STUK

GUIDE **ST 1.9** / 23 November 2016

RADIATION PRACTICES AND RADIATION MEASUREMENTS

1 General 3

2 Accuracy requirements for radiation measurements 3

2.1 Measurement uncertainty and measurement error 3
2.2 Radiation measurements involved in monitoring of working conditions and the radiation safety of members of the public 4
2.3 Measurements of radon concentration in inhaled air 4
2.4 Radiation measurements involved in individual monitoring of workers 4
2.5 Measurements involved in determining patient radiation exposure 6
2.6 Quality control measurements 6

3 Requirements and approval of radiation meters and measurement systems 6

3.1 Radiation measurements involved in monitoring of working conditions and the radiation safety of members of the public 7
3.1.1 Requirements concerning meters 7
3.1.2 Approval of meters 7
3.2 Measurements of radon concentration in inhaled air 7
3.2.1 Requirements concerning measurements, meters and measuring methods 7
3.2.2 Approval of a measuring appliance or method of measurement 8
3.3 Radiation measurements involved in individual monitoring of workers 8
3.3.1 General requirements for the dosimetry service 8
3.3.2 Requirements concerning the dosimetry system 9
3.3.3 Approval of dosimetry service and dosimetry system 10
3.4 Measurements involved in determining patient radiation exposure 10
3.4.1 Requirements concerning meters 10
3.4.2 Approval of meters 11

This Guide is valid as of 15 December 2016 until further notice.
It replaces Guide ST 1.9, Radiation practices and radiation measurements, issued on 17 March 2008.

Helsinki 2017
ISSN 0789-4368
ISBN 978-952-309-372-0 (pdf)
ISBN 978-952-309-373-7 (html)

STUK • **SÄTEILYTURVAKESKUS**
STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY

Osoite/Address • Laippatie 4, 00880 Helsinki
Postiosoite / Postal address • PL / P.O.Box 14, FIN-00881 Helsinki, FINLAND
Puh./Tel. (09) 759 881, +358 9 759 881 • Fax (09) 759 88 500, +358 9 759 88 500 • www.stuk.fi

4 QUALITY ASSURANCE OF RADIATION MEASUREMENTS 11
4.1 Use of specialists in measurements 11
4.2 Calibration of radiation meters 11
4.3 Inspection of the operating condition of radiation meters 12

APPENDIX A QUANTITIES AND UNITS REQUIRED FOR RADIATION MEASUREMENTS
APPENDIX B SUMMARY OF ACCURACY REQUIREMENTS FOR RADIATION MEASUREMENTS

Authorization

Under section 70, paragraph 2, of the Radiation Act (592/1991), STUK – Radiation and Nuclear Safety Authority (Finland) issues general instructions, known as Radiation Safety Guides (ST Guides), concerning the use of radiation and operations involving radiation.

The Radiation Act stipulates that the party running a radiation practice is responsible for the safety of the operations. The responsible party is obliged to ensure that the level of safety specified in the ST Guides is attained and maintained.

Translation. Original text in Finnish.

This Guide includes the requirements relating to the implementation of Council Directive 96/29/Euratom; OJ No. L 159, 29.6.1996, p. 1.

1 General

The general requirements for radiation measurements are set out in section 23 of the Radiation Act (592/1991), sections 11 and 12 of the Radiation Decree (1512/1991), and section 17 of the Decree of the Ministry of Social Affairs and Health on the medical use of radiation (423/2000). Dosimetry services are governed by sections 12 and 32 a of the Radiation Act and the determination of radon concentration is governed by Decision of the Ministry of Social Affairs and Health (944/1992). The requirements for radiation measurements in nuclear power plant operation are set out in YVL Guides C.2, C.3 and C.6 published by the Radiation and Nuclear Safety Authority (STUK).

This Guide presents the principal requirements on accuracy of radiation measurements and on the approval, calibration and performance checks of radiation meters, together with requirements for dosimetry services measuring the individual radiation doses of workers engaged in radiation work (approved dosimetry services. The Guide also sets out the definitions of quantities and units used in radiation measurements. The radiation protection quantities used for assessing the harmful effects of radiation and for expressing the maximum values for radiation exposure (equivalent dose and effective dose) are set out in Guide ST 7.2.

This Guide concerns measurements of ionizing radiation involved in radiation practices, the results of which are used for determining the radiation exposure of workers engaged in radiation work and members of the public, and of patients subject to the use of radiation in health services, or upon the basis of which compliance with safety requirements of appliances currently in use and of their premises of use or of the workplaces of workers is ensured. The Guide also concerns active and passive measurements of the radon concentration of inhaled air in both workplaces and dwellings. The Guide does not apply to determining the radiation exposure of aircrews, determination of exposure caused by internal radiation, or measurements made to protect the public in the event of, or in preparation for abnormal radiation conditions.

2 Accuracy requirements for radiation measurements

2.1 Measurement uncertainty and measurement error

The final outcome of a measurement may often be expressed as a product involving a meter reading, a calibration factor and various other correction factors. The *measurement uncertainty,* which here refers to the overall uncertainty, is then obtained by evaluating all of the sources of error involved in the method of measurement, calculating the root mean square of their combined effects (standard deviation)*) and multiplying the combined uncertainty thereby obtained by a coverage factor. This Guide uses a value of 2 for the coverage factor, which corresponds to a confidence level of 95% and means that there is a 95% probability that the result of measurement deviates from the true value of the quantity by no more than the estimated measurement uncertainty. The measurement uncertainty in this Guide refers to the relative measurement uncertainty i.e. the uncertainty of a measurement is expressed as percentages of the measurement result.

When the measurement uncertainty is accurately assessed, the components that affect it are divided into two groups according to the manner in which their magnitude is estimated. The magnitude of type A uncertainty components is estimated by statistical methods and the magnitude of type B uncertainty components is estimated in other ways. Measurement uncertainty is determined in accordance with an international guide [1].

In the following discussion the *error* of a measurement denotes the difference between the

*) The root mean square of the estimated standard deviations for error sources means that the squares of the deviations are summed and the square root of the result is taken. Use of this method also requires the error sources to be mutually independent.

result of measurement (M_i) and the true value of the quantity measured (M_t) when all known corrections have first been made to the result of measurement. In this Guide error always refers to the relative error I:

$$I = \frac{M_i - M_t}{M_t} \cdot 100\% \qquad (1)$$

When the performance of a radiation meter is examined in metrological standards the absolute value of the meter error is generally given the upper limit under reference conditions, i.e. at the radiation energy stated in the standard and under the notified ambient conditions. The error determined under reference conditions is called the *intrinsic error*. Upper limits are separately provided for the meter error at specified values of other quantities affecting the result of measurement (known as influence quantities, such as radiation energy, the direction of incident radiation and the ambient temperature).

2.2 Radiation measurements involved in monitoring of working conditions and the radiation safety of members of the public

The measurement uncertainty in measurements of dose and dose rate of external radiation due to radiation practices within or in the vicinity of a place of work may not typically exceed 60% [2]. The dose here refers to the ambient or directional dose equivalent (see Appendix A, item A.1.3.1). The same recommendation also applies to measurement of surface activity (see Appendix A, item A.1.3.1). The purpose of the measurements is to ensure the radiation safety of workers or of members of the public.

