to routine dosimetric services(1). TLD dosimetry has been already commercialised in the 1970s by a few companies worldwide, which offered complete dosimetric systems including systems with automatic TLD readers. This led to certain unification of equipment and techniques in the West European countries but the radiation protection regulations were created on a national basis. An attempt to unify the radiation protection regulations within European countries was undertaken in the framework of the EURATOM directive 23/96(2) by introducing, e.g. common operational quantities, dose limits, etc. Up to 1990, dosimetric services in Central and Eastern Europe developed in a certain degree of isolation, resulting from the political division of Europe and sometimes suffered owing to financial weakness. For these reasons many countries were applying their own systems of individual dosimetry, frequently based on self-developed TLDs. Some modernisation of equipment, especially in services working for Nuclear Power Plants, took place after the Chernobyl accident with international support and because of the technical co-operation programme of the International Atomic Energy Agency (IAEA)(3). The studies on the status of the dosimetric services in Central and Eastern Europe were also undertaken in the frame of 5th Framework Programme of European Commission(4).

One of the aims of the European Dosimetry Group (EURADOS)(5), an organisation that associates institutions and scientists involved in research on dosimetry in Europe, is strengthening co-operation and harmonisation of radiation protection. In the year 2000 an overview of dosemeters and dosimetric services, within the European Union (EU) Member States and Switzerland, which were able to estimate external radiation doses in the form of personal dose equivalent, $H_p(d)$, was prepared by the EURADOS Working Group and published in a special issue of *Radiation Protection Dosimetry*(6). Information for the compilation of that report was obtained from questionnaires sent to dosimetric services. Over the years 2001–2004 this same EURADOS questionnaire was distributed among dosimetric services in the EU candidate countries and other European countries, in order to obtain information on dosemeter design, photon dose calculation, background subtraction algorithms, energy and angle dependence of dosemeter response, calibration sources, performance and quality assurance. The full report providing the data obtained form this questionnaire was published in 2005 as a special report in *Radiation Protection Dosimetry*(7).

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The aim of this paper is to summarise information collected from these questionnaires on types and characteristics of thermoluminescence dosemeters applied by those services, which might be useful for the harmonisation of radiation protection within Europe. The energy response of individual dosemeters is mainly related to the energy response of the detectors, and algorithms, used to calculate dose from the reading of several detectors and filters applied. It will be demonstrated that most services in Europe, applying TLDs, are able to measure doses in terms of personal dose equivalent, H_p(d). The discussion on the properties of the dosimetric systems and the dosemeters design does not imply any comparison of the quality of the systems. Therefore, in this paper, the dosimetry performance of the services listed is presented in anonymous form to avoid any comparison between particular dosimetric services.

DETECTORS

Owing to historical and economical reasons, most individual dosimetric services in Europe using dosemeters based on TLDs are small and medium size services, which operate typically for >10 000 radiation workers. Among 91 services from 29 countries, which responded to the EURADOS questionnaire between 1997 and 2003, 61 services apply dosemeters with TLDs for the determination of personal dose equivalent H_p(d) for photons and beta radiation, and 16 services use TLDs for neutron albedo dosemeters. The other services are applying dosemeters based on dosimetric films, track etched detectors and radiophotoluminescent detectors. The list of applied TLDs is given in Table 1. More than two-third of the services are using lithium fluoride LiF:Mg,Ti detectors (mainly TLD-100, TLD-700, MTS-N and MTS-7) read in Harshaw/ThermoElectron and RADOS/Dosacus TL readers. The other most frequently applied detectors are $Li_2B_4O_7$:Cu and $CaSO_4$:Dy (used with Panasonic system), LiF:Mg,Cu,P and $Li_2B_4O_7$:Mn,Si.

