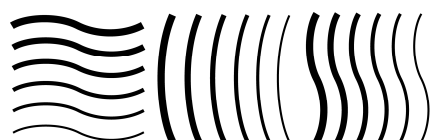# Dosimetry and quality control of brachytherapy with low-energy photon sources (^{125}I)

NEDERLANDSE COMMISSIE VOOR STRALINGSDOSIMETRIE

Report 20 of the Netherlands Commission on Radiation Dosimetry

Revised edition, June 2012

Netherlands Commission on Radiation Dosimetry
Subcommittee "Dosimetry and quality control of brachytherapy
with low-energy photon sources (^{125}I)", April 2012
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NCS, Delft, The Netherlands

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Preface

The Netherlands Commission on Radiation Dosimetry (Nederlandse Commissie voor Stralingsdosimetrie, NCS) was officially established on September 3rd, 1982 with the aim of promoting the appropriate use of dosimetry of ionising radiation both for scientific research and for practical applications. The NCS is chaired by a board of scientists, installed upon the suggestion of the supporting societies, including the Netherlands Society for Radiotherapy and Oncology (Nederlandse Vereniging voor Radiotherapie en Oncologie), the Dutch Society of Nuclear Medicine (Nederlandse Vereniging voor Nucleaire Geneeskunde), the Dutch Society for Medical Physics (Nederlandse Vereniging voor Klinische Fysica), the Netherlands Radiobiological Society (Nederlandse Vereniging voor Radiobiologie), the Netherlands Society for Radiological Protection (Nederlandse Vereniging voor Stralingshygiëne), the Dutch Society for Medical Imaging and Radiotherapy (Nederlandse Vereniging Medische Beeldvorming en Radiotherapie), the Radiological Society of The Netherlands (Nederlandse Vereniging voor Radiologie), the Dutch Society for Medical Physics Engineers (Nederlandse Vereniging van Klinisch Fysisch Medewerkers) and the Belgian Hospital Physicists Association (Belgische Vereniging voor Ziekenhuisfysici / Société Belge des Physiciens des Hôpitaux).

To pursue its aims, the NCS accomplishes the following tasks: participation in dosimetry standardisation and promotion of dosimetry intercomparisons, drafting of dosimetry protocols, collection and evaluation of physical data related to dosimetry. Furthermore, the commission shall maintain or establish links with national and international organizations concerned with ionising radiation and promulgate information on new developments in the field of radiation dosimetry.

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Dosimetry and quality control of brachytherapy with low-energy photon sources (^{125}I)

Revised edition, June 2012

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Contents

Summary

In 2003 the NCS established a new subcommittee to propose quality assurance (QA) procedures on the use of low energy photon (LEP) sources in permanent prostate brachytherapy (PPBT). As for previous subcommittees, the work was focussed typically on the Dutch and Belgian situation. As a first activity, the subcommittee circulated an extensive questionnaire to all radiotherapy institutes performing PPBT with LEP sources in the Netherlands (12) and Belgium (22), requesting information on the quality control (QC) procedures in use at that moment. In a second stage, site visits to all institutes were organized to perform source strength measurements and to investigate the local source strength measurement procedure.

Only the use of ^{125}I sources was reported, most often for PPBT, but also for eye and breast treatments. At the time of the survey, 7 different types of ^{125}I sources were used in the Netherlands and Belgium and a large variety in QC instruments and methods for verifying the air kerma strength of the seeds was observed. In total 6 out of the 34 institutes reported not having a specific instrument to verify the source strength of the seeds used for PPBT. Of the 29 instruments available in the hospitals only 3 were calibrated by a Secondary Standard Dosimetry Laboratory (SSDL), 4 were calibrated by the manufacturer. The visiting teams conducted on-site source strength measurements in 30 institutes and compared results with data stated by the supplier of the sources and if available with measurements performed by the local medical physicist. In general, the results by the NCS visiting team agreed with the results stated by the supplier within ± 5%.