The relative response of a dosemeter and a dose rate meter (= the relative variation of the response, i.e. the ratio of the reading to the true value, in respect of the reference energy) in measurements of ambient dose equivalent may not fall below 0.71 (-29%) or exceed 1.67 (+67%) in the photon energy ranges 20–150 keV or 80 keV–1.5 MeV. This requirement is satisfied if the relative response is between 0.71 and 1.67 in at least one of these ranges [3].

The intrinsic error of an alarming individual dosemeter may not exceed 30% [16].

2.3 Measurements of radon concentration in inhaled air

When measuring the radon concentration of inhaled air the measurement uncertainty may not exceed 30% (see Appendix A, item A.1.3.1).

The intrinsic error of a radon concentration meter may not exceed 20%. In repeated measurements of radon concentrations between 400 and 600 Bq·m^{-3} the standard deviation of the measurement results may not exceed 10%. The error due to environmental influence quantities such as humidity, temperature or background dose rate may not exceed 10%.

2.4 Radiation measurements involved in individual monitoring of workers

When testing a photon radiation dosimetry system for use in individual monitoring of workers, the result of measurement may not deviate from the true value with 95% confidence by more than 33% below or 50% above*) when the result of measurement corresponds to doses approaching the annual dose limit. The dose here refers to the personal dose equivalent $H_p(d)$ (see Appendix A, item A.1.3.2). The largest permitted relative deviation i.e. the dosemeter response limiting values, in the result of measurement at various doses may be expressed as a condition*) [5]:

$$\frac{2}{3} \cdot \left(1 - \frac{2H_0}{H_0 + H_t}\right) \le R \le \frac{3}{2} \cdot \left(1 + \frac{H_0}{2H_0 + H_t}\right) \qquad (2)$$

where $R = H_m / H_t$ is the dosemeter response, i.e. the ratio between the dose H_m determined by the dosemeter and the true value of the dose H_t, and H_0 is the registration threshold. The registration thresholds are set out in Guide ST 7.4. The "trumpet curves" derived from formula (2) are shown in Figure 1 (a value of H_0 = 0.1 mSv was used for the registration threshold in the graph of personal dose equivalent $H_p(10)$ and value of H_0 = 1 mSv was used in the graph of personal dose equivalent $H_p(0.07)$ when drawing the trumpet curves). The accuracy of a measurement result must be sufficient to ensure that the ratio of the dose determined by the dosemeter and the true value of the dose remains within the trumpet curve.

*) It should be noted that the deviation of -33% and +50% only holds for photon radiation. The deviation may be greater for electrons and for neutrons of unknown energy [6].

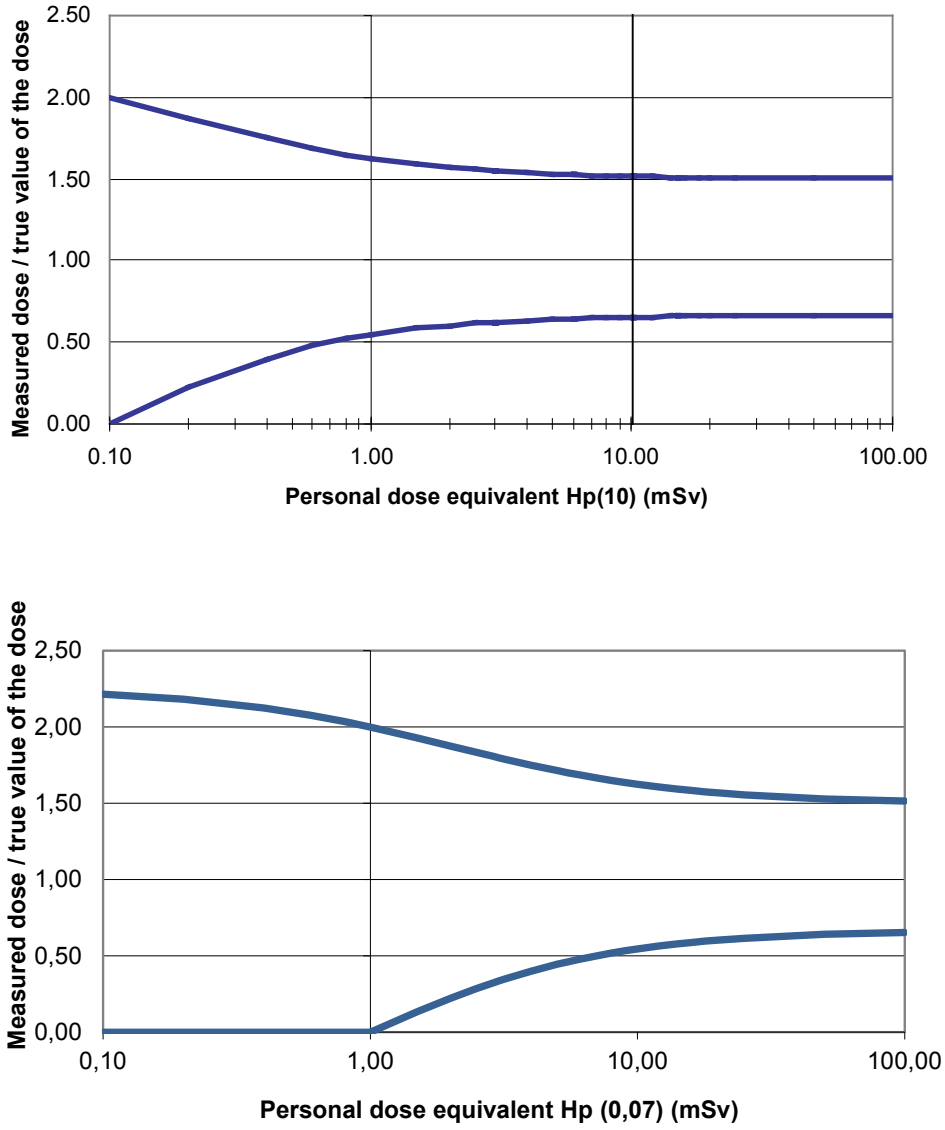

Figure 1. Trumpet curves describing the ratio of the dose determined by a dosemeter to the true value of the dose as a function of the dose.

The calculated measurement uncertainty (see item 2.1) of a dosimetry system may not exceed 42% [5]. This value was determined on the basis of the condition expressed in formula (2).

Factors to consider when assessing the accuracy of a dosimetry system include the type and energy of the radiation to be measured, the range of dose rate and dose, and any pulsation of the radiation in question. Ambient conditions, such as the temperature and humidity of air, electromagnetic fields or other radiation to be disregarded, may not cause substantial errors in measurement.

2.5 Measurements involved in determining patient radiation exposure

The uncertainty in measuring radiation exposure of a patient in X-ray diagnostics (entrance surface dose, dose-area product, mean glandular dose (MGD), dose-length product, and weighted multiple scan average dose; see Appendix A, item A.2.1) may not exceed 25%. The same accuracy requirement also applies to instruments with a monitor indicating the calculated radiation exposure of a patient. In measurements of the radiation output (air kerma/current-time product [11]) of a diagnostic X-ray appliance the measurement uncertainty may not exceed 7% when the result is used for determining the radiation exposure of a patient [15].

