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WORKSHOP ON PERSONAL DOSIMETRY
50 years of dosimetry at the SCK·CEN

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FIFTY YEARS OF DOSIMETRY AT THE SCK•CEN

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Abstract

It is not very well known when personal monitoring for radiation exposure began. In the pre-World War II period, films were used for detection of ionising radiation, rather then for an accurate measurement. The Manhatten project introduced pocket ionisation chambers (Victoreen) that were not very reliable, but useful if used in pairs. Near to the end of the project, more reliable direct reading pocket ionisation chambers were introduced. The reproducibility and other characteristics of film were also enhanced. In the first publication of the ICRP after World War II (1955), it was recommended that “*film badges or ionization chambers may be used*” to test for external radiation.

Fifty years ago (1956), the first Belgian Reactor BR1 became operational and the follow-up of personal doses was necessary. A specific dosemeter based on film was developed to start dosimetry services at SCK•CEN. These services extended in the next years to include not only the detection and measurement of effective gamma and X-doses, but also skin dosimetry, finger dosimetry, criticality dosimetry and beta- and neutron dosimetry.

The evolution of personal dosimetry at SCK•CEN since the start will be described with an overview of the dosemeters and of the related research programmes.

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APPROVAL OF DOSIMETRY SERVICES IN BELGIUM

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Abstract

According to the European Directive 96/29/Euratom, each Member State has to make the necessary arrangements to recognize the capacity of the approved dosimetric services. In 2001, the Belgian Royal Decree laying down the general regulations for the protection of the population, the workers and the environment against the hazards of ionizing radiation assigned this task to the Federal Agency for Nuclear Control. Until the publication of the criteria in the Belgian Official Journal, only types of dosimeters are approved.

The recognition of dosimetric services is to cover the entire chain of personal dosimetry. Therefore, not only the requirements, type testing and performance criteria for the dosimeters are included, but also the dose record keeping and information system, as well as the management and administration of the dosimetric service and its overall quality system. Taking into account the free movement of persons within Europe and the fading of the boundaries, it is furthermore necessary to ensure harmonization of the criteria within Europe. This is why most European countries tend to base their approval criteria on international standards and reference documents.

In this document, the status of the implementation of the European basic safety standards with respect to dosimetric services in Belgium will be commented.

1. REGULATORY FRAMEWORK

The European Directive 96/29/Euratom of May 13, 1996 laying down Basic Safety Standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation [1] stipulates that (art. 25) "Individual monitoring shall be systematic for exposed category A workers. This monitoring shall be based on individual measurements which are established by an approved dosimetric service…" and that (art. 38) "Each Member State shall make the necessary arrangements to recognize the capacity of the approved dosimetric services".
The Directive does not give any other preconditions about approval criteria. Thus, each Member State is free to formulate its own set of criteria. Taking into account the free movement of people, in particular workers, within the European Union, and the possibility for dosimetry services to provide their services across country borders, harmonization of the criteria in the different European countries is strongly recommended.

The Belgian Royal Decree of July 20, 2001 laying down the general regulations for the protection of the population, the workers and the environment against the hazards of ionizing radiation [2] stipulates that (art. 30.6) the different types of personal dosimeters and their readout system have to be recognized by the Agency, the individual monitoring of the workers is based upon measurements executed by a dosimetry service that is approved by the Agency and the criteria and modalities for approval [of dosimetry services] are determined by the Agency. The approval of dosimetry services can include the approval of the types of personal dosimeters used.
Furthermore, it sets as transitional provision (art. 81.3) that the compulsory approval of the dosimetry services becomes effective 2 years after the publication of the criteria and modalities of approval, fixed by the Agency, in the Official Journal.

Before the Royal Decree of July 20, 2001 came into force, the Royal Decree of February 28, 1963 stipulated that the different types of personal dosimeters and their readout system were subject to an approval by the Ministry of Employment and Labour. The applications for approval were evaluated on the basis of a number of tests that had to be carried out to assess the performance of the dosimeter. However, no standardized criteria were used. Approval of dosimetry services was not foreseen.

2. DOSIMETRY SERVICES IN BELGIUM (EXTERNAL DOSIMETRY)

In Belgium, actually 12 institutions provide service for external dosimetry. They can be grouped into five categories:

1. Belonging to a recognized body
   - AIB-Vinçotte Controlatom (AVC)
   - Techni-Test (TT)
2. Belonging to a research centre
   - SCK•CEN (SCK)
3. Belonging to a university
   - Université Catholique de Louvain (UCL)
   - Université Libre de Bruxelles (ULB)
   - SUCPR Université de Liège (ULG)
   - Universiteit Gent (UG)
   - Katholieke Universiteit Leuven (KUL)
4. Belonging to a nuclear facility
   - Belgoprocess (BP)
   - Belgonucleaire (BN)
   - Institut des Radio-éléments (IRE)
5. Laboratory Department of Defence (DLD)

Compared to neighbouring countries, Belgium has a lot of relatively small dosimetry services.
All institutions hosting a dosimetric service have this service incorporated in (as part of) their health physics department, except SCK•CEN.
In some cases, especially at universities, dosimetry service and health physics are executed by the same person(s).
Although military applications are excluded by the Royal Decree, the Laboratory Department of Defence would like to apply these regulations on a voluntary basis.

In 2004, a survey was carried out as the starting point for the process of setting criteria and modalities for approval of dosimetry services. The aim of this survey was to get an idea about what was already present in the services, in terms of types of dosimeters used, technical expertise and daily practice. Most of the services were visited as well.

In total, about 40 000 occupationally exposed persons are monitored in Belgium. This number includes temporary or external workers and visitors. Approximately 1 600 persons are monitored for extremities (wrist, finger, finger tip), and approximately 1 000 for internal dosimetry (total body count, urine analysis, thyroid). This last number is probably underestimated, because services that only offer internal dosimetry were not included in the survey.
For roughly half of the total number of occupationally exposed persons, AIB Vinçotte Controlatom is the dosimetry service. Some services monitor a few thousand workers (SCK•CEN, Techni-Test, and the universities), other services only a few hundred. Dosimetry in Belgium is of a rather fragmented nature.

During the survey, the services were asked to formulate their own expectations regarding the approval procedures. The answers could be grouped into two main concerns: quality and feasibility. The services expect that the approval procedure mainly concerns the installation of quality assurance systems. They express the need for common calibrations, possibly organised by the FANC, and the need for intercomparisons, possibly organised by the FANC. Finally, they want the criteria to be based on clearly defined requirements based on international standards. On the other hand, they want to avoid too much paperwork, and they wish that the practical difficulties when providing the service be taken into account.

The table below gives an overview of the types of dosimeters used by the dosimetry services.

Dosimetry service	Type(s) of dosimeter used
AVC	Film KODAK Personal Monitoring Type 2 holder R30 WS/MK 2 LOXFORD TLD Harshaw 4-el LiF (3x7Li, 1x6Li) TLD Panasonic TLD Neutron Albedo Harshaw
TT	Film KODAK Personal Monitoring Type 2 holder NRPB/AERE.ERP30
SCK•CEN	TLD Harshaw/Bicron in TNO holder bubble detectors for neutrons criticality dosimeters extremity TLD (ring)
IRE	TLD ($Li_2B_4O_7$) STUDSVIK distributed by RADOS
UCL	TLD Panasonic TLD-100 Harshaw/Bicron in UCL holder
ULB	TLD ^{7}LiF TELEDYNE Isotopes
ULG	Film KODAK Personal Monitoring Type 2 in holder LOXFORD BS/MK 1A TLD-100 (LiF) Harshaw
UG	Film KODAK Personal Monitoring Type 2 in holder AERE-RPS Finger tip : TLD-100 (Thermo-Electron Corp)
KUL	TLD-100, 600, 700 Harshaw (Thermo-Electron Corp)
BP	TLD-100 Harshaw, card LG 1110
DLD	TLD/Film Active dosimeters for the troops

In Belgium, mainly two categories of dosimeters are used: film (all use Kodak Personal Monitoring Film type 2, in different holders but these holders are all quite similar) and TLD (most Harshaw, also Panasonic and Teledyne). Compared to neighbouring countries, still a lot of film is used in Belgium.

In the future, some services would like to use active dosimeters or hybrid types like the DIS (Direct Ion Storage) or DOSICARD, more specific dosimeters for specific situations like for neutrons (bubble detectors) or radon, or other types of TLD (CaSO4).

The services were also asked whether their quality assurance system is accredited according to an international standard. For most of the services, this was not the case in 2004. At that time, two services were accredited according to the international standard ISO 17025 but only for their calibration service. In 2006, SCK•CEN obtained an extension of its accreditation for its dosimetry service.

6. APPROVAL OF DOSIMETRY SERVICES IN FRANCE

In France, the competent authority is the ASN (Autorité de Sûreté Nucléaire). Approval of dosimetry services is regulated in the « Décret n° 2003-296 du 31/03/2003 relatif à la protection des travailleurs contre les dangers des rayonnements ionisants » [3] and the « Arrêté du 6/12/2003 relatif aux conditions de délivrance du certificat et de l'agrément pour les organismes en charge de la surveillance individuelle de l'exposition des travailleurs aux rayonnements ionisants » [4].

The criteria applied in France can be summarized as follows:

- the external dosimeters, and the devices for anthropogammametry and the radiotoxicological analyses have to fulfil the relevant AFNOR1, CEN2, ISO3 or IEC4 standards
- the independence with regard to the monitored entities should be guaranteed
- the IRSN organises intercomparisons
- in emergency or abnormal situations, the dosimetry data should be available within 48 hours
- the service has to be accredited according to the standard NF EN ISO/ CEI 17025 by COFRAC5.

7. APPROVAL OF DOSIMETRY SERVICES IN THE NETHERLANDS

In the Netherlands, the competent authority is SZW (Ministerie van Sociale Zaken en Welzijn). Approval of dosimetry services is regulated in the "Besluit Stralenbescherming (16 July 2001)" [5] and the "Regeling

1 AFNOR : Association Française de Normalisation
2 CEN : Comité Européen de normalisation
3 ISO : International Organization for Standardization
4 IEC/CEI : International Electrotechnical Commission
5 COFRAC : Comité Français pour l'Accréditation

voorzieningen stralingsbescherming werknemers (25 February 2002)” [6]. Dosimetry services should comply with the following criteria:

- the quality management system of the service should meet the requirements of the international standard NEN-EN-ISO 9001
- the dosimetry system, including the calibration system, should fulfil the standard ISO 17025
- the service meets the recommendations of the European Commission, as reflected in the document RP73 “Technical Recommendations Report” EUR 14852 EN (1994)
- the service should be managed by an expert
- the service should participate in (inter)national intercomparison exercises according to ISO 14146 (2000).

Similar sets of approval criteria can be found in other European countries.

8. DRAFT CRITERIA FOR APPROVAL OF DOSIMETRY SERVICES IN BELGIUM

8.1. Basic ideas

The basic ideas that can be distilled from the previous include that there should be a quality assurance system for the laboratory as a whole, that there should be technical performance requirements for dosimeters and readout and that participation in (inter)national intercomparison exercises is an important issue.
We furthermore observe that most countries make use of internationally accepted standards or recommendations.

8.2. Options

Different options could be taken to define the approval criteria.
Defining our own criteria would however imply that no mutual approval is possible with other European countries. Basing the criteria on existing international standards and documents of relevance, leads to a more or less natural harmonization of criteria within Europe, making mutual approval easier.

As far as the compliance with international quality standards is concerned, ISO 9001 certification only guarantees a good management, but gives no guarantee about technical validity of results.
ISO/IEC17025 is the international standard for laboratories. Accreditation according to this standard guarantees a good general laboratory practice. Accreditation can be obtained at the Belgian Accreditation Structure BELAC, which has mutual recognition agreements with EA (European Co-operation for Accreditation), ILAC (International Laboratory Accreditation Co-operation) and IAF (International Accreditation Forum).
In case no coupling is foreseen between approval of dosimetry services and approval of types of dosimeters, no guarantee can be given about correct use of dosimeter. If approval of the dosimetry service includes the approval of the type of dosimeter used, the correct use of the dosimeter can be guaranteed. In this case, the whole dosimetry chain is evaluated.

8.3. Choice

In this way, a draft decree fixing the approval criteria and modalities has been developed, based on three main criteria for approval:
- the dosimetry service should obtain an accreditation according to the NBN EN ISO/IEC 17025 standard by BELAC or an equivalent organisation that has a mutual recognition within EA
- the dosimetry service has to fulfil the recommendations of the European Commission, as reflected in the document RP73
- the dosimetry service accepts to participate in periodic national or international intercomparison exercises. For X- and gamma-radiation, the requirements of ISO 14146 should be met.

The standard ISO/IEC 17025 « General requirements for the competence of testing and calibration laboratories » [7] deals with, in addition to the general categories scope, normative reference, terms and definitions, some management requirements such as organisation, management system, document control, complaints, corrective actions, internal audits, etc., and with some general technical requirements about staffing, accommodation and environment conditions, test and calibration methods and method validation, equipment, measurement traceability, etc.
In fact, this standard describes the good rules of practice for a well-working

laboratory, but it is not specific for dosimetry purposes. Therefore, the European Commission document RP73 « Technical recommendations for monitoring individuals occupationally exposed to external radiation » [8] is used as a second criterion. It gives some general information about individual monitoring, such as the objectives and principles. It reviews the dosimetric concepts in individual monitoring and details the technical performance of the dosimeters, covering the general requirements for personal dosimeters, type testing of personal dosimeters, performance testing. It also gives guidance for dose record keeping and information systems, aspects of management and administration and quality assurance in individual monitoring. For example, in the performance requirements, it utilises the famous and generally applied trumpet curves initially based on ICRP recommendations, and it gives guidelines about how to test for angular response and for energy response.
Finally, the standard ISO 14146 [9] describes in a brief but clear way how intercomparisons should be carried out: the frequency, the test conditions, how many dosimeters have to be supplied, between which limits the performance is considered as successful, etc.

As such, these three criteria allow us to evaluate the service provided as a whole, including the validity of the dose data.

Being aware of the fact that the procedure for accreditation is a very lengthy procedure, and bearing in mind the wish of the dosimetry services to foresee enough transition time, several steps have been built in. For a first approval application, if there is not yet a formal accreditation, a notification of BELAC that the accreditation procedure is in progress is also accepted. Only upon application for the first prolongation, accreditation covering the domain for which approval is asked should have been obtained.
Since it is not realistic to really start the accreditation without having prepared the quality handbook, the following temporary measure has been proposed: during 5 years after coming into force of the decree, the FANC can approve services without accreditation/notification of accreditation procedure in progress. This means that from the moment the decree will be published, the services have a period of 5 years to establish their quality manual. At that moment, they still have some years to really obtain the accreditation.

9. APPROVAL PROCEDURE AND MODALITIES

How can a service apply for approval according to the draft decree? In addition to the definition of the scope of approval and the identification of the service and its head, the accreditation attestation or notification should be provided, as well as a report reflecting the main elements of the document RP73 and the ISO 14146 standard, including the specifications of the used types of dosimeters, the results of intercomparisons (at least 1 during a 3 year period preceding the date of application), and the description of the dose registration system, the management and administration, the quality system (progress in the procedure), an overview of innovations in the past 3 years and an overview of planned innovations in the coming 3 years.

Fees are due for the application for approval of a dosimetry service and for the application for approval of a type of dosimeter.

Approval can be limited in time, to certain subdomains or to certain application areas.
In principle, for the first approval, the duration of the approval is limited to a maximum of 3 years. For a subsequent approval, it is limited to a maximum of 6 years. Approval will be published in the Official Journal.

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[4] Arrêté du 6/12/2003 relatif aux conditions de délivrance du certificat et de l'agrément pour les organismes en charge de la surveillance individuelle de l'exposition des travailleurs aux rayonnements ionisants, J.O. nº 5 du 7 janvier 2004 page 473.

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[6] Regeling voorzieningen stralingsbescherming werknemers (25 February 2002), Staatscourant 28 februari 2002, nr. 42/pag. 29.

[7] General requirements for the competence of testing and calibration laboratories (ISO/IEC 17025:2005).

[8] Technical recommendations for monitoring individuals occupationally exposed to external radiation, EUR 14852 EN (1994).

[9] Radiation protection - Criteria and performance limits for the periodic evaluation of processors of personal dosimeters for X and gamma radiation, ISO 14146:2000.

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DOSIMETRY STATISTICS :
A TOOL IN RADIOLOGICAL PROTECTION

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Abstract

In the general concept of radiological protection one has to apply the optimisation principle (ALARA) to justified practices. Moreover, the legal dose limits have to be respected. The occupational exposure of radiation workers is monitored using personal dosemeters and is filed both at the health physics and the occupational medicine department.
Performing statistical analysis on these dose results in terms of dose evolution in time, distribution of doses with respect to different categories of workers or different types of installations one can point out categories with more risks or with more possibilities for dose reduction.
We zoomed in on the category of nuclear medicine departments and have identified some of the dose determining factors. Once identified, this knowledge can be used in the framework of the optimisation principle.

1. INTRODUCTION

Two main elements in the general concept of radiological protection are the optimisation principle (ALARA) and the use of dose limits (constraints or legal). Dosimetry data can be used to assess both these elements.
The comparison of individual or collective doses can help to examine the effectiveness of proposed protective measures as the installation of shielding, the changing of work attitudes or procedures,… . It is also clear that the absolute dosimetry data, the individual doserecords can be used to verify the compliance with the legal doselimits.
Dosimetric data are thus a valuable tool in the day to day work of the health

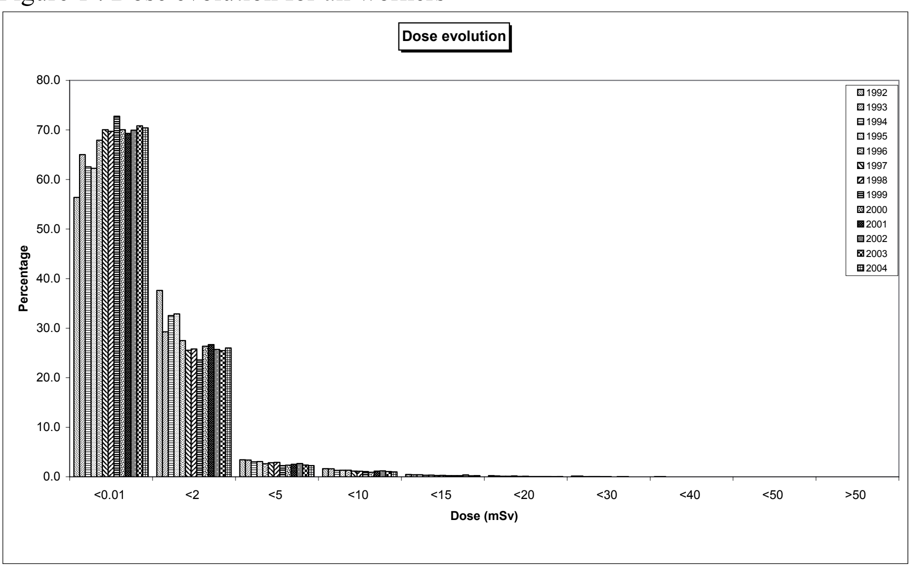
physics and occupational medicine departments. Furthermore, performing statistical analysis on these data can help to improve radiological protection by identifying specific categories of workers or by identifying dose determining factors.

