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Report of a Consultants meeting on Dosimetry in Diagnostic Radiology

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1. INTRODUCTION

During its biennial meeting in 1996, the Standing Advisory Committee "SSDL Scientific Committee", recommended extending the long experience of the Agency in the field of standardization and monitoring dosimetry calibrations at radiotherapy and radiation protection level for the Secondary Standard Dosimetry Laboratory (SSDL) Network, to the field of diagnostic x-ray dosimetry. It was emphasized that *"Measurements on diagnostic x-ray machines have become increasingly important and some SSDLs are involved in such measurements. The Agency's dosimetry laboratory should, therefore, have proper radiation sources available to provide traceable calibrations to the SSDLs."*

2. OBJECTIVES OF THE CONSULTANTS' MEETING

The purpose of the consultants' meeting was to advise the Agency on dosimetry in diagnostic radiology. They were specifically requested to overview scientific achievements in the field and to give advice to the Agency on the need for further developments. The list of participants in the meeting is given in Appendix II.

3. BACKGROUND

3.1. CLINICAL DOSIMETRY

Medical ionizing radiation sources give by far the largest contribution to the population dose from man-made sources. In developed countries it is comparable to that from the natural background excluding radon. About 90% of this contribution is due to x-ray diagnostics and 10% to nuclear medicine. Since the risk for stochastic effects (induction of cancer and genetic disorders) is believed to be without a threshold, the detriment to the population increases with increasing population dose. An increasing part of the dose [1] from diagnostic x-rays is due to the use of dose-demanding procedures such as fluoroscopy, interventional radiology and computerized tomography (CT). Patient dose measurements are therefore becoming increasingly important. For example, in the International Basic Safety Standards [1] it is stated that representative dose values shall be determined in radiological examinations. The European Union has adopted a directive towards "health protection of individuals against the dangers of ionizing radiation in relation to medical exposures" which requires extensive dose measurements [2]. There is therefore a need to control this dose and to optimize the design and use of x-ray imaging systems. It is generally recognized that even a 10% reduction in patient dose is a worthwhile objective for optimization. In this context it is important to note that the image quality should always be sufficient for the clinical need.

It is clear from the above that it is essential to standardize the procedures for dose measurement in the clinic. In many situations, it is of interest to make measurements directly on the patient, but for the control of technical parameters, for the comparison of different systems and for optimization it is preferable to make measurements using a standard phantom to simulate the patient. With the exception of mammography, where there is a European protocol [3], there is hardly any international advice available for the performance of such measurements or for the selection of phantoms to be used in different situations.

3.2. THE NEED FOR SPECIALIZED INSTRUMENTATION

Various examination techniques are used in x-ray diagnostics. They include fluoroscopy, including interventional radiological procedures, mammography, CT, dental and conventional[2] radiography. In some cases specialized dosimeters are required, whose design and performance must be matched to the needs of the clinical measurement. The use of such dosimeters and/or the interpretation of the results obtained may require

[1] Whenever the terms dose or patient dose are used without qualification, they are used in a generic sense.
[2] In this document the term conventional radiology is used to cover all x-ray imaging modalities other than dental radiography, fluoroscopy, mammography and CT.

specialized techniques and knowledge, but with the exception of mammography (ibid.) limited international guidance is available. In addition there are special requirements for the calibration of such instruments at the SSDLs. Methods to perform such calibrations are not yet completely developed.

3.3. DEVELOPMENTS AT PSDLs AND SSDLs

The need for establishing and offering an extended range of calibration conditions in order to meet the widened requirements as expressed in diagnostic clinical practice has previously been recognized by some Primary Standard Dosimetry Laboratories (PSDLs) and SSDLs. It is being taken into account by an increasing number of PSDLs and SSDLs.

Calibrations directly traceable to primary standards are currently available for most radiation qualities employed in mammography, fluoroscopy, and conventional radiography, both as unattenuated beams and as beams simulating the field behind the patient. Also dedicated instruments such as CT-chambers (see below) used in computerized tomography are calibrated against primary standards. Recently conducted intercomparisons between several PSDLs have demonstrated the mutual equivalence of the primary standards also for the radiation qualities developed in order to meet clinical requirements.

