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Article de synthèse

Individual dosimetry*

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ABSTRACT **An international workshop on the impact of recent publications of ICRP and ICRU was held in May 1993 and the consequences of these recommendations, especially the introduction of the new quantities – organ equivalent dose, effective dose and personal dose equivalent – were discussed. The fact that the quality factor-LET relationship used for the operational quantities and the radiation weighting factor used for the limiting quantities were not consistent for neutrons, and that the new operational quantities were not in all cases conservative with regard to the new limiting quantities was a central issue. Nevertheless, it was concluded that the immediate implications of the ICRP and ICRU recommendations appeared to have been assimilated and that most remaining conceptual problems can be solved. For photon dosimetry, existing techniques and procedures sufficiently fulfill the new requirements, whereas, dosimetry for neutron radiation is not yet satisfactory and remains a difficult task. Within Europe, harmonisation of standards requires greater emphasis to be placed on performance testing, quality assurance and record keeping.**

RÉSUMÉ **En mai 1993 a eu lieu un atelier international sur l'impact des publications récentes de la CIPR et de la CIUR ; y furent débattues les conséquences de ces recommandations, tout particulièrement l'introduction des nouvelles quantités : dose équivalente à l'organe, dose efficace et équivalent de dose individuel. Un point central a été le fait que la relation "facteur de qualité-TLE" utilisée pour les quantités opérationnelles et que le facteur de pondération radiologique employé pour les quantités limites n'étaient plus corrects dans le cas des neutrons ; de plus, les nouvelles quantités opérationnelles n'étaient pas, dans tous les cas, conservatoires pour ce qui est des nouvelles quantités limites. Néanmoins, la conclusion fut que les implications immédiates des recommandations de la CIPR et de la CIUR semblent avoir été assimilées, et que l'on peut trouver une solution à la plupart des problèmes conceptuels qui demeurent. Dans le cas de la dosimétrie des photons, les procédés et les techniques actuels répondent à ces nouvelles conditions ; par contre, la dosimétrie des neutrons n'est pas encore satisfaisante, et reste un challenge difficile. Au niveau européen, l'harmonisation des étalons nécessite de tenir beaucoup plus compte des contrôles de performance, de l'assurance de qualité et de la tenue des dossiers.**

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1. Introduction

Individual monitoring plays an important role in the concept of protection against occupational exposure by external radiation. It serves as an individual control of occupational exposure to ionising radiation, may supply a warning against unexpected exposure and is aimed to limit the individual exposure to a level acceptable as an occupational risk. It is designed to meet certain requirements laid down in national regulations which are based largely on the recommendations of ICRP and ICRU (International commission on radiological protection and International commission on radiation units and measurements) .

In May 1993 the Commission of the European Communities (CEC), the European radiation dosimetry group (Eurados), the Radiation metrology section of the Paul Scherrer Institut (PSI), Switzerland, and the US Department of energy (US DOE) jointly held a workshop [22] aimed at examining the consequences of the recent ICRP and ICRU recommendations for individual monitoring. The workshop attracted 120 scientists and officials from research, operational and regulatory areas, and provided a forum for intensive exchange of information and discussion.

The workshop addressed most questions pertinent to individual monitoring, including: the system of radiation dose quantities and their interrelationship, type testing and calibration of personal dosemeter, required accuracy and dose thresholds, performance requirements and tests, record keeping and regulatory aspects, quality control and quality assurance, and new detector developments. A considerable part of the discussion focused on perceived shortcomings or inconsistencies of the ICRP and ICRU recommendations, in particular the fact that the quality factor-LET relationship used for the operational quantities and the radiation weighting factor used for risk limiting quantities were not congruent for neutrons, and that the new operational quantities were not in all cases conservative with regard to the new limiting quantities. Concern was also expressed that available methods of individual dosimetry might be inadequate, in particular for neutrons and mixed radiation fields, due to the reduced dose limits, introduction of the weighting factor and allocation of dose constraints in ICRP 60.

In 1994, the European Commission published technical recommendations for monitoring individuals occupationally exposed to external radiation [18] to provide guidance for the practical implementation of individual dosimetry.