Four different treatment planning systems (TPSs) were in use in Belgian and Dutch radiotherapy institutes, all with the American Association of Physicists in Medicine Task Group-43 (AAPM TG-43) dose calculation formalism implemented. However, a large variability in calculation models was observed and in 9 institutes the AAPM TG-43 update (2004) was not followed. The TPS tests revealed variations in dose calculation results due to incorrect application of the anisotropy model and to the use of source data which were since 2004 no longer recommended. Only for a small number of combinations of TPS, institute and seed type the 1D dose calculation errors were smaller than ±1% in the calculation points at distances between 0.5 and 6 cm. Misinterpretation of the TPS test and/or misunderstanding of the TG-43 dose calculation formalism caused larger errors and missing data for the 2D calculation tests. Most institutes apply the 1D model to calculate the prostate brachytherapy dose distributions. Most TPSs proved to underestimate the volumes in dose-volume histogram (DVH) calculations. The accuracy of DVH calculation depended on dose grid

resolution and number of sampling points. Dose summation and representation of isodose lines proved to be correct in all reports.

The data obtained from the questionnaires were compared with recommendations given in international reports on QC of brachytherapy and on QC of TPS. With this background, recommendations have been formulated for dosimetry and quality control of low-energy photon sources (^{125}I) to be used in the clinical practice of PPBT in Belgium and the Netherlands.

Abbreviations

AAPM	American Association of Physicists in Medicine
ABS	American Brachytherapy Society
ADCL	Accredited Dosimetry Calibration Laboratory
BRAPHYQS	Brachytherapy Physics Quality assurance System
BT	Brachytherapy
BTSC	Brachytherapy Subcommittee of the AAPM
CLA	Calibration Laboratory Accreditation Subcommittee of the AAPM
CZT	Cadmium zinc telluride
DVH	Dose-volume histogram
EAU	European Association of Urology
EORTC	European Organisation for Research and Treatment of Cancer
EQUAL	ESTRO Quality Assurance Network
ESTRO	European Society for Radiotherapy and Oncology
EURAMET	European Association of National Metrology Institutes
GEC-ESTRO	Groupe Européen de Curiethérapie-ESTRO
GROVEX	Grossvolumen extrapolationskammer (high volume extrapolation chamber)
HGR	Hoge Gezondheidsraad (Superior Health Council, B)
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
ICWG	Interstitial Collaborative Working Group
IEC	International Electro technical Commission
IPEM	Institute of Physics and Engineering in Medicine
ISO	International Organization for Standardization
LDR	Low dose rate
LEP	Low-energy photon
LNHB	Laboratoire National Henri Becquerel, F
MSKCC	Memorial Sloan-Kettering Cancer Centre, U.S.
NCS	Nederlandse Commissie voor Stralingsdosimetrie (Netherlands Commission on Radiation Dosimetry)
NIST	National Institute of Standards and Technology, U.S.
NMI	National Metrology Institute
NVKF	Nederlandse Vereniging voor Klinische Fysica
NVRO	Nederlandse Vereniging voor Radiotherapie en Oncologie
NPL	National Physical Laboratory, UK
PMMA	Polymethyl metacrylate
PPBT	Permanent prostate brachytherapy
PTB	Physikalisch Technische Bundesanstalt, D
QA	Quality Assurance
QC	Quality control
RAKR	Reference air kerma rate
RT	Radiotherapy
SSDL	Secondary Standard Dosimetry Laboratory
TG-43	AAPMs task group-43
TNO	Nederlandse Organisatie voor Natuurwetenschappelijk Onderzoek
TPS	Treatment planning system
TURP	Trans urethral resection of the prostate
VSL	Van Swinden Laboratorium (previously Nederlands Meetinstituut), Nl
VROM	Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (presently, Ministry of Infrastructure and Environment), Nl

WAFAC   Wide angle free air chamber

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1. Introduction

Low-energy photon-emitting (LEP) brachytherapy sources are used in many radiotherapy departments either for permanent implantations in prostate, brain and breast, or for non-permanent treatments such as the irradiation of eye tumours. These sources are most commonly used in the form of seeds.