When measuring the dose from external radiotherapy the measurement uncertainty of the absorbed dose to water (see Appendix A, item A.2.2) at the reference depth along the central axis of the radiation field in a water phantom [12] may not exceed 3% in measurements of photon radiation and 4% in measurements of electron radiation. The properties of the meter are governed by Finnish SFS-EN standards [8]. The measurement uncertainty of the absorbed dose to water may not exceed 5% in dose measurements for individual patients (*in-vivo* measurement). In measurements of brachytherapy photon sources the measurement uncertainty of the reference air kerma rate (see Appendix A, item A.2.2) may not exceed 5%, nor may the measurement uncertainty of the reference dose rate in measurements of beta sources (see Appendix A, item A.2.2) exceed 15% of the air kerma rates or dose rates that are typical for therapy.

In measurements of the activity of radiopharmaceuticals in nuclear medicine examinations and treatments (using an activity meter or dose calibrator) the intrinsic error may not exceed 10% when measuring activities larger than 3.7 MBq [9]. The intrinsic error may be greater when measuring activities smaller than 3.7 MBq, but the maximum possible intrinsic error must be estimated. When an activity measurement of a radiopharmaceutical to be administered to one patient is repeated in the same measurement geometry, the deviation from the mean result of any individual measurement result in a series of ten measurements may not exceed 5% at activities that are typical in treatments. Any nonlinearity in activity meter response may not exceed 5% at high activities.

2.6 Quality control measurements

The accuracy of any meter used for measurements and quality control of the operational and safety features of radiation equipment must ensure that the uncertainty in measurement results does not exceed the permitted measurement uncertainty for the quantity to be measured.

The measuring uncertainty may not exceed 20% when measuring the dose rate from leakage and scatter radiation of a diagnostic X-ray appliance [7]. This requirement applies to any dose rate corresponding to the acceptable limits imposed for dose rate from leakage and scatter radiation in the appliance standards.

3 Requirements and approval of radiation meters and measurement systems

Under section 23 of the Radiation Act, the measurements required for monitoring radiation exposure and ensuring radiation safety must be made using a method of proven reliability and any radiation meter or radiation measuring appliance that is used for measurements must be properly calibrated. Under section 12 of the Radiation Decree, monitoring of working conditions that affect the radiation exposure of workers engaged in radiation work must be

arranged using methods approved by STUK.

The accuracy of a radiation meter must comply with the requirements specified in section 2 of this Guide. Radiation meters and measurement systems must be calibrated in accordance with the requirements of item 4.2.

3.1 Radiation measurements involved in monitoring of working conditions and the radiation safety of members of the public

3.1.1 Requirements concerning meters

A radiation meter must be suitable for measuring the radiation to be measured at the values of the said quantity and at the types and energies of radiation that occur at the place where radiation is used and in surrounding areas (see Appendix A). If, for example, an unsealed beta radiation source is used at a workplace, then any meter for radioactive surface contamination must be capable of detecting beta radiation at the energies in question for values of surface activity at least corresponding to the maximum allowable surface contamination. The suitability of a meter will also depend on whether the meter is intended to determine the value of a radiation quantity or merely to detect the radiation to be measured.

Special care must be taken when measuring radiation from particle accelerators to ensure that the radiation meter is suitable for measuring the pulse form radiation generated by an accelerator.

The meter must include an overload indicator if the radiation dose rate at a place of use of radiation or in the surrounding area can exceed the upper limit of the meter operating range under abnormal conditions.

A radiation meter must be suitably designed and sufficiently robust for operation under the ambient conditions at the place of radiation use and its surroundings, including air temperature and humidity. For example, the outdoor operability of a meter must be verified.

Meter operation must not be disrupted by external factors such as electric and magnetic fields, or unacceptably influenced by factors other than the radiation type to be measured, having regard to the required accuracy of measurements.

3.1.2 Approval of meters

STUK approves radiation meters for a proposed use when issuing safety licences or inspecting the practices. Acceptability is assessed on the basis of meter type inspection data, test results, and other reliable information demonstrating the properties of the meter.

3.2 Measurements of radon concentration in inhaled air

Monitoring of working conditions that affect the radiation exposure of workers with respect to radon concentration at the workplace must be arranged using methods approved by STUK. The radon concentration of inhaled air in dwellings must be determined using a method of measurement approved by STUK (section 3 of Decision (944/1992) of the Ministry of Social Affairs and Health on the maximum values of radon concentration in ambient air).

3.2.1 Requirements concerning measurements, meters and measuring methods

The action levels and maximum values stipulated for radon concentration in section 27 of the Radiation Decree, Guide ST 12.1 and the Decision (944/1992) of the Ministry of Social Affairs and Health are annual radon concentration averages. The best method for assessing the annual average is through long-term measurement during the heating season [26].

A determination of the radon concentration of inhaled air must be based on an integrating measurement taken over a continuous period of not less than two months. If no integrating measurement can be taken at a workplace due to the conditions of measurement (e.g. underground mines and quarries) or owing to some other justified, workplace-specific reasons, then the measurement may also exceptionally be made over a short or momentary period. Any sizeable error involved in a short or momentary measurement must be taken into consideration when drawing conclusions based on the measurement results. The radon concentration during hours of work must be investigated by a measurement lasting for a continuous period of not less than seven whole days.

The maximum capacity of a measuring appliance for measuring the radon concen-

tration of inhaled air must extend to a radon concentration of at least 5000 Bq·m^{-3} if the appliance is used for verifying that an action level or maximum value for the radon concentration of inhaled air has been exceeded at a workplace or dwelling and if a typical measuring time is used for the appliance. The maximum capacity of an appliance for measuring the radon concentration of inhaled air must extend to a radon concentration of at least 10 000 Bq·m^{-3} if the appliance is used for monitoring the working conditions of a worker (with the dose sustained by the worker computed from the measurement result) and if a typical measuring time is used for the appliance. The lower limit of an appliance used for measuring the radon concentration of inhaled air may not exceed 20 Bq·m^{-3}, in order to verify the effectiveness of radon mitigation.

3.2.2 Approval of a measuring appliance or method of measurement

Applications for approval of a measuring appliance or method of measurement for the radon concentration of inhaled air must be submitted to STUK in writing. Approval will be issued on the basis of the documents and test results submitted. STUK may also test the appliance where necessary. The approval decision will also stipulate conditions and limitations governing use of the measuring appliance or method of measurement where necessary.

Approval of a measuring appliance or method of measurement for inhaled air radon concentration will be issued for a specified period not exceeding five years, after which the said approval may be extended on application. Decisions on measuring appliances are applicant- and type-specific. It should also be noted that each applicance must be calibrated separately (see item 4.2).

If the holder of an approved radon measurement applicance lends the appliance to another user, he/she is responsible for its condition and calibration. The person lending the appliance must also ensure that the recipient knows that when the measurement results are reported to customers and authorities, the report must include a reference to the approval decision (registration number of the decision).

3.3 Radiation measurements involved in individual monitoring of workers

Individual monitoring of doses sustained by workers must be based on individual dose measurements or other individual dose determinations performed by an approved dosimetry service. Under section 12 of the Radiation Act, an *approved dosimetry service* denotes an operational unit or service provider that is responsible for measuring and determining individual radiation doses as part of the process of monitoring the radiation exposure of workers, the competence of which for the said function has been verified by STUK.