Some SSDLs have attempted to establish diagnostic calibration services and others have requested guidance on doing so. The radiation qualities available and ionization chambers used for measurement are variable among the SSDLs. Some use qualities that are applicable to this activity; however, the chambers employed would be questionable according to the requirements needed for the diagnostic application. A greater uniformity amongst the SSDLs is needed for these applications.

3.4. PRESENT STATUS OF IAEA DOSIMETRY PROGRAMME IN DIAGNOSTIC RADIOLOGY

Due to the increased need for quality assurance in diagnostic radiology, it has become important to provide traceability of measurements in this field. As noted above, the SSDL Scientific Committee recommended in 1996 extending the experience of the IAEA in the field of standardization at radiotherapy and radiation protection levels for the IAEA/WHO Network of SSDLs, to the field of x-ray diagnostics. This recommendation has led the Dosimetry and Medical Radiation Physics (DMRP) Section to start the development of the necessary facilities and procedures for the calibration of ionization chambers. Recognizing that their currently used ISO qualities are not appropriate for diagnostic applications, the DMRP is implementing suitable qualities. Because of the importance of mammography examinations world-wide, as the first step in this process the IAEA Dosimetry Laboratory has acquired a mammography x-ray unit and the necessary measuring equipment. Seventeen radiation qualities have been established with tube voltages between 23 kV and 40 kV that represent entrance and exit beams for molybdenum and rhodium targets. A suitable ionization chamber has been selected as a reference standard. At present, the necessary steps are being undertaken to calibrate this chamber at a PSDL. This will allow the IAEA to provide a new service to SSDLs in member states. The IAEA Dosimetry Laboratory will ensure traceability in the measurement through the calibration of their secondary standards at mammography radiation qualities.

4. MEETING FORMAT

After the welcome and introductory remarks defining the objectives of the meeting by P. Andreo and F. Pernicka, the four consultants each gave a one hour presentation:

- Properties and measurement of radiation qualities and x-ray tube potential by H.-M. Kramer
- Instruments and their calibration for diagnostic applications by L. A. DeWerd
- Clinical dosimetry in diagnostic radiology, part 1 by G. Alm Carlsson
- Clinical dosimetry in diagnostic radiology, part 2 by D. R. Dance.

The presentations were followed by an in-depth discussion of the current situation in clinical dosimetry and of the consequences resulting thereof in view of services to be provided within the IAEA Dosimetry Programme and by SSDLs. As a result of this discussion, the consultants made six recommendations. These are explained and justified in this report, which was prepared by the consultants during the remainder of the meeting.

5. JUSTIFICATION

This section provides explanation and justification for the recommendations made by the consultants.

5.1. DEFINITIONS AND SCOPE OF INSTRUMENTATION

The most common type of radiation detector for diagnostic radiological dose measurement is a parallel plate ionization chamber. Parallel plate ionization chambers (also known as plane-parallel chambers) use two parallel, flat electrodes separated by a few millimeters. They are calibrated with their plates oriented perpendicularly to the beam axis, which is also the orientation in which they should be used.

Ionization chambers are made in different designs for specialized applications such as those listed above. There may be special requirements for the calibration and use of each type of chamber. All ionization chambers should have a sufficiently flat response over the range of the relevant radiation qualities. Mammographic ionization chambers generally require a thin entrance window and a construction using low atomic number materials, e.g. air equivalent or plastic materials. A CT-chamber, often called a pencil chamber, has an active volume in the form of a thin cylinder about 100 mm in length. Its response should be uniform along its entire axial length. In fluoroscopy there is a need to measure the input air kerma rate to the image intensifier and the patient dose. The chambers used for each aspect need to be of adequate design and size. Air Kerma Area Product (KAP) meters are also used in fluoroscopy. These are parallel plate chambers which are optically transparent. They are mounted on the x-ray head and their sensitive area extends over the entire cross-section of the beam. The signal from a KAP meter is proportional to the product of air-kerma and field size at any plane perpendicular to the beam axis. Dental ionization chambers need to be cylindrical so they are suitable for panoramic applications. The chambers should also be suitable for x-ray tube voltages between 50 kV and 80 kV. Chambers designed for conventional radiographic and fluoroscopic applications should have a flat response over the range of tube voltages 50 kV to 150 kV.