As for all sources of ionising radiation used in radiotherapy, the clinical or medical physicist is responsible for the quality assurance (QA) including the quality control (QC) of the sources and treatment planning calculation methods and algorithms. The dosimetric properties of the sources, as well as the clinical dosimetry procedures and equipment to be applied, have been well described by the AAPM Task Group 43 [1,2,3]. However, for sources that are used for permanent implantations some specific problems may arise during this quality control: the sources arrive sterilized in the hospital, therefore all handling and measurement of the sources should be done while maintaining sterile conditions; often a large number of sources (up to 100 or more) is used for an individual patient; sources are offered as loose seeds, stranded seeds, loose seeds in a cartridge, or stranded seeds in a cartridge, which makes QC of each individual source impossible or impractical. For these reasons the general guidelines for QC in brachytherapy such as the recommendations in NCS report 13 [4] and AAPM Task Group 56 [5] are not always fully applicable and specific recommendations for the use of low-energy photon sources are needed.

An important aspect of quality control is the independent verification of the source strength by the medical physicist before use in the clinic. Due to the low dose rate the use of an appropriate measurement device, such as a well-type chamber, is recommended. As the dosimetric properties of a source are highly dependent on the seed construction and its internal composition, the measurement device has to be calibrated for each specific source model that is used by the hospital.

However, traceable calibrations for these devices are difficult to obtain. Until about 2008 only one primary standard for low-energy photon sources was available worldwide at the National Institute of Standards and Technology (NIST, U.S.). In the mean time a second primary standard has become available at the Physikalisch-Technische Bundesanstalt (PTB) in Germany, and other national metrology institutes (NMIs) have projects running. However, no traceable calibration services provided by European secondary standards laboratories are yet available at the user level.

1.1 Purpose and scope

The primary aim of this NCS report is to give recommendations on quality control procedures for low-energy photon sources as they are clinically applied in Belgium and the Netherlands. Clinical practice was investigated during on site visits and with an extensive questionnaire on quality control with respect to the use of low energy photon sources. At the time of preparation of this report only iodine-125 (^{125}I) sources were used in Belgium and the Netherlands, mainly for permanent prostate implantation. The recommendations given focus on the use of ^{125}I seeds for this treatment technique, but should also be applicable or at least be able to serve as a basis for other LEP emitting radionuclides and brachytherapy techniques. Measurement systems suitable for the dosimetry of low-energy photon sources are presented and action levels for deviations in source strength are set.

In addition to these dosimetric aspects, recommendations are provided on the quality control of the ultrasound imaging system, the mechanical needle guidance and seed delivery system used during the application. As often, specific treatment planning systems are used in these applications; recommendations for commissioning and quality control of these systems, as well as some guidelines with respect to the evaluation of the treatment delivery (post-planning evaluation) are also given.

1.2 Outline of chapters

After this paragraph, clinical indications for brachytherapy with low-energy photon sources are presented. A description of the low-energy photon sources currently in use for clinical applications in the Netherlands and Belgium is given in Chapter 2.

Chapter 3 discusses the calibration methods and standards. The current primary standards and calibration services that are available are described in detail, as well as the calibration and QC performed by the different manufacturers. Some comments with respect to the detectors used for QC measurements are formulated.

In Chapter 4 the results of a survey on the clinical practice in the Netherlands and Belgium are presented. To better understand the current status of QC of LEP sources and to be able to formulate recommendations on QC, on-site visits were organized in the period 2005-2007 to the institutions in both countries performing brachytherapy with ^{125}I seeds. Materials and methods of the source strength verification measurements performed during these on-site visits are described in Chapter 5, together with the results and an evaluation. Associated to

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the on-site visits, tests on the treatment planning systems as used in the hospitals were conducted. The methodology used and the results of these tests are presented.

Recommendations on calibration, measurement procedures and detectors for dosimetry of low-energy photon sources in clinical practice are discussed in Chapter 6. Also the number of sources to be assayed is specified as well as action levels for deviations in source strength. Furthermore in this chapter recommendations are given on quality control of the ultrasound equipment, the mechanical seed placement guidance system and the treatment planning system. Chapter 7 presents a summary of the recommendations as endorsed by the NCS.

In Appendix A.1 the dosimetric data for a number of relevant sources in use in Belgium and the Netherlands are given. As an example, the tests for verifying the treatment planning systems are given in the Appendix A.2. Safety aspects and issues regarding radiation protection are discussed in Appendix A.3.

