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Clinical dosimetry — Beta radiation sources for brachytherapy

Dosimétrie clinique — Sources de radiation bêta pour curiethérapie

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Contents

Page

Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 21439 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*.

Introduction

Clinical dosimetry covers the methods by which values of the relevant physical quantity, absorbed dose to water, can be measured at a given point by the use of calibrated instruments in a clinical setting. The application of beta radiation sources for brachytherapy requires new and skilled methods for adequate clinical dosimetry necessitated by the short range of the beta radiation. This causes large dose-rate gradients around beta radiation sources, and hence it is necessary that the detector volumes for absorbed-dose measurements be extremely small. This leads to the requirement for highly specialized detectors and calibration techniques, and it is necessary to scrutinize closely every calibration obtained in one beta radiation field and determine if it is applicable in another field.

It is necessary that an appropriate quality system be implemented and maintained in the hospital for clinical beta radiation source dosimetry. It is the responsibility of the medical physicist to carry out testing and calibration activities for any source in such a way as to meet the requirements for adequate dosimetry. This International Standard gives guidance on how to satisfy these needs.

Clinical dosimetry — Beta radiation sources for brachytherapy

1 Scope

This International Standard specifies methods for the determination of absorbed-dose distributions in water or tissue that are required prior to initiating procedures for the application of beta radiation in ophthalmic tumour and intravascular brachytherapy [1], [2], [3]. Recommendations are given for beta radiation source calibration, dosimetry measurements, dose calculation, dosimetric quality assurance, as well as for beta radiation brachytherapy treatment planning. Guidance is also given for estimating the uncertainty of the absorbed dose to water. This International Standard is applicable to "sealed" radioactive sources, such as plane and concave surface sources, source trains of single seeds, line sources, and shell and volume sources, for which only the beta radiation emitted is of therapeutic relevance.

The standardization of procedures in clinical dosimetry described in this International Standard serves as a basis for the reliable application of beta radiation brachytherapy. The specific dosimetric methods described in this International Standard apply to sources for the curative treatment of ophthalmic disease, for intravascular brachytherapy treatment, for overcoming the problem of restenosis and for other clinical applications using beta radiation.

This International Standard is geared towards organizations wishing to establish reference methods in dosimetry aiming at clinical demands for an appropriately small uncertainty of the delivered dose. This International Standard does not exclude the possibility that there can be other methods leading to the same or smaller measurement uncertainties.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the cited document (including any amendments) applies.

ISO/IEC Guide 98-3, *Uncertainty in measurement — Part 3: Guide to the expression of uncertainty in measurement* (*GUM:1995*)

ISO/IEC Guide 99, *International vocabulary of metrology — Basic and general concepts and associated terms* (*VIM*)

ISO 6980-2, *Nuclear energy — Reference beta particle radiation — Part 2: Calibration fundamentals related to basic quantities characterizing the radiation field*

ICRU Report 51, *Quantities and Units in Radiation Protection Dosimetry*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ICRU Report 51, ISO Guide 99 and ISO 6980-2, and the following apply.

3.1
absorbed dose
D
quotient of $d\bar{\varepsilon}$ by dm, where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm, as given by Equation (1):

$$D = \frac{d\bar{\varepsilon}}{dm} \tag{1}$$

NOTE The absorbed dose is designated in units of joules per kilogram, with the special name of gray (Gy).

3.2
absorbed dose to water
D_w
quotient of $d\bar{\varepsilon}$ by dm, where $d\bar{\varepsilon}$ is the mean energy imparted to water by ionizing radiation to a medium of mass dm, as given by Equation (2):

$$D_w = \frac{d\bar{\varepsilon}}{dm} \tag{2}$$

NOTE The absorbed dose to water is designated in units of joules per kilogram, with the special name of gray (Gy).

3.3
acceptance test
contractual test carried out by the user on receipt of a new instrument or source(s) in order to verify compliance with contractual specifications

NOTE 1 An acceptance test of an instrument is carried out after new equipment has been installed, or major modifications have been made to existing equipment.

