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Clinical dosimetry — Dosimetry with solid thermoluminescence detectors for photon and electron radiations in radiotherapy

Dosimétrie clinique — Dosimétrie avec détecteurs thermoluminescents solides pour les rayonnements de photons et d'électrons en radiothérapie

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

This second edition cancels and replaces the first edition (ISO 28057:2014), which has been technically revised.

— The clause on terms and definitions and the clause on rules for TLD measurement procedures, including quality assurance measurements at clinical accelerators, have been complemented and sharpened to ensure the safe application of TL dosimetry in the radiation therapy of cancer.

— Batch dependent changes of the k_Q values have been correlated with the simultaneously occurring mass density variations of TL discs (see 4.4.5.5).

— The response of TL materials to the neutrons, occurring within and around photon beams in megavoltage radiotherapy due to the photonuclear effect and eventually generating considerable components of the indicated values, has been dealt with in more detail (see 4.4.5.5).

— It is high-lighted that the k_E values of clinical electron beams are energy independent (see 4.4.5.5).

— Recent experimental results concerning the contribution of “intrinsic effects” to the response of TL detectors have been considered (see 4.4.5.5).

— The French title and the numbering of some subclauses of 5.4 have been corrected; Table 9 has been equipped with a heading.

Introduction

The thermoluminescence dosimetry (TLD) with lithium fluoride (LiF) detectors has several advantages, in particular:

— small volumes of the detectors;

— applicability to continuous and pulsed radiation;

— fair water equivalency of the detector material;

— few correction factors needed for absorbed dose determinations.

The main disadvantage of thermoluminescence (TL) detectors is that, prior to each dosimetry application, they have to be regenerated by a pre-irradiation annealing procedure. Unfortunately, it is not possible to restore the former response of the detectors perfectly by this annealing. Provided, however, that all detectors of a production batch always undergo the same thermal treatment, one can at least determine the mean alteration of the response of these detectors, with sufficiently small fluctuations of the individually indicated values. From this mean alteration, a correction factor can be derived.

The essential aim of this document is to specify the procedures and to carry out corrections which allow one to achieve

a) a repeatability of the indicated value within a fraction of a percent[17] and thus;

b) a total uncertainty of measurement (including the calibration steps tracing to the primary standards) of a few percent, as in ionization chamber dosimetry[18][31][25][61][62].

The specifications in this document comprise special terms used in TLD, rules for the measurement technique, and requirements for the measurement system. The defined requirements and the testing techniques can, in whole or in part, serve as a basis for stability checks and acceptance tests. The TLD procedures described in this document can be used for photon radiation within the energy range from 20 keV to 50 MeV, including photon brachytherapy, and for electron radiation within the energy range from 4 MeV to 25 MeV, excluding beta radiation brachytherapy. In order to achieve the repeatability and total uncertainty stated above, this document is applicable in the dose range above 1 mGy. The upper limit of the minimum measuring range is in the order of magnitude of 10 Gy to 100 Gy. In clinical dosimetry, TL detectors are applied taking into account the requirements of high spatial resolution, i.e. in the study of the dose distributions with high gradients occurring in small stereotactic radiation fields and around brachytherapy sources. The other common application is the measurement of dose distributions in large absorbers, e.g. geometrical or tissue equivalent phantoms, either within the radiation field or in its periphery. A further usage is the quality assurance of clinical dosimetry by postal dose intercomparison[1][2][10][12][20][22][26][27][55].

The role of this document is not to anticipate national or international codes of practice in clinical dosimetry, neither for external beam therapy, brachytherapy, whole-body irradiation, mammography, nor dose measurements outside the treatment field or radiation protection of the staff. The authors of this document are well aware of the wide spectrum of the methods of clinical dosimetry, in which TL dosimetry is merely occupying a small sector. But within this framework, this document provides reliable concepts and rules for good practice for the application of TLD methods. The items covered include the terms and definitions, the rules for TLD measurement procedures, and the requirements on the TLD system; this document addresses medical physicists as well as instrument producers. Notably, the numerical examples given are valid for the TL detector materials and products stated in the publications referred to, and tests may be necessary to check whether they apply to TLD materials of other producers. The practical examples given, e.g. for the TL probe calibration conditions and for the numerical values of correction factor, k_Q, accounting for the dependence of the detector response on radiation quality, Q, are not conceived to be pre-emptive in relation to more general standards of the methods of clinical dosimetry or dose intercomparisons. Rather, this document provides access to the reliable application of TLD methods based upon the published results of worldwide development.

The long-standing experience in the clinical usage of TLD, expressed in a set of valuable textbooks, protocols, and recommendations[6][13][25][28][29][42][43][61][62][54], has been accounted for.

Clinical dosimetry — Dosimetry with solid thermoluminescence detectors for photon and electron radiations in radiotherapy

1 Scope

This document describes rules for the procedures, applications, and systems of thermoluminescence dosimetry (TLD) for dose measurements according to the probe method. It is particularly applicable to solid "TL detectors", i.e. rods, chips, and microcubes, made from LiF:Mg,Ti or LiF:Mg,Cu,P in crystalline or polycrystalline form. It is not applicable to LiF powders because their use requires special procedures. The probe method encompasses the arrangement, particularly in a water phantom or in a tissue-equivalent phantom, of single TL detectors or of "TL probes", i.e. sets of TL detectors arranged in thin-walled polymethyl methacrylate (PMMA) casings.

The purpose of these rules is to guarantee the reliability and the accuracy indispensable in clinical dosimetry when applied on or in the patient or phantom. This document applies to dosimetry in teletherapy with both photon radiation from 20 keV to 50 MeV and electron radiation from 4 MeV to 25 MeV, as well as in brachytherapy with photon-emitting radionuclides. These applications are complementary to the use of ionization chambers.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60601-1, *Electromedical equipment — Part 1: General instructions pertaining to safety*

IEC 61000-4-2, *Electromagnetic compatibility (EMV) — Part 4-2: Test and measurement procedure — Test of immunity against static electric discharges*

IEC 61000-4-3, *Electromagnetic compatibility (EMC) — Part 4-3: Testing and measurement techniques — Radiated, radio-frequency, electromagnetic field immunity test*

IEC 61000-4-4, *Electromagnetic compatibility (EMC) — Part 4-4: Testing and measurement techniques — Electrical fast transient/burst immunity test*

IEC 61000-4-5, *Electromagnetic compatibility (EMC) — Part 4-5: Testing and measurement techniques — Surge immunity test*

IEC 61000-4-6, *Electromagnetic compatibility (EMC) — Part 4-6: Testing and measurement techniques — Immunity to conducted disturbances, induced by radio-frequency fields*

IEC 61000-4-8, *Electromagnetic compatibility (EMC) — Part 4-8: Testing and measurement techniques — Power frequency magnetic field immunity test*

IEC 61000-4-11, *Electromagnetic compatibility (EMC) — Part 4-11: Testing and measurement techniques — Voltage dips, short interruptions and voltage variations immunity tests*

IEC 61187, *Electrical and electronic measuring equipment — Documentation*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
absorbed dose
energy imparted to matter in a suitably small element of volume by ionizing radiation, divided by the mass of that element of volume

Note 1 to entry: All statements of absorbed dose need to be completed by a specification of the material for which the absorbed dose is stated, e.g. absorbed dose to air, D_a, or absorbed dose to water, D_w. In this document, the term absorbed dose, sometimes abbreviated as dose, means the absorbed dose to water, D_w, if not otherwise specified.

3.2
background value
M_0
<clinical TL dosimetry> *indicated value* (3.16) of a *TLD system* (3.46) during evaluation of a non-irradiated *TL detector* (3.45) according to the operating instructions

Note 1 to entry: A change in the background value can be caused by a change in the *TL-indicating instrument* (3.47), by an insufficient *pre-irradiation annealing* (3.28), or by contamination of the *detector* (3.45).

Note 2 to entry: The background value may also be determined from the average of the individual values measured with a group of detectors.

3.3
batch
<clinical TL dosimetry> number of *TL detectors* (3.45) of the same type originating from the same manufacturing process and corresponding in their entirety both to the requirements defined in this document and to the quality properties guaranteed by the manufacturer with regard to their *response* (3.39), their *individual variation* (3.17), and their *nonlinearity* (3.24)

3.4
calibration
<clinical TL dosimetry> determination of the correlation between the *indicated value* (3.16) of a *TL detector* (3.45) and the conventional true value of the *measured quantity* (3.20), *absorbed dose* (3.1) to water, under *reference conditions* (3.32)

Note 1 to entry: Calibration serves to determine or check the *calibration coefficient* (3.5).

Note 2 to entry: The conventional true value of the *measured quantity* (3.20) by the *measured value* (3.21) determined directly or indirectly with a primary standard.

3.5
calibration coefficient
N_i
<clinical TL dosimetry> relation valid under *reference conditions* (3.32)

$$N_i = \frac{D}{M_i - M_0}$$

in this formula, D is the conventional true value of the *measured quantity* (3.20), $M_i - M_0$ is the difference resulting from the *indicated value* (3.16) of a single *TL detector* (3.45) i and the *background value* (3.2)

Note 1 to entry: Thus, the calibration coefficient is the reciprocal value of the *response* (3.39) under *reference conditions* (3.32).

3.6
casing
capsule, usually made from PMMA of 1 mm front wall thickness and shaped as a flat circular cylinder, in which a small set of *TL detectors* (3.45) can be placed in the same plane

Note 1 to entry: The setup consisting of the *detectors* (3.45) and the casing is the *TL probe* (3.48).

Note 2 to entry: Other forms of the casing may be chosen to fit the respective application, e.g. for intracavitary measurements or measurements on the patient surface. Low-density materials such as PMMA are recommended for the construction of the casing.

3.7
conditioning of a batch
conditioning
multiple irradiation and *pre-irradiation annealing* (3.28) of a *batch* (3.3) of *TL detectors* (3.45)

Note 1 to entry: Whether conditioning is sufficient is examined by the *reusability* (3.40); test of reusability according to 5.3.3.

3.8
correction factor
<clinical TL dosimetry> factor applied to the *indicated value* (3.16) in order to compensate for the measurement deviation caused by an *influence quantity* (3.18) or by the *measured quantity* (3.20)

Note 1 to entry: Examples for using a correction factor are the corrections for *fading* (3.13), *energy dependence* (3.12), and *nonlinearity* (3.24) (see 4.4.5).

3.9
correction summand
summand added to the *indicated value* (3.16) in order to compensate for the measurement deviation caused by an *influence quantity* (3.18)

Note 1 to entry: The *background value* (3.2) is an example for corrections using a correction summand (see 4.4.2).

3.10
directional dependence of response
directional dependence
<clinical TL dosimetry> dependence of the *response* (3.39) of a *TL detector* (3.45) on the direction of radiation incidence

3.11
direction of preference
direction referring to the *TL detector* (3.45) or *TL probe* (3.48) that is considered as a reference value for the direction of radiation incidence as an *influence quantity* (3.18)

3.12
energy dependence of response
energy dependence
dependence of the *response* (3.39) of a *TL detector* (3.45) on *radiation quality* (3.30)

3.13
fading
F
quotient of the alteration of the *measured value* (3.21) of the *absorbed dose* (3.1) during the time interval between the end of the irradiation and the evaluation, e.g. caused by the influence of the ambient temperature, and the value of the *absorbed dose* (3.1) measured immediately after irradiation

Note 1 to entry: Fading is expressed as a percentage.

Note 2 to entry: The alteration of the measured value of the *absorbed dose* (3.1) may be positive (increment) or negative (decrement).

3.14
fading rate

$\dot{F}$

fading (3.13) in a time interval, divided by this time interval

Note 1 to entry: The fading rate is expressed as a percentage per day.

3.15
glow curve
<clinical TL dosimetry> *measured value* (3.21) of the light emission of the *TL detector* (3.45) as a function of the temperature or time during the evaluation process

3.16
indicated value
M
<clinical TL dosimetry> numerical value of a parameter displayed by a *TL-indicating instrument* (3.47)

Note 1 to entry: The indicated value, M, for a *TL detector* (3.45) is assessed from the *glow curve* (3.15) by the *TL-indicating instrument* (3.47) (see 4.3.8.3). The *measured value* (3.21) of the dose is determined from the indicated value by applying the *calibration coefficient* (3.5), the *correction factors* (3.8), and the *correction summands* (3.9) (see 4.4).