1.3 Treatment indications

In Belgium and the Netherlands (as in many countries) the use of low-energy photon sources has increased over the last years due to the strong increase in number of patients treated with permanent seed implantation for localized prostate cancer (Figure 1). In both countries exclusively ^{125}I sources are used for this treatment. At present permanent prostate brachytherapy has become by far the largest field of application for these sources, while some experience exists for other sites (e.g. meningioma, eye) or is still investigational (breast), but with a rather limited number of patients treated annually.
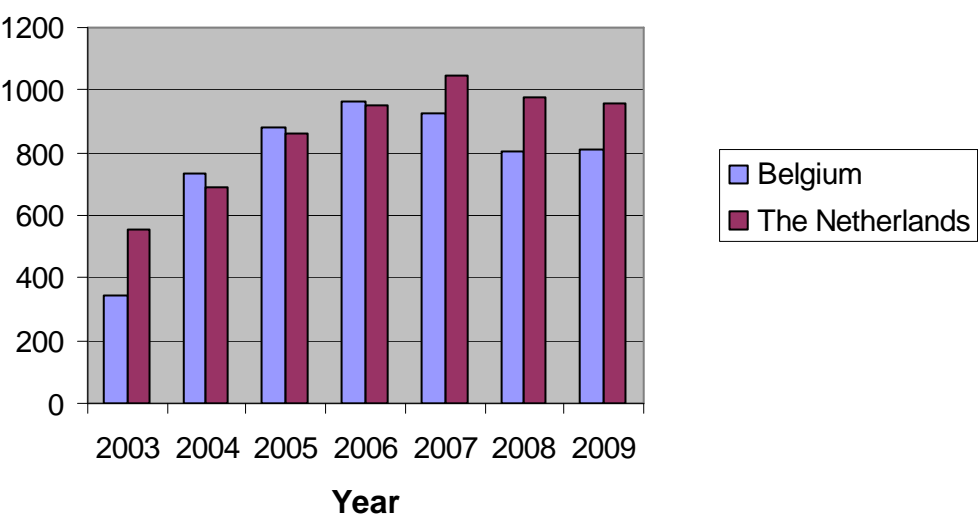
Figure 1: Evolution of the number of patients treated with permanent prostate brachytherapy over the period 2003-2009 in Belgium and the Netherlands (Source: Belgium: survey by the NCS subcommittee, The Netherlands: annually survey NVRO).

2. Source description and dose calculation methods

2.1 Source description

^{125}I has a half life of 59.43[1] days and decays by electron capture to stable tellurium-125 (^{125}Te) with the emission of characteristic x-rays (27.4 keV and 31.4 keV) and a low energy (35.5 keV) gamma ray. The average photon energy is about 28 keV. Palladium-103 decays with a half life of 17.0 days via electron capture to stable rhodium-103 (^{103}Rh). The average photon energy is about 21 keV. Because of the relatively low energy of ^{125}I and ^{103}Pd photons, significant absorption of photons occurs in the titanium encapsulation of the seeds, especially in the end welds and in any radio-opaque marker. Emitted electrons resulting from the electron capture process are fully absorbed by the titanium wall of the seed. In addition, the energy spectrum (dependent on the isotope used) is perturbed by the presence of fluorescence x-rays generated in the silver or gold radio-opaque markers.

In this chapter, we briefly describe the design of seven different source types that were in use in The Netherlands and Belgium at time of the preparation of this report. These sources are: Source Tech Medical model STM1251 (BARD), IsoSeed models I25.S06 and I25.S17 (Bebig), ^{125}I model 2301 (Best), InterSource model 1251L (IBt), selectSeed model 130.002 (Isotron), and Oncoseed model 6711 (Oncura). The description of the Best ^{125}I source model 2301 was included, because Best Medical International became a significant supplier of LEP seeds for radiotherapy institutes in Belgium and The Netherlands since 2008.

Source geometry and internal construction are highly manufacturer specific. The source models vary with regard to weld thickness and type, construction of radioactivity carrier, capsule wall thickness, and presence, shape and type of radio-opaque material. All of these properties can affect the dosimetric properties of the source.

2.1.1 Bard Source Tech Medical model STM1251

The source design of the Source Tech Medical model STM1251 is shown in Figure 2. The outer dimensions of the titanium capsule are 4.55 mm length and 0.8 mm diameter. The core consists of a cylindrical gold rod (0.361 mm diameter) which is inside a 3.81 mm long hollow

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[1] The value of 59.43 days has been adopted from the NIST (WAFAC) calibration certificates

aluminium wire (0.51 mm diameter). This aluminium wire is at all sides coated with a layer of nickel/copper onto which the radioactive iodine is adsorbed [6,7,8].