In the following, some data and conclusions of two studies on individual dosimetry in several countries are given, the main issue of the recent publications of ICRP and ICRU – the new quantities and their implications for individual dosimetry – is presented and the results of the workshop are summarised. A description of recent developments in detector technology fills the gap between the approved systems being used at the end of the 80s and the actual state of the art.

2. Individual dosimetry in several countries at the end of the last decade

In 1986 and 1988, a study was made of the ways in which protection of workers from radiation hazards were handled in the member States of the European Community, Japan and USA [15]. The general conclusion of this study was that the various member States of the European Communities have adopted somewhat different ways of dealing with the practical aspects of radiation protection. Such divergence between procedures did not necessarily imply that some of them were not complying with the relevant Euratom directives, since those directives set out to establish general principles, and leave the decisions about means of implementation to the individual States. Not surprisingly, different regimes were adopted in different countries.

The organisational structure of individual dosimetry services differs between USA and Europe. In the USA the services, with a few exceptions, are either purely commercial or belong to semi-private contractors of government agencies, whereas in Europe (except Italy and Switzerland) the services are directly operated or licensed by government institutions. In the USA, similarly in Japan, there are separate services for radiation workers in the nuclear field under the supervision of the atomic energy authorities, and for medical radiation workers where the ministry of public health or national environmental protection agencies are in charge.

Two fields were identified where new initiatives seemed to be required at that time: a) quality assurance within dosimetry services, b) record keeping.

A later study on assessment of occupational exposures to ionising radiation of workers [15] concluded similarly: "As might have been expected one conclusion from the study is that there are significant variations in the format and extent of occupational radiation dose data available". In Table I a summary of results of individual dosimetry in various European countries is given. Most of the personal dosemeters used were film and thermoluminescent dosemeters (TLD), few are based on radioluminescence (RPL). No information was available on the proportion of neutron dose, but it was expected that this contribution was extremely small.

3. New recommendations of ICRU and ICRP

In 1991, ICRP in Publication 60 [31] published new recommendations for radiation protection which include basic concepts and guidelines for radiation protection, a modified concept of radiation protection quantities and new reduced limits for occupational and public exposure. In the following the changes with respect to ICRP Publication 26 [29] relevant to individual dosimetry will be presented and discussed.

TABLE I

Number of radiation workers, collective dose and dose distribution in several European countries for 1987 [16, 19]
Nombre de travailleurs, dose collective et distribution des doses dans plusieurs pays d'Europe en 1987 [16, 19]

Country	Total number of controlled workers	Collective dose (man Sv)	Number of workers with dose > 5 mSv	Number of workers with dose >15 mSv	Number of workers with dose >50 mSv
Belgium	32 000	33.3	1863	473	4
Denmark	13 000	2.5	56	2	0
Eire	2 600	0.9	8	0	0
France	176 000	150.9	4488	883	55
Germany	274 000	114.2	5721	1270	25
Greece	5 500	5.1	192	85	18
Italy	34 000	12.5	440	102	20
Luxembourg	740	0.2	5	2	0
Netherlands	25 000	16.4	839	178	10
Portugal	5 400	2.3	106	7	0
Spain	62 000	74.7	1347	194	16
Switzerland	53 000	18.8	1003	224	1
United Kingdom	144 000	116.6	5802	1228	10

3.1 Concept of radiation protection quantities

The development of specific quantities for radiation protection purposes has a long history and the path of the ideas and concepts proposed and introduced has not always followed a straight line. Its basis has already been laid in the 1970s.

The international commissions ICRP and ICRU have developed a hierarchy of quantities for radiation protection applications which can be described by: primary limiting quantities (now also called "protection quantities") taking account of human body properties and operational quantities for radiation protection monitoring of external exposure.

The basic idea of a primary limiting quantity is to relate the *"risk"* due to exposure to ionising radiation to a single (dose) quantity which takes account of the human as a receptor, of the different radiation sensitivities of various organs and tissues and the different radiation qualities. Other parameters, however, *e.g.* the influence of dose rate or sex and age of a person exposed on the biological response, were not explicitly expressed in the definition of these quantities.

Operational quantities are quantities defined for use in radiation protection measurements for external exposure, either area or individual monitoring. Usually they should provide an estimate or upper limit to the value of the limiting quantities due to an exposed or potentially exposed person and are often used instead of those quantities in practical regulations.