Note 2 to entry: The indicated value is also termed the reading of the *TL-indicating instrument* (3.47).

3.17
individual variation of the response
individual variation
deviation of the *response* (3.39) of single *TL detectors* (3.45) from the mean *response* (3.39) of a *batch* (3.3) of *TL detectors* (3.45) under identical irradiation and evaluation conditions

3.18
influence quantity
<clinical TL dosimetry> a quantity which is not a *measured quantity* (3.20) but nevertheless influences the result of a measurement

Note 1 to entry: Influence quantities can develop influences as external disturbances (temperature, humidity, line voltage, etc.), as properties inherent to the instrument, i.e. caused by the instrument itself (zero drift, aging of the system components, post-irradiation stabilization, etc.), or as adjustable quantities affecting the result of the measurement [e.g. *radiation quality* (3.30) or direction of radiation incidence during dose measurement].

Note 2 to entry: The correction of the impact of an influence quantity may require the application to the *indicated value* (3.16) of a *correction factor* (3.8) [multiplicative influence quantity, e.g. *fading* (3.13)] or of a *correction summand* (3.9) [additive influence quantity, e.g. *background value* (3.2)].

Note 3 to entry: If an influence quantity is not taken into account by applying a *correction factor* (3.8) or a *correction summand* (3.9), the *correction factor* (3.8) is set equal to one or the *correction summand* (3.9) is set equal to zero, respectively.

3.19
linear energy transfer
LET
average energy locally imparted to a medium by a charged particle of a specified energy along a suitably small element of its path, divided by the length of that element

Note 1 to entry: The value of LET (in keV/µm) is usually stated for water as the medium traversed by the charged particle.

Note 2 to entry: In ICRU 85a, this quantity is called the „unrestricted linear energy transfer" and denoted as L_∞ or simply L.

[SOURCE: ICRU 85a[81]]

3.20
measured quantity
<clinical TL dosimetry> physical quantity to be determined by the measuring system

Note 1 to entry: According to ICRU 62[82], the measured quantity in clinical dosimetry is the *absorbed dose* (3.1) to water at the *point of measurement* (3.26).

Note 2 to entry: The measured quantity is a variable which can adopt various values. These are denoted as *measured values* (3.21).

3.21
measured value of a TLD system
measured value
<clinical TL dosimetry> value of the *measured quantity* (3.20), *absorbed dose* (3.1) to water, determined with a *TLD system* (3.46) at the *point of measurement* (3.26)

Note 1 to entry: According to Formula (1), the measured value is determined from the individual *indicated values* (3.16), the *background value* (3.2) the individual *calibration coefficients* (3.5) and the *correction factors* (3.8).

3.22
measurement cycle
sequence of working steps in TL dosimetry consisting of *pre-irradiation annealing* (3.28), irradiation, *post-irradiation annealing* (3.27), and evaluation of *TL detectors* (3.45)

3.23
measuring range
<clinical TL dosimetry> range of measured values (3.21) in which the *TLD system* (3.46) meets the requirements for the operation characteristics

Note 1 to entry: The measuring range of a *TLD system* (3.46) is always part of and within the interval spanned by the smallest and the highest *measured value* (3.21).

3.24
nonlinearity of response
nonlinearity
<clinical TL dosimetry> change in dose dependence of the *response* (3.39)

Note 1 to entry: Linearity means constant *response* (3.39), supralinearity denotes an increase in *response* (3.39), and sublinearity denotes a decrease in *response* (3.39) with increasing dose.

3.25
parameters for tests
values of *influence quantities* (3.18) agreed upon for testing the impact of other *influence quantities* (3.18)

3.26
point of measurement
<clinical TL dosimetry> the point on or in the patient's body or water phantom at which the *absorbed dose* (3.1) to water is measured

Note 1 to entry: See also References [13], [39], [40] and ICRU 35[69].

Note 2 to entry: The point of measurement defined in the coordinate system of a phantom or patient is distinguished from the *reference point of a TL probe* (3.34) defined in the coordinate system of the TL probe. The *reference point of the probe* is usually positioned at the point of measurement in or on the phantom or patient.

3.27
post-irradiation annealing
<clinical TL dosimetry> controlled heat treatment (annealing) of a *TL detector* (3.45) after irradiation and before evaluation

Note 1 to entry: Post-irradiation annealing serves to reduce the *fading* (3.13).

3.28
pre-irradiation annealing
<clinical TL dosimetry> controlled heat treatment of already evaluated *TL detectors* (3.45) before reuse

Note 1 to entry: Pre-irradiation annealing serves to delete the radiation-induced TL signal remaining after evaluation and approximately restores the original response.

3.29
radiation damage
<clinical TL dosimetry> permanent alteration of the *response* (3.39) of a *TL detector* (3.45) due to pre-irradiation beyond a detector-specific dose

Note 1 to entry: The value of this dose may depend on the temporal pattern of pre-irradiations (dose fractionation, dose protraction) and on the radiation type and quality of the pre-irradiations.

3.30
radiation quality
Q
parameter for the classification of the relative spectral particle fluence of a radiation type at a specified location

Note 1 to entry: In clinical dosimetry, simply measurable parameters such as the quality index of a photon radiation or the 50 % range of an electron radiation are used for the characterization of radiation quality (see ICRU 35[69], ICRU 62[82], ICRU 83[80] and Reference [25]).

3.31
rated range of use
variation range of an *influence quantity* (3.18) causing a change in *response* (3.39) that does not lead to a transgression of agreed upon values of the measurement deviation or to a transgression of defined values of the correction of its influence

3.32
reference conditions
<clinical TL dosimetry> set of reference values of all *influence quantities* (3.18) and of the *measured quantity* (3.20)

Note 1 to entry: If one or more *influence quantities* (3.18) or the *measured quantity* (3.20) deviate from their *reference values* (3.35, 3.36) (Table 2), the conditions of measurement are denoted as non-reference conditions, see 4.4.5.5, note 1. The correction for use of *detectors* (3.45) under non-reference conditions is dealt with in the context of Table 4.

3.33
reference detector
<clinical TL dosimetry> *TL detector* (3.45) used to determine the *correction factor* (3.8) for the change in *response* (3.39) during successive *measurement cycles* (3.22)

Note 1 to entry: See 4.4.5.3.

Note 2 to entry: The average change of the response during successive measurement cycles can be determined by accompanying measurements performed with a group of reference detectors, see 4.4.5.3.

3.34
reference point of a TL probe
point defined within or on the surface of the *TL probe* (3.48) whose spatial coordinates serve to specify the position of the *TL probe* (3.48) in its surroundings

Note 1 to entry: The position of the reference point within or on the *TL probe* (3.48) is defined by the manufacturer. In clinical dose measurements, the reference point of a *TL probe* (3.48) is placed at the *point of measurement* (3.26) either on or in the phantom or the patient's body. For *calibration* (3.4), the reference point of a *TL probe* (3.48) is placed at the point at which the *absorbed dose* (3.1) to water under *reference conditions* (3.32) is known.

3.35
reference value for tests
initial value for the variation of an *influence quantity* (3.18) when testing its effect on the *response* (3.39)

3.36
reference value for calibrations
value of an *influence quantity* (3.18) or of the *measured quantity* (3.20), to which the *calibration coefficient* (3.5) refers and for which it is valid without further corrections

Note 1 to entry: Due to *nonlinearity* (3.24), a reference value has also been set for the *measured quantity* (3.20).

3.37
repeatability
<clinical TL dosimetry> degree of compliance of the *measured values* (3.21) of a given quantity that have been successively obtained in the same laboratory under the same conditions or *repetition conditions* (3.38)

Note 1 to entry: Repeatability is quantified by the empirical standard deviation of the single *measured value* (3.21) and may be expressed as a percentage of the *measured value*. It should be stated whether the measurement of repeatability has been performed with a single detector or with a group of detectors (see 4.4.5.3).

Note 2 to entry: By contrast, comparability marks the degree of compliance when a given quantity is measured in different laboratories by using different measuring instruments of the same type.

3.38
repetition conditions
<clinical TL dosimetry> conditions under which measurements are repeated in the same laboratory under similar measurement conditions according to a defined measurement procedure with short time intervals between repetitions

3.39
response
$R_{D,i}$
<clinical TL dosimetry> difference between the *indicated value* (3.16), M_i, for a single *TL detector* (3.45) i and the *background value* (3.2), M_0, divided by the conventional true value of the causing *absorbed dose* (3.1) to water, D_w

$$R_{D,i} = \frac{M_i - M_0}{D_w}$$

Note 1 to entry: This definition of response as the quotient of the background-corrected *indicated value* (3.16) and the conventional true value of the measured *quantity* (3.20) complies with IEC 60050-88[78]. It is different from the less strict terminology where "response“means *indicated value* (3.16).

Note 2 to entry: The response of a *TL detector* (3.45) may not only depend on the *absorbed dose* (3.1), but also on the *radiation quality* (3.30), the direction of radiation incidence, the material and size of the *detector* (3.45), the type of the *detector* (3.45), the *casing* (3.6), and the TL-reading instrument.

Note 3 to entry: In the definition of the response it is presupposed that the *TL detector* (3.35) or *TL probe* (3.48) is placed with its reference point (3.34) at the *point of measurement* (3.26) (see 4.4.1). The *reference points* (3.34) are specified in Tables 4 to 8.

Note 4 to entry: If air kerma, K_a, instead of *absorbed dose* (3.1) to water, D_w, is used as the reference quantity, i.e. as the denominator of the formula for response, this modification of the definition of response shall be clearly stated.

Note 5 to entry: If the term response is used in the sense of a relative response, i.e. as the quotient $R_{D,i}/R_{D,j}$ of two radiation qualities i and j, this has to be clearly stated.

3.40
reusability
usability of *TL detectors* (3.45) in several successive *measurement cycles* (3.22)

Note 1 to entry: The reusability of a *TL detector* (3.45) is an essential prerequisite in TL dosimetry, because for each single *detector* (3.45), the determination of the *calibration coefficient* (3.5) is followed by the dose measurement, so that at least two *measurement cycles* (3.22) shall be performed with this *detector* (3.45) (see 4.4.5.3).

3.41
stability check device
<clinical TL dosimetry> instrument for checking the dosimeter response

Note 1 to entry: The stability check device allows one to reach a certain dose in a specified time in a reproducible manner.

3.42
test conditions
<clinical TL dosimetry> set of *parameters for tests* (3.25) of all *influence quantities* (3.18)

Note 1 to entry: The rated range of test conditions is the agreed-upon range of variation of an influence quantity.

3.43
test light source
<clinical TL dosimetry> light source with constant illuminance used for operation checks of the *TL-indicating instrument* (3.47) (except for the heating device)

3.44
thermoluminescence
TL
light emission in a visible or adjacent spectral range, based on the radiation-induced occupation of trapping centres by the charge carriers of certain ion crystals, and emitted when the transition of these charge carriers into activator levels occurs as a consequence of heating

3.45
thermoluminescence detector
TL detector
detector
quantity of TL material of a certain chemical composition in homogeneous, e.g. crystalline or polycrystalline form

Note 1 to entry: The properties of a TL detector are determined by its material composition, mass, and shape, as well as by pre-irradiation or special thermal pre-treatment.

Note 2 to entry: New TL detectors generally need a defined thermal and irradiation treatment in order to establish the required *reusability* (3.40). TL detectors pre-treated in this way are designated as “conditioned detectors”.

Note 3 to entry: TL materials in the form of powders embedded in non-luminescent materials are not covered by this document because *correction factors* (3.8) k_Q and k_E are not available for these materials.

3.46
thermoluminescence dosimetry system
TLD system
system consisting of a number of *TL detectors* (3.45) of a certain type, which are placed, if necessary, in groups forming *TL probes* (3.48), as well as of the associated *TL-indicating instrument* (3.47), and, if there is a need, the supporting instruments, the operating instructions containing the description of the evaluation procedure, and the calibration instructions for the TLD system

3.47
thermoluminescence-indicating instrument
TL-indicating instrument
reader
instrument for measuring the thermoluminescence light emitted by a *TL detector* (3.45)

Note 1 to entry: The instrument is equipped with devices for heating the *TL detector* (3.45), for recording the light emitted by the *TL detector* (3.45), and for the indication of a measurement signal proportional to the TL (3.44) light emission.