The gold core serves as an x-ray marker to allow visualisation of the seed implant using radiographic techniques.
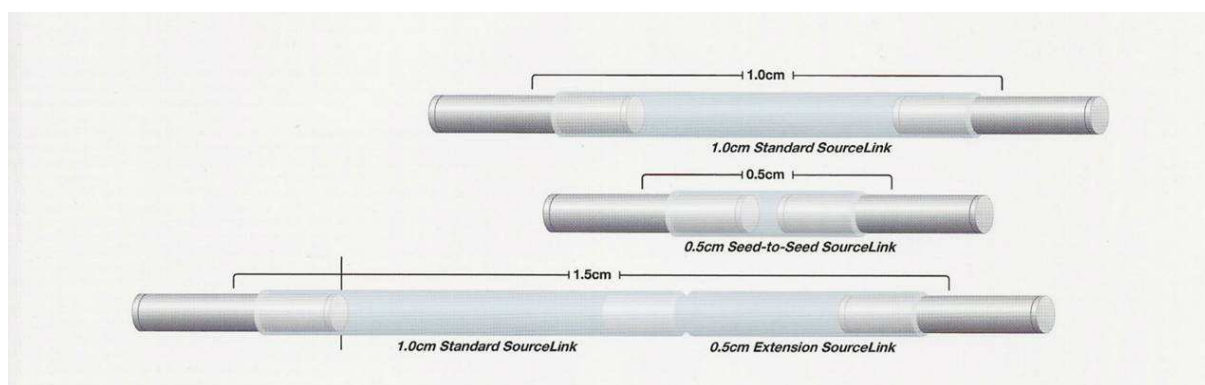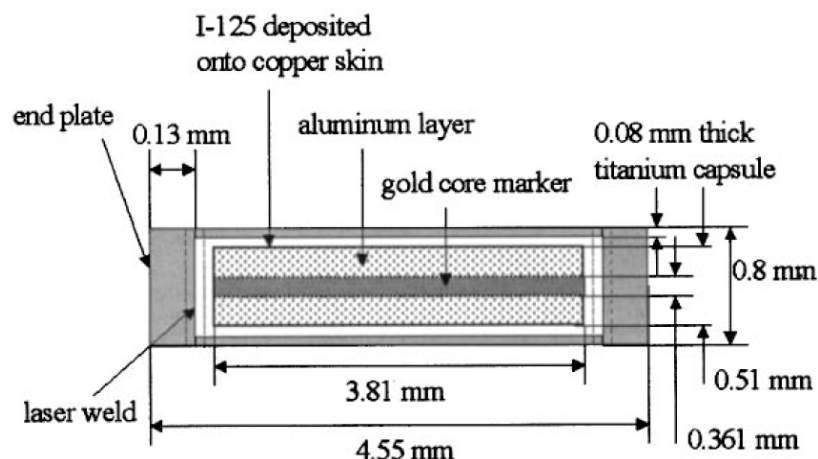
Figure 2: Schematic diagram of the Source Tech Medical model STM1251(top) and examples of the Bard SourceLink system (bottom).

2.1.2 Bebig IsoSeed model I25.S06

IsoSeed source model I25.S06 produced by Bebig (Bebig GmbH, Berlin, Germany) is shown in Figure 3. The source capsule consists of a 0.05 mm thick titanium tube, spherically laser welded at both ends. The welds have a thickness of about 0.44 - 0.48 mm. The radioactive core consists of a 3.5 mm long cylindrical ceramic annulus within which the radioactive ^{125}I is uniformly distributed. A gold rod placed inside the ceramic core, 3.5 mm long and with a 0.17 mm diameter, serves as a radio-opaque marker. The total seed length is 4.56 mm and the external diameter is 0.8 mm [9,10,11].