In neutron albedo dosimetry, pairs of TLDs with different sensitivity to thermal neutrons are applied, exploiting enhanced cross section for (n,α) reactions with ^{6}Li or ^{10}B. Among 25 services, which provided neutron dosimetry service, 16 were applying pairs of ^{7}LiF/^{6}LiF detectors, mainly TLD-700/TLD-600 and MTS-7/MTS-6. Among the 31 200 radiation workers monitored with individual neutron dosemeters, 20 000 workers were usually from the nuclear industry. Energy response of albedo dosemeters is poor for energies above a few MeV and cannot be applied for higher neutron energies, e.g. around high-energy accelerators.

The photon energy response of a detector is calculated as the ratio of the detector signal measured for the given type of radiation and energy, to the signal obtained after irradiation of the detector with the same dose in tissue (or kerma in air) of reference radiation, e.g. ^{137}Cs gamma rays. The reason for the popularity of lithium fluoride and lithium borate detectors is their flat photon (X rays) energy response. To the first approximation the photon energy response of the detector depends on the material composition, which determines the cross sections for photon interaction within the detector, as compared with tissue (air). The energy response of a bare TLD can be estimated by its effective atomic number Z_{eff}, calculated as a weighted average of atomic numbers of all constituents of the detector.

Table 1. List of TLDs applied in European individual dosimetric services, based on information collected form the EURADOS questionnaire.

TLD type	TLD name	Producer	No. of services
LiF:Mg,Ti	TLD-100, TLD-600, TLD-700	St Gobain (former Harshaw/Bicron NE)	23
	MTS-N, MTS-6, MTS-7 (LiF-N, LiF-6, LiF-7 when distributed by RADOS, Finland named as)	TLD Poland (former TLD Niewiadomski)	13
	DTG-4	Russia	1
	LiF	Unspecified	6
LiF:Mg,Cu,P	MCP-N, MCP-Ns (thin layer detector)	TLD Poland (former TLD Niewiadomski)	3
	GR-200	Beijing Shiying Radiation Detector Works, China	3
$Li_2B_4O_7$:Mn,Si	distributed by RADOS, Finland	Tartu University, Estonia	5
MgB_4O_7:Dy,Na		Vinca, Serbia and Montenegro	1
$Li_2B_4O_7$:Cu,Ag,P		Vinca, Serbia and Montenegro	1
$Li_2B_4O_7$:Cu		Panasonic, Japan	8
$CaSO_4$:Tm		Panasonic, Japan	8
$CaSO_4$:Dy		Unspecified	3
CaF_2		Unspecified	1

A substance is considered tissue equivalent with respect to interactions with photons if its Z_{eff} is close to that of soft tissue, which is equal to 7.4. With $Z_{eff} = 7.35$ for lithium borate and $Z_{eff} = 8.3$ for lithium fluoride the predicted energy response, normalised to air kerma at 662 keV (^{137}Cs gamma rays), should not be >30% for energies <30 keV (Figure 1). The measured energy response of LiF:Mg,Ti detectors is ~10% higher owing to the variation of TL efficiency for conversion of deposited energy into TL light (LET effect). On the contrary in LiF:Mg,Cu,P detectors the measured response is up to 25% lower than predicted from the cross sections. Therefore, for the design of personal dosemeters one should apply only the experimentally determined detector energy response.

DOSEMETERS AND THEIR ENERGY RESPONSE

A typical dosemeter used in individual monitoring consists of a detector (or set of detectors) placed within the holder. The holder protects the detector from disturbing environmental factors, corrects the energy and angular response and assures the response at the appropriate depth. An ideal dosemeter responding in terms of H_p(d) should demonstrate readings proportional to dose (dose equivalent) to tissue at the given depth independently of the radiation energy and proportional to the total dose at the surface of the body, to take into account the contribution of backscattered radiation from the body. Therefore, the design of dosemeters has to take into account mainly the energy response, thickness and physical shape of the detector(s) and the composition, thickness and shape of the filters applied.