3.3.1 General requirements for the dosimetry service

General

The operations of the dosimetry service must be organized in a manner ensuring that the service can be properly inspected and supervised pursuant to current Finnish legislation. The dosimetry service must be capable of serving customers in the national language that is used as the working language of the operating site in question. A dosimetry service using a language (other than the working language) that the customer understands may be approved for justified reasons in individual cases.

Accreditation and quality control

The dosimetry service must be accredited. Only for exceptional and justified reasons may this requirement be waived. In such cases the dosimetry service must be able to show that it has a quality system certified in accordance with Finnish standard SFS-EN ISO/(IEC) 17025 [10].

The dosimetry service must have a documented quality control programme. It must supervise the reliability of its dosimetry systems by suitable methods, and the description of these methods must be included in the quality control programme. The quality control programme must also include a description of the functions involved in periodic servicing of the dosimetry system. Where possible the dosimetry service must also participate in international comparisons of measurement.

At least the following matters must be

included in the quality control programme:

- periodic calibrations and realization of calibration results
- monitoring of the validity of dose determination results
- inspection and follow-up of cases in which quality control action level are exceeded
- inspections of the condition of dosemeters and their constituent materials
- attention to replacement of dosemeters and their constituent materials.

The quality control programme must specify the intervals between tests, the action levels and the procedures for documenting results, and must describe measures to be taken in the event that action levels are exceeded.

Data processing, recording and reporting of results

The dosimetry service must have appropriate data systems for processing worker exposure data.

The dosimetry service must ensure the reliability of results of measuring individual radiation doses and must request additional information from the party running a radiation practice (hereafter the responsible party) when this is necessary for verifying the result. The dosimetry service must have written procedures for detecting abnormal measurement results and verifying their validity. The validity of measurement results must be verified where necessary in collaboration with the responsible party.

The dosimetry service must retain all data pertaining to dose determinations for not less than five years unless otherwise stipulated when the dosimetry service is approved.

The dosimetry service must furnish the responsible party with results of the individual worker dose determinations without delay, and not later than two weeks after determining the doses and three weeks after the service receives the dosemeters.

The dosimetry service must notify the responsible party without delay of any personal dose equivalent $H_p(10)$ determined from a dosemeter that exceeds 10 mSv or of any personal dose equivalent $H_p(0,07)$ determined from a finger dosemeter that exceeds 100 mSv.

The dosimetry service must have the systems that are necessary for transmitting exposure data to the Dose Register of STUK. The detailed requirements governing the submission of exposure data are specified in Guide ST 7.4.

3.3.2 Requirements concerning the dosimetry system

A dosimetry system denotes an arrangement including individual dosemeters, reading appliances and all peripheral hardware together with dose determination software and rules of procedure. The details of a dosimetry system must be documented.

Quantities and units

The dosimetry system must use the personal dose equivalent quantity $H_p(d)$ (see Appendix A, item A.1.3.2). The quantity is generally $H_p(10)$ for high-energy radiation and $H_p(0.07)$ for low-energy radiation. $H_p(10)$ is also used when determining the dose due to neutron radiation. $H_p(0.07)$ is used when determining the dose to the fingers. The personal dose equivalent $H_p(3)$ is used when determining doses to the eye.

The unit of all of the foregoing quantities is the sievert (Sv). Measured doses must be reported in millisieverts (mSv).

Calibration

The dosimetry system must be calibrated before it is taken into use and periodically thereafter as stipulated by STUK when the dosimetry system is approved.

Technical performance of the system

The dosimetry system must be tested to assess its technical performance before it is taken into use. The tests required for various dosimetry systems and their acceptability limits are set out in the dosimetry system standards (see for example IEC and ISO). The latest or newest applicable standard must always be used for the tests. Regardless of the dosimetry system, at least the following properties of the system and of the dosemeter that it incorporates must be tested:

- the dependence of the dosemeter response on the dose

- the dependence of the response on the radiation energy
- the dependence of the response on the direction of incident radiation
- the dosemeter detection threshold
- the effect of ambient conditions.

Accuracy
The accuracy requirements for a dosimetry system are set out at item 2.4.

External tests
STUK performs annual blind tests to supervise the operations of the dosimetry service. In these blind tests dosemeters are irradiated with known doses of radiation qualities (radiation types and energies) corresponding to the conditions of meter use. The meters are sent to the dosimetry service, which determines the doses in the customary way. The ratio of the measured and true doses of photon radiation must satisfy the condition set out in equation (2) at item 2.4. This condition is applied to electron and neutron radiation as a matter of discretion.

3.3.3 Approval of dosimetry service and dosimetry system

Applications for approval of a dosimetry service and a dosimetry system must be submitted to STUK in writing. The details to be submitted to STUK for the approval process include the following:

- the trade name of the dosimetry service any enterprise or corporate identity number, the name of the person responsible for the dosimetry service, the contact details and all other possible dosimetry service operating sites in the event that these differ from the address of the dosimetry service
- a detailed description of the dosimetry system and documents concerning calibrations and tests
- copies of any accreditation decision and reports of periodic evaluations by the accreditation service.

Further details and instructions on applying for approval are available from STUK.

Approval is governed by report Radiation Protection 160 [24], Finnish standard SFS-EN ISO/IEC 17025 [10] and international standards for dosimetry systems. Approval is issued on the basis of the documents and test results submitted and of an inspection of the dosimetry service conducted by STUK. STUK may also test the dosimetry system where necessary. System approval involves reviewing the system as a whole, meaning that no individual test result is decisive and the significance of test results is always separately considered in each individual case. However, the measurement uncertainty of dose measurements must satisfy the requirements imposed on it (see item 2.4).

A dosimetry service is approved for a specified period not exceeding five years, after which the said approval may be extended on application. The new application must be filed two months before the previous approval expires or in accordance with the conditions laid down in the approval decision.

3.4 Measurements involved in determining patient radiation exposure

Section 17 of the Decree of the Ministry of Social Affairs and Health (423/2000) includes provisions requiring that:

- radiation doses caused by X-ray examinations are regularly measured or numerically assessed
- the activity to be administered to the patient in nuclear medicine examinations is measured using an activity meter.

Section 31 of the Decree prescribes that new X-ray equipment to be commissioned shall, where necessary, include a monitor or corresponding device indicating the radiation exposure of the patient.

In all cases the quality assurance programme for radiotherapy equipment must include a dose calibration performed by the responsible party (see Guide ST 2.1).

3.4.1 Requirements concerning meters

A meter used for determining the radiation exposure of a patient must be suitable for:

- determining a quantity describing the radiation exposure of a patient under X-ray

examination within the X-radiation energy range generated by the X-ray imaging or fluoroscopy appliance concerned
- measuring the absorbed dose to water generated by a therapy appliance in external radiotherapy for the radiation type and radiation energy range employed
- measuring the reference air kerma rate generated by a photon source and the reference dose rate of the absorbed dose to water generated by a beta source in brachytherapy
- measuring the activity of a radiopharmaceutical administered to a patient undergoing nuclear medicine examination or treatment.

A monitor indicating the calculated radiation exposure of the patient from an X-ray examination appliance is governed by the same requirements as a corresponding meter.