3.48
thermoluminescence probe
TL probe
probe
setup consisting of one or more *TL detectors* (3.45) and the corresponding casing (3.6)

Note 1 to entry: The *reference point of a TL probe* (3.34) is defined by the manufacturer.

Note 2 to entry: In radiation protection, *TL detectors* (3.45), including their casing (3.6), are occasionally called TL dosimeters.

3.49
type of radiation
ionizing radiation whose properties are specified by the nature or origin of its particles or by particular properties of its spectrum

3.50
type of thermoluminescence detector
type of TL detector
<clinical TL dosimetry> characteristic type of all *TL detectors* (3.45) which have been manufactured from the same material and according to the same specifications (shape, size) and have the same dosimetric properties except for some minor differences (batch variation) due to the manufacturing process

Note 1 to entry: Differences between batches of the manufactured TL material may result from differences in mass density, see 4.4.5.5, Note 4.

3.51
uncertainty of measurement
parameter obtained by measurement or calibration which, together with the *measured value* (3.21), marks the range of values in which the true value of the *measured quantity* (3.20) lies

Note 1 to entry: The uncertainty of measurement is the positive root obtained from the sum of the squares of the standard uncertainties, for all uncertainty components.

4 Rules for the TLD measurement procedure

4.1 Principle of measurement

TL dosimetry is based on the measurement of light that is emitted when irradiated TL detectors are heated in a well-defined and reproducible manner. The signal obtained during this heating corresponds to the emitted amount of light and is related to the absorbed dose imparted to the TL detector. The relation between the reading and the quantity of absorbed dose to water is determined by means of calibration.

4.2 Measured quantity

The measured quantity is the absorbed dose to water, D_w, at the point of measurement in the absence of the TL probe. The unit of this quantity is the Gray (Gy). Measured values of the absorbed dose to water can be converted into those of the absorbed dose to other materials or tissues of interest.

4.3 Measurement cycle

4.3.1 General requirements

When TL dosimetry is used for dose measurements according to the probe method, the application of the rules laid down in 4.3.2 and 4.3.8 is required for every work step within the measurement cycle and for the sequence of measurement cycles. In this case, it is necessary to operate the TLD system in accordance with the operating instructions.

4.3.2 Sequence of measurement cycles

In order to determine values of the absorbed dose to water, the TL detectors shall pass the following measurement cycles:

— several measurement cycles for the determination of an individual calibration coefficient for each detector (see 4.4.4);

— one measurement cycle for the determination of values of the absorbed dose to water at the points of measurement in the radiation field (see 4.4.1).

4.3.3 Common passing of the measurement cycles

All detectors of a batch shall have the same thermal history. Having the same thermal history means that they shall be annealed as well as be read out in the same reading cycle, even though some of them might not have been irradiated. If necessary, several measurement cycles are required for a new batch in order to achieve a sufficient degree of repeatability.

4.3.4 Handling of TL detectors

4.3.4.1 General remarks

Reliable dose determination implies that TL detectors should not be contaminated and interchanges between detectors should be avoided. This raises requirements concerning the handling and treating of the detectors, as well as the tools applied during the measurement cycles.

4.3.4.2 Tweezers

TL detectors should not be touched by fingers. If air suction is not available, tweezers should be used for all operations, i.e. putting the detectors in a probe casing, in the TL-indicating instrument, or in a casing for thermal treatment. Ensure that the tweezers do not damage the TL detectors and they should be manufactured from non-abrasive material. The use of so-called vacuum tweezers is particularly recommendable.

4.3.4.3 Casings for thermal treatment (annealing casings)

As stainless steel casings sometimes show chemical reactions with TL detectors at high temperatures, which may lead to advanced fading[17], aluminium casings should preferably be used for pre-irradiation annealing and post-irradiation annealing. The dimensions of the annealing casings have to be adapted to the annealing oven. During each annealing process, the detectors have to be tightly covered by a lid made of the same material as the casing. This prevents contamination and ensures homogeneous heating of all detectors. In order to reach fast heating and cooling down of the detectors, the annealing case, which consists of the annealing casing and the lid, should be as small as possible. The maximum temperature at which aluminium casings can be used is 420 °C.

In case the annealing casing or the covering lid is contaminated, it can be cleaned with acetone first, then with methyl alcohol or ethyl alcohol, and lastly, submitted to a heat treatment without the TL detectors.

4.3.4.4 Cleaning

By improper handling, the response of TL detectors may get altered; usually it is reduced. Alterations of this kind may arise from contaminations or damages of the detector surface (see 4.3.4.2).

If single or all detectors of a batch are contaminated, the whole batch shall be cleaned. The kind of cleaning solution to be selected depends on the detector material. It is recommended to clean by means of an ultrasonic bath using ethanol. Cleaning time should be as short as possible. After each cleaning, a pre-irradiation annealing of the whole batch has to be carried out.

Cleaning should not be carried out routinely, but only if it is necessary. Pellets of lower density and detectors consisting of LiF:Mg,Cu,P should not be cleaned.

4.3.5 Pre-irradiation annealing

The course of the temperature during pre-irradiation annealing influences the response of the detectors[53] and has to be selected depending on the detector material and detector type (see 5.2.3).

The time interval between pre-irradiation annealing and the next irradiation might influence the response of the detectors. Hence, it should not exceed one week.

4.3.6 Irradiation

The user should record the following conditions of the irradiations: date of irradiation, quality of radiation, dose or expected dose range, field size, phantom, depth of measurement, and type and design of the probe.

4.3.7 Post-irradiation annealing

The course of the temperature during post-irradiation annealing can be selected depending on the detector material and detector type (see 5.2.3).

NOTE The post-irradiation annealing is also called stabilization since most of the fading (see 4.4.5.4) is suppressed by this treatment.

4.3.8 Reading

4.3.8.1 General remarks

Test light measurements prior or, if necessary, during the reading of a batch are carried out according to the manufacturer's instructions (see 5.4.7). Before the reading of irradiated detectors is started, the determination of the background value shall be carried out (see 4.4.2).

4.3.8.2 Heating procedure for generating glow curves

For generating glow curves, the stabilized TL detectors shall be submitted to a reproducible heating process (see 5.2.3). This process can be done by placing them either on a heated "planchet" (contact heating) or in a heated inert gas flow.

NOTE The shape of the glow curves depends on the heating profile used. The analysis of the glow curve as described in Reference [59] presumes that the heating rate is approximately constant.

When using contact heating, the sample chamber shall be flushed with inert gas to suppress air-related combustion of potential organic or inorganic surface contaminations of the TL detectors or heated planchet which might mimic a radiation induced signal. This effect holds particularly for measurements in the lower dose range.

4.3.8.3 Determination of the TL reading

The TL reading is determined by integrating the whole glow curve or a defined part of it. For better control of the correct temporal position of this integrating interval and for the detection of any abnormalities of the glow curve, the course of the glow curve shall be recorded during the whole heating process, even though only a part of it is essential for the absorbed dose determination.

NOTE This proceeding allows one to compare the actual reading with a typical glow curve of the TLD system in case a malfunction of the reader might have occurred.

4.4 Measurement of the absorbed dose to water

4.4.1 Basic formula for the determination of the absorbed dose to water

The measured value of the absorbed dose to water, D_w, results from the indicated values, M_i, of the n detectors of a thermoluminescence probe according to Formula (1)

$$D_w = \frac{1}{n}\sum_{i=1}^{n} N_i \left(M_i - M_0\right) \cdot \prod k_v \tag{1}$$

where

M_0 is the background value (see 4.4.2);

N_i is the individual calibration coefficient of the i^{th} TL detector for the reference radiation quality, ^{60}Co-gamma radiation (see 4.4.4);

$\Pi\, k_v$ is the product of the correction factors (see 4.4.5).

The rules for the determination of the individual terms of Formula (1) are discussed in 4.4.2 to 4.4.5. If a calibration with ^{60}Co-gamma radiation is replaced by a calibration with another radiation quality (see 4.4.4.2), the reciprocal value of the response determined by the calibration shall be used instead of N_i and the correction factors k_E, k_Q, and k_N (see 4.4.5.2 and 4.4.5.5) shall be adjusted accordingly.

For irradiation, the reference point of a TL probe or a single TL detector shall be placed at the point of measurement either on or in the phantom or patient's body. The position of the reference point within the TL probe shall be indicated by the manufacturer in the operating instructions (see 5.3.2). Generally, the reference point is in the midplane of the TL detector (see 4.4.5.5 and Tables 4 to 8).

If the manufacturer choses to define the reference point of a TL probe other than in the mid-plane of the assembly of the detector(s) contained in the probe, it is his obligation to inform the users of this choice. Furthermore, in all communications about the results of measurements with a TL probe, information about the position of the reference point within the probe is indispensable.

4.4.2 Determination of the background value, M_0

The following parameters contribute to the background value:

a) dark current of the photomultiplier (PM);

b) room illumination, if the housing of the PM is not sufficiently shielded;

c) light emission, not caused by irradiation, from the detector surface or from the surface of the contact planchet at high temperature.

In order to minimize the dark current, the voltage of the PM should not be higher than necessary and the recommendation by the manufacturer of the PM shall be respected. As a rule, voltages between 600 V and 900 V suffice in the dose measurement range of this document. Due to the strong increase of the

light emission not caused by irradiation at temperatures higher than 200 °C, this temperature should be exceeded during evaluation only to the level necessary to record the complete glow curve.

Provided the surfaces of the detectors are clean and undamaged and the TL reader functions properly, the background values correspond to absorbed dose values of about 0,1 mGy. Under these circumstances, the reading of any other non-irradiated TL detector may be used as background value for all TL detectors during each measurement cycle in the absorbed dose range covered by this document. In special cases, however, especially after low dose irradiations, a detector-specific background value obtained by a measurement cycle of the unirradiated detectors can be attributed to each detector.

In the starting phase of the use of a new batch of TL detectors it is recommendable to determine the background values of a group of detectors individually and to calculate M_0 as the average of these values.

4.4.3 Determination of the indicated value, M_i

The irradiation within the assigned radiation field is performed using the radiation quality, Q (photons) or E (electrons). For the n TL detectors (i = 1...n) of the TL probe, the measurement cycle yields the indicated values, M_i.

Even though the TL detectors placed in a TL probe have been calibrated jointly, differences between the individual product values, N_i ($M_i - M_0$), in Formula (1) inevitably occur. These differences require the determination of the average according to Formula (1). Values of N_i ($M_i - M_0$) that lie beyond the 3s range (s = empirical standard deviation) shall not be included in the average according to Formula (1). If more than 20 % of the measured values of a TL probe shall be rejected on the basis of the 3s criterion, the dose measurement shall be critically checked.

4.4.4 Determination of the individual calibration coefficients, N_i

4.4.4.1 Calibration with ^{60}Co-gamma radiation

In order to meet the accuracy requirements laid down in this document for the dosimetry in radiation therapy, an individual calibration of each TL detector is necessary. For this purpose, the TL probe shall be irradiated with a known dose under calibration conditions (see Table 1). The reference point of a TL probe is placed at the point of measurement at the calibration depth in the water phantom. The absorbed dose to water at this point of measurement, $D_{\mathrm{w}}^{\mathrm{ion}}$, is determined by means of a calibrated ionization dosimeter. The individual calibration coefficient, N_i, of the i^{th} detector results as the quotient

$$N_i = \frac{D_{\mathrm{w}}^{\mathrm{ion}}}{(M_i - M_0)} \tag{2}$$

where

M_i is the reading of the i^{th} detector;

M_0 is the mean reading of unirradiated detectors.

The calibration radiation quality is ^{60}Co-gamma radiation; exceptions are laid down in 4.4.4.2. The reference values of the additional influence quantities, to be used for calibrations, are defined in Tables 13 and 14. The calibration depth of 5 cm and the calibration field size of 10 cm × 10 cm or 10 cm diameter shall be strictly observed because the fraction of the dose due to scattered radiation, which affects the calibration coefficient, depends on depth and field size[9][46][56].

The standard measurement uncertainty of the calibration coefficient, N_i, includes the standard measurement uncertainties of the quantities $D_{\mathrm{w}}^{\mathrm{ion}}$ and ($M_i - M_0$).