Both types of quantities can be related to "basic physical quantities" as specified in ICRU Report 33 [25] which are generally used in radiation metrology, and in radiation dosimetry in particular, and are defined without considering any specific aspect of radiation protection. Basic physical quantities are quantities whose units are obtained directly through primary standards at national standards laboratories, *e.g.* the fluence of neutrons and exposure or air kerma for photons. All these quantities are point quantities and have long been well defined.

The other types of quantities mentioned above – mostly dose equivalent or equivalent dose quantities – are either not directly measurable or cannot be obtained by primary standards. For this reason, knowledge of the numerical relations between the basic physical quantities and these other quantities is a very important condition for the practical implementation of the whole system of radiation protection quantities. It is therefore absolutely vital that an agreed set of data accepted by national and international authorities is available in order to avoid confusion. In 1987 the ICRP in its Publication 51 [30] published a complete set of conversion coefficients to be used for the implementation of their recommendations published in 1977 [29]. Because of ICRP 60, this set of data has to be revised. For neutron radiation, in particular, a complete set of new conversion coefficients is necessary.

In 1992, the ICRP and ICRU had therefore agreed to set up a joint task group. Its main objectives are to study the impact of ICRP 60, on data of conversion coefficients between basic physical quantities and primary limiting or operational quantities, to supply a new consistent set of data necessary for the implementation of the whole concept into practice and to discuss the relations between the various types of quantities. In autumn 1995, the report of the task group was accepted for publication by both Commissions.

3.2 Limiting quantities

In 1977, the ICRP in Publication 26 [30] introduced the organ (or tissue) dose equivalent, H_T , and the effective dose equivalent, H_E , which includes in its definition the relative variation of the tissue response with different types of radiation and for different tissues or organs in the human body. While in general this concept has not been changed in ICRP 60, however, important modifications have been recommended which will be summarised in the following.

Absorbed dose and equivalent dose in an organ or tissue

In ICRP 60 it is said that "... it is the absorbed dose averaged over a tissue or organ (rather than at a point) ... that is of interest". Hence a new quantity organ (or tissue) average absorbed dose, D_T, has been defined. The idea of a mean organ dose as a dose averaged over the volume of an organ or tissue is not new and has already been used for the definition of the effective dose equivalent in ICRP 26 [29] but at that time without defining a new quantity.

A new quantity equivalent dose in an organ or tissue, $H_T = \Sigma\, w_R\, D_{T,R}$, has also been defined in ICRP 60, where $D_{T,R}$ is the mean organ dose from radiation of type R incident on the human body and w_R are newly introduced radiation weighting factors replacing the mean quality factor used before. The sum is performed over all types of radiation involved.

Radiation weighting factors

For external irradiation, the values of the radiation weighting factors are given by the parameters of the external radiation field only (radiation type and spectral distribution). This means that w_R represents a body-averaged mean weighting factor. While the former quality factor concept took into account variations of the radiation quality within the body and a possible dependence on the direction of radiation incidence on the body, these effects are now ignored.

The w_R values for various types of radiation are specified in ICRP 60 in a table. For photons, electrons and muons of all energies a value of one is fixed with the exception of Auger electrons emitted from nuclei bound to DNA, but this is of no importance for external irradiation. The radiation weighting factor for neutrons depends on the neutron energy. Different w_R values are given by either a step function or a continuous function. In order to avoid confusion only one function should, however, be used in practice. The new data of conversion coefficients evaluated by the ICRP/ICRU task group are given for the continuous function only. This avoids unjustified steps in the conversion functions with energy.

Effective dose

The new quantity effective dose, E, is introduced as the weighted sum of 13 organ equivalent doses, H_T , to replace the effective dose equivalent, H_E, defined before as the weighted sum of six tissue and organ dose equivalents plus the mean "remainder" dose (weight: 30%) from five organs with the highest doses of 12 residual organs. Twelve tissues and organs are now specified with individual weights and the additional "remainder" weight now amounts to only 5%. The dose value of the remainder is defined as the mean value from 10 specified organs and tissues. This definition avoids the difficulty encountered in ICRP 26 in selecting the most important residual organs which in a non-isotropic radiation field was previously dependent on the orientation of the body in that field. For external whole-body exposure the organs specified in the remainder are obviously less important for the determination of the effective dose than before. On the other hand, detailed tables of conversion coefficients must now be available for more organs than before.