Meter operation must not be disrupted by external factors such as electric and magnetic fields, or unacceptably influenced by factors other than the radiation type to be measured, having regard to the required accuracy of measurements (see chapter 2). Particularly in radiotherapy, achievement of the stipulated accuracy requirements requires the use of several corrective factors in order to allow for the effect of other quantities that influence the result of measurement.

Determination of patient radiation exposure from X-ray examinations in health care is discussed in a guidebook published by STUK [11]. Dosimetry of radiotherapy appliances used in external radiotherapy is discussed in a report published by STUK [12].

3.4.2 Approval of meters

STUK approves the procedure for determining patient radiation exposure and the radiation meters used when issuing safety licences or inspecting the practices. Acceptability is assessed on the basis of meter type inspection data, test results, and other reliable information demonstrating the properties of the meter. Comparison measurements are made when necessary.

4 Quality assurance of radiation measurements

4.1 Use of specialists in measurements

The radiation measurements set out in this Guide are used to ensure the radiation safety of workers engaged in radiation work, members of the public and medical patients. Persons responsible for these measurements must be fully familiar with the method of measurement and meters used, and have expertise in performing such measurements. A qualified expert (see Guide ST 1.4) may be consulted where necessary for assessing the suitability of the measuring method and meters and verifying the reliability of measurements. It is a requirement of radiation measurements in health services that a medical physics expert has verified the suitability of the methods and radiation meters to be used (see Guide ST 1.4).

4.2 Calibration of radiation meters

Calibration of a radiation meter denotes a procedure whereby known radiation qualities (radiation types and energies) are used for determining the difference between the meter reading and the true value of the radiation quantity measured. The true value of the quantity is determined using a metrological standard, which is a precise and reliable radiation meter or radiation source. The result of the calibration is generally reported as a calibration factor that is the ratio of the true value of the quantity and the meter reading. When using a meter the final measurement result is obtained by multiplying the meter reading by the calibration factor corresponding to the radiation quality to be measured, unless a new calibration factor can be set in the meter.

Radiation meters must be calibrated for the radiation quantities and radiation qualities that the meter will be used to measure. The dependence of the radiation meter response on various values of the radiation quantity such as a dose rate must either be known on the basis of the type properties of the radiation meter or the calibration must allow for this dependence.

A radiation meter must be calibrated in a manner enabling demonstration of the traceability of the calibration to an international measurement system. Traceability refers to the connection between a measurement result from a meter and a metrological standard through an unbroken chain of comparison in which the uncertainties have been reported for all comparisons. According to the radiation application, radiation meters are calibrated at either a standards laboratory or a calibration laboratory, or at the place of use of radiation. A dosemeter for use in dose calibration of a radiotherapy appliance (see Guide ST 2.1) must be calibrated at a national standards laboratory falling under the scope of a Mutual Recognition Arrangement*) or at an accredited calibration laboratory. Calibration irradiations of the dosimetry system for individual doses of workers must also be performed at a national standards laboratory falling under the scope of a Mutual Recognition Arrangement or at an accredited calibration laboratory.

The radiation meters used for monitoring working conditions must be calibrated before these meters are taken into use and thereafter at intervals not exceeding five years during use of the meters unless otherwise stipulated by STUK when approving the method of measurement or practice or because of other reasons. The initial calibration performed by the manufacturer is often sufficient for taking such a radiation meter into use if the traceability of the said calibration to metrological standards has been ensured. Calibration with a single radiation quality suffices for external photon radiation dosemeters and dose rate meters satisfying the accuracy requirements set out at item 2.2.

An integrating measurement system for the radon concentration of inhaled air must be calibrated at least once a year. The calibration must be based on exposure of no fewer than 20 detectors. A continually registering meter approved for monitoring the radon concentration of inhaled air must be recalibrated at intervals not exceeding two years.

A dosimetry system used for measuring the individual doses of workers must be calibrated before it is taken into use and periodically thereafter, as stipulated by STUK when the dosimetry system is approved (see item 3.3.2).

Meters (including calculating monitors) that are used for determining the radiation exposure of patients in X-ray diagnostics must be calibrated before these meters (or calculating monitors) are taken into use and thereafter at intervals not exceeding five years unless otherwise stipulated by STUK when approving the method of measurement or practice or because of other reasons. Meters that are used for dose calibration of appliances used in external radiotherapy and meters or radiation sources that are used for calibrating radiation sources in brachytherapy must be calibrated at intervals not exceeding three years. A calibrated activity meter must be used in nuclear medicine. The initial calibration performed by the manufacturer will be sufficient if the traceability of the calibration to metrological standards has been ensured.

4.3 Inspection of the operating condition of radiation meters

The operating condition of a radiation meter must be checked at regular intervals between calibrations. This will include checking the general condition of the meter and making a performance check using a suitable radiation source. The operating condition of a dosimetry system (see item 3.3.2 in this guide) and the operating condition of measuring appliances used for dose calibration of therapy equipment and other quality assurance measurements in radiotherapy must be monitored in accordance with a written quality control programme (see Guide ST 2.1).

An *inspection of the general condition* of a meter must be performed before each use of the meter. The inspection of general condition must at least verify that the meter is free of visible damage and that its dials or buttons are operating normally, that the background radiation reading is normal, and that any drying

*) *Mutual Recognition Arrangement (MRA)* refers to an agreement whereby the national standards laboratories falling within the scope of the agreement recognize the equality of one another's certificates of measurement and calibration.

cartridge and the batteries of any battery-operated meter are in working order. In meters with a separate detector element that is connected to the electronic element by a cable or connector (e.g. an electrometer and ionization chamber), the inspection of general condition of the meter must also take note of any cable bends, of worn insulation and of the cleanliness of contacts.

The *performance check* of a meter refers to the test operation of the meter under known and reproducible radiation conditions. The operating test may be performed using radiation that arises in normal operations at the workplace, such as leakage radiation from a radiation source. Some meters include a separate check source. The measurement results obtained in the performance check must be compared with radiation values that are known on the basis of previous corresponding measurements or with a reference value measured using the check source. If the deviation from the known radiation values or reference value exceeds the measurement uncertainty associated with the performance check and reference values, then the operating condition of the meter must be verified by closer investigation and the meter must be recalibrated where necessary. The performance check must be performed at regular intervals (more often for meters that are more often used) and whenever any change in the operating condition of the meter is suspected on the basis of an examination of the general condition of the meter or for other reasons.

Performance checks of meters are also discussed in STUK's Guide VAL 4, which applies to radiation meters used by the rescue services and in civil protection.

Bibliography

1 ISO/IEC Guide 98-3:2008. Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995). Geneva: International Organization for Standardization.

2 International Commission on Radiation Units and Measurements. Measurements of dose equivalents from external photon and electron radiation. ICRU Report 47. Bethesda, MD: ICRU; 1992.

3 SFS-EN 60846:2014. Radiation protection instrumentation. Ambient and/or directional dose equivalent (rate) meters and/or monitors for beta, X and gamma radiation. Helsinki: Suomen Standardisoimisliitto SFS.

4 IEC 61577-2:2014. Radiation protection instrumentation - Radon and radon decay product measuring instruments - Part 2: Specific requirements for ^{222}Rn and ^{220}Rn measuring instruments. Geneva: International Electrotechnical Commission.