Table 1 — Calibration conditions and ranges of test parameters

Measured quantity	Calibration conditions	Range of test parameters
Absorbed dose to water[a]	Determined during calibration; should be approximately 1 Gy	
Influence quantity		
Radiation quality	^{60}Co-gamma radiation	^{60}Co-gamma radiation
Phantom size	Water phantom 30 cm × 30 cm × 30 cm	Water phantom[b] 30 cm × 30 cm × 30 cm
Depth of measurement	5 cm	5 cm
Field size	10 cm × 10 cm or 10 cm diameter	10 cm × 10 cm or 10 cm diameter
Time interval between calibration irradiation and evaluation	24 h[c]	0 h to 72 h
Source-surface distance (SSD)	Isocentre distance	60 cm to 120 cm

NOTE For calibration of TL detectors to be used in brachytherapy, the depth of measurement is 5 mm to 6 mm of water or PMMA[11][44][50].

[a] Due to the nonlinearity of the response of TL detectors, a calibration condition for the dose shall be assigned. The absorbed dose at calibration should amount to approximately 1 Gy in order to make sure that it corresponds to the order of magnitude that is applied per fraction of radiation therapy. In special procedures, i.e. interoperative irradiation with electrons, the dose at calibration shall lie in the dose range applied.

[b] In case of calibrations in a phantom made of water-equivalent material (PMMA, polystyrene), the influence of the phantom material shall be determined by comparison with a calibration in a water phantom.

[c] Valid for a measurement cycle without post-irradiation annealing. If *post-irradiation annealing* is applied, the indicated value can be read out immediately after the end of this thermal treatment.

4.4.4.2 Calibration by means of other radiation qualities

If the calibration radiation quality ^{60}Co-gamma radiation for the measurement of the individual calibration coefficients is not available, the individual response shall be determined by irradiations with another radiation quality Q'. The ^{137}Cs gamma radiation, as well as high-energy photon radiations from accelerators, are appropriate for this purpose (see Table 1).

When absorbed dose determinations according to Formula (1) are to be carried out, it has to be taken into account that the correction factors k_Q and k_E refer to calibrations with ^{60}Co-gamma radiation only. Hence, they have to be replaced by the quotient $k_Q/k_{Q'}$ or $k_E/k_{Q'}$, respectively, if a radiation of quality Q' has been used for the determination of the calibration coefficients, N_i.

Table 2 — Field sizes and depths for calibrations using radiation qualities other than ^{60}Co-gamma radiation

Radiation quality, Q' (nominal)	Field size	Calibration depth	Focus-surface distance (FSD)
Photons 6 MV to 50 MV	10 cm × 10 cm	10 cm	100 cm
^{137}Cs-gamma radiation	10 cm × 10 cm	1 cm	60 cm

4.4.4.3 Determination of individual calibration coefficients by means of repeated calibration irradiation

The uncertainty of dose determinations according to Formula (1) can significantly be reduced by calculating, for each detector of a batch, a mean calibration coefficient from a series of many calibration measurements[18][21]. In general, the first calibration irradiation of this series is used as reference calibration. It may, however, be any irradiation of the series, since the absorbed dose is always the same. All indicated values of the calibration irradiations shall be multiplied by a factor k_M according to Formula (5) (see 4.4.5.3). In Formula (5), the values M_{i1} are the readings of the reference calibration and

M_{i2} are the readings of the other calibration irradiations. For each detector, the individual calibration coefficient results from the ratio of the calibration dose and the mean value of these corrected readings.

NOTE 1 The more calibration measurements are carried out, the more the random uncertainty of the mean calibration coefficient is reduced.

NOTE 2 The variations of the factor k_M reflect the alterations of the average batch response from the measurement cycle of the reference calibration to that from another cycle.

NOTE 3 By application of this calibration procedure, the standard deviation of the individual calibration factor will achieve a value small compared with the standard deviation of the measured value obtained in a clinical dose measurement. When a clinical dose measurement is based on this type of calibration, the resulting standard deviation of the measured absorbed dose is reduced by a factor of roughly $\sqrt{2}$ compared with the application of repeated calibrations in which correction factor k_M is not applied[17][18][70].

4.4.5 Determination of the correction factors, k_v

4.4.5.1 General remarks

Rules to be applied for the determination of the correction factors k_v are given in 4.4.5.3 to 4.4.5.5. A summary of the influence quantities and the corresponding correction factors is given in Table 3.

Table 3 — Influence quantities and corresponding correction factors (overview)

Measured quantity, influence quantities	Correction factors	See
Absorbed dose to water	k_N	4.4.5.2
Repeated use of the TL detectors	k_M	4.4.5.3
Time interval between irradiation and evaluation	k_F	4.4.5.4
Radiation quality	k_Q, k_E	4.4.5.5

A summary of influence quantities, whose effects are not accounted for by correction factors, is given in Tables 11 and 14.

4.4.5.2 Correction factor k_N for nonlinearity

Nonlinearity of the response depending on the dose may happen within the whole dose range covered by this document or be restricted to a limited range only[18][37][64]. It can be affected by the heating rate during the reading and by the deposition of traces of water vapor upon the TL material during the pre-irradiation annealing and reading of the detectors[17][38]. Nonlinearity is explained by LET- and dose-dependent complex intrinsic mechanisms[5][24][41][54][56]. Additionally, it sometimes varies for different batches manufactured from the same detector material. For testing the uniformity of the nonlinear behaviour of all detectors of a batch, see 5.3.4.2.

For correction of the nonlinearity, the dose-dependent correction function Formula (3), is used.

$$k_N = f(D, D_0) \tag{3}$$

where

D is the uncorrected measured dose;

D_0 is the reference dose.

Factor k_N takes into account that the response of a TL detector exposed to any dose D deviates from its response determined for the reference dose D_0. Depending on the difference ($D - D_0$), this deviation may either increase (supralinearity) or decrease (sublinearity).

The correction function $f(D, D_0)$ might also depend on the radiation quality. Therefore, it should be determined, by means of this radiation quality, when dose values are expected to deviate from the reference dose by more than a factor 2.

In the rated range of use, the nonlinear behaviour of TL detectors has largely to be taken into account by the correction according to Formula (3). For details of the correction, see the operating instructions. The nonlinearity, which remains after the correction according to Formula (3), is characterized by the nonlinearity parameter:

$$L = \frac{q_{\max} - q_{\min}}{q_{\max} + q_{\min}} \tag{4}$$

The values, $q_{\max}$ and $q_{\min}$, are the quotients of the dose values determined according to Formula (1), i.e. including all corrections inclusive of the nonlinearity correction and their conventional true values. The nonlinearity correction is considered to be sufficient for $L \leq 1$ % in the absorbed dose range 0,01 Gy to 10 Gy and for $L \leq 0{,}5$ % in the absorbed dose range 10 Gy to 30 Gy. In order to determine maximum and minimum values, $q_{\max}$ and $q_{\min}$, measurements of at least five dose values, evenly spread over the dose range of interest, shall be carried out. The uncertainty, which still remains after that procedure, is included in the total uncertainty of the measurement.

If detectors from different batches are used, the investigation of the remaining nonlinearity according to Formula (4) shall be carried out for each batch separately.

4.4.5.3 Correction factor k_M for alterations of the response during successive measurement cycles

The shape of the glow curve and the response of TL detectors can significantly depend on the thermal pretreatment and on the previous irradiation. This mainly concerns new TL detectors during their first measurement cycles. Whenever a batch of TL detectors is reused, the mean alteration of the batch response has to be accounted for by the corresponding correction factor k_M.

For the measurement of the correction factor k_M, the detector batch is subdivided in such a way that aside from the TL detectors used for the actual dose measurement (referred to as the "measurement detectors"), a group of m reference detectors is formed. Regarding irradiation and thermal treatment, the reference detectors should have a history representative for the whole batch. For this reason, the same TL detectors should not be used as reference detectors for all measurements performed with this batch.

The reference detectors are irradiated with the same dose (reference dose) under the same conditions (reference conditions) both at the time of calibration of the measurement detectors (t_1) and on the measurement day (t_2). The mean value of the m background-corrected readings obtained at time t_1 is considered as reference value during calibrations for recording the systematic change in the response of the detector batch. The correction factor accounting for the change in the response is then the quotient:

$$k_M = \frac{1}{\frac{1}{m}\sum_{i=1}^{m} \frac{M_{i2} - M_{02}}{M_{i1} - M_{01}}} \tag{5}$$

If the quotient $(M_{i2} - M_{02})/(M_{i1} - M_{01})$ yielded by a detector exceeds the $3s$ range of these values, it shall not be included in the average determination according to Formula (5). In the case that the calibration coefficient has been determined according to 4.4.4.3, the mean background-corrected value, $\overline{M}_i$, determined according to 4.4.4.3, replaces $(M_{i1} - M_{01})$ in Formula (5).

4.4.5.4 Correction factor k_F for fading

TL detectors frequently show fading, dependent on the ambient temperature, even though a post-irradiation annealing is performed during a measurement cycle.

To measure fading, two groups of m and n TL detectors are taken from the batch of TL detectors that have been calibrated according to 4.4.4. These two groups are irradiated with the same dose, the same radiation quality, and under the same general conditions, but separated by a time interval of t days and evaluated within the same measurement cycle. The time interval between the second of the two irradiations and the evaluation should be as short as possible. The numerical value of fading then results from Formula (6):

$$F = \frac{\frac{1}{n}\sum_i N_i(M_i - M_0)_0 - \frac{1}{m}\sum_i N_i(M_i - M_0)_t}{\frac{1}{n}\sum_i N_i(M_i - M_0)_0} \tag{6}$$

where

M_i is the indicated value of the TL detector i;

M_0 is the background value determined according to 4.4.2;

N_i is the individual calibration coefficient.

The group consisting of the n detectors is irradiated immediately prior to evaluation (index 0) and the group consisting of the m detectors is irradiated t days earlier.

The fading rate is determined according to Formula (7):

$$\dot{F} = \frac{F}{t} \tag{7}$$

Due to the dependence of fading on the temperature pattern during the fading time interval, a single determination of the fading rate is not sufficient. The fading rate should, therefore, be determined for each measurement after a time interval of some days has elapsed between the irradiation and the evaluation of the TL detectors. In the case of shipped TL detectors, for instance in connection with the quality assurance of therapy dosimeters, non-irradiated TL detectors and TL detectors irradiated with the reference dose shall also be sent with the shipment for the determination of the fading rate, $\dot{F}$. The user should be advised that the TL detectors shall not be exposed to radiation. The non-irradiated TL detectors sent with the shipment are irradiated with the reference dose immediately before evaluation of the batch. The fading rate is determined according to Formulae (6) and (7) from the indicated values of the TL detectors that have been irradiated with the reference dose before shipment and shortly before evaluation, respectively. In that case, t is the time between the irradiation (before shipment) and the measurement. In this case, the correction factor for the TL detectors irradiated by the user is:

$$k_F = \frac{1}{1 - \dot{F} \cdot t} \tag{8}$$

where t is the time interval between the irradiation by the user and the evaluation.

NOTE Formula (6) complies with the definition of fading according to 3.13 because the correction factors k_N, k_Q, and k_E are cancelled out.

4.4.5.5 Correction factors k_Q and k_E for the consideration of radiation type and radiation quality

If TL detectors are used for dose measurements with radiation qualities other than the calibration radiation quality (see Table 1), correction factor k_Q (for photon radiations) or k_E (for electron radiations) shall be applied according to Formula (1) and by application of Tables 4 to 8. These correction factors account for the radiation quality dependence of energy deposition in the TL material at the point of measurement. Energy-dependent influences of the secondary electron transport within the detector, of attenuation differences between water and the materials of the TL probes, as well as of electron

backscatter and secondary electron emission from the casing material of the TL detectors, are superimposed[59]. The correction factors also account for that part of the energy dependence of the detector response which is due to LET-dependent solid-state effects (intrinsic energy dependence of the response)[5][11][24][41][47][50][56].

Values of correction factors k_Q and k_E, valid for LiF:Mg,Ti probes calibrated in a ^{60}Co-gamma-ray beam at 5 cm depth in a water phantom (probes intended for use in photon and electron beams in the MeV range)[1][25][13] and behind a 5 mm PMMA plate (probes intended for use in photon brachytherapy)[11][50][44][63] are summarized in Tables 4 to 8. These tables do not apply to other TL materials[30]. The values of k_Q and k_E are stated with three decimals in order to comply with those authors who have published estimates of their uncertainties below 1 %. Other authors, however, have estimated higher values of the uncertainties; in this case, the third decimal becomes irrelevant.