2. DOSE DISTRIBUTION OF WORKERS

2.1. All workers

The dosimetry and health physics department of AV-Controlatom follow approximately 20,000 exposed workers. **Figure 1** shows the evolution during the last years (from 1992 to 2004) of the 12 gliding month (12M) doses of these workers.
One can see that there is a gradual increase in the number of persons having doses less than 2 mSv and a gradual decrease of the number of persons having doses higher than 5 mSv. This evolution is the result of the efforts made in applying the ALARA principle to a great number of exposure situations in the medical, industrial and educational sectors. In table 1 the number of persons having doses higher than 20 mSv is given for a number of years.
In this table we can see the impact of the reduction of the legal dose

Figure 1 : Dose evolution for all workers



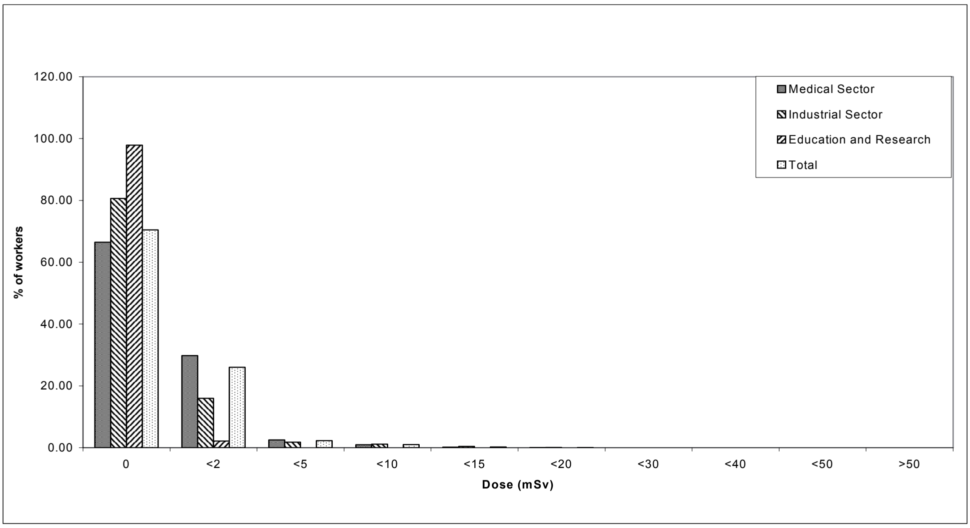
limit from 50 mSv to 20 mSv/12 gliding months. Where in 1993 still 41 persons were above the 20 mSv limit, only 3 persons had doses higher than 20 mSv in 2004. In fact, after the publication of the Euratom Basic Safety Standards in 1996 extra efforts were made by our health physicists to reduce the doses of these individuals were chronic exposure was the reason for the high dose values. Now exposures higher than 20 mSv are rarely due to chronic exposure, but result from accidental exposures. The causes of these accidental exposures have to be determined and actions have to be taken to prevent them from happening again so that individual workers do not exceed the legal limits. This will, however, not result in a dramatic decrease in the collective dose of the exposed workers given their limited number.

Table 1 : Number of persons with doses > 20 mSv

Year	Total number of monitored persons	Number of persons with dose > 20 mSv
1993	18644	41
1996	22308	14
1999	19040	8
2002	20510	3
2004	21973	3

The statistical data for a given year can be plotted in function of the sector where the exposed persons work : the medical, industrial or educational sector (**figure 2**). It can be seen that the fraction of workers having a non zero dose is significantly higher (dose range < 2mSv) for the medical sector than for the industrial sector. Moreover the total number of exposed persons in the medical sector is larger than those in the industrial or educational sector. So it is worthwhile to try to concentrate the optimization efforts on this sector because most probably it will result in a larger and faster decrease in collective dose.

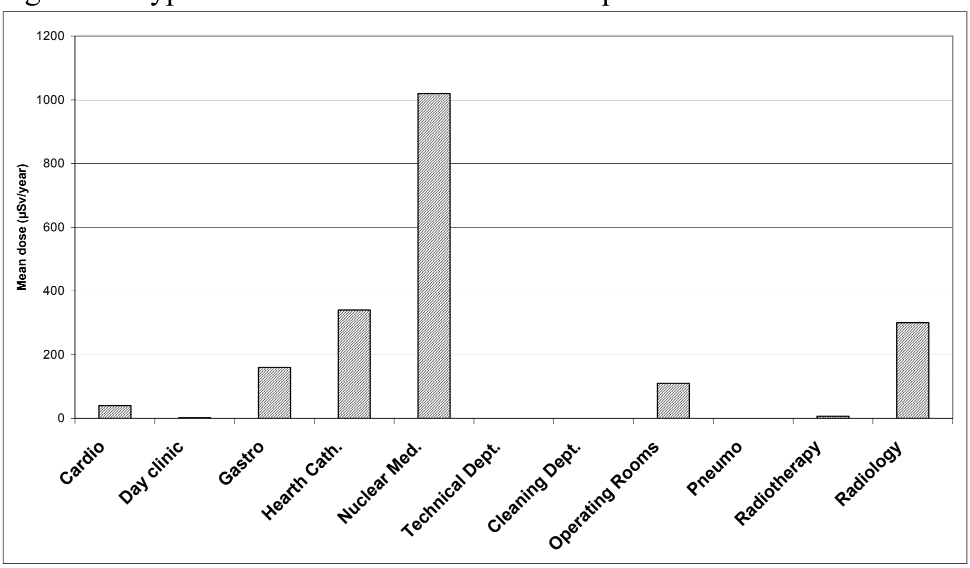
Figure 2 : Dose distribution in 2004 over the different sectors



2.2. Medical sector

In the medical sector one can distinguish different workplaces, resulting in different (chronic or accidental) exposure patterns.

Figure 3 : Typical mean annual doses in an hospital in function of different w



Some of the departments hardly have a (chronic) exposure pattern : eg. the cleaning staff and workers from the technical department in general only enter the controlled area if f.i.the X-ray equipment is off or if the radioactive sources are shielded. In external radiotherapy the design of the shielding of the irradiation rooms is such that in normal conditions no or very limited exposure is observed. The doses in a radiotherapy department can be very high in accidental conditions. In all these cases measures to prevent high accidental exposures have to be taken.
On can observe that the highest mean annual doses are recorded in the nuclear medicine department. This observation has led us to examine the nuclear medicine department more closely on a statistical basis.

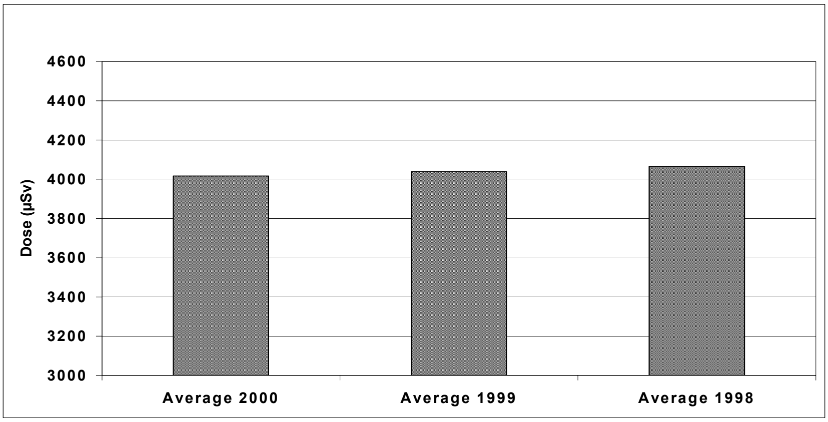
3. EXPOSURES IN THE NUCLEAR MEDICINE DEPARTMENT

Two statistical studies were performed on a number of nuclear medicine departments. One covering the period of 1998-2000 and one covering the period 2003-2005. The first study only used statistical dosimetric data, the second study combined the statistical data with information obtained by consulting the field.

3.1. 1998-2000 study

In this study 20 nuclear medicine departments were examined. Only dosimetric data were taken into account. No information on the working hours per week of the staff or other details of the different departments was available at that time. One can see from **figure 4** that the average dose in the nuclear medicine departments is rather constant over the years. This suggests that the doses obtained in nuclear medicine have a chronic and stable nature and are not due to accidental exposures.

Figure 4 : Average nuclear medicine doses (1998-2000)



This also means that, if one could identify some of the dose determining factors one could start a more effective optimization process.
As could be expected the technologists of the department had higher doses than the physicians. A mean yearly dose of 5.14 mSv was observed for the technicians versus 1.03 mSv for the physicians. This can be easily explained by the fact that most of the manipulations (preparation of the syringes, administration of the activity, positioning of the patient,..) are performed by the technologists.

3.2. 2003-2005 study

In this study 15 nuclear medicine departments (with 1500 – 6000 patients/ year) were included. In total, the doses of 38 technologists were taken into account. In order to have more details of the different departments, the study was accompagnied by an 'in depth' evaluation on site by a health physicist. This evaluation aimed to caracterise the department and the technologists and was performed using a small questionnaire.
Parameters as working hours/week, experience of staff, attitudes of the staff, size of hotlab and cameraroom, cleanliness,….were collected.
In table 2 the average dose of a technologist normalized for 'Full Time Equivalent (FTE)' is shown. These values are higher than the average values obtained in the 1998-2000 study due to the fact that now the doses are normalized to FTE and only the doses of the technologists are considered.

Table 2 : Normalized average technologist doses

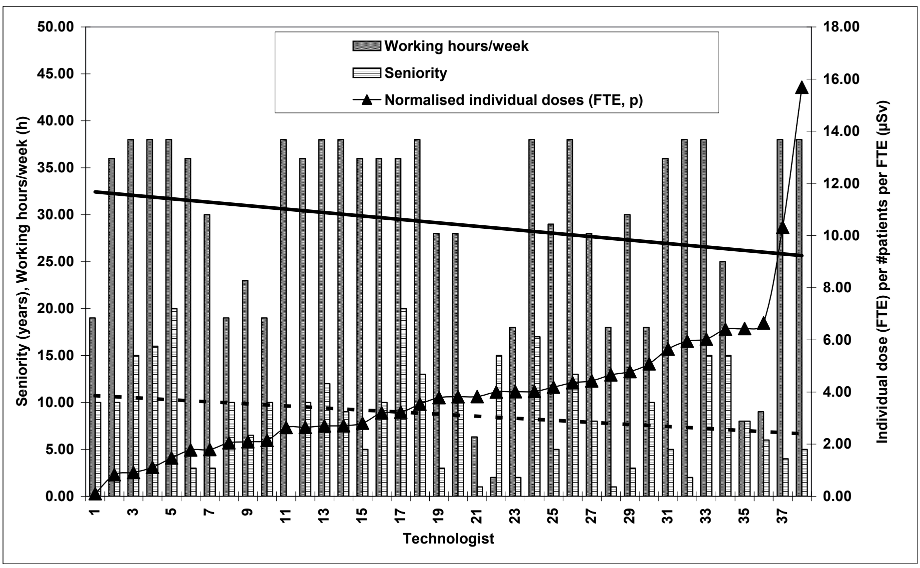
Year	2003	2004	2005
Average dose FTE (mSv)	6.32	6.66	5.96

80% Of the doses are lower than 5 mSv, but a large difference between the minimum (1.22 mSv) and maximum (14.43 mSv) dose is observed.

In **figure 5**, a summary is given of the doses of the technologists normalized to the FTE and to the number of patients undergoing a nuclear medicine examination in the department. Additionally for each technologist an histogram with the number of working hours/week and the number of years of experience as nuclear medicine technologist (seniority) is given. One can observe two trends in this figure :

- the technologist's dose increases with decreasing seniority (-----)
- the technologist's dose increases with decreasing working hours/week (-----)

Figure 5 : Normalized technologist dose, working regime and seniority



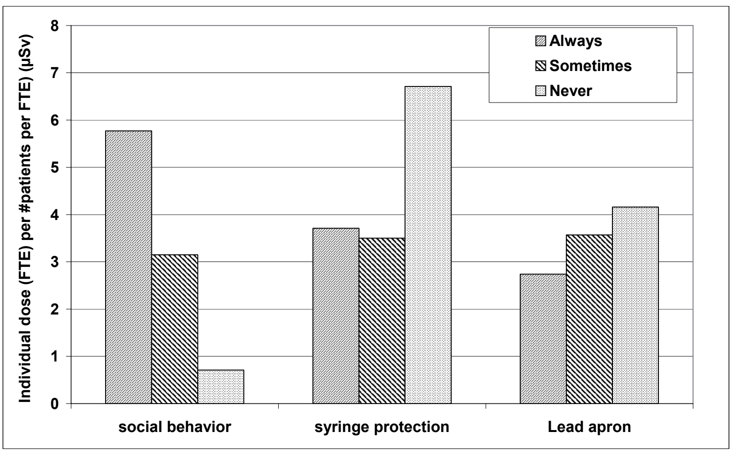
This trend shows clearly that experience is a positive factor in reducing the dose. As such, this parameter can not be changed by the health physicist but it leads to the recommendation that (a lot of) practical exercises are essential in the education of a nuclear medicine technologist.

Also different attitudes of the technologists were examined :

- are they wearing a lead apron for all the manipulations, for some manipulations or never
- are they using syringe protections
- how is their behaviour towards the patient

In **figure 6** the influence of these attitudes on the normalized (FTE, #patients) dose is given.

Figure 6 : Influence of attitude on dose



The most important factor is the 'social behaviour'. This means that having a long and close contact with the patient : eg. explaining to the patient the nuclear medicine procedure after the administration of the activity, staying aside the patient when the images are collected… will have an adverse effect on the dose. Paying attention to this behaviour with respect to the patient, can reduce drastically the received dose.
The use of a syringe protection can reduce the dose to the technologist by as much as a factor of two. Using a lead apron can reduce doses with approximately 30%.

Also the influence of the surface of the hotlab and camera room on the doses were studied.
We used the following criteria to classify the different rooms :

- Hotlab : Small (<10 m²),Medium (<16 m²) and Large (>16m²)
- Camera room : Small (<16 m²), Medium (<25 m²) and Large (>25m²).

It can be seen from **figure 7** that having a large nuclear medicine department has a positive effect on the doses. This is quite logical since in a larger department the sources (patients, lead castle,..) are on the average more distant to the staff members. One could use this information in the construction of new departments where one could recommend miminum room sizes.
The health physicists were asked to give an overall impression of the departments. They gave a score (max. 5) for different criteria :

- clean : are there regularly important radioactive contaminations ?
- neat : is all the material properly stowed away ?
- organization : is the patient 'throughput' well scheduled ?

In **figure 8**, the scores are plotted for the different departments along with the collective dose (normalized to the number of patients examined per year in the department).

Figure 7 : Influence of room size on dose

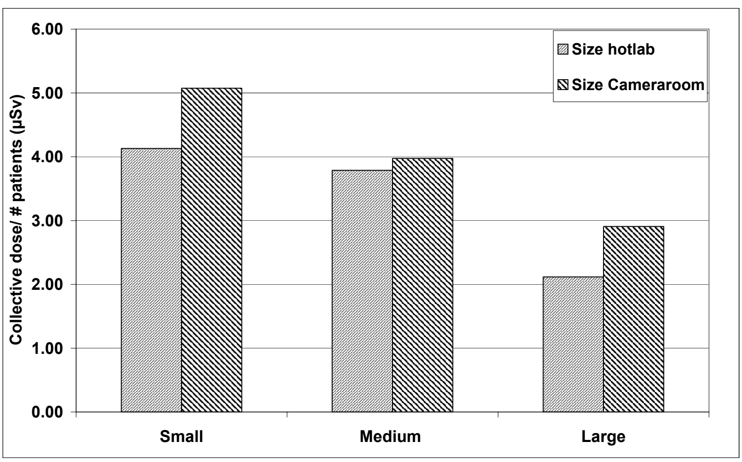
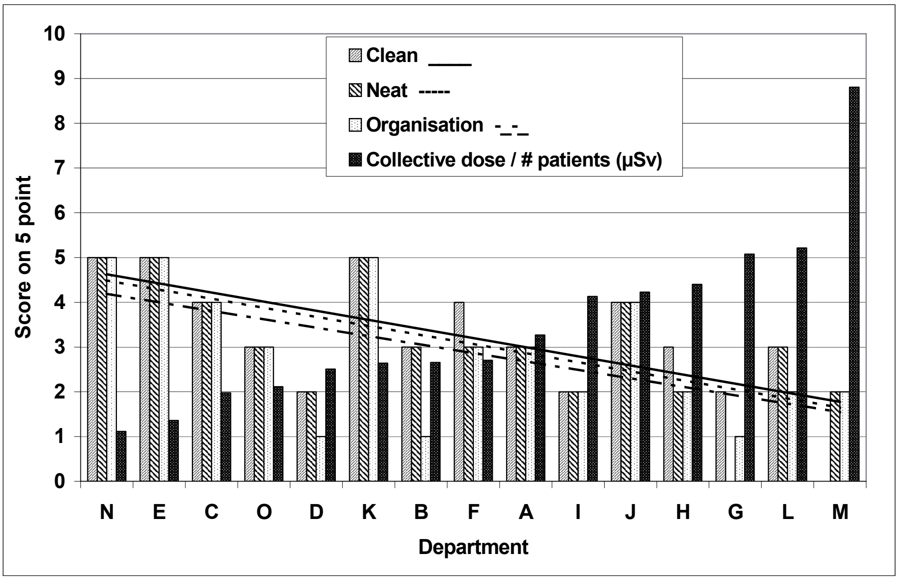


Figure 8 : Overall impression of the department



The order of the departments is in function of the increasing collective dose. Again three trends seem to appear : one can observe an increase in the collective dose if the scores of the overall impression (clean, neat, organization) of the department decrease.

4. CONCLUSION

We have seen that statistical analysis of dosimetric data can show trends and can reveal dose determining parameters. It can be a valuable tool in health physics for continuously reducing the individual doses.
In the particular case of the nuclear medicine department some important dose determining parameters were discovered :

- the seniority and working regime
- the attitude of the staff member
- the design of the department
- the organization and cleanliness of the department.

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FILM DOSIMETRY AT THE GSF INDIVIDUAL DOSE MONITORING SERVICE AND ITS FUTURE

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Abstract

The GSF monitoring service is one of the largest individual dose monitoring services (IMS) in Europe processing about 1.8 Mio dosemeters a year. More than 50 years we have used films, as the main dosemeters for monitoring the occupationally exposed persons and GSF had an important and leading role in the development and improvement of the practical aspects of the field of film dosimetry. Today film dosimetry is used on a high level of performance including automation and quality assurance. Nevertheless the GSF is planning to build up an alternative not film based dosimetry system for the use in a large scale IMS, in order to be ready for future changes in the world wide dosimetry and film suppliers market. There are legal and practical constraints that influence the decision about the selection of a new system.

1. INTRODUCTION

The measurement of the optical density of X-ray films after radiation exposure is the oldest method of dosimetry since the discovery of the X-rays by Conrad Roentgen more than 100 years ago. Since these times the technique of film dosimetry has been optimized and improved. It became the most important dosimetry technique, slowly replaced now by other techniques of solid state dosimetry like thermoluminescence (TL), radio photoluminescence (RPL) or optically stimulated luminescence (OSL). Today four out of the six biggest IMS world wide still use film dosemeters, issuing together about 1.0 Mio. dosemeters per month. In contrast to this importance there have been only very few scientific publications about improvements in film dosimetry in the last 20 years. Even discussions within the dosimetry community show that many believe that film dosimetry is more related to interpretation than to exact measurement. For many it seems to be no more state of the art.