NOTE 2 An acceptance test of a source is carried out on each source before being put into service for the first time. If a consignment contains more than one source, it is carried out on all sources of a particular type.

3.4
active source length
ASL
length of the source over which the absorbed dose rate at a defined distance from the source axis is within a specified ratio of the maximum absorbed dose rate at this distance

3.5
afterloading
automatically or manually controlled transfer of one or more sealed radioactive sources between a storage container and pre-positioned source applicators for brachytherapy

3.6
average beta energy
E_{ave}
quotient of beta energy averaged over the distribution, Φ_E, of the beta particle fluence with respect to energy as given by Equation (3):

$$E_{ave} = \frac{\int_0^{E_{max}} E\,\Phi_E(E)\,dE}{\int_0^{E_{max}} \Phi_E\,dE} \quad (3)$$

where $\Phi_E = d\Phi/dE$

3.7
brachytherapy
intracavitary, interstitial, superficial (including ophthalmic), or intraluminal (e.g. intravascular) radiotherapy in the immediate vicinity of one or more sealed or unsealed radioactive sources

3.8
calibration
set of operations that establish, under specific conditions, the relationship between values of a quantity and the corresponding values traceable to primary standards

NOTE 1 For an instrument, a calibration establishes, under specific conditions, the relationship between values of a quantity indicated by a measuring instrument or measuring system and the corresponding values realized from the standards.

NOTE 2 For a source, a calibration establishes, under specific conditions, the value of a quantity produced by the source.

3.9
clinical target volume
CTV
gross tumour or target volume (GTV) with the addition of a margin that accounts for cells that are clinically suspected but have unproven involvement

NOTE In malignant disease, e.g. ophthalmic tumours, these oncological safety margins account for subclinical disease. In restenosis treatment, the CTV includes the full interventional length (IL) of the vessel with all vessel wall layers and with the addition of proximal and distal safety margins to include all tissue possibly injured during the interventional process.

3.10
detector test source
radiation source used for the determination of the long-term stability of a radiation detector

3.11
dosimeter
⟨beta radiation therapy⟩ equipment that uses detectors for the measurement of absorbed dose, or absorbed dose rate, in beta radiation fields as used in radiation therapy

NOTE A radiotherapy dosimeter contains the following components: one or more detector assemblies, a measuring assembly (including possibly a separate display device), one or more detector test sources (optional) and one or more phantoms (optional).

3.12
dwell time
time a radioactive source or source train remains at a selected treatment position

3.13
effective point of measurement
P_{eff}
point at which the absorbed dose rate in an undisturbed medium is determined from the detector signal

3.14
extrapolation chamber
ionization chamber capable of having a collection volume that is continuously variable to a vanishingly small value by changing the separation of the electrodes, which allows the user to extrapolate the measured ionization density to zero collecting volume

NOTE The extrapolation chamber serves as a primary standard, under proper conditions of use (see Annex C).

3.15
fluence
Φ
quotient of $\mathrm{d}N$ by $\mathrm{d}A_{\text{s}}$, where $\mathrm{d}N$ is the number of particles incident on a sphere of cross-sectional area $\mathrm{d}A_{\text{s}}$, as given by Equation (4):

$$\Phi = \mathrm{d}N/\mathrm{d}A_{\text{s}} \tag{4}$$

3.16
gross tumour or target volume
GTV
macroscopic extent and location of target tissue that can be observed or visualized using applicable imaging modalities

NOTE In malignant disease, e.g. ophthalmic tumours, target tissue means the demonstrable tumour growth. In restenosis treatment, the GTV includes the full vessel extent injured during the interventional process.