The complete set of currently known corrections referring to, e.g. the effective point of measurement, the wall effects, and the spatial resolution of the ionization chambers used in comparison experiments, has been applied to derive the k_Q and k_E values of Tables 4 and 5 which apply to the high-energy photon and electron radiations used in external beam radiotherapy. Their total uncertainty is estimated as ±0,01. For values of Q deviating from those in Table 4, the k_Q values should be obtained by linear interpolation. Note 1 deals with the use of TL probes under non-reference conditions. Table 6 is essentially valid for orthovoltage and mammography X-rays, while Tables 7 and 8 apply to photon sources used in brachytherapy. The values of k_Q given in Tables 4, 6, 7, and 8 mainly reflect the influence of the photoelectric effect, but also reflect the intrinsic energy dependence of the response, which in this document is accounted for by stating measured values of k_Q. Both influences increase with decreasing photon energy and therefore account for the depth- and field size-dependent fraction of low-energy scattered radiation.

Tables 4 to 8 as well as notes 1 to 17 all refer to the TL material TLD-100. In notes 5, 6, 10 and 12 the TL materials TLD-700 or the TL-600/TLD-700 system have also been addressed.

Table 4 — Experimentally determined k_Q values for high-energy photon radiation valid for LiF:Mg,Ti detectors[a], calibrated with ^{60}Co-gamma radiation at 5 cm water depth (SSD: 100 cm, field size: 10 cm × 10 cm, on beam axis)

Nominal acceleration voltage MV	Radiation quality index, Q	Depth of measurement cm	k_Q		Sources
			LiF:Mg,Ti rods[b]	LiF:Mg,Ti chips[c,d]	
6	0,68	10	1,025	1,036	References [4], [47] and [66]
18	0,78	10	1,033	1,051	References [4], [47] and [66]

[a] TL detectors within a casing of 1 mm front wall thickness (PMMA).

[b] For LiF rods, diameter is 1 mm, length is 6 mm, and material is LiF:Mg,Ti (see 5.3.2 and Table 10). Reference point is the rod centre.

[c] For LiF chips, diameter is 5 mm, thickness is 0,9 mm, and material is LiF:Mg,Ti (see 5.3.2 and Table 10). Reference point is the chip centre.

[d] The chips addressed here are called “discs” according to their circular shape.

NOTE 1 The values of k_Q, indicated in Table 4, are valid under reference conditions, i.e. for 100 cm SSD, 10 cm × 10 cm field size, on axis, at a depth of 10 cm in a water phantom. The additional correction factor k_{NR}, needed when TL detectors are applied under non-reference conditions, such as other depths, field sizes, and off-axis distances, is described in the literature[9][15][35][46][56]. Values $k_{NR} < 1$ are correcting for overresponse and values $k_{NR} > 1$ for underresponse. References [9] and [56] have shown that in a very good approximation, k_{NR} is a unique function of the mean photon energy, $E_m = \int E\,\Phi(E)\,dE / \int \Phi\,(E)\,dE$, where $\Phi(E)$ is the spectral photon fluence at the point of measurement. For use with 6 MV photons and LiF:Mg,Ti, the approximation formula for this function is $k_{NR} = 1{,}01 - 0{,}142 \exp(-2{,}21\,E_m) - 0{,}300 \exp(-13{,}5\,E_m)$, with E_m in MeV[8][9]. The total uncertainty of these k_{NR} values is estimated as ±0,01.

NOTE 2 The contributions to the PM reading by light emitted from the front and rear of the detectors may depend upon the type of the reader and therefore, the k_Q values may also slightly depend on the type of reader. Moreover, k_Q values of TLD chips can change in the order of 1 % between different production batches.

NOTE 3 The k_Q values hold for LiF pellets and are valid in the range 1,25 MV to 21 MV[30].

NOTE 4 According to recent knowledge [74] the k_Q values of TLD-100 discs for high-energy photon radiations show batch-dependent changes by about 1 % simultaneously with mass density variations of the discs from (2,300 ± 0,016) g/cm^3 to (2,500 ± 0,034) g/cm^3. For a given batch and for given TPR20/10 values of 0,65, 0,70, 0,75 and 0,78 the k_Q values of rods (diameter 1 mm, length 6 mm, mass density 2,5 g/cm^3) are 1,027, 1,039, 1,047 and 1,051. The confidence intervals of these k_Q values have a width of ±0,4 %. These intervals comprise any possible variation due to accelerators from different manufacturers. An accelerator-dependent trend of k_Q at a given TPR20/10 value has not been observed.

NOTE 5 Radiotherapeutic high-energy photon beams at maximum energies exceeding about 7 MeV as well as the surrounding out-of-field regions regularly contain, as a side effect, a field of neutrons generated by photonuclear processes within the accelerator's beam head, e.g. in the bremsstrahlung target, the primary collimator and the flattening filter[35][36][51][60][65]. The neutron field is subsequently modified by neutron absorption, scattering and spectral moderation in the accelerator head as well as in the patient, phantom, treatment table, shielding walls etc. Therefore, the thermal neutron nuclear reaction ^{6}Li(n,α)^{3}H has to be considered as contributing to the total indicated value of a TL detector due to the thermoluminescence generated along the tracks of the ^{4}He and ^{3}H ions in the TL material. The relative contribution of this reaction to the total indicated value depends a) on the relative magnitudes of the photon and neutron fields at the point of measurement, and b) on the relative content of the isotope ^{6}Li in the mixture of lithium isotopes in the used TL material. In natural lithium, as in TLD-100 detectors, the relative ^{6}Li content is 7,5 %, in TLD-600 it is 95,6 % and in TLD-700 it is <0,03 %[75][76].

Monte Carlo simulations of the neutron field admixed to an 18 MV nominal voltage photon beam[75][76] have shown that on the axis of the radiotherapy radiation field at field size 10 cm × 10 cm in 0,5, 5 and 10 cm depth in water the fraction of the total indicated value of a TLD-100 detector associated with the ^{6}Li(n,α)^{3}H reaction amounts to less than 10^{-3}. The contribution to the indicated value attributable to neutron contamination can therefore be neglected in TLD-100 dose measurements if the point of measurement lies on the axis of the radiotherapy photon beam.

NOTE 6 When TL detectors are placed in the periphery of clinical high-energy photon beams, the TL signal may contain a non-negligible contribution due to the nuclear reaction of ^{6}Li with neutrons. For out-of-field applications, the TLD-100 measurement should therefore be replaced by a pairwise measurement with TLD-600 and TLD-700[34][36][60][65][75][76]. The TLD-600/TLD-700 pair is also recommended in any case of doubt about the relative magnitude of the neutron contamination of a high-energy photon field.

Table 5 — Experimentally determined k_E values for high-energy electron radiation valid for LiF:Mg,Ti probes, calibrated with ^{60}Co-gamma radiation at 5 cm water depth (SSD: 100 cm, collimator: 20 cm × 20 cm, on beam axis)

Nominal electron energy E_0 MeV	Most probable electron energy $E_{p,0}$ MeV	Depth of measurement d_{max} cm	k_E		Sources
			LiF:Mg,Ti rods[b]	LiF:Mg,Ti chips[c]	
4,7	4	0,8	1,055	1,075	References [4], [19] and [68]
6,4	6	1,3	1,055	1,075	References [4], [19], [47] and [66]
8,3	8	1,7	1,055	1,075	References [4], [19], [47] and [66]
9,6	10	2,1	1,055	1,075	References [4], [47] and [66]

[a] TL detectors within a casing of 1 mm front wall thickness (PMMA).

[b] For LiF rods, diameter is 1 mm, length is 6 mm, and material is LiF:Mg,Ti (see Table 10). Reference point is the rod centre.

[c] For LiF chips, diameter is 5 mm, thickness is 0,9 mm, and material is LiF:Mg,Ti (see Table 10). Reference point is the chip centre.

Table 5 *(continued)*

Nominal electron energy E_0 MeV	Most probable electron energy $E_{p,0}$ MeV	Depth of measurement d_{max} cm	k_E		Sources
			LiF:Mg,Ti rods[b]	LiF:Mg,Ti chips[c]	
11,5	12	2,5	1,055	1,075	References [4], [19], [47] and [66]
14,9	15	2,6	1,055	1,075	References [4], [19], [47] and [66]
17,1	18	3,0	1,055	1,075	References [4], [19], [47] and [66]
19,2	20	2,8	1,055	1,075	References [4], [47] and [66]

[a] TL detectors within a casing of 1 mm front wall thickness (PMMA).

[b] For LiF rods, diameter is 1 mm, length is 6 mm, and material is LiF:Mg,Ti (see Table 10). Reference point is the rod centre.

[c] For LiF chips, diameter is 5 mm, thickness is 0,9 mm, and material is LiF:Mg,Ti (see Table 10). Reference point is the chip centre.

NOTE 7 The values of k_E, indicated in Table 5, are valid for the indicated depth of measurement, The errors due to deviating depth of measurement are described in References [47], [48] and [57].

NOTE 8 The k_E values of TLD chips indicated in Table 5 can change in the order of 1 % between different production batches.

NOTE 9 According to recent knowledge[74] the k_E values are energy independent and have the values 1,054 ± 0,42 % for rods and 1,074 ± 0,61 % for discs.

Table 6 — Experimentally determined k_Q values for X-rays and gamma rays, valid for LiF:Mg,Ti detectors calibrated in a ^{60}Co-gamma ray beam at 10 cm × 10 cm field size in PMMA

Tube voltage kV	Effective energy[a] keV	Thickness of front layer mm	Relative response, referred to air kerma	Relative response, referred to absorbed dose to water	k_Q for LiF:Mg,Ti detectors[d]	Source
20	11,5	0,025[b]	0,947	1,014	0,986	Reference [50]
30	15,5	0,025[b]	1,151	1,244	0,804	Reference [50]
40	19,8	0,025[b]	1,279	1,389	0,720	Reference [50]
50	22,4	0,025[b]	1,310	1,431	0,699	Reference [50]
60	26,9	0,025[b]	1,372	1,505	0,664	Reference [50]
80	33,5	0,025[b]	1,365	1,497	0,668	Reference [50]
100	42,1	0,025[b]	1,313	1,434	0,697	Reference [50]
120	49,9	0,025[b]	1,279	1,381	0,724	Reference [50]
150	67,0	0,025[b]	1,243	1,301	0,769	Reference [50]
200	99,8	0,025[b]	1,155	1,173	0,853	Reference [50]
250	145	0,025[b]	1,122	1,128	0,887	Reference [50]
Cs-137	662	2,9[c]	1,056	1,056	0,947	Reference [50]

[a] As stated in [50].

[b] Kapton foil.

[c] PMMA front plate.

[d] Dimensions of LiF:Mg,Ti chips are 3,2 mm × 3,2 mm × 0,9 mm.

Table 6 *(continued)*

Tube voltage kV	Effective energy[a] keV	Thickness of front layer mm	Relative response, referred to air kerma	Relative response, referred to absorbed dose to water	k_Q for LiF:Mg,Ti detectors[d]	Source
Co-60	1250	5,2[c]	1,000	1,000	1,000	Reference [50]

[a] As stated in [50].

[b] Kapton foil.

[c] PMMA front plate.

[d] Dimensions of LiF:Mg,Ti chips are 3,2 mm × 3,2 mm × 0,9 mm.

NOTE 10 The relative response of LiF:Mg,Ti (and also of LiF:Mg,Cu,P) materials at photon energies in the range from 10 keV up to ^{60}Co-gamma rays and 6 MV X-rays has been the subject of various experimental and Monte Carlo studies[5][11][14][16][32][33][47][49][50]. There is agreement that the energy dependence of the response does not only reflect the energy-dependent radiation interaction coefficients, but also the LET-dependent solid-state effects causing the "intrinsic energy dependence" of the response. Table 6 contains the most recent experimental data obtained with narrow X-ray spectra or gamma rays[50]. The depth dependence of k_Q in water has been studied in [46] and [47]. The post-irradiation annealing temperature has been identified as influencing the energy dependence of k_Q[5].