2. Film dosimetry at the GSF and current status

In Germany about 290 000 film dosemeters are used every month in individual monitoring (ESOREX, 2007). Approximately 124,000 of them are issued and processed every month by the GSF monitoring service in Neuherberg near Munich. All together (film, TL and RPL) about 150 000 dosemeters are processed monthly. The IMS is one of the largest in Europe. The GSF service uses personal monitoring films from AGFA Gevaert N.V., Mortsel, Belgium as all other German film IMS. Conjointly they receive about 70% of AGFA's production of dosimetry films. Due to the sheer number of dosemeters to be processed every month the grade of automation is of very high importance for the service. The 3 main processing steps are the unpacking of the film pack, the developing and the densitometry/dose calculation. A specific quality assurance process is the base for a good performance of the system.

2.1. Film unpacking and developing

The unpacking of the film packs, which contain covering papers, a high and a low speed film, is very time consuming. About 15 years ago the German film IMS together with AGFA Gevaert optimized the packaging to be able to automate this process. Automated unpacking machines have been developed, which are usable under dark room conditions and process about 1000 films/h. The film numbers are read, the packs are opened, the films withdrawn and the high speed films are fixed with adhesive tape to a plastic strip. The low speed film is stored for 3 months and will be only processed on demand. The “loaded” plastic strips called “belt” hold about 800 films each and are developed in AGFA Structurix NDT M eco developing machines (3 strips in one load, 1000/h). The machines control speed and bath temperature very accurate.

For quality reasons each band includes a background film and a test film with known irradiation dose at the beginning and at the end. Every 6th strip contains a complete calibration series of films (W60 X-ray and 137Cs from 0.1 mSv to 1 Sv), dedicated to a specific developing machine.

2.2. Densitometry and dose calculation

New densitometers are capable to measure optical densities (OD) with an accuracy of about +/-0.001 OD (in the range between 0.0 to 2.0 OD and higher) which is a 1/1000 in transmission grade.

An improvement for the quality of film dosimetry was the development of the gliding shadow method for the Hp(10) badges (Ritzenhoff, 1996). Included in this concept is an enlarged measuring area of 8 mm diameter. Compared to the 3mm diameter area used in standard densitometry, this makes the measurement of the optical densities more stable and increases the upper limit of the measuring range to about 8.0 OD – an effect of the light integration over a larger area.

The densitometry reading of the films is automated and the films are checked visually only for any noticeable problems. In future the film image interpretation will also be automated partially by using a CCD-camera and automated image processing. It will give additional information like contaminations, incident angles, radiation from front/back etc. and mark all other not classifiable features for a visual check by eye. The first automated reader using this technique is currently in a testing phase at the GSF - IMS.

Like most film services, previously the GSF used non continuous algorithms based on filter analytical methods. Here quotients of the optical densities behind the different filters were used to decide between the application of different coefficients or even different equations to calculate dose values. This resulted in non continuous functions with unpredictable results in mixed radiation fields. Now the GSF uses simple linear equations for the dose calculations resulting in much more predictable results in mixed photon fields.

2.3. Quality assurance

Quality assurance (QA) in film dosimetry is a crucial point. The blackening of the very sensitive film material is highly dependent on the developing parameters like temperature of the developer bath, regeneration rate of the developer, concentration gradients in the developer bath and developing time etc.. These parameters have to be controlled very accurate in the monitoring service. To control the quality of the development a large number of QA-films is used during routine processing as described in 2.1.

The general quality of the films delivered by the manufacturer is of high importance too. As dosimetry films are the most sensitive X-ray film materials produced by the manufacturers, they are very sensitive to all changes of relevant parameters in production and development. It was recognized that the tests performed by the manufacturers during productions were not sufficient for the high sensitive materials. Originally these QA processes were developed on base of the behavior of lower sensitive industrial film material. Therefore all German film monitoring services coacted with Agfa to setup a new QA protocol. The quality tests are made before buying newly produced emulsion directly after the production and confection process. Up to 4000 test film are extracted from the produced film sheet. Their exact position on the original film roll is known, to measure the homogeneity of the produced film badge. Other parameters are also checked, e.g. the sensitivity to 60Co radiation and the pressure sensitivity. The measurements are performed at the IMS. If a film emulsion fails these tests it might be rejected and a new production has to be made.

2.4. Performance of film dosemeters

Film material has a higher energy dependency as all other solid state materials (TL, OSL and RPL) commonly used in personal dosimetry (Ambrosi, 2004). Especially at higher photon energies and low doses this results in a higher level of uncertainty for the measured personal dose than for the other detector materials. This makes a film dosemeter not the best dosemeter from a metrological point of view. However, due to its high sensitivity at lower X-ray energies and its imaging capabilities it is an ideal dosemeter for radiation protection from the practical point of view. In dosimetric relevant cases the image on a film dosemeter can deliver more additional information than any other dosimetry system, about field and irradiation circumstances, incident angle, energy information, scattered/unscattered radiation and contaminations etc.. This information reduces the errors as soon as effective doses values have to be calculated. In routine dosimetry it reduces also the number of false personal doses caused by application errors, e.g. wrong wearing or irradiations "free in air" by fault or purpose. At the GSF in more than 90% of all cases with dose values > 10 mSv the dosemeters have not been worn at the body.

The described optimizations in film dosimetry result in a good overall performance of the film dosemeters, comparable to other solid state dosimetry systems. This can be seen at the results of the German regular annual intercomparisons for whole body dosemeters from the last years (see Figure 1). These tests are required by German law and performed by the Physikalisch Technische Bundesanstalt (PTB). Every year 10 dosemeters of each official personal dosemeter type are irradiated with photon energies in the range covered by the dosemeter specification (e.g. 15 keV – 1.3 MeV), angles between 0° - 60°, and doses in the range 0.05 mSv – 1 Sv. Additionally, any mixture of energy, angle and dose can be irradiated. All parameters are unknown for the IMS. The date of the intercomparison and the irradiation is also unknown to the IMS. The processing of these dosemeters at the IMS site is supervised by a member of the bureau of weights and measure.

The graph shows that the performances of the film dosemeters are within the trumpet curve requirement, despite a few outliers. It is similar to the

TLD systems (TLD-100 one detector systems; the photon component of TL albedo dosemeters). Best performance is shown by the RPL glass dosimetry systems.

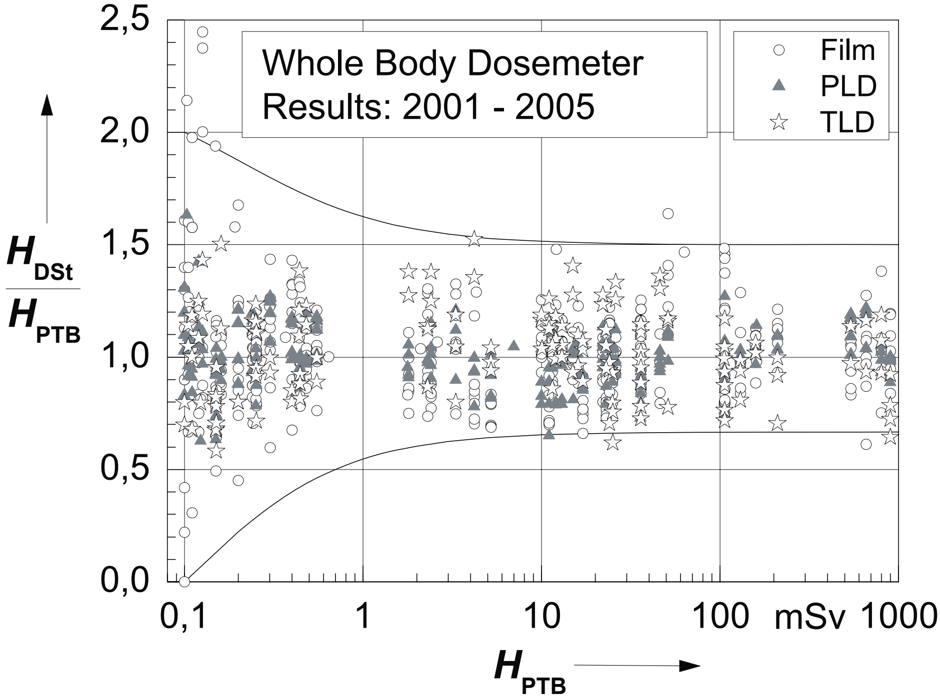

Figure 1: Performance of all official whole body dosimetry systems used in Germany in the regular annual intercomparison by PTB between the year 2001 and 2005. (by courtesy of Mrs. Ankerhold, PTB)

3. Film dosimetry world wide

For more than 20 years people say that film dosimetry is not stat of the art and will die in near future. Nevertheless, film is still the most used dosimeter type world wide. In Europe more than 700 000 radiation exposed workers (Lopez, 2004; ESOREX, 2007) are monitored with film dosemeters, about 290 000 in Germany. This is more than 50% of all monitored people in Europe.

In the last 5 years there have been big changes in the market of film dosimetry. Landauer Inc., USA, with world wide more than 1 Mio. monitored workers, changed from film dosimetry to optically stimulated luminescence (OSL) dosemeters. In Europe the IRSN in France, Europe's biggest film dosimetry service, plans to switch from film to RPL glass dosemeters completely until 2008. Kodak as the world's largest producer of dosimetry films closed its production in Europe and increased its film prices dramatically. In the medical field digital imaging methods are becoming more and more popular and replace the common X-ray films. In industrial radiography the replacement is going much slower. At AGFA Geveart the production of dosimetry films is connected to the later field of business. Nevertheless, there will be a high pressure to dosimetry film manufacturers to reduce production capacities or to sell or even close production sites in future. For a large IMS as the GSF monitoring service it is an important issue to be ready for such changes. This means that it has to implement alternative dosimetry systems to be able switch over whenever there are problems in film production.

4. Alternative dosimetry systems

For the use of a dosimetry system in a service with the size of the GSF - IMS there are several criteria. The dosimetric properties of such a system are only one part of them and not the most important ones. The costs of detectors, badges and reader systems are other criteria of higher importance for example. The implementation has to go fast and a large number of detectors and badges have to be bought in a relatively short time period. The amount of dosemeters needed is about 3 times the number of possible users, due to the overlap of wearing and readout periods. As an example, this would result in an investment of about € 4.5 Mio. to switch only 50% of the GSF monitored people to a new system with detector/badge costs of € 30,- each. The systems must have a short processing time with a throughput of at least 10 000 – 20 000 dosemeters/day. A high grade of automation is also a very important factor. The dosimetric material should be nearly tissue equivalent to make the dosemeter design simple (not much filtering) and to make any future changes in dosimetric quantities and applications easier. Preferred is material that is already established in routine individual monitoring with well known properties and behavior. The dosimetric performance must be compliant with the new IEC62387 standard, currently in CDV draft status. The dosemeter should provide not only a dose value, but as much additional dosimetric information as possible (similar to film dosemeters). The uncertainties should be reduced compared with the film dosemeter. Finally the manufacturer and provider of dosemeters and system have to be reliable partners in the long term. In the following the pros and cons of each system are described in brief.

Table1. Advantages and disadvantages of film dosemeters.

Pros	cons
Dosemeter costs (<€ 1,- each)	Not tissue equivalent material
Well known tested and established material	No more research and development
World wide in use	Processing chemistry needed
Several manufacturers	Very sensitive to developing conditions
Additional information (imaging)	Sensitive to temperature, light, pressure and humidity
Automation possible	Low sensitivity to photons > 150 keV
Reread able	

4.1. TL dosemeter

Table 2. Advantages and disadvantages of TL dosemeters.

Pros	cons
Tissue equivalent material	Dosemeter costs (~€ 25,- each)
Well known tested and established material	Reader costs (~€150 000,-)
World wide in use and under research	Nitrogen gas needed (not all systems)
Several manufacturers (detectors and cards)	Readout process time consuming (linear heating)
Several readers commercially available	Complex heating system (linear heating)
Automation possible	Not reread able
Reusable	Annealing procedures needed

TL-dosemeters are the best known and the most used dosemeters world wide after film. Several different systems are available with well known performances and characteristics. There are many “middle size” IMS with up to 40 000 monitored workers and experience in process automation is available. In the last years attempts were also made to use TL-material for imaging, but the lower dose limits are still at about 10 mGy for these methods (Budzanowski, 2006; Marczewska, 2006; Nariyama, 2006).

4.2. RPL glass dosemeter

Table 3. Advantages and disadvantages of RPL glass dosemeters.

Pros	cons
System already used in GSF	Not tissue equivalent material
Well known tested and established material	Dosemeter costs (~€ 40,- each)
Fast readout (<10 s)	Reader costs (~€200 000,-)
Additional information (energy and incident angle)	Annealing procedures (dosemeter reset, Hp(10) > 0.7 mSv)
Reread able	Not world wide in use (only Germany and Japan)
Automation possible	No $H_p(0.07)$ value (Asahi SC-1 dosemeter)
Reusable	Only one manufacturer
No heating	

Although RPL glass dosemeters are good reliable dosemeters the costs are very high. This might be different for another type of RPL glass dosemeter distributed by Chiyoda Technol Corporation, Japan, that will be used by the IRSN in France. Up to now the systems were not sold outside Japan and prices are not public.

4.3. OSL dosemeter

Table 4. Advantages and disadvantages of OSL dosemeters.

Pros	cons
Dosemeter costs (<= € 2,-)	Not tissue equivalent material (Al_2O_3)
No heating	Annealing/lighting procedures (dosemeter reset)
Fast readout (<2 s)	Only one manufacturer (dosimetry service)
Additional information possible (imaging capability via laser scanning))	Light sensitive
Reread able	Material and technique not well tested in dosimetry community
Automation possible	Material and technique not free available (Al_2O_3)
"Simple" readout technology -> reader costs	
"Reusable" (complete reset is not possible in reader)	

Prices of OSL dosemeters are similar to those of film dosemeters. Additionally, it has the best imaging capability of all solid state dosemeters due to the readout procedure with laser. The major problem is the current situation about manufacturer and free availability of detector material.

4.4. Electronic dosemeter

Table 5. Advantages and disadvantages of electronic dosemeters.

pros	cons
Reread able	Dosemeter costs (~€ 500,- each)
Reusable	Use as legal dosemeter not possible up to now
Several dosemeters commercially available	Complicated IT infrastructure necessary
Additional information possible (dose rate, energy etc.)	Non tissue equivalent detector material
No reader in IMS necessary, data transfer online	No big experience in legal dosimetry
	EMC sensitive
	Limited battery life
	Regular calibration check

EPDs are very interesting for users due to the direct reading capabilities and the possible use as alarm dosemeters. On the other hand the current prices for the systems and the legal problems in using them as official dosemeters make it very difficult to use them in large scale.

5. Conclusion

World wide film dosimetry is still the most used technique in individual monitoring. At the GSF monitoring service film dosimetry is performed on a high level of dosimetry performance. This is achieved by a high grade of automation and quality assurance. Due to changes in the dosimetry market film IMS have to look for alternative systems. An ideal system combining the main advantage of films and the other solid state dosemeters, as low dosemeter costs, perfect imaging quality for extended dose information, tissue equivalence and higher measurement accuracy is not available at the moment. All currently available dosimetry systems have both advantages and disadvantages for the use in a big IMS like the GSF monitoring service. At current a discussion about a second future system has been started. As long as there is no clear alternative and films are available, film dosimetry will stay one of the main dosimetry systems at GSF. The dosimetry with films is a reliable and state of the art system for individual monitoring.

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ACTIVE PERSONAL DOSEMETERS: AN OVERVIEW

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Abstract

In modern radiation protection practices, active personal dosemeters (APDs) are becoming absolutely necessary operational tools for satisfying the ALARA principle. Despite their success, they are relatively new for individual monitoring of workers. This presentation will start by giving an overview of a EURADOS working group report on active personal dosemeters (APDs). In this report, a first status description of active personal dosemeters (APDs) and their implementation in European countries was presented. A catalogue of commercially available APDs was composed and end-user feedback experience and requirements were reported.

Next, the main results of an intercomparison of APDs will be discussed. This intercomparison was organized as a joint venture project between the IAEA and the European Dosimetry Group (EURADOS) to assess the technical capabilities of all types of electronic personal dosimeters an available on the market.

Finally some comments are made on the use of APDs as legal dose of record.

1. INTRODUCTION TO ACTIVE PERSONAL DOSEMETERS (APDs)

APDs are defined in the context of this report as all devices with personal dose equivalent direct reading capability. Some dosemeters which are in this definition considered as APDs do not have an alarm function, like the DIS (Direct Ion Storage). In this paper we will not talk about active personal dosemeters for neutrons, since they are very new on the market and a whole range of different problems need to be considered for them.
The APDs have some interesting characteristics compared to passive devices, some quite obvious like instant or direct reading and the possibility for an audible alarm. They are also more suited for data transfer to and from a computer network and some have dose memory options for distant read out. In general they can also have a lower detection limit than passive devices.

2. A CATALOGUE OF APDs

In 2001, a second EURADOS working group on "Harmonisation of Individual Monitoring" was formed, funded by the European Commission in the fifth framework program, and by the participating institutes. The working group consisted of experts from almost all EU Member States, several candidate Member States and other European countries. The work addressed issues on standards and documents of relevance, the integration of internal and external dosimetry, uncertainties in passive external dosimetry and there was also a separate working group on active personal dosemeters.
The results of the investigations were published in Radiation Protection Dosimetry journal(1) and presented during the Individual Monitoring Workshop, IM2005, in Vienna. Within the APD working group, a catalogue of the most extensively used active personal dosimeters suitable for individual monitoring was made(2). The catalogue contained information on the legal status of APDs in the various countries, the relevant standards, the dosimetric characteristics of the devices and on type tests performed by both manufacturers and independent organizations. In the catalogue 31 dosemeters from 16 manufacturers are described.

They can be divided in three types:

- Photon dosemeters with Geiger-Muller tube (e.g. Automess, Graetz, Mini Instruments, Polimaster, SAIC)
- Photon or beta-photon dosemeters with one or more silicon detectors (e.g. AEA Technology, Aloka, Canberra Dosicard, Comet, Dositec, Fuji Electric, MGP, Saphymo, Rados, Thermo Electron)
- Others (Rados DIS dosemeter, Unfors (extremity))

The information gathered of these devices was on their radiological performance, physical characteristics, environmental performance, mechanical performance and dose recording procedure. Following this analysis it was concluded that APD are widely used in many countries, mainly as operational dosimeters in nuclear power plants.

3. INTERNATIONAL STANDARDS

A large number of standards are available for radiation protection and individual monitoring purposes, a thorough review of them can be found in reference[3]. However, for the purpose of the active personal dosemeters, the IEC 61526:2005[4] standard is of major importance:

IEC 61526:2005 Radiation protection instrumentation – Measurement of personal dose equivalents *Hp(10) and Hp(0,07)* for X, gamma, neutron and beta radiations – Direct reading personal dose equivalent meters and monitors and personal warning devices

This international Standard applies to non-passive direct reading personal dose equivalent meters and monitors used for measuring the personal dose equivalents $H_p(10)$ and $H_p(0,07)$ for X, gamma, neutron and beta radiations and to personal warning devices used to give an indication of the personal dose equivalent rate. It provides requirements on the general and mechanical characteristics, dosimetric, electrical, electromagnetic and environmental performance of the dosimeters. It is the second edition of the international standard IEC 61526, which was first published in1998, and replaces the former standards IEC 61283, IEC 61323 and IEC 61525 in one standard. Moreover, it includes technical changes such as the determination of the uncertainty of the measured dose value and the consideration of the

relevant ISO standards on reference radiations and calibration.
In table 1 the characteristics of the devices (as given by the manufacturers) from the catalogue are compared with the requirements from the standard. E.g. for the size of the APD all devices pass, as is graphically presented in figure1. The problems are with the radiological characteristics like the photon energy response and the beta response. In Figure 2 it can be seen that only few devices measure lower than 50 keV.