The change from effective dose equivalent, H_E, to effective dose, E, will not result in very pronounced quantitative changes for external photon and beta radiation. In photon fields, the effective dose E is in general a few percent less than the effective dose equivalent H_E due to the increase of the number and the difference in the weighting of the organs considered. A photon dosemeter, the reading of which provides a conservative estimate of H_E, will behave similarly with respect to E and it will therefore not be necessary to change anything in the record keeping of photon doses when changing from H_E to E.

For neutrons, however, it is different. While in ICRP Publication 51 [30] it has been recommended as a first step to simply double the conversion coefficients for the organ and effective dose equivalent for neutrons until a new approach is finally found, the new concept of ICRP 60 now allows the conversion coefficients for the effective dose equivalent, H_E, to be compared with those for the effective dose, E. For example, data of Hollnagel [20] and Leuthold and Schraube [37] show that for neutrons above thermal energies and below about 1 MeV, under all irradiation conditions the ratio E/H_E is always higher than 2 with a maximum of about 7.5 for PA irradiation at about 50 keV neutrons.

3.3 Quality factor

In principle, the definition of dose equivalent, $H = Q\ D$, has not been changed by ICRP 60, but its use is now restricted to the definition of operational radiation protection quantities. The quality factor function $Q(L)$ (L: linear energy transfer of a charged particle in water) has, however, been modified. While for photons and electrons ($Q = 1$ for photons and electrons of all energies) the situation stays as before, for neutrons the change of $Q(L)$ results in an increase of Q_n (mean quality factor in a small piece of ICRU tissue irradiated by neutrons). With respect to the new operational quantities (see below), this change results in an increase of the dose equivalent values by up to a factor of about 1.7 depending on neutron energy. This value is much less than the increase of the organ equivalent dose values compared to the organ dose equivalent values used before which run up to a factor of about 4 at low neutron energies.

3.4 Operational quantities

The new operational radiation protection quantities for monitoring external exposure are dose equivalent quantities defined either for penetrating radiation (*e.g.* photons above about 12 keV and neutrons of all energies) or for low penetrating radiation (*e.g.* β-particles and α-particles). The latter is mainly absorbed in the skin and not in deeper lying organs. In considering this the ICRP has, in addition to limits for the effective dose, also defined specific limits for the skin dose.

Due to the different tasks in radiation protection monitoring – area monitoring for controlling the radiation at working places and defining controlled or forbidden areas – or individual monitoring for the limitation of individual exposure – different operational quantities have been defined. This takes into account the fact that in general in a given position an area dosemeter free in air sees a different radiation field than an individual dosemeter worn on a body, where the radiation field is strongly influenced by the backscatter and the absorption of radiation in the body. The new operational quantities may then be presented in the following scheme:

	Limiting dose quantity	Quantities for area monitoring	Quantities for individual monitoring
Penetrating radiation	effective dose	ambient dose equivalent $H^*(10)$	personal dose equivalent $H_p(10)$
Low penetrating radiation	skin equivalent dose	directional dose equivalent $H'(0.07,W)$	personal dose equivalent $H_p(0.07)$

In rare cases where a limitation of the dose to the eye lens becomes relevant a further personal dose quantity, $H_p(3)$, is recommended.

For individual monitoring the quantity personal dose equivalent, $H_p(d)$, has been proposed. The quantity is defined as the dose equivalent in ICRU tissue at a depth d in a human body below the position where an individual dosemeter is worn. For penetrating radiation a depth $d = 10$ mm is recommended, while for low penetrating radiation $d = 0.07$ mm is proposed. In special cases of monitoring the dose to the eye lens a depth of 3 mm may be appropriate.

The operational quantities for individual monitoring met several criteria. They are equally defined for all types of radiation, additive with respect to various directions of radiation incidence, take into account the back scattering of the body and are approximately measurable with a dosemeter worn on the body.

Other requirements which the quantities should satisfy can, however, only be fulfilled with additional specifications.