NOTE 11 The k_Q values of TLD chips indicated in Table 6 can change in the order of 1 % between different production batches.

NOTE 12 The photon-energy dependent response of TLD-700 chips has recently been experimentally determined in the range from 30 kV X-rays to 6 MV high-energy photons[70]. The result closely agrees with the k_Q values of TLD-100 chips[50] stated in Table 6 as well as with earlier TLD-100 chip values[72]. The results of [70] confirm the influence of the intrinsic effects upon the TLD response[73].

Table 7 — Experimentally determined k_Q values of LiF:Mg,Ti probes for high-energy brachytherapy photon sources[a] at different depths in water or polystyrene phantoms under full backscatter conditions[b]

Nuclide	Mean photon energy[c] keV	Depth of measurement cm	k_Q LiF:Mg,Ti rods[d]	k_Q LiF:Mg,Ti chips[e]	Sources
Co-60	1 250	1 (water)	1,12		Reference [18]
		2 (water)		1,002	Reference [46]
		5 (water)	1,000	1,000	References [18] and [46]
		9 (water)	0,995		Reference [18]
		10 (water)		0,999	Reference [46]
		20 (water)		0,990	Reference [46]
		40 (water)		0,979	Reference [46]
Ir-192	350	1,36 (polystyrene)		1,000	Reference [44]
		3,34 (polystyrene)		0,978	Reference [44]

[a] A small fraction of the dose produced by Ir-192 sources is due to characteristic K and L radiation.

[b] For full backscatter conditions, the thickness of backscatter material behind the TL detector shall be ≥15 cm for high-energetic, ≥10 cm for medium-energetic, and ≥5 cm for low-energetic brachytherapy photons[52].

[c] Calculated according to Reference [3]. For depth-dependent spectra, see References [8] and [44].

[d] For LiF:Mg,Ti rods, diameter is 1 mm, length is 6 mm, and casing thickness for Co-60 is 1 mm PMMA. Point of reference is rod centre.

[e] For LiF:Mg,Ti chips, surface is 3,18 mm × 3,18 mm, thickness is 0,89 mm, and casing thickness for Co-60 is 1 mm PMMA. Point of reference is chip centre.

[f] After calibration in a 4 MV X-ray beam in a PMMA phantom[44].

Table 7 *(continued)*

Nuclide	Mean photon energy[c] keV	Depth of measurement cm	k_Q LiF:Mg,Ti rods[d]	k_Q LiF:Mg,Ti chips[e]	Sources
		5,32 (polystyrene)		0,957	Reference [44]
		7,27 (polystyrene)		0,943	Reference [44]
		10,27 (polystyrene)		0,922	Reference [44]

[a] A small fraction of the dose produced by Ir-192 sources is due to characteristic K and L radiation.

[b] For full backscatter conditions, the thickness of backscatter material behind the TL detector shall be ≥15 cm for high-energetic, ≥10 cm for medium-energetic, and ≥5 cm for low-energetic brachytherapy photons[52].

[c] Calculated according to Reference [3]. For depth-dependent spectra, see References [8] and [44].

[d] For LiF:Mg,Ti rods, diameter is 1 mm, length is 6 mm, and casing thickness for Co-60 is 1 mm PMMA. Point of reference is rod centre.

[e] For LiF:Mg,Ti chips, surface is 3,18 mm × 3,18 mm, thickness is 0,89 mm, and casing thickness for Co-60 is 1 mm PMMA. Point of reference is chip centre.

[f] After calibration in a 4 MV X-ray beam in a PMMA phantom[44].

NOTE 13 The response of TLD materials to ^{137}Cs and ^{60}Co-gamma rays has also been studied in References [11] and [58]. For the response to ^{192}Ir photons, see also References [49], [54] and [55]. For a small ^{60}Co, ^{137}Cs, or ^{192}Ir source in a large water phantom, the spatial variation of k_Q has been shown to be essentially determined by the mean photon energy at the point of measurement, $E_m = \int E\,\Phi(E)\,dE / \int \Phi(E)\,dE$, where $\Phi(E)$ is the spectral photon fluence[7].

NOTE 14 For an ^{192}Ir phantom positioned in the center of a cylindrical water phantom (R = 20 cm, H = 40 cm), k_Q as function of the mean photon energy $\bar{E}_F$ at the point of measurement can be numerically described by the fit function $k_Q = 0{,}892\,5 \exp(0{,}007\,8\ \bar{E}_F) - 0{,}358\,7 \exp(-14{,}44\ \bar{E}_F)$ with $\bar{E}_F$ in MeV[71].

NOTE 15 The k_Q values of TLD chips indicated in Table 7 can change in the order of 1 % between different production batches.

Table 8 — Experimentally determined k_Q values for low-energy brachytherapy phantom source, valid for LiF:Mg,Ti probes calibrated with ^{60}Co-gamma radiation at 5 cm water depth

Nuclide	Mean photon energy[a] keV	Depth of measurement[b] cm	k_Q		Sources
			LiF:Mg,Ti microcubes[c]	LiF:Mg,Ti chips[d]	
I-125	26,4	0,5 to 10		0,714 ± 3 %	References [45] and [49]
Pd-103	19,0	0,5 to 10	0,709		Reference [67]

[a] Calculated according to Reference [3].

[b] Measurement in various water-equivalent solid-state phantoms with chip centre as point of reference.

[c] Dimensions are 1 mm × 1 mm × 1 mm.

[d] Surface is 3,2 mm × 3,2 mm and thickness is 0,9 mm.

NOTE 16 For previous determinations of k_Q for I-125 photons, see References [23] and [63].

NOTE 17 The k_Q values of TLD chips indicated in Table 8 can change in the order of 1 % between different production batches.

4.5 Uncertainty of measurement of the absorbed dose

The uncertainty of measurement of the measured value of the absorbed dose to water is determined in accordance with ISO/IEC Guide 98-3[77], using Formula (1). Type A methods (statistical methods) are applied to determine the standard uncertainties when the indicated values ($M_i - M_0$) and the correction factor k_M are the input variables. Type B methods (other methods) are used to determine

the standard uncertainties when the calibration coefficients N_i and all other correction factors are the input variables.

It is recommended that the estimate of the uncertainty of the measured value should comprise the following items listed in Table 9. The numerical values of the estimated uncertainties vary in accordance with the applied methods. Some typical values, taken from References [18], [61] and [62] are reproduced here as an example.

Table 9 — Typical sources of uncertainty and numerical estimates of relative uncertainties

Source of uncertainty	Estimated relative uncertainty, s %
Reference radiation source[a]	0,1 to 1,1
Calibration of TL detectors	0,3 to 0,75
Repeated calibration of TL detectors	0,3 to 0,75
Nonlinearity correction	0,1 to 1,5
Determination of k_Q or k_E	0,5 to 1,5
Fluctuation of the indicated value (reading) in a measurement[b]	0,3 to 0,5
Overall uncertainty	0,9 to 2,8
[a] i.e. traceability to the primary standard.	
[b] Repeatability.	

4.6 Reusability

The test for reusability is described in 5.3.3.

4.7 Stability check

The long-term stability of TLD systems is ensured by means of calibrations provided in 4.4.4, which are performed prior to each clinical dose measurement. To what extent the response of TLD systems is subject to long-term changes can be verified by comparing the temporal changes in the calibration factors.

4.8 Staff

Due to the complexity of TL dosimetry procedures, qualified operating staff is required.

5 Requirements for the TLD system

5.1 General information

5.1.1 Classification of the requirements

The requirements for a TLD system are primarily addressed to the manufacturer and comprise the requirements for the completeness of the TL system (see 5.2), for the TL detectors (see 5.3), for the TL-indicating instruments (see 5.4), for the auxiliary instruments (see 5.5), for the TLD system as a whole (see 5.6), for the calibration irradiation device (see 5.7), and for the accompanying papers (see 5.8). Compliance with the requirements pertaining to the operation characteristics of the TLD system and its components laid down in 5.3 to 5.6 ensures to a large extent that the uncertainties of measurement described in Table 12 are not exceeded. The rules regarding the acceptance tests are laid down in 5.9. The requirements for the TL detectors (5.3) and for the TL-indicating instrument (5.4) can only be checked using devices applied in routine use in conjunction.

5.1.2 Requirements for operation characteristics

The impact of the influence quantities, when these quantities deviate from their reference values within their rated ranges of use, shall comply with the following limits. To check compliance with the limit valid for a single influence quantity, all other influence quantities have to be kept unchanged.

For influence quantities whose impact on the measured value is accounted for by a correction factor (e.g. radiation quality or nonlinearity), the estimated relative deviation of the corrected value from the true value shall not exceed the range indicated in Tables 13 and 14.

For influence quantities whose impact on the measured value is not accounted for by a correction factor (e.g. irradiation temperature), the estimated relative deviation of the uncorrected value shall not exceed the ranges indicated in Tables 11, 13, and 14.

5.2 Completeness of the TLD system

5.2.1 Technical components

A TLD system shall contain at least the following technical components:

a) a number of TL detectors of the same type, eventually furnished with an appropriate conditioning (3.7); TL detectors can be placed in groups in TL probes;

b) an indicating instrument for TL measurements, equipped with one or more devices for the heating of TL detectors and for the measurement and indication of the thermoluminescence light;

c) auxiliary instruments, such as vacuum tweezers and an oven for heat treatment.

5.2.2 Hardware and software components

A TLD system shall allow dose determination from the indicated value of the TL-indicating instrument. The hardware required for this purpose is part of the TLD system.

5.2.3 Operating instructions

5.2.3.1 General requirements

The operating instructions shall contain information about the description, the construction, the mode of operation, and the procedures to be carried out by the user in order to achieve the accuracy of measurement guaranteed by the producer. The operating instructions shall be supplied with each TLD system. The operating instructions shall contain the following information about the TLD system:

a) safety instructions pertaining to the instruments;

b) safety instructions pertaining to the (partly toxic) TL material;

c) description of the intended use;

d) information about the pre-irradiation annealing process including all parameters;

e) information about the post-irradiation annealing process including all parameters;

f) description of the reading procedure with all the parameters, including information about the light detection system such as current integration or pulse counting;

g) function and operation of all keys, switches, and turning knobs, and meaning of the output plugs, indicator scales, and signal lights;

h) information about the replacement of the wearing parts by the user (e.g. batteries und fuses); if necessary, this information shall contain the following indications: check of the operating ability of the wearing parts and the type of the wearing parts supplied as replacement parts;

i) block diagram;

j) for a mains-operated instrument: information about the required supply voltage, the rated range of use of the supply voltage and frequency, and line voltage switching, if necessary;

k) information to help decide whether a TL detector shall not be used anymore; if necessary, indicating the facilities where TL detectors can be made reusable;

l) information about the adjustment and the calibration of the TLD system after wearing parts have been replaced;

m) stabilizing time of the TL-indicating instrument;

n) indication on the necessity of gas flushing of the detector housing during evaluation; in the case of gas heaters, information on the type, temperature, and volume flow of the heating gas;

o) for the TL-indicating instrument, information about the type and size of the required detectors;

p) dimensions, density, and type of the detector casing material and, if necessary and supplied, of the auxiliary components;

q) information about storage, cleaning, and waste disposal;

r) warning, if longer storage at high humidity can be damaging;

s) admissible method for cleaning and drying of TL detectors, if required.

5.2.3.2 Imperative information about technical data

The following technical data shall be provided:

a) type of the TLD system, type designation, as well as designation of the manufacturer and the licence owner;

b) measured quantity as well as radiation quality for which the TLD system is intended;

c) indication range and measuring range for the dose;

d) rated range of use of TL probes and other components of the TLD system together with the corresponding values for the following influence quantities:

   1) photon energy and direction of radiation for parallel incidence of the photon radiation;

   2) dose rate during dose measurement;

   3) ambient temperature and relative humidity;

   4) sunlight;

   5) mechanical shock;

   6) electromagnetic disturbance tests;

   7) supply voltage;

e) information or marks defining the position of the reference point and the direction of preference;

f) diagram of the energy dependence and the directional dependence of the response;

g) information on nonlinearity, with diagram, if necessary;

h) variation coefficient of the response of a sample, with diagram, if necessary;

i) information on computer interfacing;

j) computer platform necessary to support supplied software;

k) software media;

l) installation procedure;

m) backup of data;

n) critical software parameters;

o) passwords;

p) software revision date and updates.