Charateristic	**IEC 61526 requirement**	**Typical values for APD**
Size	< 250 cm^3	100 cm^3 (31/31)
Mass	< 200 g	80 g (31/31)
Mechanical resistance	±10%, 1.5 m drop test	Some do not pass (25/31)
Environmental immunity	±10%, e-m interference	Older types do not pass (28/31)
Range	1 µSv – 1 Sv	1 µSv – 1 Sv (25/31)
Photon fields (33 keV-2 MeV)	±15%	50 keV – 2 MeV (11/31)
Beta fields (90Sr/90Y, 204Tl)	±15%	(4/31)

Table 1: Characteristics of the APDs compared to the IEC 61526 standard requirements

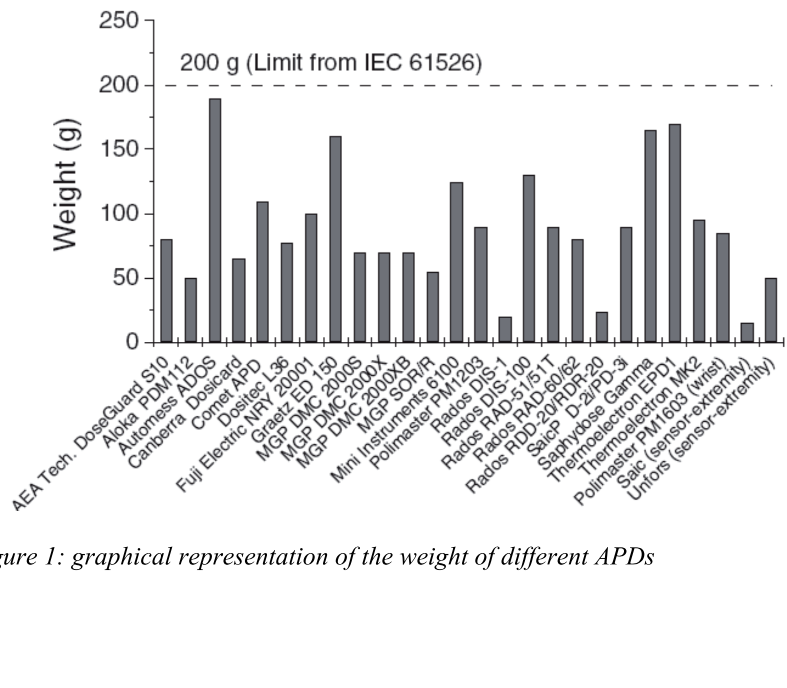

Figure 1: graphical representation of the weight of different APDs

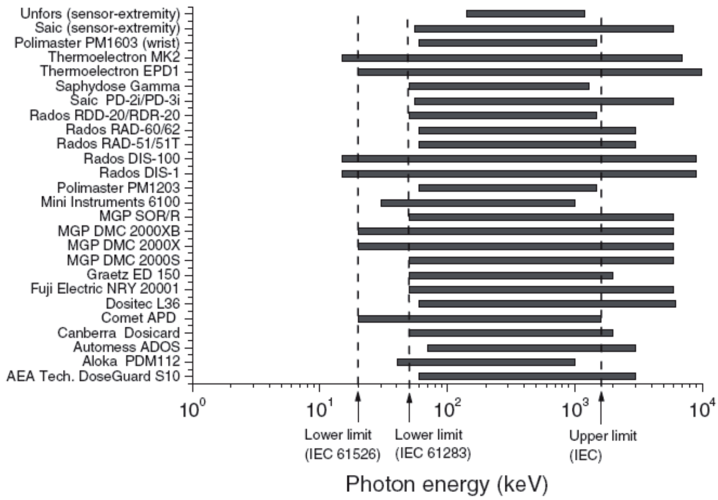

Figure 2: Energy range of different APDs as indicated by the manufacturers

4. IAEA/EURADOS INTERCOMPARISON OF APDs

Following the results from the EURADOS working group on APDs, the organization of an international intercomparison, which would address active personal dosimeters, was considered of great value to the dosimetric community. The common interest of IAEA and EURADOS in the project lead to the organization of this intercomparison to assess the technical capabilities of all types of electronic personal dosimeters. The intercomparison is the first organized on international basis and can stimulate constructors to improve their instruments and give end-users suggestions for calibration procedures and for applicability in the different fields of interest.

The overall objective was to verify performance of the different APD types available in the market. The scope of the intercomparison was aimed at electronic dosimeters capable to measure the quantity Hp(d) in photon and beta fields. Several technical characteristics have been tested, excluding the alarm function.

The irradiation program was shared between three laboratories: SCK-CEN (Belgium), IRSN (France) and LNE/LNHB-CEA (France). All irradiation were performed on the ISO slab phantom and with parallel or nearly parallel beams.

The following characteristics have been checked:

1. Reproducibility of response between 3 different units of every tested dosimeter.
2. Repeatability of the response (5 readings for each irradiation condition in one unit of each tested dosimeter).
3. Photon energy response (ISO 4037-1 qualities): S-Cs, S-Co, N-30, N-80, N-120.
4. Beta energy response (ISO 6980 qualities): 90Sr-90Y, 85Kr, 147Pm
5. Angular response for S-Cs: 0º, 45º and 60º
6. Angular response for beta radiation: 90Sr-90Y (0º, ± 30º, ± 60º), 85K (0º, ± 30º)
7. Influence of dose rate (relative response at 1.00 Sv/h and 1.00 mSv/h).

To investigate the APD response in simulated work-place fields the following additional irradiation fields were foreseen:

1. Pulsed fields defined in IEC 61267, pulse width of 1600 μs; 16 mAs; 60 kV (RQR4) and 120 kV (RQR9)
2. Mixed photon field: S-Cs and N-80 for normal incidence.

The results of this intercomparison will be published in detail as an IAEA Tecdoc[(5)]. We will only show a few results in this paper.
No problems with all tested APDs were found using standard radiation qualities like S-Cs, S-Co, N-120 and N-80. Also the mixed field response and the angular dependence were well within the limits of the standard (see e.g. figure 3). Also the dose rate dependency test was passed by all types (figure 4). The only problems that were detected were with the use of pulsed fields and low X-ray energies (N-30). It can be seen in figure 5 that a majority of the devices underestimate low energy X-rays. It is important to mention that this agrees with the technical specifications of these APDs since they were not designed to measure low energies.

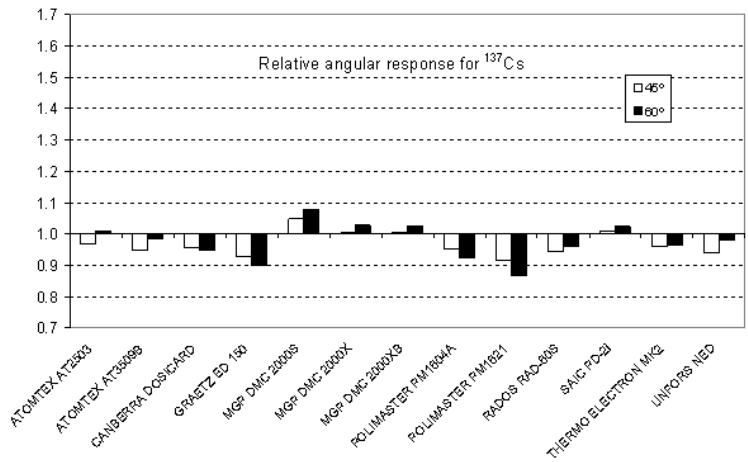

Figure 3: Angular dependence of the APDs in the intercomparison

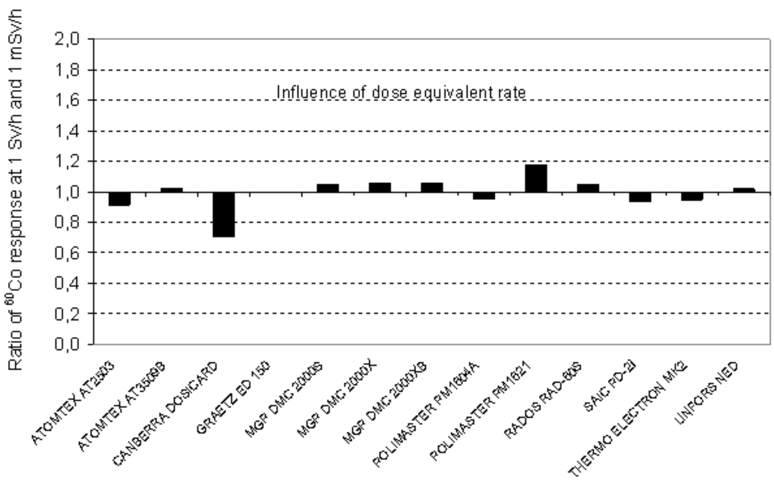

Figure 4: Ratio of the ^{60}Co response at 1 Sv/h and 1 mSv/h

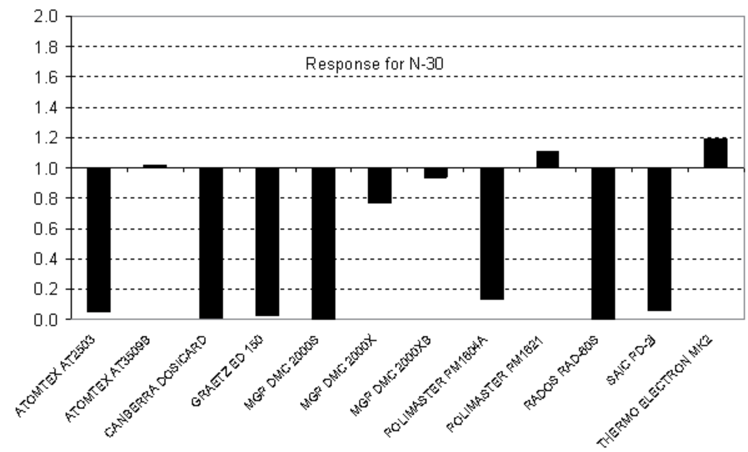

Figure 5: Response to N-30 X-rays of the tested APDs.

The intercomparison results show that the general dosimetric performance of the tested APD is comparable to the performance of standard passive dosimetric systems(6). The accuracy at reference photon radiation, the reproducibility and repeatability of measurements are even better than for most passive dosimeters. However, the study highlights that not all the devices have been designed for any radiation field and that the end-user should take into account at least information about the pulsed dose rate and energy ranges before using the dosimeter.

5. WILL APDs BE USED AS LEGAL DOSEMETER?

Because the APDs have interesting technical features in comparison with passive systems, it has brought about general concerns about accepting them as legal primary dosimeters. This would mean that it would be enough to wear only an active dosemeter and their results are used to check the legal dose limits. No passive dosemeter system would be necessary anymore.

In the 96/29 Euratom Directive there is no specification on which type of dosemeter needs to be used, only that it should estimate the effective dose. So in principle it should be possible to use the APDs as legal dosemeter. However, only few countries, such as the United Kingdom or Switzerland, have already established formal approval or accreditation procedures to use an APD as a primary legal dosimeter. In these cases it is only a specific APD system that is approved in a specified workplace. In Germany a pilot project is ongoing. In the majority of countries, APDs have not undergone accreditation programs and a passive system is still obliged.

Using only APDs would be cost-effective, but the main questions are if they are reliable enough, and if they are technically good enough.

The technical aspects of the APDs have been described above. It is clear that the angular and energy dependence of the present APDs is as good, or even better than the existing passive systems. The lower detection limit is mostly even lower than for passive systems, but it can be questioned if this is necessary to check the dose limits. The direct read-out and data transfer capabilities can facilitate the follow up of the doses received by the workers. The major point of attention is to make sure that your APD is suited for the work place field under study. Some APDs underestimate for low energy X-rays, beta-fields and pulsed fields. In these cases a passive system often has better performance.

The present passive systems (film, thermoluminescence, optically stimulated luminescence, glass dosemeters) have shown through the years that they provide a technically adequate solution for legal dosimetry. They are smaller and cheaper than the APDs, and are in general more robust than APDs.

To judge on the reliability, there are not many data available for APDs. In the UK, the Thermo Mk2 has been used as legal dosemeter for many years in the nuclear power plants of BNFL. They received a specific approval to use these dosemeters, and they had to install extensive quality control measures for the data transfer and data management, including periodic calibrations of the APDs. After several years it could be concluded that the computer systems for data management were reliable enough. Only 0.06% of the data have been lost, mostly through physical loss of the dosemeter or technical malfunctions of the APD. It must be stressed that these low numbers are only valid for this nuclear power plant case where the follow up is very strict. In other industries these numbers could be much higher.

Also for passive systems there are not too many data on reliability and loss of data. EURADOS has distributed a questionnaire on this issue(7) a few years ago to the dosemeter services. They were asked what percentage of the dosemeter results were lost. Numbers between 0 and 20% were reported, with a mean of 1%. Most stated causes of the loss of the dosemeter result were incorrect wearing of the dosemeter, loss in a washing machine, and loss during processing. It is important to note that if a passive dosemeter result is lost, more data is lost than when an active dosemeter is lost.

6. CONCLUSION

It can be concluded that APDs have reached a state-of-the-art where they are ready to be used as legal dosemeter to control the dose limits. The data transfer and reliability are sufficient compared to passive systems, and also the technical characteristics are sufficient or better than passive. Care needs to be taken for specific fields like low energy X-ray fields and pulsed fields. Several authorities in Europe are starting to accept APDs as legal dosemeters. Still, the approval procedures must be very strict and must take into account the specific workplace situation. Extensive quality control needs to be applied, and regular calibration of the dosemeters needs to be done. Therefore it will not always be possible to do this in-house, and the aid of a dosimetry system can be necessary. Using two systems (passive and active) like it is now done in practice has some clear advantages in case of loss of data or in case of high doses. It is clear that an APD system will be more expensive, while the small and easy passive system is often sufficient at the moment. So, many users will stay with passive systems, even if APDs will be approved through dosemeter services.

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DOSE TO WORKERS IN BELGIAN INTERVENTIONAL RADIOLOGY CENTERS

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Abstract

The purpose of this project was to investigate radiation doses to the medical staff that perform high x-ray dose procedures in Belgium. In contrast to standard radiological investigations where the operator is protected behind the lead screen of the console, interventional radiological (IR) procedures require the presence of the medical staff next to the patient in order to perform the procedure. Consequently, scatter radiation doses to the staff members can be substantial. Routine personal dosimetry methods may not be valid for staff members that wear lead aprons and that are partially exposed to a complex scatter field geometry. Another concern is the dose to the parts of the body that are not shielded by the lead apron. Surface doses to the hands, legs and the dose to the forehead (eyes) can also be substantial during high dose procedures.
The project consisted in two parts: (1) calculation of effective dose, and (2) measurement of extremity doses

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The project consisted in two parts: (1) calculation of effective dose, and (2) measurement of extremity doses. The project was financially supported by the Belgian Federal Agency of Nuclear Control.

1. Calculation of effective dose to staff using Monte-Carlo simulations

The objective this part was to propose a multiple dosimeter algorithm that can be used for estimating the effective to dose workers that wear a lead apron. The approach that was followed in this study can be summarized as follows: a Monte Carlo simulation environment was set up to calculate both the effective dose in the staff following the (theoretical) exposure of a patient and the dose that would be measured with a dosimeter at different positions (Hp(10)thorax, under apron, Hp(10)neck, etc….). The simulations were performed for (1) different exposure geometries in clinical practice (tube over couch, under couch and for different viewing angles), (2) different beam qualities (from 70 kVp with 3 mm Al up to 90 kVp with 6 mm Al), and (3) for typical positions of the staff during interventional work (both translation and rotation). It was then searched for the best prediction of the effective dose based on selected measurable doses and for this mix of typical conditions. The dosimeter reading with the highest Pearson's correlation to the simulated effective dose was selected for each case to estimate the effective dose. A maximum underestimation of 10%, as recommended by the US National Council on Radiation

Protection and Measurements in NCRP Report 22, was used to determine the proportionality coefficient of the estimation algorithm. A suitable two-dosimeter algorithm was determined if a complementary dosimeter was found to improve the adjusted coefficient of determination R^2 of a linear regression model without intercept significantly ($p<0.05$). The second degree of freedom in a double dosimetry algorithm was used to minimize overestimation while still controlling for underestimation at the 10% level. NCRP Report 22 recommends a maximum overestimation of 200%. A linear two-dosimeter algorithm satisfying both criteria could not be found in all cases. Given the risk implied by personal effective dose estimates, strict adherence to the underestimation limit of 10% was preferred.

Based on the simulations performed, a double dosimetry algorithm is proposed, which can be adapted or refined to the situation at hand.
The following general algorithm (1) is proposed for radiography/ fluoroscopy in general (for all tube positions, all positions of the worker and all beam qualities):

(1)
Eest = 2.25 × Hp(10)th,under + 0.12 × Hp(10)neck, over

Figure 1 shows the effective dose in function of the effective dose estimated with this double dosimetry algorithm (1) for all performed simulations, thus all exposure cases. The figure shows that the algorithm is severely constrained by the 10% maximum underestimation condition. This limit is reached for examinations where the staff member is positioned relatively far away from the patient, hence the low effective dose. It should be noted that this is not the most common situation for the physician who is standing next to the table, but not unusual for assisting personnel. The overestimation increases to 291.4%, with this maximum observed with the worker at short distance to the beam and low effective beam energy. Thus, applying this general algorithm (1) for physician's that stand in close proximity to the patient will overestimate their effective dose considerably.
<u>Algorithm for physicians standing in close proximity of the x-ray tube</u>

Figure 1 has shown that the previously introduced double dosimetry algorithm (1) will over-estimate E strongly for the cases where the highest risk exist to exceed the imposed yearly effective dose limit, thus for the physician who stands close to the patient. Therefore an adjusted algorithm is provided based on only the simulations performed with a worker distance to the centre of the patient entry field less than or equal to 50 cm. This algorithm (2) is thus valid for the physician that carries out the procedure.

(2)
Eest = 1.64 × Hp(10)thorax,under + 0.075 × Hp(10)neck, over

Influence of lead collar
Additional simulations performed with a lead collar of 0.25mm Pb (single voxel layer) show that the effective dose can be reduced by at least 40%. Under the simulated conditions for the physician at close proximity to the patient, and allowing for a maximum under-estimation of E by 10%, the adjusted double dosimeter algorithm, which can be applied when a collar is used, is:

(3)
Eest = 1.64 × Hp(10)thorax,under + 0.058 × Hp(10)neck, over collar

Table 1 lists the organ dose reduction factors that are obtained when wearing a lead collar for exposure geometries when the x-ray tube is positioned under the couch and lateral. This is the most common exposure geometry in interventional radiology. The dose reduction by wearing a collar is in these exposure geometries less pronounced than in the over-couch tube case, because the contribution of thyroid dose to the effective dose is smaller. Dispersed tissues like the skin and the bone surface were no longer significantly (dose reduction factor >99%) shielded by a lead collar. For these tissues the main contribution to organ dose when using under-couch projections will arise from the unprotected parts of the extremities. It is recommended to use additional lead collar protection whenever available. The use of an additional collar results in high organ dose reductions for all organs at risk in the neck region, and additionally for organs exposed to secondary scattering by the neck and shoulder holes of the apron.
The results of this study also showed that error margins for dose estimates of lead apron workers based on single dosimeter readings are very large (up to 800%). Therefore, the use of only a single dosimeter for routine dose monitoring is not recommended. Also, a dosimeter worn above the

apron at neck level can be used to estimate the dose to the eye lens. For most situations Hs(0.07) will overestimate this eye lens dose by a safe margin of 25%. This is shown by figure 2.