An operational quantity for individual monitoring should allow the effective dose to be assessed or should provide a conservative estimate under nearly all irradiation conditions. Obviously this is not always possible. For example, this condition cannot be fulfilled if a dosemeter is worn at the front of the body and the body is exposed from the back, because most of the radiation will then be absorbed by the body itself and not reach the position of the dosemeter and the point where the value of the operational quantity is defined. Even if the dosemeter measures $H_p(10)$ correctly in this case, it will not be a conservative estimate of the effective dose E. It is therefore an additional requirement in individual dosimetry that the personal dosemeter is worn at a position on the body which is representative for the body exposure. For penetrating radiation and a dosemeter position in front of the trunk, however, the quantity $H_p(10)$ delivers mostly a conservative estimate of E even in cases of lateral or isotropic radiation incidence to the body.

A further requirement for an operational quantity is that it allows dosemeters to be calibrated under reference conditions in terms of that quantity. The personal dose equivalent is defined in the individual human body and it is obvious that individual dosemeters cannot be calibrated in front of a real human body. For a calibration procedure the human body has therefore to be substituted by an appropriate phantom. This topic is discussed in the next section.

3.5 Calibration of individual dosemeters

The calibration of individual dosemeters should in principle be performed in front of an appropriate phantom substituting the human body. While at first in ICRU Report 39 [26] the ICRU sphere was mentioned as a possible phantom, in ICRU Report 47 [27] a more convenient slab phantom (30 cm x 30 cm x 15 cm in depth) has been introduced as the reference phantom in front of which dosemeters should be calibrated in terms of $H_p(d)$. Reference values of $H_p(d)$ are then given by the dose equivalent at the specified depth d in the slab phantom of ICRU tissue material below the point where the dosemeter is positioned.

In 1994, the International standards organisation (ISO) [32-33] has agreed to standardise three phantoms for the calibration of personal dosemeters depending on their applications:

– a slab phantom (30 cm x 30 cm x 15 cm in depth) for the calibration of individual dosemeters worn on the trunk,

– a pillar phantom (7.3 cm in diameter, 30 cm in length) for the calibration of dosemeters for the wrist or leg and

– a rod phantom (1.9 cm in diameter, 30 cm in length) for the calibration of dosemeters for the finger.

The true value of the quantity $H_p(d)$ which should be used as the reference value in the calibration, is the dose equivalent at the depth d in a phantom of

ICRU soft tissue with the shape of the actual phantom used (see above) below the point where the dosemeter would be positioned. In calibration laboratories this value is usually determined by measuring basic free-in-air quantities like air kerma or fluence and applying specific conversion coefficients.

In practice, ICRU tissue equivalent material is not available for all types of radiation. ISO has therefore agreed to recommend the following materials for the three phantoms in practical use:

– a water slab phantom (30 cm x 30 cm x 15 cm in depth): the front face of the phantom consists of a 2.5 mm thick PMMA plate; the other phantom walls are of 10 mm thick PMMA;

– a water pillar phantom (7.3 cm in diameter, 30 cm in length): the walls of the phantom consist of PMMA; the circular walls are 2.5 mm in thickness and the end walls are 10 mm thick;

– a rod phantom (1.9 cm in diameter, 30 cm in length) of PMMA.

The backscattering characteristics of these phantoms are similar to those phantoms of ICRU tissue material (deviations of less than 2% for photons in total) and therefore no further correction factors should be applied in the calibration due to the differences in the materials of the phantoms.

3.6 Dose limits

An important part of the new ICRP recommendations is dealing with new dose limits for occupational and public exposure. They are mainly based on new findings from the follow-up of the exposed population in Hiroshima and Nagasaki and as a consequence in the introduction of the multiplicative risk model for tumor induction. The effective dose limit for occupational exposure is recommended to be reduced from 50 mSv per year to 20 mSv per year averaged over 5 years with a maximum of 50 mSv within one year. For the public the recommended effective dose limit is 1 mSv per year (in addition to natural background). 20 mSv received by nearly continuous occupational exposure during 12 months would result in a mean dose per month of about 1.7 mSv. An individual dosemeter which is used for monthly recording of doses should be able to register at least about 10% of this dose with sufficient accuracy. This requirement can be simply fulfilled with modern dosemeters for photon radiation, *e.g.* systems based on thermoluminescent or photoluminescent detectors, but other systems may have difficulties in achieving a sufficient sensitivity.