5 Christensen P, Julius HW, Marshall TO. Technical recommendations for monitoring individuals occupationally exposed to external radiation. Radiation Protection 73. EUR 14852 EN. European Commission; 1994.

6 International Commission on Radiological Protection. General principles for the radiation protection of workers. ICRP Publication 75. Annals of the ICRP 1997; 27 (1).

7 Wagner LK, Fontenia DP, Kimme-Smith C, Rothenberg N, Shepard J, Boone JM. Recommendations on performance characteristics of diagnostic exposure meters: Report of AAPM Diagnostic X-Ray Imaging Task Group No. 6. Medical Physics 1992; 19: 231–241.

8 SFS-EN 60731:2012. Medical electrical equipment. – Dosimeters with ionization chambers as used in radiotherapy. Helsinki: Suomen Standardisoimisliitto SFS.

9 IEC 61145:1992. Calibration and usage of ionization chamber systems for assay of radionuclides. Geneva: International Electrotechnical Commission.

10 SFS-EN ISO/IEC 17025:2005. Testaus- ja kalibrointilaboratorioiden pätevyys. Yleiset vaatimukset. General requirements for the competence of testing and calibration laboratories. Helsinki: Suomen Standardisoimisliitto SFS.

11 Röntgentutkimuksesta potilaalle aiheutuvan säteilyaltistuksen määrittäminen. (Determining the patient's exposure to radiation in X-ray examinations). Advice from STUK 1/2004. Helsinki: STUK; 2004.

12 Kosunen A, Sipilä P, Parkkinen R, Jokelainen I, Järvinen H. Sädehoidon annosmittaukset. Ulkoisen sädehoidon suurenergisten fotoni-

ja elektronisäteilykeilojen kalibrointi. (Determination of absorbed dose to water in radiotherapy. Calibration of high energy photon and electron radiation beams in external radiotherapy.) STUK-STO-TR 1. Helsinki: STUK; 2005.

13 International Commission on Radiological Protection. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Annals of the ICRP 1991; 21 (1-3).

14 International Commission on Radiological Protection. Conversion coefficients for use in radiological protection against external radiation. ICRP Publication 74. Annals of the ICRP 1996; 26 (3-4).

15 International Commission on Radiation Units and Measurements. Patient dosimetry for X rays used in medical imaging. ICRU Report 74. Journal of the ICRU 2006; 5 (2).

16 ANSI N42.32:2006. American national standard performance criteria for alarming personal radiation detectors for homeland security. Washington D.C.: American National Standards Institute.

17 SFS-EN 60325:2004. Radiation protection instrumentation. Alpha, beta and alpha/beta (beta energy > 60 keV) contamination meters and monitors. Helsinki: Suomen Standardisoimisliitto SFS.

18 ISO 12794:2000. Individual thermoluminescence dosemeters for extremities and eyes. Geneva: International Organization for Standardization.

19 ISO 21909-1:2015. Passive neutron dosimetry systems – Part 1: Performance and test requirements for personal dosimetry. Geneva: International Organization for Standardization.

20 IEC 62387: 2012. Radiation protection instrumentation – Passive integrating dosimetry systems for personal and environmental monitoring of photon and beta radiation. Geneva: International Electrotechnical Commission.

21 IEC 61526:2010. Radiation protection instrumentation – Measurement of personal dose equivalents $H_p(10)$ and $H_p(0,07)$ for X, gamma, neutron and beta radiations - Direct reading personal dose equivalent meters. Geneva: International Electrotechnical Commission.

22 IEC 60601-2-44:2009 + AMD1:2012 + AMD2: 2016. Medical electrical equipment – Part 2-44: Particular requirements for the basic safety and essential performance of X-ray equipment for computed tomography. Geneva: International Electrotechnical Commission.

23 International Commission on Radiation Units and Measurements. Quantities and Units in Radiation Protection Dosimetry. ICRU Report 51. Bethesda, MD: ICRU; 1993.

24 European Commission (EC). Technical recommendations for monitoring individuals occupationally exposed to external radiation. Radiation Protection No 160. Luxembourg: Publications Office of the European Union; 2011.

25 Toroi P, Järvinen H, Könönen N, Parviainen T, Pirinen M, Tapiovaara M, Tenkanen-Rautakoski P. Potilaan säteilyaltistuksen määrittäminen mammografiassa. (Determination of the radiation exposure of a patient in mammography.) STUK-TR 11. Helsinki: STUK; 2011.

26 International Commission on Radiation Units and Measurements. Measurement and reporting of radon exposures. ICRU report 88. Journal of the ICRU 2012; 12 (2).

APPENDIX A

Quantities and units required for radiation measurements

This appendix sets out the quantities that are required for measuring radiation in radiation practices together with the concepts and units that are necessary for defining these quantities. The dosimetric base quantities required for defining these quantities are also explained. The quantities required for technical quality control of instruments are not discussed. The radiation protection quantities required for applying and calculating maximum values for radiation exposure are set out in Guide ST 7.2.

The present Guide only discusses measurement of ionizing radiation, which is defined as follows:

Ionizing radiation
Ionizing radiation is the transfer of energy in the form of particles or electromagnetic waves of wavelength not exceeding 100 nm, or a frequency of not less than $3 \cdot 10^{15}$ Hz, that is capable of directly or indirectly producing ions.

A.1 Radiation protection of workers and members of the public

A.1.1 General

The maximum values (dose limits) for radiation exposure of workers engaged in radiation work and of members of the public are specified in the Radiation Decree using the concepts of equivalent dose and effective dose (radiation protection quantities). These quantities, like the committed equivalent dose and committed effective dose required for assessing the radiation dose caused by internal exposure to radiation, are calculated quantities that cannot be measured directly. Measurable quantities that provide sufficiently precise approximations of the said quantities or enable these approximations to be calculated are therefore required for monitoring exposure to radiation [2,13,14].

A.1.2 The base quantities

Particle fluence
The particle fluence Φ is the number of particles dN entering a sphere of cross-sectional area da, divided by this area:

$$\Phi = \frac{dN}{da} . \qquad \text{(A1)}$$

The unit of particle fluence is m^{-2}.

Absorbed dose
The absorbed dose D is the mean energy $d\bar{\varepsilon}$ imparted by ionizing radiation to a mass element dm in the matter, divided by this mass element:

$$D = \frac{d\bar{\varepsilon}}{dm} . \qquad \text{(A2)}$$

The unit of absorbed dose is the gray (Gy). 1 Gy = 1 $J \cdot kg^{-1}$.

Dose equivalent
The dose equivalent H is the product of the absorbed dose D and the quality factor Q:

$$H = Q \cdot D . \qquad \text{(A3)}$$

The unit of dose equivalent is the sievert (Sv). 1 Sv = 1 $J \cdot kg^{-1}$.

Average absorbed dose
The average absorbed dose D_T of a tissue or organ T is the total energy ε_T imparted by ionizing radiation to the tissue or organ divided by the mass of the tissue m_T:

$$D_T = \frac{\varepsilon_T}{m_T} . \qquad \text{(A4)}$$

The unit of average absorbed dose is the gray (Gy). 1 Gy = 1 $J \cdot kg^{-1}$.