2. Extremity doses to personnel in Belgian IR centers

The purpose of this part was to measure extremity doses to the medical staff in various Belgian centers where various types of interventional radiological (IR) procedures were carried out. These were both angiography (radiology) and vascular surgery centers. The characteristics in this study were: (1) the multi center set-up in Belgium, (2) the use of high sensitive TLDs to monitor extremity doses of individual procedures, (3) the monitoring of up to three persons per procedure and (4) the availability of complete data on the individual procedures (thus enabling an analysis of extremity dose in terms of DAP), the working practice from the point of view of radiation protection of the workers and on the equipment in more general terms.
Individual extremity doses were monitored per procedure at five positions: the forehead, both hands and both legs. The dosimeter at the forehead was attached to the skin between the eyes, for both hands the detectors were attached to the dorsum of the base of the index finger. This location is chosen as it is observed that this is the area of the hand that receives the highest dose for the majority of IR procedures. For both legs the detectors were attached to the trousers, anterior on the tibia, 5 cm below the lead apron border in order to exclude any shielding from the apron. Thermoluminescent detectors (TLDs) were used of type MCP-7 (LiF: Mg,Cu,P) with diameter 4.5 mm and thickness 0.9 mm. Calibration was performed individually with N-80 beam quality (by ISO 4037 standard) with 48 keV effective beam energy and a filtration of 0.6 mm Cu and 4 mm Al. The detectors were calibrated in shallow soft tissue Hp(0.07) dose unity.

Measurements were obtained of 218 procedures. For every center, the median dose per procedure to the physician is shown in table 2. The data of the dose to the legs is plotted in figure 3.

Figure 4 shows the observed dose per procedure for the physician (left) and the assistant (right) at the level of the head, legs and hands shows the data for the physician and the assistant separately. Note that the graphs use different scales. For both type of workers, the dose to the legs is much higher than the dose to the head due to the x-ray tube under-table exposure geometry. This geometry is most frequently encountered during interventional radiological procedures. From all the procedures during the dose collection, 83% were carried out with this posterior-anterior (PA) under-table x-ray tube geometry.

From the three monitored types of workers, the physician received the highest dose. The doses to the assisting personnel and the nurse were significantly lower due to their larger distance to the exposed patient region and due to the fact that they are often shielded by the physician. Normalizing the doses to procedure DAP showed that the doses to the physicians in vascular surgery centers were significantly higher than the doses to the physicians in angiography centers.

In five angiography centers the physician removed himself from the patient during acquisition of the images and protected himself behind a lead screen at a large distance. They are marked as “Angiography centers + RP” in figure 5. This resulted in significantly reduced personnel doses. These centers carried out a large variety of procedures and indicate that angio procedures can be performed with acceptable doses despite a high workload. Figure 5 shows for the physicians an extrapolation of the obtained data to annual doses to the legs. One physician (doctor A) is likely to exceed the 500 mSv skin dose level. The annual workload of the physicians is also presented. A High workload is not necessarily related to high doses.

Figure 1. Effective dose in function of the effective dose estimated with double dosimetry algorithm (1) for all exposure conditions simulations.

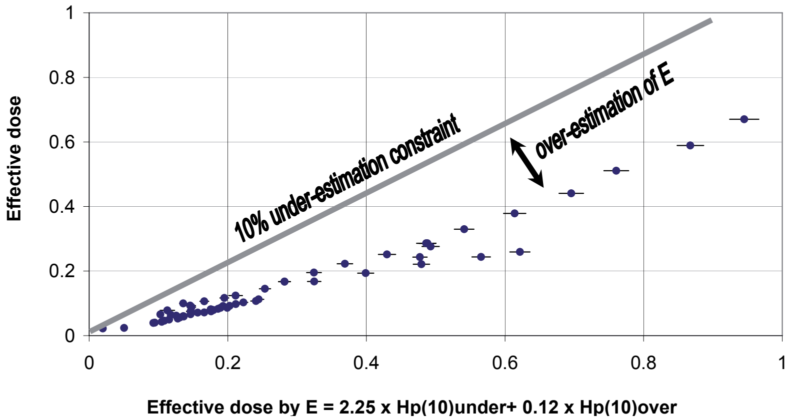


Table 1. Organ dose reduction factors for 0.25*mm* Pb lead collar, under-couch and lateral projections.

Organ	$H_{organ,with\ collar}$ / $H_{organ,without\ collar}$
Thyroid	31.3%
Trachea	48.2%
Thymus	80.7%
Esophagus	82.6%
red bone marrow	95.3%
Lungs	97.0%
Brain	97.8%
Breasts	98.2%

Figure 2. Correlation between dose to the eye lens and a neck dosimeter, for all simulations performed, except for the geometries with lateral tube at the side of the worker.

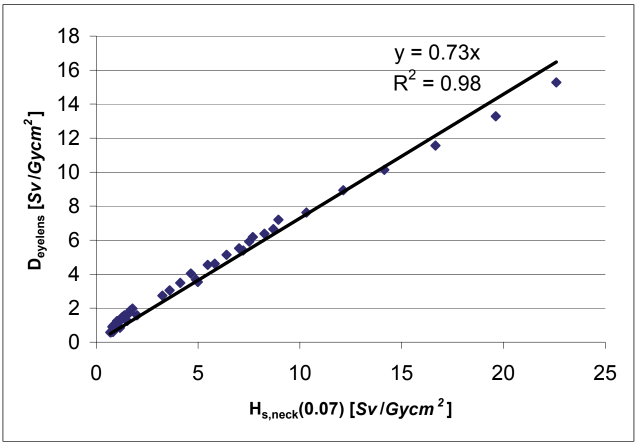


Table 2. Observed Hs(0.07) dose data to the physician per procedure at the level of the head, hand and leg in all centers.

Location	N	Head (µSv/proc)		Hand (µSv/proc)		Leg (µSv/proc)	
		median	75 perc.	median	75 perc.	median	75 perc.
Center 1	46	59	135	113	223	125	328
Center 2	19	16	30	39	85	98	168
Center 3	23	29	47	95	163	70	105
Center 4	23	80	139	478	864	273	790
Center 6a	11	22	34	130	205	35	54
Center 6b	4	32	56	69	119	29	180
Center 7	26	17	25	18	69	11	30
Center 8	19	0	21	0	23	0	30
Center 9	21	51	83	189	241	399	609
Center 10	12	15	24	37	57	55	62
Center 11	11	57	61	228	574	368	744
Center 15	10	219	257	821	1457	930	1215
Center 16	15	135	170	262	382	177	264
Center 17	6	115	166	290	337	239	302
Center 18	21	89	130	226	326	181	321
Center 19	7	49	69	262	331	131	268
Center 20	6	131	151	906	1650	406	596
Total	280						

Figure 3. Median Hp(0.07) dose per procedure to the leg of the physician

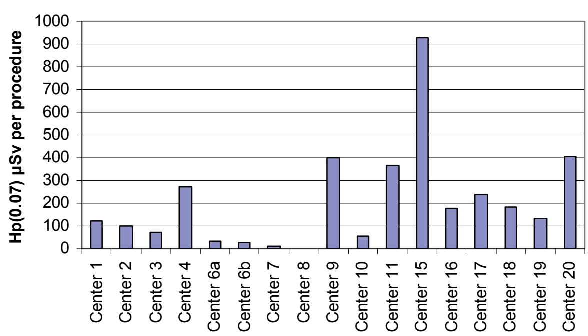


Figure 4. Observed dose per procedure for the physician (left) and the assistant (right) at the level of the head, legs and hands.

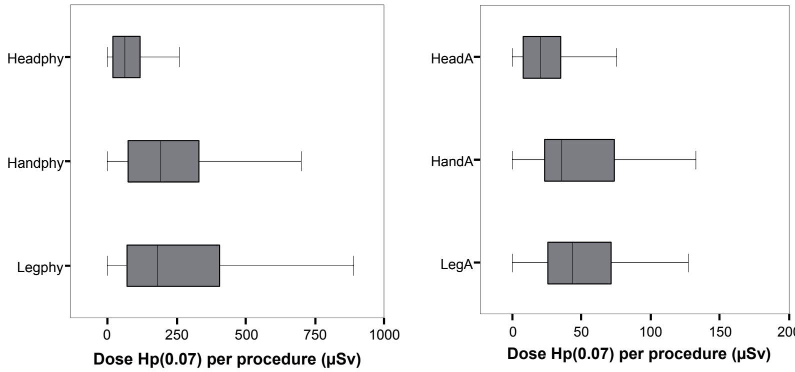
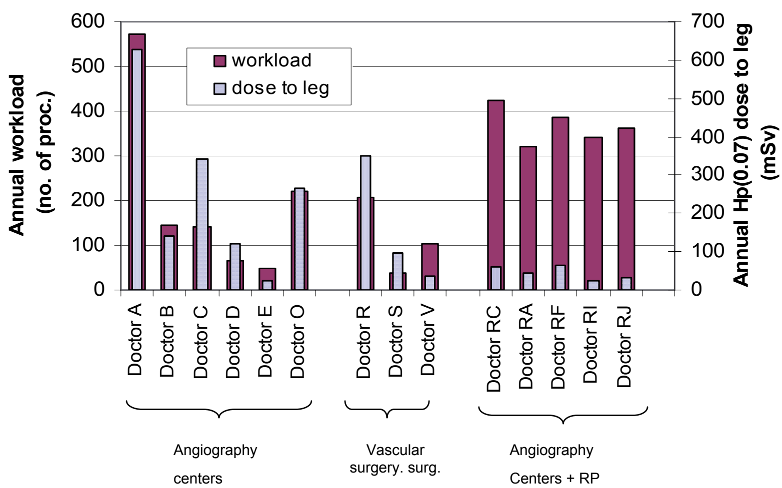


Figure 5. Annual workload and estimated annual dose to the leg for a selection of physicians.



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NEW DEVELOPMENTS IN THERMOLUMINESCENCE DOSIMETRY OF IONISING RADIATION

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Abstract

Thermoluminescent (TL) dosimetry began around 1950 when Daniels (USA) applied TL powder for evaluating nuclear tests. Some ten years later, solid TL detectors in the form of crystals and sintered material became commercially available. Since then many different TL materials and various techniques of reading their signal by manual or automatic TL readers have been developed. Their common feature was the use of a photomultiplier (PM) tube for reading the TL light to measure TL light output versus heater temperature, i.e. the glow-curve. Modern CCD cameras are sensitive enough to read the TL signal and are able display a two-dimensional (2D) image of the dose distribution within a TL crystal or pellet, or over a larger area if a foil TL detector is applied. 2D-imaging of the dose distribution within a TL detector makes it possible to distinguish between static and dynamic X-ray exposure of dosimetric badges worn by radiation workers. At the Institute of Nuclear Physics in Krakow (IFJ PAN) we demonstrated the possibility of determining the direction from which a standard personal dosimetry badge with TL detector was irradiated. These, and other recent developments in thermoluminescent dosimetry, will be presented.

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SUMMARY OF THE NEUTRON DOSEMETER RESULTS OF THE EVIDOS PROJECT

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Abstract

EVIDOS ("Evaluation of Individual Dosimetry in Mixed Neutron and Photon Radiation Fields") is an European Union (EU) sponsored project that aimed at a significant improvement of radiation protection dosimetry in mixed neutron/photon fields. The performance of personal dosemeters and survey instruments was tested in selected workplace fields. Reference values for the dose equivalent quantities, H*(10) and Hp(10) and the effective dose E, are determined using different spectrometers that provide the energy distribution of the neutron fluence. Also newly

developed devices are used that determine the energy and directional distribution of the neutron fluence. Under- and over-readings by more than a factor of two for the same dosemeter in different workplace fields indicate that in most cases the use of field-specific correction factors is required.

In this paper we will give a short overview of the methods used for the determination of the reference values, and focus on the results of the personal and ambient dosemeters in the different fields.

1. INTRODUCTION TO NEUTRON DOSIMETRY

Radiation protection dosimetry in mixed neutron/photon fields is still far less established than for photon radiation alone. Usually readings are accepted which are lower or higher than the conventional true value up to a factor two. In practice, passive devices are used with high dose threshold and not ideal energy characteristics. Active neutron personal dosemeters are used rather infrequently still in workplaces and have become available only during the past few years.Also area monitors readings can deviate significantly from the radiation protection quantities.

Neutron dosimetry never had much priority. In general the neutron doses are lower than 10% of the total dose. In nuclear power plants the dose from neutrons is only around 1% of the total collective dose. So mostly only few people at few workplaces need to wear a neutron dosemeter.

Now neutron dosimetry is also more difficult than gamma dosimetry. The neutrons are mostly accompanied by strong gamma fields, which makes it difficult to separately measure the neutrons. A neutron dosemeter needs to measure both the thermal and the fast neutrons, which means that the dosemeter should be able to measure over an energy range of 9 orders of magnitude (from some eV to tens of MeV). Thirdly, an ideal neutron dosemeter should measure the dose equivalent, so the dosemeter response should follow the energy response of the conversion factors from fluence to dose equivalent. Because of the weighting factors this means that a neutron dosemeter should have 50 times more response for a fast neutron than for a thermal neutron, and this for the same amount of absorbed dose.

2. OBJECTIVES OF THE EVIDOS PROJECT

Within its 5th Framework Programme, the EC funded the project EVIDOS which performed an EValuation of Individual DOSimetry in mixed neutron and photon radiation fields at workplaces of the nuclear fuel cycle, with special regard to neutrons[1].

The main objective of this project was to evaluate different methods for individual dosimetry in mixed neutron-photon work-places in the nuclear industry. This required the capabilities and limitations of personal dosemeters to be determined. The development of reference methods for the determination of personal dose equivalent in workplace fields was a central part of this project. Because no current dosemeter can provide correct results in all neutron fields, reference values were derived from spectrometry (with respect to energy and direction of the radiation) and fluence-to-dose equivalent conversion coefficients.

In order to achieve this goal, workplaces in the nuclear industry where workers can receive significant neutron doses were selected, and the following tasks were carried out:

- determination of the energy and direction distribution of the neutron fluence
- derivation of the (conventionally true) values of radiation protection quantities
- determination of the readings of routine and innovative personal dosemeters and of area monitors
- comparison between dosemeter readings and values of the radiation protection quantities

The measurements took place in selected mixed-radiation environments representative of the nuclear fuel cycle, including reactors, fuel processing, reprocessing, transport and storage facilities. These environments permitted thorough testing of the dosemeters since the fields differed widely in terms of dosimetric and environmental parameters. Selection of the measurement positions, the measurements and the analysis of the dosimetric results was done in collaboration with the radiological safety officers of the facilities.

3. WORKPLACE FIELDS

An extensive measurement programme was performed in selected mixed-radiation environments representative of the fields encountered in the nuclear fuel cycle. In total 19 workplace fields were visited:

(1) Two simulated workplace fields in Cadarache: Sigma and CANEL

(2) Four workplace fields at the BWR Krummel: KKK Reactor Top, KKK SAR, KKK Cask midline, KKK Cask Side

(3) Two workplace fields at the Venus research Reactor at the SCK-CEN: Venus Control Room, Venus Reactor Side

(4) Four workplace fields at the MOX fuel facility Belgonucléaire: Belgo P1 Bare rods, Belgo P2A Unshielded Rack, Belgo 2B Shielded Rack, Belgo P3 Stockroom

(5) Four workplace fields at the PWR in Ringhals: RH Pos L Entrance Lock, RH Pos A Containment, RH Pos D: Cask midline, RH Pos N Cask End

(6) Three workplace fields in a nuclear facility: NF1, NF2, NF3

The cask fields differed because at Ringhals the neutron shield was attached to the cask resulting in a much more thermalised field. Because the dose rate at the Venus control room was too low, no differential spectrometry could be done there and only Bonner Sphere data as reference are available. At the nuclear facility the program had to be restricted as well due to boundary conditions, so several instruments could not be used there.

4. ANGULAR AND ENERGY SPECTROMETRY RESULTS

The Bonner-sphere system determines only isotropic quantities like ambient dose equivalent and total fluence for the entire energy range. In the EVIDOS project an effort has been made to determine also values for non-isotropic quantities, such as personal dose equivalent and effective dose. The measurements of the double-differential (energy and direction) neutron fluence are performed with a novel instruments based on Si-diodes[2].

The directional spectrometer based on the Si-diodes consists of six detector capsules - each containing a stack of 4 detectors - mounted onto the surface of a 30 cm diameter polyethylene sphere, and electronics to amplify and record the pulse height spectra of all detectors. The pulse height spectra measured in workplace fields are analyzed using unfolding codes with respect to energy and direction both for neutrons and photons. Ratios of personal dose equivalent $H_p(10)$ for different direction of incidence to ambient dose equivalent are derived by multiplying the fluence distributions by the corresponding fluence-to-dose conversion coefficients. These ratios are multiplied by the $H^*(10)$ values determined by the Bonner Spheres to yield the $H_p(10)$ values to which we will compare the bubble detector results. The estimated uncertainty on the resulting $H_p(10)$ values is 30%.

A second method is called HpSLAB, and consists of a superheated detector inserted in 10 mm depth in a PMMA phantom. As the superheated drop detector has a nearly dose equivalent response, the result of the device should count as a reference instrument for $H_p(10)$.

The neutron spectra measured at all the fields can be found elsewhere[1,3], but we can classify them in this paper according to their average conversion factor *h*(10)* from fluence to ambient dose equivalent, as determined with the Bonner Spheres. This ranges from 23 pSv.cm² for the very thermalised Sigma field, to 260 pSv.cm² for the bare fuel rods at point 2A of Belgonucléaire.

Measurement Position	*h*(10)* [pSv.cm²]
CADARACHE	
IRSN SIGMA	22.6 ± 0.7
IRSN CANEL	43.3 ± 2.3
KRUMMEL	
BWR SAR – Control rod room	37.4 ± 1.5
BWR T – Top	41.1 ± 1.7
Cask NTL M – Centre	185.1 ± 6.0
Cask NTL S - Side	156.0 ± 6.1
MOL - VENUS	
SCK-CEN VENUS F – Side shielding	48.4 ± 2.7
SCK-CEN VENUS C – Control room	37.2 ± 1.3
MOL – BELGONUCLEAIRE	
Belgonucléaire 1 – Bare MOX fuel rods	253.4 ± 8.1
Belgonucléaire 2A - Unshielded rack	260.0 ± 8.1
Belgonucléaire 2B – Shielded rack	142.5 ± 4.9
Belgonucléaire 3 – Storage room	114.8 ± 4.1
RINGHALS	
PWR Ringhals L – Entrance lock	39.1 ± 1.3
PWR Ringhals A – Inside containment	30.2 ± 1.0
Cask TN D – Centre of long side	49.6 ± 1.9
Cask TN D – Centre of end plate	38.6 ± 1.6
NUCLEAR FACILITY	
Nuclear Facility 1 - Door	115.8 ± 3.6
Nuclear Facility 2 - Corridor	55.8 ± 1.9

Table 1: The average conversion factor h(10) from fluence to ambient dose equivalent, as determined with the Bonner Spheres, for all workplaces*

5. AMBIENT DOSEMETER RESULTS

Four moderator-type neutron area monitors were used at almost all of the workplaces. These were the Studsvik 2202D, the Harwell Leake N91, the Berthold LB6411 and the Wendi-2. A few other designs of moderator-type survey instruments were also used at a subset of the workplaces but those partial datasets are not discussed here. Additionally, a less conventional TEPC-type (tissue equivalent proportional counter) design was used at most workplaces[4].