Although ionization chambers are the main devices used for dosimetric measurements, other devices with special properties are frequently used. Important examples are semiconductor diodes and thermoluminescent dosimeters (TLDs). Because of the inherent problems involved in the use of these two devices, they should not be used for calibrations at SSDLs. They are used for quality control and in clinical dosimetry. In each case, the response of the dosimeters needs to be carefully considered to achieve accurate measurements.

The contrast in a radiographic image is mainly determined by the x-ray tube voltage. It is standard practice, therefore, to measure this voltage as part of quality control. Non-invasive instruments are mostly used for this purpose. Such instruments require calibration.

Because of the increasing importance of interventional radiology, the consultants wish to note explicitly that the requirements for these procedures are the same as those for fluoroscopy.

5.2. REQUIREMENTS FOR CALIBRATIONS AT SSDLs

Approximately 40% of SSDLs are currently involved with calibration of diagnostic ionization chambers. At present the manner in which calibrations at diagnostic radiation qualities are performed at SSDLs is not co-ordinated. Many use different radiation qualities and standards, some of which may be unsuitable. Quality control can only work satisfactorily if correct measurements are made. This speaks to the need for a Code of Practice (CoP) to give guidance to these laboratories and to those that may wish to join them in the future.

The chamber and electrometer (or charge-measuring device) both need to be calibrated, either separately or as a system. Generally they are calibrated as a system; if the chamber and electrometer are calibrated individually, the system factor is the product of the electrometer factor and the chamber factor. The quantity for which the calibration was performed must be stated.

Past work has indicated a significant energy dependence of response of some chambers. For this reason the SSDLs need to establish radiation qualities suitable for each area. It is recommended that radiation qualities given in IEC 61267 [4] be used and a reference radiation quality be chosen as in IEC 61674 [5]. Where such recommendations do not exist, appropriate radiation qualities must be identified. The CoP should include the requirement that each SSDL have chambers calibrated at the reference radiation qualities and a ratio to other qualities be

included. For example, for the conventional diagnostic range this would include a quality at 70 kV (RQR5) and at least two other qualities covering the range from 50 kV (RQR 3) to 120 kV (RQR 9). For a chamber with a sufficiently flat energy dependence, interpolation can be done for any intermediate point. In this context sufficiently flat means a maximum variation within ±3% at most across the energy range of use.

The range of tube voltages in x-ray diagnostics extends from 22 kV to 150 kV. For mammography (22 kV to about 35 kV) anode materials different from tungsten are frequently used. Radiation qualities are usually designated by tube voltage, first and second half value layer (HVL). Measurements of HVL are performed with ionization chambers. These measurements can be affected by the energy dependence of response [6], and by the beam diameter used. Directions need to be given in the CoP for the correct measurement of HVL and other parameters of the fields. It is also important to measure the temperature and pressure at the time of calibration, unless the chamber is sealed to the atmosphere or if the electrometer device automatically corrects for the density of air. The CoP should describe the methodology to check if the correction is done appropriately.

The CoP should elaborate on the procedures and requirements for the calibration of non-invasive tube voltage measuring instruments. It is suggested that as a minimum, the SSDLs should obtain two such devices, instead of purchasing an invasive voltage divider. The two meters will act as quality control devices for each other. Other non-invasive tube voltage measuring instruments can thus be calibrated against the standard.