Quality factor
The quality factor Q is a factor which depends on the linear energy transfer L, and which seeks to allow for the different ability of various radiation qualities to cause damage to health (especially stochastic damage).

The dependency between Q and L is shown in Table A1.

Table A1. Quality factor Q as a function of linear energy transfer L [13].

Linear energy transfer *L* in water (keV·μm^{-1})	**Quality factor *Q (L)***
< 10	1
10–100	0.32 *L*–2.2
> 100	300 / √ *L*

The quality factor is used for defining the dose equivalent (see formula A3).

Mean quality factor
The mean quality factor $\overline{Q}$ at a point in tissues where the absorbed dose is caused by particles of varying linear energy transfer may be calculated as follows:

$$\overline{Q} = \frac{\int_0^\infty Q(L) \cdot D_L dL}{\int_0^\infty D_L dL}, \qquad \text{(A5)}$$

where

$D_L = dD(L)/dL$ is the distribution of the absorbed dose D in relation to the linear energy transfer L,

$Q(L)$ is the quality factor corresponding to linear energy transfer L, and

$\int_0^\infty D_L dL = D$ is the absorbed dose at the monitoring point.

Unrestricted linear energy transfer
The unrestricted linear energy transfer L_∞ is the mean energy dE released in a medium by a particle of energy E in traversing a distance dl in the medium, divided by this distance:

$$L_\infty = \frac{dE}{dl}. \qquad \text{(A6)}$$

The unit of unrestricted linear energy transfer is J·m^{-1}. A unit of keV·μm^{-1} is also commonly used. 1 J·m^{-1} ≈ 6.24·10^9 keV·μm^{-1}.

In this Appendix the quantity L_∞ is called the linear energy transfer and denoted by L.

Activity
The activity A of a radionuclide is the number of spontaneous nuclear transformations dN taking place in the relevant number of nuclides N in a time interval dt, divided by this time interval:

$$A = \frac{dN}{dt}. \qquad \text{(A7)}$$

The unit of activity is the becquerel (Bq). 1 Bq = 1 s^{-1}.

A.1.3 Measurable quantities

A.1.3.1 Monitoring of working conditions

Some concepts employed

ICRU sphere
The ICRU sphere is a body defined by the International Commission on Radiation Units and Measurements (ICRU), which approximately corresponds to the human body with regard to the absorption of the energy of ionizing radiation [2]. It is a sphere of tissue equivalent material with a diameter of 30 cm, a density of 1 g·cm^{-3}, and a composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen.

Expanded field
An expanded field is a radiation field in which the particle fluence and its directional and energy distributions are the same throughout the volume of interest as at the reference point in the actual field.

Expanded and aligned field
An expanded and aligned field is a radiation field in which the particle fluence and its energy distribution are the same as in the expanded field, but the fluence is unidirectional.

The expanded field and the expanded and aligned field are imaginary radiation fields derived from actual radiation fields for defining ambient dose equivalent and directional dose equivalent.

Quantities

Ambient dose equivalent
The ambient dose equivalent $H^*(d)$ is the dose equivalent at a point in a radiation field which would be caused by the corresponding expanded and aligned field in an ICRU sphere at a depth d on the radius opposing the direction of the aligned field.

Directional dose equivalent
The directional dose equivalent $H'(d,\Omega)$ is the dose equivalent at a point in a radiation field which would be caused by the corresponding expanded field in an ICRU sphere at a depth d on a radius in a specified direction Ω.

The unit of ambient and directional dose equivalent is the sievert (Sv).

The ambient and directional dose equivalents are generally determined at a depth of 10 mm for penetrating radiation, and at a depth of 0.07 mm for the skin and 3 mm for the eye for soft radiation. This depth is measured inwards from the surface of the sphere.

Activity concentration
The activity concentration c is the activity A of a radioactive substance in the monitored volume or mass, divided by the said volume V or mass m:

$$c = \frac{A}{V} \text{ or } c = \frac{A}{m} . \qquad \text{(A8)}$$

The unit of activity concentration is $Bq \cdot m^{-3}$ or $Bq \cdot kg^{-1}$.

Activity concentration is most commonly used when measuring radioactive substances in air. The activity concentration of radon in inhaled air is generally abbreviated to *radon concentration*.

The quantity obtained on dividing by the volume may also be called the volume activity and the quantity obtained on dividing by the mass may also be called the mass activity.

Surface activity
The surface activity A_s is the activity A of a radioactive substance on a given surface in the area under inspection, divided by the area S of this surface:

$$A_s = \frac{A}{S} . \qquad \text{(A9)}$$

The unit of surface activity is $Bq \cdot m^{-2}$.

A.1.3.2 Individual monitoring of workers

Personal dose equivalent
The personal dose equivalent $H_p(d)$ is the dose equivalent at a point at depth d in soft tissues of the body.

The unit of personal dose equivalent is the sievert (Sv).

The personal dose equivalent is generally determined at a depth of 10 mm for penetrating radiation, and at a depth of 0.07 mm for the skin and 3 mm for the eye for soft radiation.

The personal dose equivalent $H_p(10)$ is often a good approximation of the effective dose when no personal protective devices are used. If, on the other hand, the body is largely protected and $H_p(10)$ is measured on the exposed side of the protective device, then the effective dose will be substantially smaller that $H_p(10)$ and must be calculated from the measured value of $H_p(10)$ in each individual case.

The personal dose equivalent $H_p(0.07)$ is an approximation of the localized equivalent dose to the skin, and $H_p(3)$ is an approximation of the equivalent dose to the lens of the eye.

Intake
Intake is the activity of a radioactive substance that has entered the body.

The unit of intake is the becquerel (Bq).

The calculation, based on intake and using dose conversion factors, of the committed effective dose sustained from internal radiation is explained in Guide ST 7.3.

A.2 Radiation protection of patients

A.2.1 X-ray diagnostics

Air kerma

Air kerma (K_a) is the sum of the initial kinetic energies of the charged particles produced by uncharged ionizing particles in a small element of air, divided by the mass of that element of air.

The unit of air kerma is the gray (Gy).

Air kerma rate is the increase in air kerma over a short interval divided by that interval.

Entrance surface dose

The entrance surface dose (*ESD*) is the absorbed dose to air at the point of intersection of the central axis of the radiation beam with the entrance surface of the patient, including radiation scattered from the patient to this point.

The unit of entrance surface dose is the gray (Gy).

Another quantity corresponding to the absorbed dose to skin at the foregoing point also appears in the literature by the same name. These quantities may be considered numerically equivalent (conversion coefficient of 1.0 ± 0.05) for practical purposes in X-ray imaging.

Dose-area product

The dose-area product (*DAP*) is defined as an integral:

$$DAP = \int_{A_M} D(x,y)\, dxdy\ , \qquad \text{(A10)}$$

where $D(x,y)$ is the absorbed dose to air on a plane perpendicular to the axis of the radiation beam. The integration area A_M in practice denotes the area of the DAP meter, which must clearly exceed the geometrical cross-section of the radiation beam at the meter.

The unit of dose-area product is Gy·m² (or more commonly Gy·cm²).