The results from the survey instruments are presented firstly as the response in terms of the ratio of the instrument reading to the reference $H^*(10)$ rate from the Bonner sphere measurements. Secondly, the responses are "predicted" based on the known energy dependence of response of the instrument and the energy distribution of the field as determined. For all four of the moderator-type instruments, this is done using the assumption that all of the field is incident from the reference direction. Differences between the predicted and measured response may derive from deficiencies in the angle dependence of response of the instrument, or from deficiencies in the reference dosimetry.

Both the measured and calculated responses of the four moderator-type area monitors are shown in Figure 1, where they are plotted against the mean fluence to $H^*(10)$ conversion coefficient for the field. The measured responses (blue) reveal a tendency to underestimate in hard fields for all four designs, although the underestimates are never more than 30%. In the softer fields, the different instruments show less similarity, with the Wendi-2 consistently overestimating and the Studsvik 2202D and Leake N91 tending to underestimate.

Generally, the instruments provide good estimates of the reference $H^*(10)$ rate. The largest overestimates are for the Wendi-2 when used in relatively soft fields: they reach as much as 76% for the BWR SAR field. This is caused by the over-response to intermediate neutrons not being balanced by an under-response to thermal neutrons for this instrument. Generally, however, the overestimates are less than 50%, the other exception being the PWR L field which has a significant intermediate energy component.

Small underestimates of the soft fields may not be considered to be of great concern, because in such fields the $H^*(10)$ to effective dose ratio is generally large. In fact, for the fields investigated in this work that ratio ranges from about 2 to 3 so in no instance is the underestimate of $H^*(10)$ an underestimate of effective dose. Overestimates of $H^*(10)$ are of concern because they could cause over-restriction of work practices or expensive modifications to the plant.

The predicted responses show reasonable agreement with the measured values, although there are some significant exceptions.

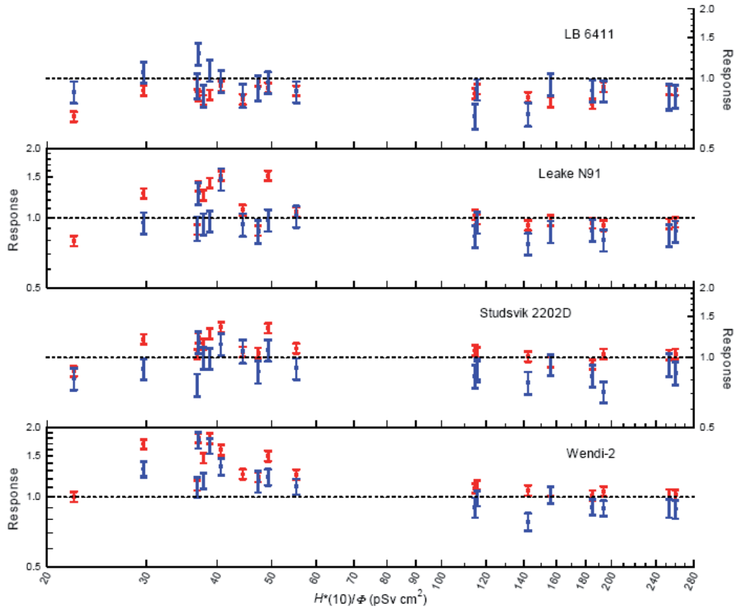

Figure 1: Measured response (blue) and calculated response (red) for the moderator-type area monitors.

6. PERSONAL DOSEMETER RESULTS

The electronic personal dosemeters used are the few devices which have been commercially available in the past few years (Thermo Electron EPD-N, Aloka PDM-313). They are dosemeters from first industrial prototype series (Thermo Electron EPD-N2, Saphydose-n) and laboratory prototypes which were in the stage of light-weight battery-operated instruments (PTB DOS-2002, DMC2000GN). In addition, dosemeters with (almost) immediate readout (BTI bubble detectors, Rados DISN) were used as well as passive dosemeters (nuclear track detectors from PSI and NRPB) and the TLD dosemeters of the facilities visited (Nuclear power plants Krümmel, Ringhals).
The dosemeters were attached to the front and back side of an ISO phantom (30 cm x 30 cm x 15 cm), with the reference point at the front side surface. The front surface was usually directed towards the source (reactor, cask, fuel elements), with the exception of a position below the

reactor in Krümmel where the front was directed towards the lock while the main source was above.

The dosemeter response from the front direction, i.e. the measured value divided by the reference value, is shown for some selected dosemeters in Figure 2. The lowest spread of the results (but still a factor of 2 to 3) is obtained for the dosemeters which are based on the superheated drop detectors HpSLAB and SCK-CEN PND+BDT and for those based on the nuclear track detectors NRPB PADC. The HpSLAB and the SCK-CEN PND+BDT indicate mean values which are by a factor of 1.4 and a factor 1.8 higher and the NRPB PADC indicates mean values which are by a factor of 1.1 lower than the reference values $\dot{H}_p(10)$ obtained from spectrometry.

The response of the electronic dosemeters (Thermo EPD-N2, Saphydose-n, PTB DOS-2002) varies by about a factor of ten. The ALOKA dosemeter shows a spread of response of two orders of magnitude. It over reads at reactors by up to a factor of 60.

The DISN 4% device is the favored one among the devices with different wall material and shieldings. Although its neutron response is comparable to - or even better than - those of the electronic devices, its main drawback is that a photon reading has to be subtracted. This, in fields with a high photon dose contribution (KKK SAR, see Table 1), resulted in zero readings.

The dosemeters which chiefly indicate thermal and epithermal neutrons (Thermo EPD-N and BTI-BDT) showed responses below unity.

In general, the response values observed in reactor fields are higher than those found in fields at the transport casks and at the MOX fuel factory. This allows a field-specific correction factor to be used for a special class of workplace fields. This can be done either by using the results of a spectrometric campaign or by using a more appropriate calibration field.

In general, no trend of higher or lower response values depending on the photon contribution in the fields was observed.

As TLD dosemeters require field-specific correction factors which depend on the dosemeter itself and on the characteristics of the fields, only the local devices as used in the facilities visited were used. The albedo dosemeters at Krümmel were evaluated by means of calibration factors which for the measurements at the cask were by a factor of two higher than inside the reactor. The dosemeters at Ringhals are usually used with field-specific correction factors. Three different over response factors, depending on where the person has been working, are used. These factors have been determined using knowledge from earlier spectrometric investigations of the workplaces at Ringhals. Despite a dosemeter which uses no albedo shielding and chiefly detects thermal and epithermal neutrons, the spread of the measured responses is acceptable and the mean response close to unity. The results of the campaign will be used to improve the field-dependent correction factors.

In general, the local devices showed variations of the response of a factor of 2 to 3 and did not perform worse than the electronic devices.

The high deviations of the readings from Hp(10) in workplaces can be explained by the monoenergetic response functions of the dosemeters which are not ideal. The high overreadings observed in the reactor fields are a result of high dosemeter overresponses for intermediate energy neutrons and an appreciable contribution of these neutrons in the fields.

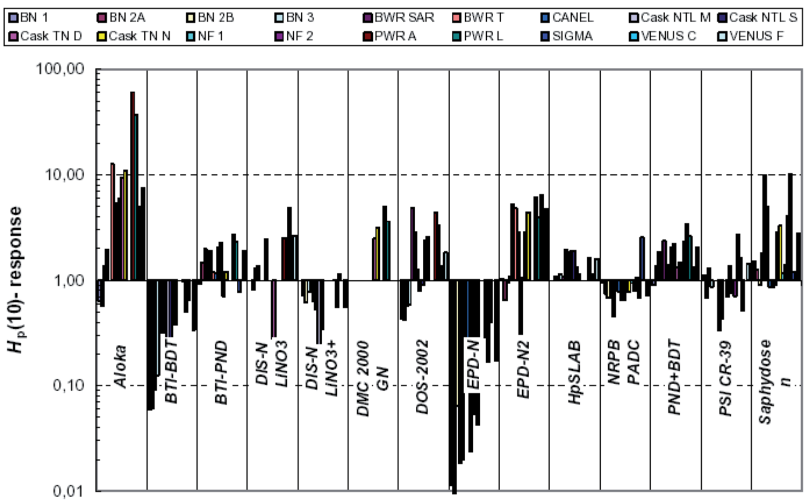

Figure 2: *Measured response of all used personal dosemeters in the different radiation fields for irradiation at 0°*

7. CONCLUSIONS

A large amount of data has been generated by the EVIDOS program. A better characterisation of workplace fields has been done by trying to measure both the angular and energy distribution of the neutron fluence. It was shown that the directional distribution of neutrons is important for the determination of operational quantity $H_p(10)$.
The ambient neutron monitors showed a relative good response in the different fields. Except for the Wendi-2 they gave results within 30% of the reference dose.
All currently available neutron personal dosemeters show large variations in response in different workplace fields. A field specific correction factor is necessary in most cases for the dosemeters. In view of this, the limited but fairly constant result from the bubble detectors and the NRPB track etch detectors in different field show that they are well suited as personal neutron dosemeter, especially when no detailed information on the field is available.
Electronic personal neutron dosemeters are becoming widely available. But for the determination of the neutron dose equivalent, the electronic personal dosemeters still require field-specific correction factors. The measurements performed within the EVIDOS project in 14 real workplace fields and two simulated ones reveal that mean correction factors can be used for some classes of workplace fields, such as reactors, transport casks and MOX fuel.

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AN OVERVIEW OF OPTICALLY STIMULATED LUMINESCENCE DOSIMETRY USING Al_2O_3:C

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Abstract

Optically Stimulated Luminescence (OSL) is now an established method widely used in personal dosimetry. The main advantages of the OSL technique with respect to the thermoluminescence (TL) technique are related to the fast optical readout method and high sensitivity of Al_2O_3:C. This paper reviews the main OSL properties of Al_2O_3:C and the fundaments of the OSL and pulsed OSL (POSL) technique applied to various areas, from personal to space dosimetry.

1. INTRODUCTION

The concept behind the Optically Stimulated Luminescence (OSL) technique for dosimetry applications, *i.e.,* the idea of using light to stimulate radiation-induced luminescence from solid state detectors, has been around for more than 50 years (e.g., Antonov-Romanovsky et al., 1956; Bräunlich et al, 1967; Sanborn and Beard, 1967). Although the technique was developed and applied for luminescence dating of sedimentary materials (Huntley et al., 1985; Aitken, 1998) and for imaging applications (Lakshmanan and Rajan, 1994; von Seggern, 1999), its was fully developed for personal dosimetry only with the introduction of Al_2O_3:C, a material highly sensitive to ionizing radiation and also very light sensitive (Akselrod et al., 1990). During the development process, the readout scheme became more sophisticated, with continuous stimulation being replaced by pulsed stimulation to achieve better signal-to-noise ratios (McKeever and Akselrod, 1999), lowering the detection limits and decreasing the readout time. The single-crystal dosimeters were replaced by more homogeneous dosimeters made of Al_2O_3:C powder in a plastic binder (Bøtter-Jensen et al., 2003), opening the possibility of dosimeter imaging (Akselrod et al., 2000).

OSL is now a well-established technique used in personal dosimetry, space dosimetry, environmental radiation monitoring, luminescence dating, and imaging (Bøtter-Jensen et al., 2003). As one may expect, there is significant activity in the field of luminescence dosimetry using OSL, and several groups in Belgium, Denmark, France, Japan, and the US, to name a few, are currently developing active research using OSL. Research continues to develop the OSL technique for neutron dosimetry and imaging (Kobayashi et al., 2005; Mittani et al., 2007), in-vivo and passive medical dosimetry (Polf et al., 2002, 2004; Andersen et al., 2003, 2006; Marckmann, 2006, Yukihara et al., 2005), and detection of radioactive materials (Klein et al., 2005).

This paper provides a brief overview of the fundaments of the OSL technique, instrumentation, and current research from the point of view of the research group at Oklahoma State University. For broader overview, we refer to Bøtter-Jensen et al. (2003) and references therein.

2. FUNDAMENTS OF OPTICALLY STIMULATED LUMINESCENCE

The OSL technique is based on a process similar to the well-known thermoluminescence, namely: (a) exposure of the dosimeter to ionizing radiation leads to the creation of electron/hole pairs via ionization, which are trapped at defects within the structure of the crystal; (b) subsequent thermal or optical stimulation releases these trapped charges leading to recombination of the electron-hole pairs; (c) the recombination process results in light emission which can be detected and related to the absorbed dose to which the dosimeter was exposed (McKeever, 2001). Readout of TL dosimeters requires heating, possibly causing adverse effects such as changing the structure of defects and dosimeter properties (McKeever et al., 1995; McKeever and Moscovitch, 2003). The readout of OSL dosimeters can be done by simply illumination with light of appropriate wavelength and detecting the resulting light emission. The advantages and disadvantages of OSL dosimetry relative to TL dosimetry are discussed in

greater detail by McKeever and Moscovitch (2003).
The all-optical nature of the OSL technique is an important advantage. It avoids the problem of having to establish good thermal contact between the heater element and the dosimeters and also provides a fast and versatile readout method. Figure 1 shows a typical example of an OSL curve for an Al_2O_3:C detector, obtained under continuous green light stimulation. This readout mode is referred to as continuous-wave OSL or CW-OSL (McKeever, 2001). It can be seen that the OSL signal is produced instantaneously as the optical stimulation is switched on at $t = 0$ s, decaying to zero as the stimulation continues due to emptying of the charges from the traps. However, instead of stimulating the detector for 300 s as in the example in Figure 1, a short stimulation of 1 s or less is sufficient to produce enough OSL signal for estimation of the absorbed dose. Therefore, the readout can be fast and the dose can continue to accumulate within the detector, since after a short stimulation most of the trapped charge remains available for a future readout, and the readout can be made nearly non-destructive. If needed, the dosimeter could be reset (bleached) by prolonged exposure to

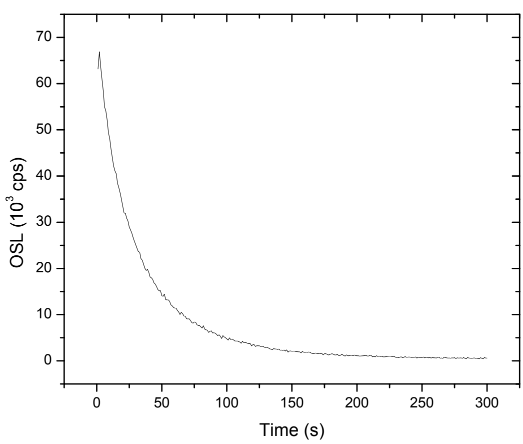

Figure 1. OSL signal of an Al_2O_3:C single crystal exposed to an absorbed dose of 1.91 mGy. The readout was performed using the Risø TL/OSL-DA-15 reader equipped with green LEDs (525nm) with a stimulation power of approximately 10 mW/cm^2. Hoya U-340 filters were used in this measurement.

the same light source used for stimulation.

The decay of the OSL signal as a function of time is modulated by the intensity of the stimulation light. In the simplest OSL model in which only a single type of trapping center and a single type of recombination center

$$I \propto n_0 \sigma \phi e^{-\sigma \phi t}, \quad (1)$$

are considered, the OSL decay is given by:
where n_0 is the initial concentration of trapped charge carriers after irradiation, $\boldsymbol{\sigma}$ is the photoionization cross-section of the trapping center, and $\boldsymbol{\phi}$ is the photon fluence rate of the stimulation light (photons cm^{-2} s^{-1}). This means that the rate of OSL decay and the level of the initial OSL intensity can be chosen by the appropriate stimulated intensity and wavelength. The decay becomes faster and the initial intensity larger with increasing stimulation light intensity.

3. INSTRUMENTATION AND READOUT TECHNIQUES

The OSL readout consists in illuminating the dosimeters with light of appropriate wavelength, while detecting the dosimeter luminescence as a function of stimulation time. The separation between the luminescence from the dosimeter and the stimulation light is achieved using optical filters in front of the photomultiplier tube.
The optimum stimulation and detection wavelengths need to be determined for each OSL material. In the case of Al_2O_3:C, the OSL emission is dominated by a broad band centered at 420 nm attributed to F-centers (Markey et al., 1995), and filters such as the Corning 5-58 are suitable to detect this emission band. However, depending on the equipment, UV transmitting filters such as the Hoya U-340 are necessary to block the green or blue LED stimulation light completely. This filter transmits only the short-wavelength side of the F-center emission band of Al_2O_3:C, but, because of the high sensitivity of this material, the detected OSL signal is still sufficient to estimate low doses.
Improved signal-to-noise ratios can be obtained if the pulsed OSL technique (POSL) is employed. In the POSL technique, the stimulation source is pulsed with an appropriate frequency and pulse width, and the

OSL signal is detected only in between the stimulation pulses (Akselrod and McKeever, 1999). This time-discrimination between the stimulation and OSL signal is only possible because of the very long (35 ms) lifetime of the F-center luminescence in Al_2O_3:C (Lee and Crawford, 1979; Markey et al., 1995).

POSL dosimetry was originally implemented using short laser pulses, but it is also possible to perform POSL measurements using LEDs (Denby et al., 2006). Because of the long lifetime of the luminescence centers, the stimulation pulses can be relatively long. **Figure 2** shows the OSL of Al_2O_3:C with pulsed green LED stimulation. In **Figure 2**(a), the OSL measurements of an unirradiated and irradiated dosimeter were made using pulsed stimulation, but measuring the PMT signal continuously. In Figure 2(b) identical dosimeters were measured, this time the counter was gated to count only the PMT signal emitted between the stimulation pulses. The reduction in the background signal due to stimulation light is dramatically, significantly improving the signal to noise ratio.

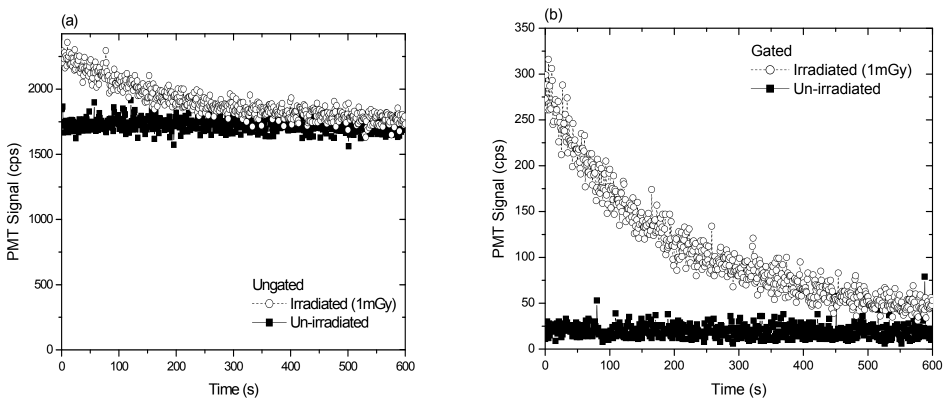

Figure 2. POSL curves of Al_2O_3:C dosimeters obtained using a portable POSL reader. In (a), the counter was not gated and the PMT signal was counted continuously; in (b) the counter was gated and only the PMT signal arriving between the laser pulses was counted. The stimulation was accomplished using green LEDs pulsed at 100 Hz. The LED pulse width was 1 ms. Corning 5-58 filters were used in front of the PMT to block the stimulation light.