3.17
influence quantity
quantity that can have a bearing on the result of a measurement without being the subject of the measurement

3.18
interventional length
IL
length of the vessel injured during the interventional process

3.19
lesion length
LL
stenotic or occluded length of the vessel segment as determined by the interventionalist

3.20
maximum beta energy
E_{max}
highest value of the energy of beta radiation emitted by a particular radionuclide that can emit one or several continuous spectra of beta radiation each with a characteristic maximum energy

3.21
measurement standard
instrument that defines, represents physically, maintains or reproduces the unit of measurement of a quantity (or multiple or sub-multiple of that unit) in order to transfer it to other instruments by comparison

3.22
planning target volume
PTV
clinical target volume (CTV) plus safety margins to account for physiological movements and changes, as well as for various set-up uncertainties

3.23
point of test
point at which the conventional true value is determined and at which the reference point of the dosimeter is placed for calibration and test purposes

3.24
primary standard
measurement standard (of the highest metrological quality) that defines, represents physically, maintains or reproduces the unit of measurement of a quantity (or a multiple or sub-multiple of that unit) in order to transfer it to other instruments by comparison

NOTE 1 The primary standard is operated by a national laboratory under reference conditions and its accuracy has been verified by comparison with the comparable standards of institutions participating in the International Measurement System.

NOTE 2 A primary standard realizes the quantity being measured without reference to any other standard of the same type.

3.25
ionizing radiation
emission and propagation of energy through space or through a material medium in the form of electromagnetic waves or particles that have the potential to ionize an atom or molecule through atomic interactions

3.26
radiation detector
equipment, generally a sub-assembly, or substance that, in the presence of radiation, provides by either direct or indirect means a signal or other indication suitable for use in measuring one or more quantities of the incident radiation

3.27
reference absorbed dose to water
D_o
absorbed dose to water at the reference point

3.28
reference conditions
set of influence quantities for which the calibration is valid without any correction

NOTE The reference conditions for the quantity being measured may be chosen consistent with the properties of the instrument being calibrated. The quantity being measured is not an influence quantity.

3.29
reference isodose length
RIL
vessel length at the reference distance enclosed by a certain defined percentage isodose of the reference dose at P_{Ref}

NOTE 1 The reference distance is measured from the source axis to a line parallel to the source axis on which P_{Ref} is located.

NOTE 2 For example, ESTRO recommends the 90 % isodose.

3.30
reference lumen diameter
RLD
diameter of the vessel lumen after angioplasty as determined by angiography in a representative plane within the planning target volume

3.31
reference orientation of a detector
orientation of the dosimetry detector with respect to the direction of the incident radiation stated by the manufacturer

3.32
radionuclide purity
proportion of the total activity present in the form of the stated radionuclide

NOTE The radionuclide purity is generally expressed as a percentage.

3.33
reference point
P_{ref}
⟨for source calibration⟩ point in a source radiation field at which the reference absorbed dose rate is specified, and which is also used for normalization of relative measurements

3.34
reference point of a detector
point of a detector that is placed at the point of test for calibrating or testing purposes

NOTE The distance of measurement refers to the distance between the reference points of the radiation source and of the detector.

3.35
routine calibration
calibration appropriate to a routine application of a source or an instrument

NOTE A routine calibration may be of a confirmatory nature when it is performed either to check the calibration carried out by the manufacturer together with an instrument, or to check whether the calibration is sufficiently stable during the continued, long-term use of a source or an instrument. When considering the most practical way to perform a routine calibration, results obtained in a type test can turn out to be helpful, for example in selecting the phantom.

3.36
secondary standard
standard whose value is assigned by comparison with a primary standard of the same quantity

3.37
source applicator
⟨brachytherapy⟩ device to position one or more radiation sources at the intended treatment positions

NOTE The radiation source may be a fixed part of the applicator, and the applicator may, furthermore, include protective shielding and/or a source guide.

3.38
source train
sequence of sealed radioactive sources, possibly separated by non-radioactive spacers, that is specified by a single value and calibrated as a whole

3.39
special calibration
calibration of a source or an instrument for a special case similar to that performed in connection with a type test

NOTE A special calibration is performed, for example, if the source or instrument is used under special circumstances or if the routine or type testing provides insufficient information.