Recommendation: ***SSDLs need a CoP which provides guidance on the establishment of radiation qualities and on the conduct of calibrations.***

5.3. SEPARATE REQUIREMENTS FOR MAMMOGRAPHY, FLUOROSCOPY, DENTAL RADIOGRAPHY, CT AND CONVENTIONAL RADIOGRAPHY

Specialized techniques in diagnostic radiology often require special dosimetric and radiation generating equipment. A new CoP must take this situation into account and should provide guidance to SSDLs for which physical quantity and under which conditions different kinds of dosimetric equipment should be calibrated. An example of situations in which guidance will be needed is the calibration of CT-chambers and of KAP-chambers. Although this can be performed with a CT- or a KAP-chamber, as appropriate, which can play the role of a secondary standard, this is not the only method of performing such a calibration. It can also be achieved with another calibrated ionization chamber. The CoP should give recommendations on the properties of the dosimeters to be used as secondary standards for dosimetric measurements to be performed for the various clinical diagnostic modalities. Such recommendations should include statements on maximum variations of the ionization chamber's response with half-value layer and, where necessary, on further instrument specifications such as dose rate dependence or electromagnetic compatibility etc..

Another point requiring attention in a new CoP concerns recommendations on the equipment of SSDLs with x-radiation sources both in terms of anode material and in terms of available dose rates. An example where the anode material is of importance is mammography and the dose rate can become relevant in high output fluoroscopy or in radiography. Guidance on these points will have to take into account the acceptable maximum uncertainties of measurements and the costs of setting up the various radiation fields at the SSDLs.

Recommendation: ***The CoP should identify separately the requirements for mammography, fluoroscopy, CT, dental and conventional radiology.***

5.4. INSTRUMENTATION REQUIREMENTS AND METHODOLOGY FOR CLINICALLY BASED DOSIMETRY

5.4.1. Instrumentation

When choosing an instrument for dosimetry in diagnostic radiology, it is important to match the instrument to the task. This will include the size and sensitivity of the instrument and its response to different radiation qualities. The use of an appropriate instrument is essential. In some cases, the commercially available instrumentation marketed for general or particular applications

does not meet these requirements [6] and there may be no internationally agreed specification. This can create difficulties, particularly where there is no local expertise available.

The majority of dose measurements in diagnostic radiology are made with ionization chambers (including KAP meters) and TLDs. The ionization chambers must be calibrated at the appropriate available radiation qualities at the SSDL, or locally against a chamber that has been calibrated at the SSDL (tertiary calibration). On the contrary, TLDs must be calibrated frequently and SSDL calibration is impracticable. TLDs should be preferably calibrated at a radiation quality close to that used for the dose measurement and with an instrument which has a secondary or tertiary calibration. The calibration of TLDs is well documented [7], but for completeness, details should be included in any guidance document. The need for a protocol for calibration of ionization chambers at the SSDL is noted above, but there is also a need to include a procedure for local transfer of this calibration to a tertiary instrument.

The KAP meter is a very useful instrument for dosimetry in diagnostic radiology as 'dose-area product' is more directly related to radiation risk than dose itself. It is a practical and relatively cheap device, which allows real - time monitoring of the patient dose. It is the instrument of choice for complex examinations where the size and the position of the field varies during the examination. It is now being routinely installed at hospitals in many countries.

Opinion is divided about the calibration of KAP meters, whether they should be calibrated at the SSDL or *in situ*. There are inhomogeneities in the x-ray field due to the heel effect and the presence of extra focal radiation whose magnitude will be equipment dependent. Examples of calibration procedures are given by IPEM [7] and by Larsson et al. [8]. This subject needs further research, but it is likely that a CoP for use at the SSDL and guidance for calibration in the clinic are both required. It is pointed out that in any case, separate calibration is required for the use of the x-ray tube under and above the couch [9].

Some x-ray equipment manufacturers supply instruments which measure field area from the collimator setting and estimate the dose from stored information. They produce a reading which purports to be 'dose area product' but is in fact a measurement of area to which a conversion factor has been applied. In such a situation there is great potential for a false reading and a quality control procedure is needed.

The concept of 'dose-area product' is less familiar than the concept of 'dose' and it is suggested that some guidance on the interpretation of this quantity should also be provided. This should include conversion to energy imparted, mean absorbed dose and effective dose. In this connection, it is noted that the conversion factors depend upon the radiation quality and the size of the patient.