For neutron dosemeters, not only a reduction of the limits has to be considered but also an increase of the relative radiation quality of neutrons which results in an additional decrease of the dose equivalent response for existing neutron dosemeters, because in a given neutron field the same detector reading corresponds now to a higher dose equivalent value. For most neutron fields, however, with broad energy spectra occuring in practice the change due to this effect is less than 30%.

4. New techniques

Individual dosimetry has to satisfy simultaneously physical laws, technical capabilities and national or international regulations. These needs are not always compatible. For example, the search for very low detection limits generally leads to heavy equipment unusable as an individual device for workers.

Presently, different solutions have been studied and proposed. One of the aims of the radiation protection research is to develop new detectors and monitors able to perform either integrating measurements for record keeping or real time monitoring with alarm capabilities.

The studies performed can be classified in two main groups:

1) passive systems using solid state detectors including gels,

2) active systems using electronic detectors such as silicon or gases.

The first group corresponds to the modification of physical and chemical properties of specific materials, such as radiochemical reactions on photographic films, thermoluminescence, radiophotoluminescence, exoelectronic emission, nuclear tracks, bubbles, etc. In this case the dosimetric information can be obtained only after a given lapse of time necessary to perform the readout. This type of dosimetry has been used for a long time in routine legal dosimetry by dosimetry services.

The second group corresponds to phenomena yielding electronic charges or photon emission under radiation. Their signals are transformed into electronic signals and treated on line by associated or micro-computerised electronics. Dose and dose rate are displayed on LEDs or CCD screen in real time. Dose or dose rate evolution are evaluated during management of total dose to the worker or for a working methodology.

4.1 Passive systems

Recently, further improvements were made on passive techniques for photon dosimetry and this will probably continue in the near future. Two major enhancements in radiophotoluminescence (RPL) and thermoluminescence (TL) techniques have been achieved. Some other small enhancements, based on the study of an ultra-sensitive method using forming gas for development and read-out of very lowly exposed photographic films, and on track etch systems are in progress. Improvements into the high dose range using neutron activation of residual silver have also been made.

Radiophotoluminescence

Two main improvements have contributed to the re-development of this technique [41]. The first improvement is related to the reading technique. Up to now, radiophotoluminescent glasses are read using the fluorimetry method.

The glass is excited with an incident UV light and the fluorescence is measured at larger wavelengths. Under certain conditions, for example at specific incident UV and emitted luminescence wavelengths, and ranges of absorbed dose and measurement temperature, the luminescence intensity is strictly proportional to the absorbed dose. Many authors [4, 35] demonstrated that after UV light pulse stimulation, the photoluminescence is composed of 3 components with different decay times: the pre-dose signal is due to the shortest and largest decay time while the dose signal is due to the intermediate decay time with a time constant within 2 and 20 μs. Measurement of the photoluminescence in the intermediate time range has two advantages: reduction of the pre-dose down to a few microsieverts [12] and obtaining a linear response up to doses of 10 Sv. The second improvement enables the use of glass dosemeter for approximately 100 times before a thermal treatment is necessary again.

Recent improvements using RPL glasses were reported for mixed field dosimetry. A flat RPL glass covered with a hydrogenous converter is used as a track detector. The dose measurement is performed with a microscopic scanning laser beam which detects both the continuous fluorescent light due to photon dose and the light peaks due to high damage neutron tracks [38].

Thermoluminescence

The most important improvements on TL dosimetry have been made in the development of new TL materials. Two products are widely studied: the Chinese copper doped lithium fluoride [45] and the Russian carbon doped alumina [2]. The last international conference on solid state dosimetry held in Washington (July 1992) showed the real interest for these phosphors. Their sensitivity is increased by a factor of 30 to 50 depending on the preparation method. A few tens of μSv can be measured by LiF:Cu and Al_2O_3:C, respectively. Al_2O_3:C is also suitable for photon dose measurements in (γ, n) mixed fields.

Another TL method, called cooled optically stimulated luminescence (COSL) and close to the photo-induced transfer thermoluminescence (PITL) studied and developed by Iacconi *et al.* on aluminium oxide [21], has been used for fast neutron dosimetry. The TL detector is composed of CaF_2:Mn powder embedded in a polyethylene matrix. The detector is cooled down to liquid nitrogen temperature and optically irradiated in order to fill up low temperature peaks by optical transfer. The Tl glow curve is then obtained by increasing the temperature from liquid nitrogen up to room temperature. The sensitivity of such a method is low and the minimum detectable dose close to 1 mSv. The gamma component has to be determined with a separate dosemeter [17].