4. PROPERTIES OF Al_2O_3:C

Al_2O_3:C is a well-established passive thermoluminescence (TL) and optically stimulated luminescence (OSL) detector for UV and ionizing radiation (Akselrod and Kortov, 1990; Colyott et al., 1999; McKeever, 2001). The crystal is grown in a highly reducing atmosphere in the presence of carbon, resulting in concentrations of F and F^+-centers of the order of 10^{17} cm^{-3} and 10^{16} cm^{-3}, respectively (McKeever *et al.* 1999). Much of the interest in this material arises because of its high sensitivity to ionizing radiation and the relative simplicity of the TL and OSL when compared to other materials (e.g. lithium fluoride, quartz). The OSL technique is preferred for dosimetry with Al_2O_3:C because it takes full advantage of the material's high optical sensitivity and avoids problems associated with the thermal quenching of luminescence (Akselrod et al., 1998).

The main luminescence center is the *F* center band at 420 nm (Markey et al., 1995), but a UV emission at 335 nm can be observed using time-resolved measurements (Yukihara and McKeever, 2006). OSL properties of the material such as dose response at high doses and luminescence efficiency to heavy charged particles depend on whether this luminescence center is detected or not (Yukihara and McKeever, 2006; Yukihara et al. 2006).

The OSL signal of Al_2O_3:C is linear over a wide range of doses, from the minimum detectable dose up to ~50-100 Gy, if only the F-center luminescence is detected (Akselrod and McKeever, 1999; Yukihara and McKeever, 2006). The UV emission center presents supralinearity for doses above ~10 Gy (Yukihara and McKeever, 2006). In addition, the OSL signal may decrease for doses higher than the saturation dose, a phenomenon which is explained by sensitivity changes in the crystal originating from filling of deep electron and hole traps (Yukihara et al., 2003, 2004b).

Because of the effective atomic number of Al_2O_3:C is higher than water, the material over-responds to low-energy X-rays by a factor up to 3.2 in comparison to ^{60}Co gamma rays (Akselrod et al., 1990; Mobit et al., 2006), requiring the use of compensating filter or proper calibration in the presence of low energy X-rays.

5. A MODEL FOR THE TL AND OSL PROCESS IN Al_2O_3:C

The main defects in Al_2O_3:C (Figure 3) are those associated with the main dosimetric trap (MDT) and oxygen vacancy defects, the most important being the F and F^+ centres (defects consisting of oxygen vacancies with two captured electrons, or one captured electron, respectively) (Summers, 1984). The main luminescence band, at ~420 nm, is attributed to the radiative relaxation of F centres (Akselrod et al., 1990; Lee and Crawford, 1979). It must be emphasized that the Al_2O_3:C crystals usually have a high concentration of pre-existing F and F^+ centres (McKeever and Akselrod, 1999). The main dosimetric trap is considered to be an electron trap (Molnar et al., 1999; Springis et al., 1996), although its identity is still unknown.

During exposure to ionizing radiation, free electrons and holes are created in the conduction and valence bands, respectively (**Figure 3**, transition1). The electrons are either trapped at the MDT (transition 4) or undergo recombination with F+ centres (transition 2) creating an F centre in the excited state (F+ + e- → F*), which produces luminescence in the relaxation process (F* → F + hν420nm). The holes are captured by F centres (transition 3), converting them to F+ centre (F + h+ → F+), which may also produce luminescence in the relaxation process (Skuratov, 1998). During stimulation, thermal or optical, electrons are released from the MDT and recombine with the F+ centres, resulting again in 420 nm emission (F+ + e- → F* → F + hν420nm), and the initial concentration of F and F+ centres is restored.

It is important to notice that, in the absence of the MDT or other traps, the $F^+ \leftrightarrow F$ centre inter-conversion during irradiation would be in equilibrium because the electrons would be captured by the F^+ centre ($F^+ + e^- \rightarrow F$) and an identical number of holes would be captured by the F centres ($F + h^+ \rightarrow F^+$). The presence of trapping levels, including the MDT, may disturb this equilibrium in one direction or another. The introduction of electron traps change this balance by capturing electrons that otherwise would destroy F^+ centres and create F centres during irradiation ($F^+ + e^- \rightarrow F$). As a consequence, there is an increasing trend in the F^+ centre concentration. The situation is reversed in the presence of hole traps, which capture holes that would otherwise participate in the destruction of F centre and creation of F^+ centre ($F + h^+ \rightarrow F^+$). As a result, the concentration of F^+ centres is expected to decrease.

In addition to these main defects, there is significant evidence for the existence of deep electron and hole traps in the material. In irradiated or UV illuminated samples, the F^+ centre optical absorption band shows clear increases or decreases after heating the samples to certain temperature ranges (Akselrod and Gorelova, 1993). In general, an increase in the F^+ centre optical absorption band is observed around 500-600ºC, probably due to the release of holes from a deep trapping level unstable in this temperature range and consequent creation of F^+ centres ($F + h^+ \rightarrow F^+$). At temperatures around 700-1000ºC, a decrease in the F^+ centre concentration is observed, indicating the release of electrons from deep traps and consequent destruction of F^+ centres ($F^+ + e^- \rightarrow F$). Deep electron traps (DETs) and deep hole traps (DHTs) are included in the model in Figure 1. Changes in the concentration of F^+ centres are accompanied by changes in the sensitivity of the material, which is only restored by annealing at 900ºC to empty the deep electron and hole traps (Yukihara et al., 2003; 2004).

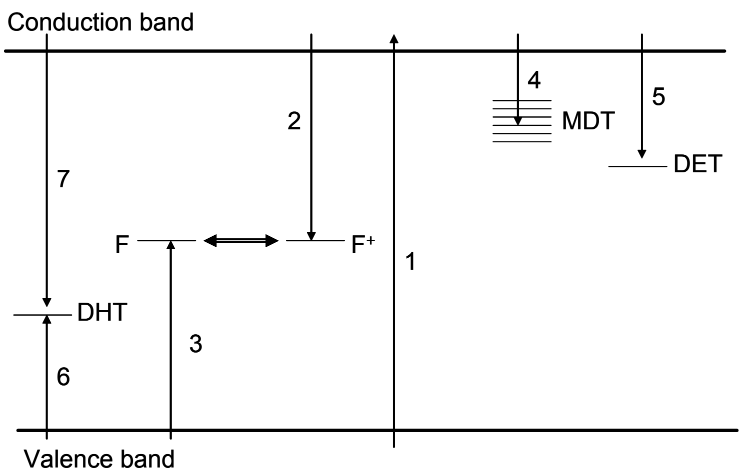

Figure 3. Band diagram model of the main defects involved in the production of TL/OSL/RL in Al_2O_3:C showing the electronic transitions during irradiation in a simplified model consisting of main dosimetric traps (MDTs), oxygen vacancy centres (F and F^+ centres), deep electron traps (DETs), and deep hole traps (DHTs).

6. APPLICATIONS

6.1. Personal dosimetry

The basis for the application of OSL in personal dosimetry is given by Akselrod and McKeever (1999) and Akselrod et al. (2000). In addition to the properties described in Section 4, additional properties related to the use of the POSL technique and appropriate parameters are the possibility of dose re-estimation and distinction between static and dynamic exposure.

The concept of dose re-estimation is related to the high sensitivity of the dosimeter. Instead of depleting completely the trapped charges associated with the OSL signal during readout, the intensity and duration of the stimulation light can be chosen to probe only a small fraction of the trapped charges. The signal depletion caused by this short readout is either insignificant or can be corrected for to enable multiple measurements of the same dosimeter (Akselrod and McKeever, 1999).

The distinction between static and dynamic radiation exposures is accomplished with a copper filter with a hole pattern placed in front of the Luxel™ Al_2O_3:C dosimeter. With this configuration, the dosimeter image reveals a pattern similar to copper filter if the exposure is static, whereas a more diffuse pattern is observed in dynamic exposures (Akselrod et al., 2000).

6.2. Neutron dosimetry

Optically Stimulated Luminescence (OSL) of carbon-doped aluminum oxide dosimeters (Al_2O_3:C) is successfully used in gamma and beta passive dosimetry, but the lack of sensitivity to neutrons is pointed out as one of the drawbacks of Al_2O_3:C OSL dosimetry in comparison to thermoluminescence (TL) dosimetry using Li and B containing phosphors (Mckeever and Moscovitch, 2003). Whereas TL materials such as LiF: Mg,Ti and $Li_2B_4O_7$:Mn enriched with ^{6}Li and ^{10}B isotopes present high sensitivity to thermal neutrons (Ayyangar et al., 1974), Al_2O_3:C does not have a high cross-section for neutron interaction. For instance, Klemic et al. (1996) showed that the neutron sensitivity of Al_2O_3:C for neutron energies between 0.3 MeV and 6 MeV is zero within the experimental uncertainties.

The possibility of developing a neutron sensitive OSL dosimeter is very attractive for extending the advantages provided by the OSL technique to neutron dosimetry. One possibility to develop OSL detectors for neutron measurements is the incorporation of neutron converters into the Al_2O_3:C OSL dosimeters. Neutron converters are used to enhance the neutron sensitivity of active and passive detectors including TLDs and image plates (Knoll, 2000; Yang et al., 2004, Masalovich et al., 2005). They interact with the neutron field through neutron capture reaction or elastic scattering, creating a secondary heavy charged particles that deposit energy in the sensitive volume, the luminescence detector in this case. Neutron capture reactions and cross-sections of some of the important isotopes as a function of energy are reviewed by van Eijk (2004).

The feasibility of using neutron converters to increase the sensitivity of Al_2O_3:C to neutrons for dosimetry applications was recently demonstrated by Mittani et al. (2007). Al_2O_3:C powder was mixed with different neutron converters and exposed to a ^{252}Cf source. The OSL signal was determined for the various combinations of Al_2O_3:C and neutron converters to determine the neutron sensitivity. **Figure 4** shows the OSL curves of Al_2O_3:C mixed with various types of neutron converters, mixed in a 1:1 ratio, after neutron irradiation. Different degrees of neutron sensitization were observed, depending on the neutron converter.

Table 1 compares the sensitivity of Al_2O_3:C mixed with different neutron converters with the sensitivity of TLD-600/TLD-700 pair of dosimeters. The neutron sensitivities obtained using ^{6}LiF neutron converters is approximately half of the sensitivity obtained with the TLD-600/TLD-700 pair, demonstrating the feasibility of this approach.

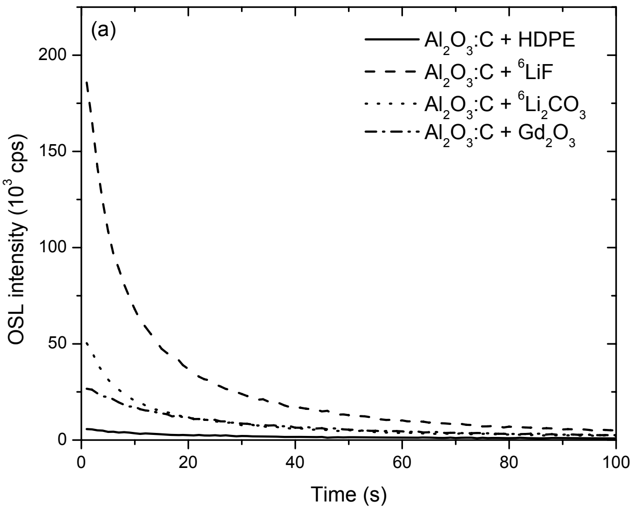

Figure 4. OSL curves of various dosimeters irradiated with a nominal personal dose equivalent of 30 mSv using the ^{252}Cf source.

Table 1. Neutron sensitivities expressed as the ratio of the detector response to the reference neutron dose D_{ref} for three different fields. R_n is the response to the total neutron field (setup A; irradiation without shadow cone), R_s is the response to the neutrons scattered by the room (setup B; with shadow cone between the dosimeters and the source), and R_0 is the response to the neutrons scattered by the phantom and neutrons coming directly from the ^{252}Cf source (total neutron response minus the response to room scattering). D_{ref} is the personal dose equivalent for a fixed nominal dose of 30 mSv, determined by the source calibration and additional measurements with near dose equivalent monitor (Vanhavere et al., 2001).

Dosimeter combination	R_n/D_{ref} D_{ref} = 45.5 mSv	R_s/D_{ref} D_{ref} = 15.5 mSv	R_0/D_{ref} D_{ref} = 30 mSv
TLD-600 / TLD-700	0.717 ± 0.013	1.42 ± 0.03	0.35 ± 0.02
Al_2O_3:C + ^{6}LiF / Al_2O_3:C	0.398 ± 0.019	0.838 ± 0.016	0.17 ± 0.03
Al_2O_3:C + ^{6}LiF / Al_2O_3:C (with HDPE)	0.348 ± 0.005	0.714 ± 0.009	0.158 ± 0.009
Al_2O_3:C + $^6Li_2CO_3$ / Al_2O_3:C	0.251	0.53 ± 0.02	0.107 ± 0.013
Al_2O_3:C + Gd_2O_3 / Al_2O_3:C + Yb_2O_3	0.056 ± 0.017	0.14 ± 0.03	0.01 ± 0.03
Al_2O_3:C + HDPE / Al_2O_3:C	0.012 ± 0.002	0.010 ± 0.003	0.013 ± 0.003

Another aspect of interest is the shape of the OSL curves for neutron irradiated samples as compared to gamma irradiated samples. In the case of TL, the shape of the TL curve of materials such as LiF:Mg,Ti and CaF_2:Tm is dependent on ionization density created by the radiation (Hoffman and Prediger, 1984) and it was proposed that this dependence can improve the neutron/gamma discrimination of TL dosimeters (e.g. Yossian and Horowitz, 1998 and references therein). As an example, the intensity of the high-temperature peaks of LiF:Mg,Ti dosimeters exposed to high-LET particles relative to peak 5 is higher than the relative intensity of dosimeters exposed to low-LET radiation (Vana et al., 1996). Since the secondary radiation produced by the neutron interaction with the converters usually have a heavy charged particle component, the shape of the TL curves will vary according to whether the dosimeter was irradiated with gamma or neutrons. In the case of the OSL of Al_2O_3:C, high-LET radiation produces OSL decay curves that are different from low-LET radiation (Yasuda et al., 2002; Yukihara et al., 2004a), which leads to the suggestion that the OSL curves after neutrons irradiation may also be different from the OSL curves for gamma irradiation when the secondary particles created by the neutron converters have high LET (Yukihara et al., 2006).

This prediction was confirmed by Mittani et al. (2007). **Figure 5** shows the OSL curves of Al_2O_3:C after gamma or neutron irradiation. The decay of Al_2O_3:C mixed with ^{6}LiF is significantly faster for neutron irradiation than for gamma irradiation, as observed before for heavy charged particles (Yukihara et al., 2004a). This is consistent with the fact that the OSL signal is induced by the secondary heavy-charged particles produced by the neutron capture reaction with ^{6}Li. Following the same line of reasoning, we expect the OSL decay curve of neutron-irradiated Al_2O_3:C mixed with Gd_2O_3 to be similar to the gamma-induced OSL decay curve, since the neutron capture reaction with ^{155}Gd and ^{157}Gd produces low-LET radiation, mostly gammas, internal conversion electrons, and X-rays. As can be verified in Figure 5, this expectation is confirmed by the experimental data. The OSL decay of Al_2O_3:C mixed with Gd_2O_3 is very similar to the OSL decay curve of the gamma irradiated sample.

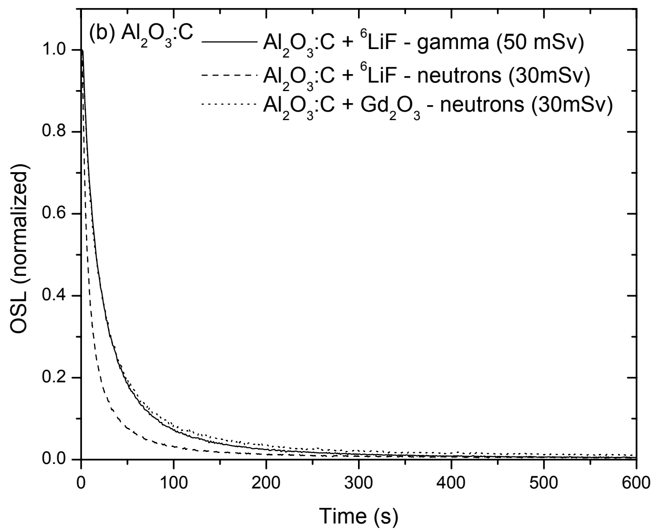

Figure 5. Comparison of the normalized OSL decay curves of Al_2O_3:C mixed with ^{6}LiF irradiated with gamma or neutrons, and the OSL curve of neutron-irradiated Al_2O_3:C mixed with Gd_2O_3.

6.3. Space dosimetry

The monitoring of crew exposure to ionizing radiation during spaceflight is recognizably one of the most challenging problems in dosimetry due to the presence of a variety of primary and secondary particles with a wide range of energies (McKeever, 2002; Benton and Benton, 2001). Because no single detector is capable of covering the whole spectrum of particles and energies encountered in space, the framework for operation radiation safety program for astronauts in low-Earth orbit includes a suite of detectors: tissue equivalent proportional counters (TEPC), active solid-state detectors, luminescence detectors (Thermoluminescence or Optically Stimulated Luminescence detectors), and CR-39 plastic nuclear track detectors (PNTD).

The principle behind the use of luminescence dosimeters (TLD or OSLD) in conjunction with CR-39 PNTD in space dosimetry is based on the complementary response of these two types of detector. TL and OSL dosimeters are very sensitive to low-LET radiation, but their sensitivity decreases with increasing LET due to saturation of trapping defects within the core of HCP tracks. The decrease in sensitivity, which typically starts to occur between 1-10 keV/μm, depends on the individual luminescent detector material. On the other hand, PNTDs are used in space dosimetry to measure the LET spectrum above ~5 keV/μm (Benton and Benton, 2001) and are insensitive to radiation of lower LET due to the minimum ionization density required to create the latent tracks.

Currently, the combination of TLDs or OSLDs with CR-39 PNTDs is considered as the best available solution for personal dosimetry in space (NCRP, 2002). The information provided by these detectors can be used to calculate the dose equivalent, *H,* using the expression:

$$H = D_{low-LET} + \int D_{high-LET}(L)Q(L)dL. \qquad (2)$$

In this expression, $D_{low\text{-}LET}$ is the absorbed dose recorded by TLDs or OSLDs from particles of LET<10 keV/μm and for which the quality factor, *Q,* equal to 1, while $D_{high\text{-}LET}$ is the absorbed dose as a function of LET recorded by PNTDs for LET>10 keV/μm, for which the quality factor, $Q(L)$, is a function of the LET value L (NCRP, 2000). The 10 keV/μm threshold is only a convenient choice because of the behavior of the $Q(L)$ function, the efficiencies of the TLDs and OSLDs, and the sensitivity of CR-39 PNTDs.