Semi-conductor devices are now available. Such devices can be as small as TLDs and have the advantage that they allow real time measurement. A problem is that the inherent response of semi-conductor devices is not sufficiently flat. This problem is compensated for by the software corrections in the instrument. There is limited experience on the calibration, quality control and use of these instruments.

Film dosimetry may also be of use in some situations, especially where dose distributions are required. When using film, it is important to control the optical density. Film has a significant energy dependence and this needs to be accounted for unless qualitative measurements are being made.

5.4.2. Measurements with phantoms

For the control of technical parameters, for the comparison of different systems and for optimization, it is preferable to make dose measurements using a phantom to simulate the patient. When a phantom is used, the measured dose will depend upon the phantom shape and size and it is essential that the phantom is Standardized so that such variations are avoided. Standard phantoms must be designed so that they offer the same primary attenuation and scatter production as a representative patient. It is important to consider both of these aspects. It is desirable that such phantoms are inexpensive and constructed from readily available materials. Some compromise may be necessary. ICRU Report 48 [10] describes most of the phantoms presently available. The NEXT programme in the USA has used such phantoms in its national surveys of patient dose [11]. It is recommended that advice is given as to the choice of phantoms for selected standard examinations, which could include adult chest, lumbar spine, fluoroscopy, mammography and CT. The latter two procedures have received much attention and are treated below. Dosimetry for paediatric radiology is also of interest. It is suggested that phantoms for such examinations are developed at a later stage.

The consultants wish to note that it is only necessary for the phantom to be representative of a typical patient. It is not the intention that the result of dose measurements with phantoms should equal that from measurements with patients.

When a phantom is used to simulate the patient, the x-ray equipment should be set up in the same way as for the real examination. There are some protocols in use which recommend the dose for a fixed optical density on the film (e.g. the Nordic mammography protocol [12] recommends the use of net OD 1.0). The consultants prefer the use of the clinical settings.

When the phantom is exposed, the dose may be determined using a dosimeter placed at a defined position on its upper surface. Alternatively the exposure conditions may be noted and the dose calculated from measurements using a dosimeter free-in-air. Practical guidance on methodology should be included in the CoP.

The doses measured using the above procedures must be specified for a standard material. Several choices are available including water, air, striated muscle, and other soft tissues. The choice of air has the advantage that no conversion factors need be applied for measurements with an ionization chamber.

Dose measurements made at the surface of the phantom include backscatter whereas those made free in-air do not. It is desirable to standardize the dose specification to avoid ambiguity. Whichever prescription is adopted, a table of standard backscatter factors appropriate to the phantom geometries should be established. This may require customized Monte Carlo calculations.

It is pointed out that the introduction of standard measurement procedures and phantoms will facilitate local and international comparison of doses and the future establishment of reference doses (see for example the recent European Directive [2]). The Agency may wish to co-ordinate such comparisons once the use of the proposed CoP has been established.

5.4.3. Mammography

During the past few decades there have been significant advances in the equipment used for mammography. Even when the latest equipment is used, there is considerable variation from centre-to-centre in the choice of imaging parameters and techniques. Thus, there may be quite large differences in breast dose. A review of the development and current status of dosimetry for mammography is given in Dance et al. [13].

The most practical dose measurement for mammography is an estimate of the incident air kerma at the surface of the breast (with or without backscatter). Since a low energy x-ray spectrum is used for the examination, the dose decreases rapidly with increasing depth in the breast. More appropriate quantities for specifying breast dose have therefore been suggested. ICRP [14] recommend the use of the average dose to the glandular tissues within the breast (AGD) and this has been generally adopted.

Direct measurement of AGD is not possible. Instead, use is made of conversion factors that relate measurements of entrance air kerma to AGD. These factors may be derived from measurements on phantoms, but it is more usual to make use of the results of Monte Carlo calculations. Several authors have made such calculations. The resulting factors depend on the model and input data used and there are differences of the order of 10-15% between the results of different workers. The factors themselves depend upon the radiation quality, breast thickness and breast glandularity, though the latter variation is sometimes ignored.