5.2.3.3 Imperative information about the radioactive stability check device

In case the radioactive stability check devices are part of the TLD system, the operating instructions shall contain the following indications:

a) procedure for the determination of the control values;

b) information on the radionuclide and its nominal activity and half-life;

c) a table or a diagram referring to the change in the control value or the check time due to the activity decay of the radiation source.

5.2.4 Access to a calibration irradiation device

For the operation of a TLD system, access to an appropriate calibration irradiation device and reference dosimetry system shall be provided (see also 4.4.4 and 5.7).

5.3 Requirements for TL detectors

5.3.1 Characteristics of TL materials

For dose determinations in radiotherapy by means of thermoluminescence dosimetry, various TL materials can be used. Some parameters of the most common TL materials are listed in Table 10; their different k_Q and k_E values are found in Tables 4 to 8.

5.3.2 Tailoring of TL materials

TL materials suited for clinical dosimetry are available as monocrystals and as polycrystals pressed into the shape of rods, chips, or microcubes.

NOTE 1 Normally chips have square form; the round slices also in use are termed discs (see Tables 4 and 5).

TL probes are available in various types and differ in material, size, shape, and number of TL detectors placed in a casing, as well as in the size and the shape of the casings.

The casing shall be watertight, and it shall enable a reproducible, geometrically defined arrangement of the TL detectors in the phantom. The operating instructions shall contain clear information about the reference point of the detectors.

Table 10 — Properties of the most common TL materials

	LiF:Mg,Ti[a]	LiF:Mg,Cu,P[a]
Z_{eff}[28]	8,2	8,2
Usable measuring range in Gy	10^{-3} to 10^{2}	10^{-3} to 10^{2}
Nonlinear behaviour (typical values of k_N at D_0 = 1 Gy, D = 2 Gy)	0,975	1,001
Notes	Significant influence of the pre-irradiation annealing on the dosimetric properties	Significant influence of the pre-irradiation annealing on the dosimetric properties
[a] The listed TL materials are sensitive to sunlight and highly intensive UV exposure. These exposures can cause the uncontrolled increase or fading of the indicated value of a TL detector.		

NOTE 2 The use of ^{7}LiF instead of LiF in natural isotope composition is not necessary as long as the influence of the neutron field associated with high-energy photon-beam radiotherapy upon *the indicated value of the TL detector* remains negligible (see 4.4.5.5, Note 5), but is necessary if the neutron influence becomes significant (see 4.4.5.5, Note 6).

5.3.3 Reusability of TL detectors

TL detectors shall be reusable. The mechanical, thermal, chemical, and optical properties of TL detectors shall allow repeated reuse without increase in the uncertainty of measurement. Test parameter T_i serves to test the reusability:

$$T_i = \left| \frac{(M_{i1} - M_{01}) - (M_{i2} - M_{02}) \cdot k_M}{(M_{i1} - M_{01})} \right| \tag{9}$$

The indices 1 and 2 denote two successive measurement cycles under reference conditions. Factor k_M has to be determined according to Formula (5). Sufficient reusability of a batch of TL detectors and of a given TLD system is ensured when 95 % of the T_i values of this charge are smaller than or equal to 0,01.

NOTE The reusability check makes sense only with conditioned batches. The processing of the reusability check is the subject of agreement between the manufacturer and the user (see 4.6).

5.3.4 Individual variation

5.3.4.1 Individual variation of the response

Each TL detector possesses an individual response that normally deviates from the mean value and whose influence on the measured value is, however, neutralized by the process of individual calibration [see Formula (1)]. By contrast, standard correction coefficients according to Formula (1) are applied for the compensation of fading and nonlinearity, so that the individual variation of the response due to these effects shall be minimized, as shown in 5.3.4.2 and 5.3.4.3.

5.3.4.2 Individual variation of the nonlinear behaviour

Precise dose determination within the whole scope of application is only possible if all detectors of a batch display, to a large extent, have the same nonlinear behaviour. To verify this requirement, the whole charge shall be irradiated with the highest dose expected during applications. In the subsequent evaluation, the product of the indicated value and the associated calibration coefficient of every single detector should not deviate more than 1,0 % from the mean value of all these products. Detectors that do not comply with this requirement should either be sorted out or only be used if the dose to be measured is not significantly higher than the reference dose.

5.3.4.3 Individual variation of fading

Prior to dispatch of the TL detectors, the uniformity of the fading of all TL detectors of the applied batch shall be verified, for instance when quality assurance of therapy dosimeters is carried out. For this purpose, the whole batch is irradiated with a dose of the same magnitude as that applied by the user and evaluated only after a period longer than the expected time span between shipment and return of the detectors. Detectors, whose evaluation yields a measured value with a fluctuation that exceeds the 3*s* value of the batch, should not be used.

5.4 Requirements for TL-indicating instruments

5.4.1 General remarks

TL-indicating instruments consist of the heating unit and the light-measuring device, as well as the control unit and the indicating unit (furnished with a separate computer).

NOTE The requirements for the uncertainty of measurement can make it necessary to connect the TL-indicating instrument to a power stabilizer.

5.4.2 Mechanical setup

If the mechanical setup of the TL-indicating instrument influences the response of the detectors or the mechanical functions (e.g. the automatic transport of detectors), the manufacturer shall point out in the operating guidelines that a horizontal or vibration-free position setup is necessary in order to avoid disturbances or measurement errors.

5.4.3 Warm-up time

The warm-up time shall be indicated in the operating instructions.

5.4.4 Indication and indication range

The following requirements are valid for the indicated value and the indication ranges.

a) The operating instructions shall contain sufficient information, e.g. a characteristic line plot, on the relationship between the indicated value of the TL-indicating instrument and the quantity of light emitted by the evaluated TL detector.

b) The indicated value of the TL-indicating instrument shall be digital. In case of a segment display, the proper design of the figures shall be verifiable.

c) The switching between the indication ranges of the TL-indicating instrument shall be automatic. In instruments furnished with more than one indication range, there should not be gaps between successive indication ranges.

d) Glow curve data should be stored automatically and be easily available in digital format.

5.4.5 Background value

Details about the determination of the background value shall be given in the operating instructions.

5.4.6 Overflow indication and effects during evaluation of high doses

A TL-indicated value exceeding a preset value, and an operating status of the TL-indicating instrument whose measurement sensitivity is impaired by the effects of the glow curve measurement performed on a TL detector irradiated with a high dose, shall be clearly indicated to the operator.

5.4.7 Test light source

A test light source may consist of an LED or of a scintillator with integrated radioactive source. It can serve as electric or photometric function control of the TL-indicating instrument or can be applied to ensure stability of the photomultiplier. However, in general, the test light source does not allow one to draw conclusions about the stability of the TL-indicating instrument and the applied TL detectors.

5.4.8 Changes in the response

If mechanical devices for changing the response or for the correction of influence quantities are available, they should not allow external accessibility or should be adequately labelled, lockable, and furnished with a scale. Changes entered into a computer shall appear on the display of the TL-indicating instrument.

5.4.9 Mechanical construction

Components needing routine maintenance and whose replacement has no influence on the long-term constancy of the response (e.g. heating device, optical filters, photomultiplier, or photomultiplier unit) should be easily accessible.

5.4.10 Light shielding

The enclosure of the TL-reading instrument shall be light-tight. If all outside surfaces of the TL-reading instrument are exposed to a bright daylight illumination of 100 $W \cdot m^{-2}$, the measured value should not increase more than 1 % within the measuring range indicated by the manufacturer.

5.4.11 Climatic influences

The TL-indicating instrument shall be so constructed as to operate within the minimal rated range of use given in Table 14. Upon checking the temperature and the humidity level, the absolute humidity should not exceed the value 10 $g \cdot m^{-3}$, e.g. 60 % relative humidity at 20 °C air temperature.

5.4.12 Electrical requirements

5.4.12.1 Power supply

The TL-reading instrument shall operate at least with line voltages of 230 V or 110 V in North America or with more than one line voltage, including 230 V. When fluctuations in the line voltage occur within the range of –10 % to +15 %, the maximum relative deviation shall not exceed 1 %.

In order to prevent the TL reading to be affected by spikes and other distortions of high frequency from the mains, the photomultiplier and its subsequent amplifier should be supplied by a highly stabilized power supply, for instance, a DC-to-AC converter completely separated from the mains or a buffered power supply.

5.4.12.2 Line frequency

The TL-reading instrument shall be so constructed as to operate at least with the line frequency of 50 Hz or 60 Hz for North America or with more than one line frequency, including 50 Hz. Upon changes in the line frequency within the range of –1 Hz to +1 Hz, the relative deviation of the individual value from the time value shall not exceed 1 %.

5.4.12.3 Electromagnetic disturbances

The entirety of all electromagnetic disturbances, i.e. of all electromagnetic fields and line-conducted disturbances, shall not exceed 0,01 D_0/N_i, see Table 11, where D_0 is the lower limit of the measuring range for absorbed dose values and N_i is the individual calibration factor of any TL detector. The

duration of the electromagnetic disturbances used for tests shall be set in such a way as to correspond to a one-hour use according to the frequency of disturbances given in Table 11.

All tests shall be performed according to the International Standards given in Table 11. For all tests, the minimal rated ranges of use have been extracted from IEC 61000-6-2[79] and summarized in Table 11 together with the frequencies of disturbance, the corresponding maximal values of the half-width of correction factor interval, and the performance criterion A, B, or C according to IEC 61000-6-2. Only criteria A and B are admissible. In case criterion B is admissible, the values given in Table 11 refer to the dose values indicated prior and after the test. If the duration of the electromagnetic disturbance does not correspond to a one-hour use, the impact of the electromagnetic disturbance shall be converted so that it corresponds to a one-hour use.

5.4.12.4 Moving connection cables

If single components of the TL-indicating instrument are connected by cables whose moving influences the measured value, the manufacturer should indicate this in the operating instructions. In addition, the cables should be labelled accordingly.

5.4.12.5 Feedback from connected instruments

Output plugs on the TL-indicating instrument used for the connection of, e.g. plotters, printers, computers, shall be short-circuit resistant.

5.4.12.6 Electrical safety

TL-indicating instruments shall comply with the requirements of IEC 60601-1.

5.4.13 Operational safety and detection of function failure

5.4.13.1 Detection of function failure

The function of parameters (e.g. high voltage, temperature, heat gas) that could influence the measured value shall continuously be controlled by the TL-indicating instrument. Their value or status should be indicated or be observable prior to each measurement. If tolerance limits are exceeded, the affected measured value shall be marked accordingly. Furthermore, the following measurement can only be performed after the user has confirmed the former measurement. The function of the data output interface for a connected instrument shall be controlled in the same manner. In case of failure, the automatic evaluation shall also be interrupted. The cause for the interruption shall be identifiable to the user (e.g. symbol, error code) and the affected measured value shall be marked accordingly. Loss of measured values caused by function errors shall be limited to two lost measured values.

5.4.13.2 Data backup

The documentation of the measured value (e.g. print out, saving to media) shall be guaranteed in order to enable the evaluation of the next TL detector.

5.4.13.3 Automatic TL-indicating instruments

With automatic TL-indicating instruments, the evaluation of TL detectors is performed successively without the user's intervention.

5.4.13.4 Indication of the operating status

The actual operating status shall be, at any time, identifiable to the user by means of an appropriate indication, e.g. by symbols or acoustic signals.

5.4.13.5 Frequency of function failures

Mechanical, optical, electronic, and electromagnetic components of a TLD system shall be so constructed as to ensure a high operation safety standard. The occurrence of function failures shall not exceed 0,01 %.