3.40
standard test conditions
conditions under which all influence quantities and instrument parameters have their standard test values

NOTE Ideally, calibrations should be carried out under reference conditions. As this is not always achievable (e.g. for ambient air pressure) or convenient (e.g. for ambient temperature), a (small) interval around the reference values may be used. In principle, corrections should be made for the deviations of the calibration factor (if dimensionless) or calibration coefficient (if the instrument indication has different units from the calibration quantity) from its value under reference conditions caused by these deviations. In practice, the uncertainty aimed at serves as a criterion to determine whether it is necessary to take an influence quantity into account by an explicit correction or whether its effect may be incorporated into the uncertainty. During type tests, all values of influence quantities that are not the subject of the test are fixed within the interval of the standard test conditions.

3.41
test
⟨of an instrument⟩ measurement intended to confirm that an instrument is functioning correctly and/or the quantitative determination of the variations of the indication of the instrument over a range of radiation, electric and environmental conditions

NOTE Four distinct categories of instrument testing, of which calibration is a part, are generally recognized: type test, acceptance test, special calibration, routine calibration.

3.42
test
⟨of a source⟩ measurement intended to confirm that a source is functioning correctly and/or that the encapsulation is intact, and/or the quantitative determination of the variations of the field of the source over a range of radiation, electric and environmental conditions

NOTE Four distinct categories of source testing, of which calibration is part, are generally recognized: type test, acceptance test, special calibration, routine calibration.

3.43
traceability
property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national standards or International Standards, through an unbroken chain of comparisons each having a stated uncertainty

3.44
transfer standard
standard used as an intermediary to compare standards and establish traceability

3.45
treatment parameter
factor that describes one aspect of the irradiation of a patient during radiotherapy, such as radiation energy, absorbed dose, treatment time

3.46
treatment time
time between initiation and termination of irradiation, excluding any time in the ready state after interruption

3.47
type test
⟨of an instrument⟩ test intended to determine the characteristics of a particular type or model of a production instrument

NOTE 1 This type test involves extensive testing over a wide range of quantities that can have a bearing on the result of a measurement without being the objective of the measurement: the “influence quantities”. For ionizing radiation detectors, such influence quantities are, for instance, energy, angle of incidence, dose or dose rate and radiation type, usually under a variety of environmental conditions.

NOTE 2 A type test is normally performed on a prototype or on an instrument taken at random from a production batch and intended to be typical of the type. A type test will normally be carried out by National or Secondary Standard Laboratories, which may make the information available to the instrument user.

3.48
type test
⟨of a source⟩ test intended to determine the characteristics of a particular type or model of a production source

NOTE 1 This type test involves extensive testing for a number of conditions that can have a bearing on the result of an irradiation.

NOTE 2 A type test is normally performed on a prototype or on a source taken at random from a production batch and intended to be typical of the type. A type test will normally be carried out by National or Secondary Standard Laboratories, which may make the information available to the source user.

3.49
water equivalence
property of a material that approximates the radiation attenuation and scattering properties of water for a specified range of radiation energies

3.50
water-equivalent material
material that absorbs and scatters a specified radiation quality to the same degree as water for a specified range of radiation energies

3.51
water phantom
water-equivalent phantom
object made from water or a water-equivalent material having essentially the same radiation interaction properties as liquid water with respect to the dosimetric procedure under consideration

4 Beta radiation sources and source data

4.1 Ophthalmic and dural brachytherapy sources

Brachytherapy has been used since the beginning of the 20th century when applications using radium and radon seeds in skin applicators were performed. Besides beta radiation, these natural radioactive sources emit alpha and gamma radiation. A typical indication is the control of the formation of keloids. The development of artificial, less radiotoxic radioactive sources allowed an increase in the activity concentration and thus a reduction in treatment time, and an improvement in radiation protection as well. With the experience of ophthalmic brachytherapy using cobalt-60 (^{60}Co) applicators, beta radiation from strontium-90/yttrium-90 ($^{90}Sr + ^{90}Y$) planar and later curved applicators also started being used in the 1950s for the treatment of lesions of the eye, such as pterygia. Often referred to as “plaques”, in this International Standard, they are referred to as “applicators” or “radioactive ophthalmic brachytherapy sources”.