Several countries have introduced protocols for dosimetry in mammography but there is wide variation in the methodology suggested. In addition, there is limited agreement for the material and size of a standard breast phantom. The consultants believe that the phantom introduced in the recent European protocol [3] could also be adopted by the CoP. They further recommend that the AGD be used as the dosimetric quantity for mammography. A standard set of conversion factors should be used to relate the measured entrance dose for the standard breast phantom to this quantity. It is noted that this conversion factor is quality dependent and is tabulated as a function of HVL. The determination of dose therefore includes a measurement of the HVL. It is suggested that guidance for the measurement of HVL be provided.

5.4.4. Computerized Tomography (CT)

CT examinations constitute about 4% of all radiographic examinations but can contribute 40% of collective dose [15]. It is therefore of considerable importance to monitor the dose for such examinations.

In conventional CT scanning, the patient dose is built up from that received from each individual CT slice. It has proved convenient to specify dose

in terms of the computer tomography dose index (CTDI) for a single slice. This is a dose integral along a line perpendicular to the scan plane normalized to the nominal width (T) of the slice. The most frequently used definition is that employed by the Food and Drug Administration in the USA.

$$CTDI = \frac{1}{T}\int_{-7T}^{+7T} D(z)\,dz$$

The CTDI may be measured using a CT chamber, a stack of TLD chips or film. CTDI can be measured in-air on the scanner axis without a phantom, or in a phantom and at various distances from the scanner axis. The relationship between in-air and in-phantom measurements of CTDI is scanner dependent because of differences in x-ray spectra, specialized beam filtration and scanner geometry. It can be argued that in-phantom measurements are more representative of the patient dose and the consultants therefore recommend the use of a phantom for these measurements. Standard phantoms are available for both body and head examinations and are in common use. For phantom measurements, the CTDI will vary with the distance from the beam axis. It has been suggested in a CEC working document that a weighted combination of CTDI measurements at the phantom centre and surface be used to represent the average CTDI [16]. The consultants recommend that guidance is given for the measurement of CTDI in the standard American Association of Physicists in Medicine (AAPM) phantoms. Within the last decade helical CT scanning has been introduced. Care must be taken to ensure that the guidance is appropriate for this imaging configuration.

It is also of interest to measure the dose profile of a CT slice. This can be achieved using TLD or film.

With knowledge of the CTDI, the number of slices, slice thickness and separation, the patient dose for a complete CT examination may be estimated. The procedure for this may not be straightforward and some guidance is required.

Recommendation: ***The CoP should include guidance on the requirements for instrumentation and methodology for clinically based dosimetry.***

5.4.5. International standards

There are few international standards related to the proposed CoP whose outline is given in Appendix I. Some are mentioned in the previous sections. Some are in preparation; for example, IEC 60580 for KAP meters and IEC 61676 for non-invasive x-ray tube voltage measurement devices. There are some national standards in the diagnostic radiology field, specifically some protocols for mammography dose measurements.

Recommendation: ***All relevant international standards and protocols should be taken into account. National protocols should also be considered.***

5.4.6. Impact of suggested recommendations on the IAEA Dosimetry Programme

In order to fulfil calibration requests for all x-ray diagnostic modalities, the scope of the services of the IAEA Dosimetry Programme must be extended. This includes a widening of the scope of the radiation qualities to be offered and of the secondary standards to be available.

Radiation qualities for the calibration of dosimeters for radiotherapy, for radiation protection and for mammography have already been successfully established at the IAEA Dosimetry Laboratory. The establishment of further radiation qualities is needed, suitable for the calibration of instruments to be used for dosimetry in dental radiography, CT, fluoroscopy and conventional radiography. The x-ray generating equipment available in the Laboratory could be used to develop the radiation qualities required. However, attention needs to be paid to the spare capacity of the calibration facility in the light of the expected significant increase in the number of calibrations per year.

There are also some requirements in terms of additional dosimetric instrumentation to enable the Laboratory to comply with the extended scope of calibrations and the increasing workload.

Recommendation: ***The IAEA Dosimetry Programme should be further extended to support the activities of the SSDLs recommended in this document.***

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