As the first guess, the thickness of the tissue-equivalent filter, for monitoring H_p(d), should correspond to the mg cm^{-2} density value. This is usually the case for dosemeters with tissue-equivalent detectors. For holders with TLD-100/700 detectors the reported thickness of the filters for H_p(10) varied between 330 and 1100 mg cm^{-2} and consist either of single material or, more frequently, of a combination of two materials. The list of reported filter materials is given in Table 2. The users of RADOS/Dosacus systems with LiF and $Li_2B_4O_7$ detectors reported the thickness of Al filter between 241 and 271 mg cm^{-2} and the additional thickness of the plastic from 130 to 209 mg cm^{-2}. For $CaSO_4$:Dy detectors high Z_{eff} elements such as Pb and Cu are used as filters, to attenuate low-energy X rays and in this way to compensate for the over response of bare $CaSO_4$:Dy detectors. For H_p(0.07) in RADOS badge no filter is used but most dosemeters apply foils (Mylar, PTFE or PP), with the thickness between 3 and 42 mg cm^{-2}.

The final value of dose is obtained from the signal measured with the TLD reader using a calculation procedure (algorithm). Three types of procedures can be considered as follows$^{(1)}$:

1. No algorithm is used and H_p(d) is calculated by application of calibration factor.
2. Combination of readings of different detectors is used to obtained the value of H_p(d).

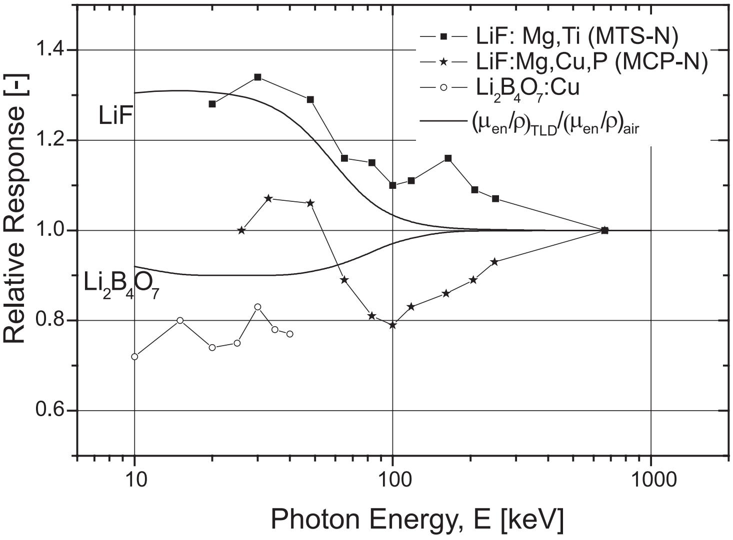

Figure 1. Photon energy response of LiF:Mg,Ti (MTS-N), LiF:Mg,Cu,P (MCP-N) and $Li_2B_4O_7$:Cu TLDs. Lines present the ratio of mass energy absorption coefficients of TL material vs. air.

3. Depending on the ratio of different detectors a different formula is used to calculate H_p(d) (If-then algorithm)

Among 45 services, which applied TLDs to determine H_p(10) and responded to the questions concerning the algorithm, 28 use no algorithm, 12 use a combination of reading and 5 the if-then algorithm. For 15 services reporting the measurements of H_p(0.07), 12 apply no algorithm and 3 a combination of readings of different TLDs. Typically, services using tissue-equivalent detectors (LiF and $Li_2B_4O_7$) apply no algorithms. For dosemeters with high Z_{eff} detectors, the combination of reading or if-end algorithms are most frequently applied.

Table 2. List of materials, reported in the EURADOS questionnaire, as filters in individual dosemeters with TLDs.