Ideally, we would like the response of TLDs and OSLDs to be zero for LET above 10 keV/μm and unity for LET values below 10 keV/μm. Since this is not the case, the contribution from high-LET HCPs needs to be subtracted from the absorbed dose measured in TLD or OSLD in order to avoid double-counting:

$$D_{low-LET} = D_{TLD/OSLD} - \int \eta_{HCP,\gamma}(L) D_{PNTD}(L) dL\,. \qquad (3)$$

In this expression, $D_{TL/OSL}$ is the total absorbed dose recorded by the TLDs/OSLDs, and $\eta_{HCP,\gamma}$ is the relative efficiency of the TL/OSL detector to HCP with respect to gamma radiation. The relative efficiency, $\eta_{HCP,\gamma}$ is defined as the OSL signal per dose of HCP radiation (S_{HCP}/D_{HCP}) divided the OSL signal per dose of gamma radiation (S_γ/D_γ), given that the same mass of material is used in both irradiations:

$$\eta_{HCP,\gamma} = \frac{S_{HCP} / D_{HCP}}{S_\gamma / D_\gamma}. \quad (4)$$

The efficiency is constant only if the doses are in the linear range of the detector dose response. It should be emphasized that, for practical purposes, in the above definition D_{HCP} and D_γ are the HCP and gamma absorbed doses in water.

Several experiments have been performed to determine $\eta_{HCP,\gamma}$ for Al_2O_3:C using ground-based accelerators at the NIRS-HIMAC, Japan, Brookhaven National Laboratory's NASA Space Radiation Laboratory (BNL-NSRL), USA, and the proton therapy synchrotron at the Loma Linda University Medical Center (LLUMC), USA (Yukihara et al., 2006).

Table 2 presents the efficiency values obtained for two types of material, (Al_2O_3:C single crystals and Luxel™ Al_2O_3:C dosimeters), two types of techniques (TL and OSL), and, in the case of OSL, for two types of detection filter combinations (Hoya U-340 filter pack, or Hoya U-340 + WG-360 filter pack). This data is the most recent compilation of our ongoing effort to characterize the OSL efficiency of Al_2O_3:C. This data is still subject to revision and updates.

The data indicate that the efficiency curve as a function of LET can be approximated by a single curve for practical dosimetric applications involving HCPs in this range of energies, as illustrated in **Figure 6** for one type of detection filter (Hoya U-340 filters) Efficiencies for LET = 2.2 keV/μm and >10 keV/μm have been extensively characterized using heavy ion beams at the NIRS-HIMAC, but it is still necessary to improve the characterization in the low-LET region below 2.2 keV/μm and between 2.2 and 10 keV/μm, in which only a limited number of data points have been obtained so far.

Al_2O_3:C single crystal OSLDs, along with other TLDs and CR-39 PNTDs were exposed on orbit as part of the ESA-funded microbial experiments MESSAGE-2 and MOBILIZATION, which took place as part of the ISS-7S (October 2003) and ISS-8S (April 2004) missions, respectively, (Goossens et al., 2006). The main conclusion from these experiments, from the space dosimetry point of view, is that the differences in absorbed dose determined by the different types of luminescence dosimeters

(Al_2O_3:C, ^{7}LiF:Mg,Cu,P, and ^{7}LiF:Mg,Ti) are related to the different efficiency of these materials, but cannot be explained only by their respective responses to the high–LET component of the radiation field. Qualitatively, the ^{7}LiF:Mg,Cu,P dosimeters gave the lowest dose measurements, ^{7}LiF: Mg,Ti gave the highest dose measurements, and Al_2O_3:C single crystals yielded intermediate values. This trend is consistent with the general efficiency curves for the three materials, as determined by the International Intercomparison for Cosmic Radiation with Heavy Ion Beams at NIRS (ICCHIBAN) (Uchihori and Benton, 2004), in the sense that the lowest dose measurement came from the material with the lowest relative efficiency (LiF:Mg,Cu,P), while the highest dose measurement came from the material with the highest relative efficiency (LiF:Mg,Ti). However, the difference between the ^{7}LiF:Mg,Cu,P and ^{7}LiF:Mg,Ti detectors was 40 μGy d^{-1}, while the contribution from the high-LET part of the spectrum (LET >5-20 keVμm) determined using PNTDs and taking into account the reduced efficiency of the TLDs and OSLDs, is on the order of 5 μGy d^{-1} only. Although these results are based on a small number of dosimeters, they highlight the importance of determining the relative TL/OSL efficiency of the detectors to low-LET radiation as well as to high-LET radiation. As noted in the ICCHIBAN report, the efficiency for various luminescent materials is significantly different even for LET values of 2.26 keV/μm (Uchihori and Benton, 2004).

Table 2. Experimental relative efficiencies determined during different experiments using the TL peak height or integrated OSL signal. The Luxel™ refers only to OSL detector itself, consisting of Al_2O_3:C powder in polyester film base (Bøtter-Jensen et al., 2003). The efficiency values are either a mean of the efficiency for several doses, or the efficiency for a dose of 50-100mGy. The experimental standard deviation in parenthesis.

Beam/Experiment	Energy (MeV/u)	LET (keV/μm)	Single crystal TL Corning 5-58	Single crystal OSL Hoya U-340	Luxel^{TM} OSL Hoya U-340	Luxel^{TM} OSL U-340+WG-360
Proton 1 GeV						
NSRL-ICCHIBAN (2004)	1000*	0.222			0.977(5)	0.908(18)
Proton 230 MeV						
LLUMC (2004)	230.0*	0.413			1.11(6)	0.951(6)
Proton 70 MeV						
LLUMC (2004)	70.0*	0.960			1.099(10)	0.928(2)
He 150 MeV/u						
ICCHIBAN-2 (2002)	143.3	2.25	0.885(6)	0.825(13)	1.034(7)	
ICCHIBAN-4 (2003)	143.3	2.25		0.85(4)	1.04(3)	
HIMAC-2 (2004)	143.7	2.25			1.040(23)	0.916(9)
HIMAC-3 (2005)	144.2	2.24			1.018(16)	0.912(6)
Eril Research Inc. (2005)	144.2	2.24			1.016(24)	0.915(5)
ICCHIBAN-8 (2005)	144.2	2.24			1.019(13)	0.894(25)
HIMAC-4 (2006)	144.2	2.24			1.004(14)	0.893(17)
C 400 MeV/u						
ICCHIBAN-2 (2002)	384.9	11.17	0.564(3)	0.534(11)	0.797(7)	
ICCHIBAN-4 (2003)	384.9	11.17		0.548(22)	0.833(1)	
HIMAC-3 (2005)	386.9	11.14			0.819(23)	0.677(7)
C 290 MeV/u						
HIMAC-2 (2004)	277.2	13.30			0.782(5)	0.607(26)
O 1 GeV/u						
NSRL-ICCHIBAN (2004)	1000	14.24			0.795(4)	0.625(8)
O 400 MeV/u						
HIMAC-2 (2004)	384.4	19.86			0.750(32)	0.597(14)
Eril Research (2005)	384.5	19.84			0.769(21)	0.609(13)
ICCHIBAN-8 (2005)	385.5	19.84			0.676(12)	0.555(4)
C 135 MeV/u						
ICCHIBAN-6 (2004)	111.2	24.41			0.626(18)	0.489(15)
Ne 400 MeV/u						
ICCHIBAN-4 (2003)	368.5	31.7		0.411(9)	0.599(2)	
Eril Research (2005)	372.9	31.51			0.560(5)	0.467(16)
HIMAC-4 (2006)	371.9	31.55			0.572(4)	0.474(4)

Si 490 MeV/u						
ICCHIBAN-2 (2002)	442.5	56.93	0.367(3)	0.326(7)	0.485(4)	
HIMAC-4 (2006)	444.8	56.8			0.469(6)	0.398(9)
Ar 500 MeV/u						
ICCHIBAN-6 (2004)	448.6	93.54			0.452(4)	0.359(19)
ICCHIBAN-8 (2005)	450.7	93.34			0.441(4)	0.369(7)
Fe 1 GeV/u						
NSRL-ICCHIBAN (2004)	968	151.4			0.358(7)	0.285(14)
NSRL (2006)	1000	150.4				
Fe 500 MeV/u						
ICCHIBAN-2 (2002)	416.8	201.8	0.318(5)	0.297(6)	0.397(3)	
ICCHIBAN-4 (2003)	416.8	201.8		0.313(6)	0.423(4)	
Eril Research (2005)	423.7	200.3			0.374(18)	0.341(20)
HIMAC-4 (2006)	423.7	200.3			0.375(6)	0.324(2)
Kr 400 MeV/u						
ICCHIBAN-6 (2004)	313.1	447.2			0.380(5)	0.316(12)
Fe 200 MeV/u						
ICCHIBAN-8 (2005)	124.9	420.6			0.341(9)	0.285(9)
HIMAC-4 (2006)	120.4	431.8			0.312(6)	0.268(4)
Xe 290 MeV/u						
Eril Research (2005)	185.5	1368			0.344(5)	0.323(11)

*Nominal energies.

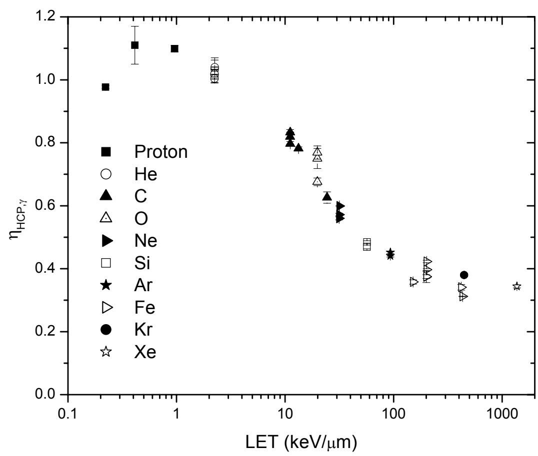

Figure 6. Efficiency values for Al_2O_3:C Luxel dosimeters obtained during various experiments using HCPs. The data was obtained using the OSL signal integrated over the whole stimulation period. The measurements were performed using a Risø TL/OSL-DA-15 reader with green stimulation and Hoya U-340 filters in front of the PMT.

6.4. Medical dosimetry

OSL has been applied to medical dosimetry for quality assurance and dose verification using either passive dosimetry or in-vivo, real-time dosimetry using optical fibers. The latter is described by Polf et al. (2002, 2004), Andersen et al. (2003, 2006), and Marckmann (2006).

Meeks et al. used OSL dosimeters (Luxel™) to investigate the extra-target dose delivered to patients during intracranial and head and neck IMRT treatments (Meeks et al., 2002). During preliminary test of the OSL dosimeters in the IMRT dose verification setup, a direct exposure to known doses (between 0 and 0.264 Gy) from 10 MV linear accelerator photon beam showed differences of up to 4.7% between the expected and measured doses.

The OSU Radiation Dosimetry Laboratory and the OUHSC Department of Radiation Oncology are collaborating since 2005 to develop the OSL technique for radiotherapy (Yukihara et al., 2005). This work resulted in the development of the "normalization dose procedure" for the OSL of Al_2O_3:C. The procedure allows high-precision measurements taking advantage of the fact that the OSL readout is all-optical and, therefore, the structure of defects in the material is preserved, while also considering sensitivity changes that occurs in Al_2O_3:C due to filling of deep electron and hole traps (Yukihara et al., 2004).

The proposed procedure consists of: (i) OSL readout of the signal S of the irradiated dosimeter; (ii) irradiation of the OSL dosimeter with a "normalization dose" delivered by a $^{90}Sr/^{90}Y$ beta source; (iii) OSL readout of the signal S_R due to the "normalization dose"; (iv) calculation of the ratio S/S_R, which is then used to determine the absorbed dose. Since the mass of the dosimeter, the dosimeter sensitivity, and the reader sensitivity affect both S and S_R in the same way, the ratio S/S_R is independent on these parameters. The dose used for "normalization" needs only to be reproducible. The absorbed dose is then determined from the value of S/S_R by constructing a calibration curve of S/S_R versus dose.

Figure 7a shows the reproducibility of the OSL signal S/S_R (normalized to the average value) for 50 dosimeters irradiated with 6 MV photons from a linear accelerator at a depth of 10 cm in a water phantom. The standard deviation of the distribution is 0.7%, indicating the uncertainty associated with a single OSL measurement. This is a significant improvement over the reported OSL precision of 4.7% (Meeks et al., 2002). To obtain a 0.7% precision with the TL technique, 4-8 measurements are required (Izewska et al., 2002).

Figure 7b illustrates the precision of the OSL calibration curve. Each data point corresponds to an average of 3 dosimeters, and the error bars, barely visible in the scale, represent the experimental standard deviation of the data (<0.6% in all cases).

Even though the OSL signal S is linear over the entire range of doses, the ratio S/S_R is not linear because of the sensitivity changes that occur in the Al_2O_3:C material (Yukihara et al., 2004b). Nevertheless, the dose response can be represented very precisely with a saturating exponential allowing the absorbed dose to be determined with high-precision. For example, in Figure 3b the maximum difference between the data points and fitted curve is 0.3%. In the case of MOSFETs, the standard deviation is around 6% for 0.25 Gy and 2 to 3% for doses higher than 0.3 Gy (Chuang et al., 2002).

We tested the OSL dosimeters in a variety of experimental conditions using the "normalization dose procedure". To carry out the irradiations as a function of depth in the water phantom, we designed and built a special holder for the OSL dosimeters.

The results obtained with the "normalization dose procedure" are illustrated in **Figure 8**, which compares OSL and ionization chamber doses at a variety of depths in a water phantom for photon and electron beams. (OSL measurements for 9, 12, and 20 MeV electron beams were also performed with similar results.) These graphs demonstrate the precision and accuracy of OSL for a variety of beams and depths in water. It should be observed that the errors bars are barely visible in this scale.

We tested the accuracy of OSL to determine machine calibration output for different photon and electron beams. The OSL dosimeters were irradiated at d_{max}, the depth in water of maximum dose, with various photon and electron energies. Figure 5 compares the OSL and ionization chamber data. In the case of OSL, a 1.53% over-response was noticed for electron beams. However, a correction of 1.53% for the electron beams brings the data in agreement with the ionization chamber measurements. After correction, the maximum difference between the ionization chamber and OSL measurements is ±0.4%.

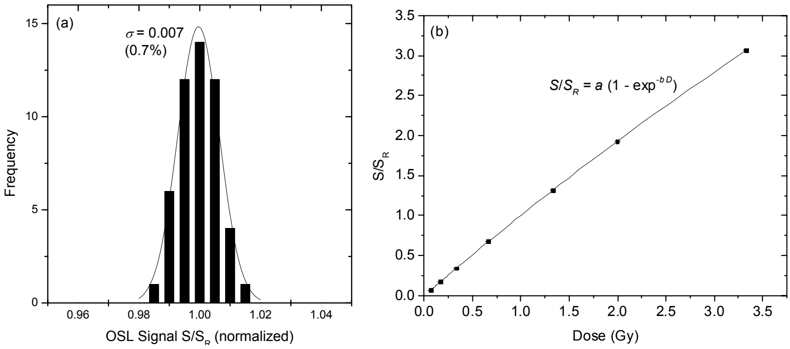

Figure 7. (a) Reproducibility of OSL dosimeters irradiated in a 6 MV photon beam at 10 cm depth in water with a dose of 0.665 Gy. (b) Dose response of the ratio S/S_R (OSL signal after irradiation divided by the signal after a normalization dose) as a function of dose. The irradiations were carried out in a 6 MV photon beam at 10 cm depth in a water phantom. The error bars (not visible in this scale) represent the experimental standard deviation of the set of 5 dosimeters (*not* the standard deviation of the mean), therefore representing the uncertainty for a single OSL measurement.

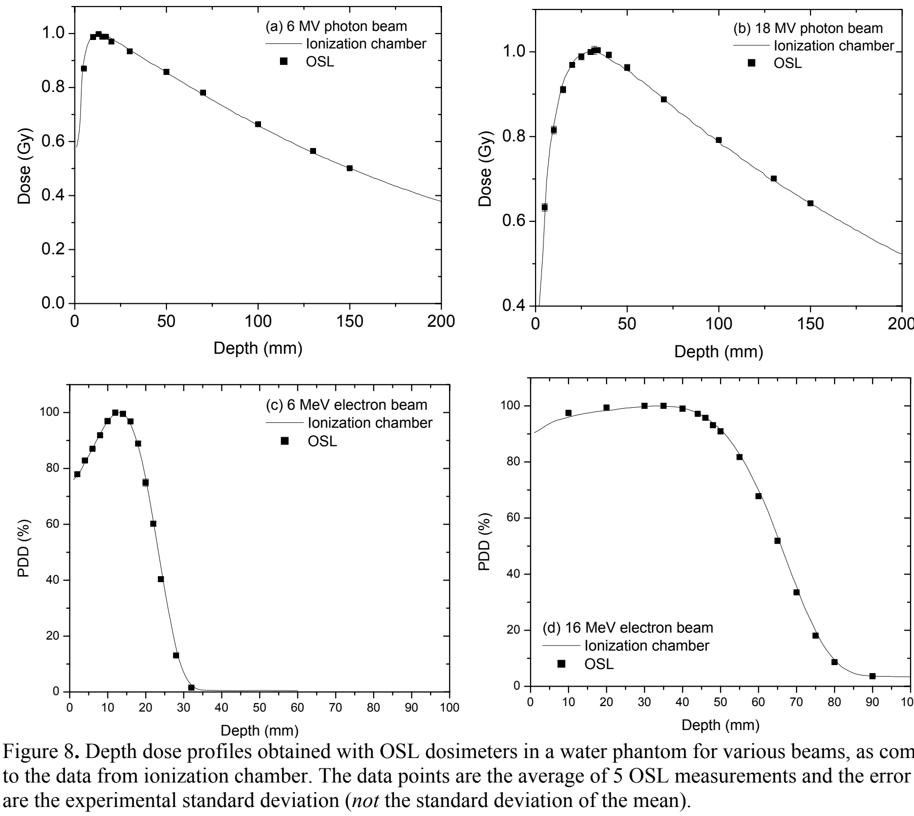

Figure 8**.** Depth dose profiles obtained with OSL dosimeters in a water phantom for various beams, as compared to the data from ionization chamber. The data points are the average of 5 OSL measurements and the error bars are the experimental standard deviation (*not* the standard deviation of the mean).

We also checked the OSL response as a function of irradiation temperature up to 37ºC, dose rate in the range between 100 and 400 MU/min, and field size from 5 cm × 5 cm up to 40 cm × 40 cm. In all cases, the OSL performance was exceptionally good.
The OSL technique provides a reliable and high-precision method that does not require significant effort in terms of readout and quality control of the technique. All the results presented were obtained over the course of a few days, without strict control of the mass or sensitivity of the dosimeters, neither of the equipment sensitivity, and using minimum input from the experimenters.

7. FINAL REMARKS

This paper provides a brief review of the fundaments of OSL and an overview of the research progresses achieved in recent years. Al_2O_3:C continues to be the most important luminescence dosimeter in OSL, but it is likely that other materials with appear with more suitable properties for some applications. As an example, the possibility of performing neutron dosimetry using the OSL of Al_2O_3:C was demonstrated with the use of neutron converters. However, better performance is likely to be achieved if a new OSL material containing ^{6}Li or ^{10}B as the main element is developed. Since the full potential of OSL for applications in different fields has not been fully explored yet, a plethora of opportunities exist for new researchers.

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