TABLE II
LiF TL dosemeters investigated and the evaluation parameters
Dosimètres LiF étudiés et paramètres d'évaluation

Dosemeter code	TLD-100	MTS-N	MCP-N	GR-200
Doping	Mg, Ti	Mg, Ti	Mg, Cu, P	Mg, Cu
Origin	Harshaw	Krakow (Poland)	Krakow (Poland)	Beijing (China)
Size (mm)	3.1 x 3.1 x 0.8	Ø 4.5 x 0.7	Ø 4.5 x 0.7	Ø 4.5 x 0.8
Reading				
T_{min} (°C)	100	100	100	70
T_{max} (°C)	240	240	240	245
Annealing				
Temp (°C)	400/100	400/100	240	240
Time (min)	60/120	60/120	10	10

Track etch system

An instrument for reading chemically etched polycarbonate elements, the Autoscan 60, has recently become commercially available. The response to neutrons over the energy range 144 keV-35 MeV has recently been assessed for different types of Cr-39 detectors. Thermal neutron sensitivity was increased by locating lithium-loaded foils in contact with the detector [44]. (A detailed description of track etch dosemeters is given in the paper on "Neutron dosimetry"; this issue p. 37-65).

4.2 Active systems

Most of active individual dosemeters in use today are still based on GM-counters. The development of new active monitors for photons is mainly based on semiconductor devices such as diodes and MOS transistors. The use of semiconductor devices in radiation dose measurement is not new [34]. The design of photon dosemeters using silicon detectors must take into account the energy dependence of the response as a consequence of the high Z of silicon. The use of partial shielding of one detector or a part of a detector array enables an acceptable energy dependence of the response within 20 keV to 10 MeV and measurement of dose rates down to a few μSv/h. The major advantage of electronic personal dosemeters is that they do not need reading systems. Each dosemeter combines detector, reader, display unit and acoustic alarms. In many systems, *e.g.* Siemens, Nomatek, Yperwatch, a data transfer network can be established with the managing computer [13, 39-40]. The new personal dosemeter system Siemens Plessy has been developed by NRPB [9]. MGP Instruments S.A./ Yperwatch SA have developed a waterproof dosimetric wrist watch able to measure doses and dose rates down to 1 μSv and 10 nSv/h, respectively [13], which can be read and controlled through a management network. Most recent developments by RADOS, based on *direct ion storage* (DIS), often completely new options for electronic dosemeters.

For neutrons, different types of detectors are presently under study including: silicon diodes [3, 6, 8], streamer chambers [5, 7], proportional counters [10-11], bubble dosemeters with acoustic complement [1, 23] and more recently SRAM [42]. (Further details about these systems are given in the paper on "Neutron Dosimetry"; this issue).

In the near future, the main trends in individual dosimetry are obviously an increase of electronic dosemeter use in conjunction, for the moment, with legal dosemeters which are generally passive dosemeters, mainly photographic films and TLD.

5. Results of the workshop [22], open problems, and future trends

5.1 Conservatism of operational quantities

Depending upon energy and orientation of photon radiation, ambient dose equivalent provides an overestimate of effective dose by factors between 1.0 and 10, but in most practical radiation fields by a factor of between 1.2 to 2.0. Personal dose equivalent gives a wider range and in some circumstances can underestimate effective dose by factors of between 1.1 to 4.0. However, in practical situations it is more likely to provide an overestimate of the effective dose by a factor of between 1.0 and 2.0. The largest over- and underestimates occur for photon energies below 60 keV, which in most circumstances are relatively unimportant contributors to the exposure.

For neutron radiation the ratios between effective dose and the operational quantities vary more with energy, and to the extent that they overestimate the effective dose they may compound the problems in some workplaces caused by the increased weight now attached to this radiation. Depending upon neutron energy and orientation, ambient dose equivalent can overestimate the effective dose by a factor of up to 10 or underestimate it by a factor of about 1.4. The range for personal dose equivalent is from an overestimate by a factor of 2.5 to an underestimate by the same factor. In practical situations the ratios are rather less. Ambient dose equivalent in general overestimates the effective dose by a factor between 1.3 to 6.5 and personal dose equivalent overestimates by a factor of up to 1.7, although in some circumstances it can underestimate the effective dose by a factor of about 1.3. Departures of the responses of actual instruments and dosemeters from the ideal required by the operational quantities may increase these factors.