Table 11 — Operation characteristics of TLD systems in the case of disturbances caused by electromagnetic fields and line-conducted disturbances

Line	Test criterion or influence quantity	Minimal rated range of use of the influence quantity	Testing method according to	Disturbance frequency	Maximum alteration of indicated value[b]	Criterion[a]
1	Total impact of the electromagnetic disturbances in lines 2 to 9	See lines 2 to 9 of this table	See lines 2 to 9 of this table		0,01 D_0/N_i	—
2	Electrostatic discharge, charging voltage	0 kV to ±8 kV air discharge 0 kV to ±4 kV contact discharge	IEC 61000-4-2	10 disturbances per hour	0,007 D_0/N_i	B
3	External electromagnetic field, field strength and modulation	80 MHz to 1 GHz 0 V/m to 10 V/m (unmodulated mean value) 80 % AM (1 kHz)	IEC 61000-4-3	10 % of time	0,007 D_0/N_i	A
4	External electromagnetic field of cellular phones, field strength and modulation	800 MHz to 960 MHz 0 V/m to 20 V/m 1,4 GHz to 2,0 GHz and 0 V/m to 15 V/m (unmodulated mean value) 80 % AM (1 kHz)	IEC 61000-4-3	10 % of time	0,007 D_0/N_i	A
5	Line-conducted disturbances caused by rapid transients/bursts, peak voltage	0 kV to ±2 kV 5/50 s (t_r/t_h)	IEC 61000-4-4	10 disturbances per hour	0,007 D_0/N_i	B
6	Conducted disturbances caused by voltage peak, peak voltage, and rise time	0 kV to ±2 kV dissymmetric 0 kV to ±1 kV symmetric 1,2/50 (8/20) µs (t_r/t_h)	IEC 61000-4-5	10 disturbances per hour	0,007 D_0/N_i	B
7	Conducted disturbances caused by high frequency, frequency, and voltage	150 kHz to 80 MHz 0 V to 10 V (unmodulated mean value) 80 % AM (1 kHz)	IEC 61000-4-6	10 % of time	0,007 D_0/N_i	A
8	Magnetic 50 Hz-field, field strength	0 A/m to 30 A/m	IEC 61000-4-8	10 % of time	0,007 D_0/N_i	A
9	Voltage dips/ short interruptions, duration	10 ms (30 % reduction) 100 ms (60 % reduction)	IEC 61000-4-11	10 disturbances per hour	0,007 D_0/N_i	B

[a] See IEC 61000-6-2.

[b] D_0 is the lower limit of the measuring range; N_i is the calibration coefficient of the detector(s) used for this test.

5.4.13.6 Failure of technical supply

In case of failure of a technical supply (e.g. line voltage, heat gas, water cooling system), the measurement cycle shall automatically be interrupted. After recovery, the measurement cycle may only be restarted by the user. Loss of measured values caused by the failure shall be limited to two lost measured values.

5.4.13.7 Failure of a connected instrument

In case of failure of a connected instrument, the automatic measuring process shall be interrupted. In the TL-indicating instrument, the data shall be saved in such a manner as to be made available again after restoring the instrument state.

5.4.14 Data output and data backup

5.4.14.1 General information

The TL-indicating instrument shall be designed to prevent data loss caused by function errors. This applies especially to automatically working TL-indicating instruments.

5.4.14.2 Measurement data

The TL-indicating instrument should possess an interface for the connection with output media. At least one interface of the TL-indicating instrument shall be standardized.

5.4.14.3 Glow curve

The TL-indicating instrument shall possess an analogue or digital interface for recording, and if required, for analysing the glow curve.

5.5 Requirements for auxiliary instruments (pre-irradiation annealing device)

5.5.1 Pre-irradiation annealing

In order to ensure their reusability, the TL detectors shall undergo pre-irradiation annealing prior to irradiation. More details shall be given in the operating instructions for an oven that would be within the TL-indicating instrument.

5.5.2 Construction

Regarding operating state, mechanical construction, and resistance against climatic influences, a separate oven shall meet the same requirements as the TL-indicating instrument.

5.5.3 Electrical requirements

Regarding line power supply, line frequency, and protection against power line disturbances and external disturbance fields, a separate oven shall meet the same requirements as the TL-indicating instrument.

5.5.4 Operation safety

The operation safety of manually operated ovens shall be ensured by clearly labelled and easily accessible operating parts. The operation safety of processor- or computer-controlled ovens shall be ensured by clearly structured programs.

5.5.5 Detection of function failure

Parameters, which influence the temperature-time profile, shall be submitted to a continuous internal control. If the limits of the temperature-time profile are exceeded with respect to time or temperature, the pre-irradiation annealing or post-irradiation annealing process shall be interrupted, and the cause of the interruption shall be indicated.

5.5.6 Indication of the operating state

At any time, the actual operating state shall be identifiable to the user by means of an appropriate indication, e.g. by symbols or acoustic signals.

5.6 Requirements for the entire TLD system

5.6.1 Minimum measuring ranges

The measuring range of a TLD system according to this document shall comprise a minimum measuring range as given in Table 12. The measuring range is that part of the indication range for which the total uncertainty of measurement, 2*s*, (see ISO/IEC Guide 98-3) complies with the indicated values given in Table 12.

Table 12 — Minimum measuring range of TLD systems for radiation therapy

Method of application	D_{min} Gy	D_{max} Gy	Admissible total uncertainty of measurement, 2*s* %
Technical control	0,5	3	3
Fractionated radiotherapy[a]	0,01	10	5
Single-dose radiotherapy[b]	5	30	5
Brachytherapy with photons	0,01	20	20

[a] For small-field applications, a larger total uncertainty may be admissible.

[b] In individual cases, higher doses within this order of magnitude can occur. For these cases, particular requirements for the pre-irradiation and post-irradiation have to be met.

The total uncertainty of measurement given in Table 12 does not comprise the influencing contribution during calibration of TL detectors by means of dose determinations using a reference dosimeter.

The application of a dose that exceeds the measuring range can cause a permanent change in the response (radiation damage, see 3.29).

5.6.2 Minimum rated ranges of use

5.6.2.1 General remarks

If an influence quantity is varied beyond its rated range of use, the maximum relative deviation given in Table 13 shall not be exceeded (see 5.1.2).

The impact of the influence quantities on the measured value shall be examined for each single influence quantity. Apart from the variation of the influence quantity throughout its rated range of use (Table 13), the additional influence quantities remain constant in their ranges of test parameters for this examination. At variation of an influence quantity throughout its rated range of use, the remaining uncertainty of measurement shall not exceed the limits given in Table 13. This requirement also applies to rated ranges of use that exceed the minimum rated range of use.

NOTE In Table 13, minimum rated ranges of use for the application of TLD systems in radiation therapy using particle accelerators are given. Minimum rated ranges of use for the application of TLD systems in brachytherapy are not defined in this document.

Table 13 — Reference values and minimum rated ranges of use for influence quantities whose variation is causally determined by the application of TL systems

Influence quantity	Reference value	Minimal rated ranges of use	Maximum relative deviation[a]	Subclause
Energy, photons	1,250 keV[b]	1,250 keV and 6 MV to 25 MV	1 %	5.6.2.2
Direction of radiation incidence, photons	Direction of preference[b]	±180	1 %	5.6.2.4
Energy, electrons	1,250 keV[b]	4 MeV to 25 MeV	1 %	5.6.2.3
Direction of radiation incidence, electrons	Direction of preference[c]	±180	1 %	5.6.2.4

[a] Maximum relative deviation of the corrected and uncorrected measured value from the true value.

[b] ^{60}Co-gamma radiation.

[c] For example, in the case of round discs, the direction of the disc axis; in the case of rods, perpendicular to the longitudinal axis.

5.6.2.2 Photon energy

Within the minimal rated range of use of the photon energy according to Table 13, the influence of the photon energy shall be corrected first by using correction factor k_Q according to Formula (1), or when the individual response is determined by means of another calibration — by applying the quotient of the correction factors ($k_Q/k_{Q'}$) (see 4.4.4.2). The maximum relative deviation in Table 13 refers to the remaining influences of photon energy that have not been eliminated by k_Q, for example, due to the influence of scattered radiation or as a consequence of radiation filtration by the body tissues.

5.6.2.3 Electron energy

Within the minimal rated range of use of the electron energy according to Table 13, the influence of the electron energy shall be corrected first by using correction factor k_E according to Formula (1), or when the individual response is determined by means of another calibration — by using the quotient of the correction factors ($k_E/k_{Q'}$) (see 4.4.4.2). The maximum relative deviation in Table 13 refers to the remaining influences of the electron energy that have not been eliminated by k_E, for example, due to the deviation of the depth of measurement from the reference depth.

5.6.2.4 Direction of radiation incidence

For the direction of radiation incidence, no correction factor is applied in Formula (1). The maximum relative deviation for the direction of radiation incidence given in Table 13 characterizes the non-corrected influence of the direction of radiation incidence.

5.6.3 Ranges of test parameters

5.6.3.1 General remarks

Ranges of test parameters apply to influence quantities whose variation does not depend upon the use of TLD systems but is caused by external factors and can only be restrictively influenced.

The impact of the influence quantities on the measured value shall be examined separately for each influence quantity. Apart from the variation of the influence quantity throughout its rated range of use (see Table 14), the additional influence quantities shall remain constant within their ranges of test parameters for this examination. When an influence quantity varies beyond its rated range of use, the maximum relative deviation shall not exceed the limits given in Table 14.

It is assumed that disturbance influences such as UV irradiation or sunlight are excluded; therefore, they are not treated as influence quantities. Operation characteristics of TLD systems in case of disturbances caused by electromagnetic fields are given separately in Table 11.

Table 14 — Reference values, ranges of test parameters, and minimal rated ranges of use for influence quantities whose variation does not depend upon the use of TLD systems but is caused by external factors

Influence quantity	Reference value	Range of test parameters	Minimal rated range of use	Maximum relative deviation[a]	Subclause
Temperature	20 °C	18 °C to 22 °C	15 °C to 25 °C	1 %	5.6.3.2
Relative humidity	50 %	30 % to 70 %, $\rho_w \leq 10$ g/m^3 [b]	30 % to 70 %, $\rho_w \leq 10$ g/m^3		
Line voltage	Nominal value	Nominal value ±2 %	Nominal value −10 % to +5 %	1 %	5.4.12.1
Line frequency	Nominal value	Nominal value ±1 Hz	Nominal value ±1 Hz	1 %	5.4.12.2
Stabilizing time	Manufacturer's indication	≥Manufacturer's indication	≥Manufacturer's indication	1 %	5.4.3

[a] Maximum relative deviation of the corrected and uncorrected measured value from the true value.

[b] ρ_w water vapour density in air, absolute humidity.

5.6.3.2 Ambient temperature and humidity

The maximum relative deviation given in Table 14 refers to the combined variation of temperature and humidity. For testing, the TL detectors are exposed for 24 h to the influence quantities temperature and humidity. The absolute humidity (water vapour density) shall not exceed 20 g/m^3.

5.6.3.3 Short-time stability

The sensitivity of the TL-indicating instrument shall sufficiently be stable during a measuring cycle. This is the case when, by performing the test for reusability according to 5.3.3, 95 % of the T_i values of a batch do not exceed 0,01.

5.7 Requirements for the calibration irradiation device

For the irradiation device applied to determine the individual response of TL detectors and to perform the corrections for the individual variation and for the systematic change in the response, the reproducibility of the applied dose shall not exceed, for radioactive sources, 0,4 % (2s).

5.8 Requirements for the accompanying papers

The accompanying papers, especially the operating instructions, shall comply with the standards of IEC 61187 as well as Clause 4 and Clause 5 of this document. The applied terms shall agree with the definitions of Clause 3 of this document. The required documentation shall be written in English or in any other language comprehended by the user.

5.9 Acceptance tests

5.9.1 General requirements

The acceptance test is the proof given by the manufacturer to the customer that the TL-indicating instrument complies with the basic accuracy and safety requirements of this document. The acceptance test applies to the whole system. The acceptance test should ensure that the TLD system meets the requirements laid down in 5.2 to 5.8. In case of the replacement of single components, e.g. of the TL-indicating instrument, the acceptance test shall be performed for each component. This is not the

case when components are purchased additionally (e.g. detectors). It is assumed that the manufacturer gives documentary evidence and certifies that the components of the system, taken alone, possess the properties described in 5.2 to 5.8. Therefore, the acceptance test exclusively consists of the evidence of reproducible measured values.

5.9.2 Number of TL detectors used

In case of a manually operated TL-indicating instrument, at least 20 TL detectors should be used for repetition of measurements. In case of an automatically operated TL-indicating instrument, the number of TL detectors used for repetition of measurements should be at least equal to the number of TL detectors possibly required for one evaluation process.

5.9.3 Type of TL detectors used

Only those types of TL detectors operated by the user should be submitted to the acceptance tests.

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