ABS	Polyacrylbutadienestyrene
Al	Aluminium
AlMylar	Aluminised Mylar
Cu	Cooper
Mylar	Polyethylene teraphthalate by Du Pont
Nylon	
Pb	Lead
PC	Polycarbonate
PE	Polyethylene
PES	Polyester
Plastic	Not specified
PMMA	Polymethylmethacrylate
PP	Polypropylene
PTFE	Polytetrafluorethylene
PVC	Polivinylo
Teflon	Polytetrafluorethylene by Du Pont

The energy response of TL detectors, appropriate filters, calibration procedure and algorithms of dose evaluation mostly influence the final energy response of individual dosemeter for photons and beta particles. In Figure 2 the measured response, H_p(10), normalised to the true value of H_p(10) is plotted as a function of energy for whole-body photon TL dosemeters for normal beam incidence. From 33 services, which delivered infomation on H_p(10) response, only 5 were outside the ±20% limit for X-ray energies >70 keV. For X-ray energies <70 keV 12 services were outside the limit. These energy reponses are the results of type test experiments in which the dosemeters were exposed to monochromatic or narrow spectrum radiation qualities all at the same angle of incidence. Dosemeters with detectors far from tissue equivalent have to rely on 'end-if' or 'muliply detectors' dose calculation algorithms. These systems may be very successful for monochromatic or narrow spectrum qualities but fail in mixed radiation situations. Therefore, a multi-detector dosemeter with a very good response characteristic (as judged from type tests) may in field conditions be inferior to dosemeters with only one detector (but which is approximately tissue equivalent), which show inferior type test response characteristics.

SUMMARY AND CONCLUSIONS

This work forms part of the activities associated with a EURADOS Working Group 2 formed by experts from several European countries involved in the process of harmonisation of individual monitoring

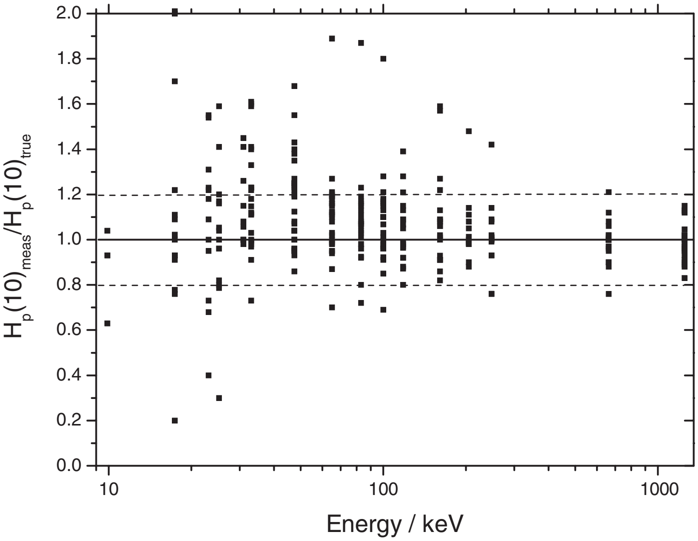

Figure 2. Response, $H_p(10)_{measured}/H_p(10)_{true}$ as a function of energy for whole-body photon TL dosemeters for normal incidence.

as part of the protection of occupationally exposed persons. The aim of this paper was to provide information about TLDs applied by the European dosimetric services and the dosimetric characteristics of dosemeters in which these detectors are applied. Owing to historical and economical reasons, most individual dosimetric services in Europe using dosemeters based on TLDs are small and medium size services, which operate typically for <10 000 radiation workers. Sixty one of the total number of 90 services, which responded, were applying TLDs for radiation monitoring. The most frequently used were standard lithium fluoride TLDs (mainly TLD-100, TLD-700, MTS-N and MTS-7, DPG-4), high-sensitive lithium fluoride (GR-200, MCP-N) and lithium borate. For neutron dosimetry, most services apply pairs of LiF:Mg,Ti TLDs with ^{6}Li/^{7}Li. The main aim of the harmonisation of radiation protection systems within European states is to allow for reliable comparison and transfer of dosimetric data for occupationally exposed people within Europe and in consequence, to facilitate the mobility of radiation workers. A large number of dosimetric services in Europe, using a great variety of dosemeters with different types of detectors, makes this task difficult. Further harmonisation work is needed, towards periodical organisation of European intercomparison of person dosemeters, and available for dosimetric services, which wish to participate.

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