In the 1980s, radiotherapy for eye malignancies (e.g. uveal melanoma, retinoblastoma, hemangioma) [4], [5], [6], [7], [8], [9] was found to offer a therapeutic alternative to enucleation, being at least equally effective in controlling tumour growth and at the same time eye- and vision-sparing. For such ophthalmic treatments, a number of different beta emitters, and also photon sources, were used in the past, e.g., strontium-90/yttrium-90 (^{90}Sr+^{90}Y), ruthenium-106/rhodium-106 (^{106}Ru+^{106}Rh), cobalt-60 (^{60}Co), iridium-192 (^{192}Ir), gold-198 (^{198}Au) and radium-226 (^{226}Ra). Presently $^{106}Ru + ^{106}Rh$ ophthalmic brachytherapy sources are widely used, especially in Europe, and remain commercially available. Also $^{90}Sr + ^{90}Y$ ophthalmic brachytherapy sources are applied for a few cases [10], although they are currently not being manufactured.

For completeness, we mention that in the US, custom-made ophthalmic brachytherapy sources employing iodine-125 (^{125}I) or palladium-103 (^{103}Pd) are mainly used. Also, eye applicators which combine iodine-125 and ruthenium-106/rhodium-106 have recently been introduced into the clinical routine at Essen University Hospital [11]. Clinical dosimetry of this applicator and photon sources are both beyond the scope of this International Standard.

Very recently, thin yttrium-90 (^{90}Y) foil applicators have been used to treat spinal dura after tumour removal to control microscopic residual disease [12].

4.2 Intravascular brachytherapy sources

In intravascular brachytherapy (IVB), the vessel section injured by the interventional process of widening is treated with either beta or photon radiation [13], [14], [15]. In the coronary artery tree, the injured section lengths are usually on the order of 2 cm to 4 cm in arteries with diameters of 2 mm to 4 mm. It is also necessary to treat longer or more complex target volumes (long lesions up to 9 cm, multifocal lesions or bifurcations) in coronaries and in large peripheral vessels (tens of centimetres). This requires line sources with a very narrow diameter, less than 1 mm, able to fit through a brachytherapy catheter. Typical arrangements include encapsulated line sources mounted on the end of wires that can be used to insert and remove the sources to and from the treatment volume. Line sources may also be realized from linear arrays of "seeds," which can be delivered to the target site either manually or automatically. Radionuclides that have been used for these sources include ^{32}P, ^{90}Sr + ^{90}Y, and ^{90}Y. The physical length of these sources varies (3 cm to 6 cm) to adequately cover the target volume. Stepping short wire sources (0,5 cm to 2 cm) are used to treat longer target volumes.

Other sources have been applied to the restenosis problem, however they were for the most part unsealed and their dosimetry is beyond the scope of this International Standard. For completeness, they include ^{188}Re and ^{186}Re radioactive liquid, ^{133}Xe gas-filled balloons, ^{32}P-coated balloons and radioactive stents [14]; no further details on these sources are given in this International Standard.

4.3 Characteristics of radionuclides

Table 1 shows a compilation of half-lives (with uncertainties), and maximum and average energies for the different beta radiation sources most commonly used for clinical applications [16].

Table 1 — Properties of radionuclides in the most commonly used clinical beta radiation sources

Beta emitter	Half life d	E_{max} MeV	E_{avg} MeV	Major photon radiation with percentage per decay
^{90}Sr	10 523 ± 22	0,546	0,195 8	none
^{90}Y	2,667 ± 0,008	2,280 1	0,933 6	none
^{32}P	14,263 ± 0,003	1,710 5	0,694 9	none
^{106}Ru	373,59 ± 0,15	0,039 4	0,010	none
^{106}Rh	(3,449 ± 0,009) E-4	3,541 0	1,410	0,512 MeV (20 %) 0,622 MeV (10 %) 1,0 MeV (1,6 %) 1,13 MeV (0,4 %) 1,55 MeV (0,2 %)

4.4 Source specification

4.4.1 General

The manufacturer of brachytherapy sources shall provide the following information:

— reference data set (RDS) of the given source type, and

— calibration data (CD) of the specific source.