5.2 Requirements for type testing of dosemeters

The problems of the exact definition of personal dose equivalent under dosemeter calibration conditions, the shape and composition of the phantom to be used in this definition and for dosemeter calibration, and the allowances made for backscattered radiation remained unresolved (ISO has recently defined specific phantoms, see chapter 3.5). Still to be fixed are detailed requirements for angular dependence of the response of dosemeters and guidelines for the application of the operational quantities for high energy neutrons (> 20 MeV). The degree to which these problems affect the protection of people from radiation in practice is probably of little importance. However, they are important for standards of measurements and their legal implications.

5.3 Quality assurance

Achievement of high performance standards requires that all aspects of a service are constantly monitored and that at all levels the staff of the service are committed to maintaining performance. It also requires that systematic records are kept of all technical procedures and of the performance criteria to be met at all stages of the dosemeter manufacture, processing, issue and return. The overall costs of implementing such quality assurance represent a considerable economic investment in equipment, procedures and in the training and motivation of staff. This investment is restrictive to the introduction of new dosemeter designs unless they have considerable advantages either in cost or performance over existing methods.

5.4 Record keeping

At present all countries require records to be kept of the radiation doses received by workers. Initially such record keeping was conceived to demonstrate that workers were not exposed beyond the legal dose limits and, due to the passive detectors generally used, these systems do not allow workers to be directly aware of their radiation doses achieved. Responsible authorities have found the records useful in identifying trends in exposure levels in different industries and sections of industries. Another purpose found for the records is as legal evidence when workers suffer from health problems that may be related to their radiation exposure and compensation claims are made. Lastly the records have found an increasing use in epidemiological studies of radiation risks. Both the use of dose records as evidence in compensation claims and in epidemiological studies raise issues as regards the dose concepts. The implications are that more details need to be determined and recorded about the actual circumstances of exposure. This may be achieved either by elaboration of personal dosemeters, which is against the current trend both of the operational dose quantities and of dosemeter design, or by more detailed measurement and recording of the radiation quality in workplaces.

5.5 Trends and needs for new dosimetry systems

Future personal dosemeters should offer a number of options besides the fulfilment of all the technical requirements specified in international standards. Among them are: direct display of dose, ev. also dose rate, acoustic alarm at high dose rate or dose, storage of the dose rate profile and the accumulated dose, codes for special work conditions and storage of personal identification. It may be expected that by the end of the decade an approved personal dosemeter with the following specifications could be in use:

a small unit of few cm linear dimension, weighing less than 50 g, with built in detectors, a data memory, a display unit, and operating keys; measurement of $H_p(10)$ and ev. $H_p(0.07)$; storage of the dose rate profile, the complete individual dose history (including dose values transferred from other dosimetry systems) as well as personal data of the radiation worker. Dose and dose rate would be directly displayed and all the other stored data would be available for display. At free programmable levels, acoustic alarms for dose rate and ev. dose would be present. Internationally standardised readers would allow a universal application of these units as personal dosemeter and official personal dose record for various institutions in different countries.

Conclusion

The immediate implications of recent ICRP and ICRU recommendations on individual dosimetry appear to have been assimilated. However, there remain some details of the definition and implementation of the personal dose equivalent concept that need further discussion and agreement.

It is assumed that the reduction of dose limits for occupational exposure and the possible inclusion of dose contributions from exposure due to natural sources will increase the number of workers which have to be included for individual monitoring and dose recording in the future.

Recent developments on radiation detectors and dosimetry systems tend to show that the next generation of active dosemeter systems could offer a wide range of new options, especially for photon dosimetry. Neutron metrology, however, is expected to remain as difficult as it was before and the demand for a better neutron dosemeter may become even more important, because more sensitive dosemeters are required.

Within Europe, the harmonisation of standards requires greater emphasis to be placed on performance testing and quality assurance. Further thought needs to be given to the adequacy of dose records, if they are to be used for more than a demonstration of compliance with legal dose limits. ■

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