If the radiation field is even and precisely delimited, then the *DAP* will be approximately equal to $D{\cdot}A$, where D is the absorbed dose to air in the centre of the area and A is the cross-sectional area of the radiation beam at this plane. If the air kerma $K_a(x,y)$ is used in equation (A10) instead of the absorbed dose to air, then the *kerma-area product (KAP or* P_{KA}*)* is obtained. There is no difference between these quantities for practical purposes in X-ray diagnostics.

Dose-length product

The dose-length product *(DLP)* is defined as an integral:*)

$$DLP = \int_{-\infty}^{\infty} D(z)\, dz\ , \qquad \text{(A11)}$$

where $D(z)$ is the absorbed dose to air arising from the examination as a function of place z (the dose profile) in the direction of the axis of rotation of the X-ray tube. The examination to be monitored may be an individual axial imaging, one rotation of the X-ray tube in helical scanning, or an entire imaging of a longer area. In the following paragraphs the expression $D_1(z)$ is used for the dose profile of an individual axial imaging or one rotation and the expression DLP_1 is used for the corresponding dose-length product.

The unit of dose-length product is Gy·m (or more commonly mGy·cm).

The dose $D(z)$ is measured as the absorbed dose to air in an IEC standard [22] phantom [11] made of acrylic plastic (polymethylmethacrylate, PMMA).

If an examination consists of N individual axial images or N rotations of the X-ray tube, then the dose-length product *DLP* of the entire

*) In practical measurements the integral limits are infinite.

examination may also be calculated on the basis of the dose profile $D_1(z)$ for an individual axial imaging or single rotation of the X-ray tube as follows:

$$DLP = N \cdot \int D_1(z)\, dz = N \cdot DLP_1 \,. \qquad \text{(A12)}$$

Weighted dose-length product

The weighted dose-length product (DLP_w) is defined as follows:

$$DLP_w = \frac{1}{3} \cdot DLP_c + \frac{2}{3} \cdot DLP_p \,, \qquad \text{(A13)}$$

where DLP_c is the dose-length product determined in the middle of an IEC standard [22] acrylic phantom and DLP_p is the dose-length product determined on the surface of the said phantom (at a depth of 10 mm, as an average of points in different directions) [11].

Weighted multiple scan average dose

In computed tomography examinations (CT scans) consisting of several individual axial images or several individual rotations of the X-ray tube in helical scanning the average absorbed dose ($CTDI_{vol}$) is generally defined as follows:

$$CTDI_{vol} = \frac{1}{d} \cdot \int_{-\infty}^{\infty} D(z)\, dz = \frac{1}{d} \cdot DLP \qquad \text{(A14)}$$

where $D(z)$ is the dose profile caused by the entire examination in the monitored area in the direction (z) of the axis of rotation of the X-ray tube and at the monitored distance from the said axis, and d is the length of the examined area in the direction of the said axis.

The unit for weighted multiple scan overage dose is Gy (or more commonly mGy).

The $CTDI_{vol}$ may also be calculated from the dose profile $D_1(z)$ measured during a single axial imaging or one rotation of the X-ray tube in helical scanning and from the corresponding table movement Δd as follows*):

$$CTDI_{vol} = \frac{1}{\Delta d} \cdot \int_{-\infty}^{\infty} D_1(z)\, dz \,. \qquad \text{(A15)}$$

When the dose $D(z)$ or $D_1(z)$ refers to an absorbed dose to air in a standard phantom, the weighted average absorbed dose $CTDI_{vol}$ in the standard phantom may be defined and measured by analogy with the weighted dose-lenght product. This will then be called the *weighted multiple scan average dose* [11]**).

On the basis of formula (A13) and (A14):

$$CTDI_{vol} = \frac{1}{d} \cdot DLP_w \,. \qquad \text{(A16)}$$

Mean glandular dose

Mean glandular dose (MGD) refers to the dose received by the glandular tissue. The determination of the MGD is based on the measurement of the air kerma (K_i) in radiation the patient is exposed to, the radiation half-value layer (HVL), and the thickness and glandular content of the breast. The measurement of MGD and HLV is discussed, for example, in a report published by STUK (Toroi et al. 2011 [25]). MGD is calculated using the formula:

$$MGD = K_i \cdot g \cdot s \cdot c \,, \qquad \text{(A17)}$$

where g is the MGD conversion factor that takes into account the quality of radiation (HVL value) and breast thickness, s factor takes into account the anode material and filtering, and c factor takes into account the glandular content of the breast.

The unit for mean glandular dose is Gy (typically mGy).

A.2.2 Radiotherapy

Absorbed dose to water

The absorbed dose to water (D_w) is the mean energy imparted by ionizing radiation to an aqueous element, divided by the mass of this aqueous element.

The unit of absorbed dose to water is the gray (Gy).

*) According to standard IEC 60601-2-44, the integral limits for practical measurements are ± 50 mm.

**) $MSAD_w$ is the old marking for weighted multiple scan average dose ($CTDI_{vol}$).

The absorbed dose rate (to water) is the increase in the absorbed dose (to water) over a short interval divided by that interval. The *reference dose rate* of an absorbed dose to water denotes the absorbed dose rate at a reference point in water [12].

Air kerma

Air kerma (K_a) is the sum of the initial kinetic energies of the charged particles produced by uncharged ionizing particles in a small element of air, divided by the mass of that element of air.

The unit of air kerma is the gray (Gy).

Air kerma rate is the increase in air kerma over a short interval divided by that interval. *The reference air kerma rate* is the air kerma rate at a distance of one metre from a brachytherapy radiation source (see Guide ST 2.1).

A.2.3 Nuclear medicine

Calculations of the absorbed dose to tissue in nuclear medicine are based on the *activity* of the radioactive medicinal product administered to the patient (see item A.1.2).

Summary of accuracy requirements for radiation measurements*)

Purpose or subject of measurement	Quantity to be measured	Accuracy requirements	
		Maximum measurement uncertainty	Other requirements
Monitoring of working conditions and radiation safety of members of the public	ambient dose equivalent	60% (recommended maximum value)	Relative response between 0.71 (-29%) and 1.67 (+67%) in the photon range of 20–150 keV or 80 keV–1.5 MeV (in either of these)
	directional dose equivalent	60% (recommended maximum value)	
	surface activity	60% (recommended maximum value)	
Individual monitoring of workers	personal dose equivalent	42%	-33% or +50% (deviation from true value, dose approaching annual dose limit)
Radon in inhaled air	radon concentration	30%	20% (intrinsic error) 10% (error, environmental influence quantities) 10% (standard deviation, repeated measurements)
Determination of patient radiation exposure (X-ray diagnostics)	ESD, DAP, MGD, DLP, $CRDI_{vol}$	25%	
	radiation output (air kerma/ electric charge)	7%	
	air kerma rate	20% (appliance leakage and scatter radiation)	
Determination of patient radiation exposure (radiotherapy)	absorbed dose to water	3% 4% (electrons) 5% (patient-specific *in-vivo* measurement)	
	reference air kerma rate	5% (brachytherapy)	
	reference dose rate	15% (beta radiation, brachytherapy)	
Determination of patient radiation exposure (nuclear medicine)	activity		10% (intrinsic error, activity > 3.7 MBq) 5% (deviation from the mean of ten measurements) 5% (nonlinearity)

*) These requirements apply to photon radiation unless otherwise separately specified.