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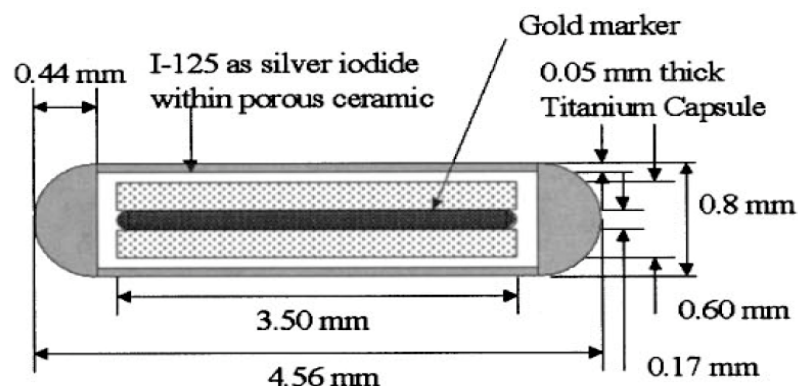
Figure 3: Schematic diagram of the IsoSeed model I25.S06

The energies of the L-edge characteristic x-rays (11-15 keV) produced within the gold core are largely absorbed by the titanium capsule [9].

IsoCord strands are composed of Bebig IsoSeed ^{125}I seeds and spacers separating the seeds and incorporated within suture material (Figure 4). The suture material and spacers are biodegradable within the body.

IsoCord seed chains are wound in a magazine (reel) and can be customized according to the individual needs using the IsoCord needle loading station, i.e. the length of the IsoCord to be implanted can be cut accordingly.

Figure 4: Close-up of IsoCord strand (top) and the cartridge (bottom).

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2.1.3 Bebig IsoSeed model I25.S17

About 2006, a new Bebig IsoSeed model was introduced on the market (Figure 5). The new model I25.S17 has the same hollow titanium encapsulation as used in model I25.S06 (4.5 mm long, 0.80 mm external diameter and 0.05 mm thick). The core of the new seed consists of a cylindrical molybdenum marker that is 3.4 mm long and 0.5 mm in diameter. This marker is larger in diameter than the gold marker used in model I25.S06 to achieve improved x-ray visibility. The molybdenum marker is coated with a nickel and pure silver layer followed by a radioactive silver iodide layer, also covering each end of the marker. The tube is sealed by laser welding of hemi-spherically shaped ends.

Besides the silver characteristic x-ray emissions (22-25 keV) a small but detectable contribution (2%) of molybdenum characteristic x-rays is emitted (17.5-20 keV) [12,13].
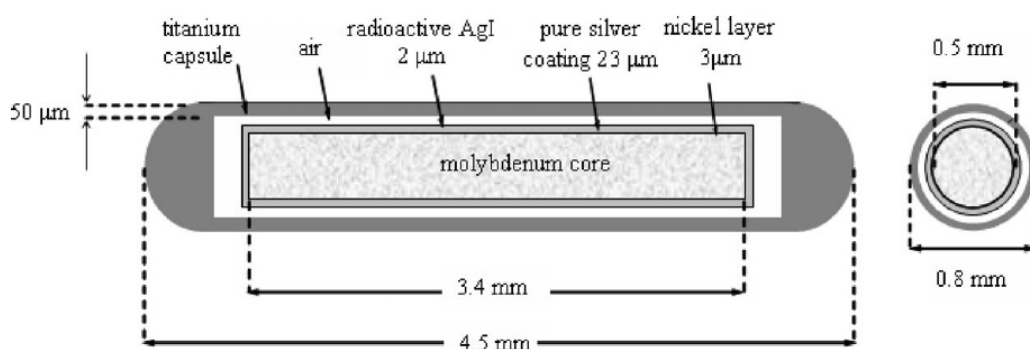
Figure 5: Schematic diagram of the IsoSeed model I25.S17

2.1.4 Best model 2301

The Best model 2301 manufactured by Best Medical International has a physical length of 4.95 mm and an outer diameter of 0.8 mm. The double walled titanium encapsulation, sealed by laser welding at the ends, is designed to provide thin walls at the ends so that the corresponding angular distributions are more isotropic (Figure 6).
A tungsten rod with a length of 3.75 mm and diameter of 0.25 mm serves as the radiographic x-ray marker. This rod is coated with a 0.1 mm thick organic matrix containing [125]I. Unlike in silver markers, no characteristic K-shell x-rays are produced in tungsten during ^{125}I decay.

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The L-edge x-rays are readily absorbed in the encapsulation [8,14,15]. The sources are available in customized strand configurations.
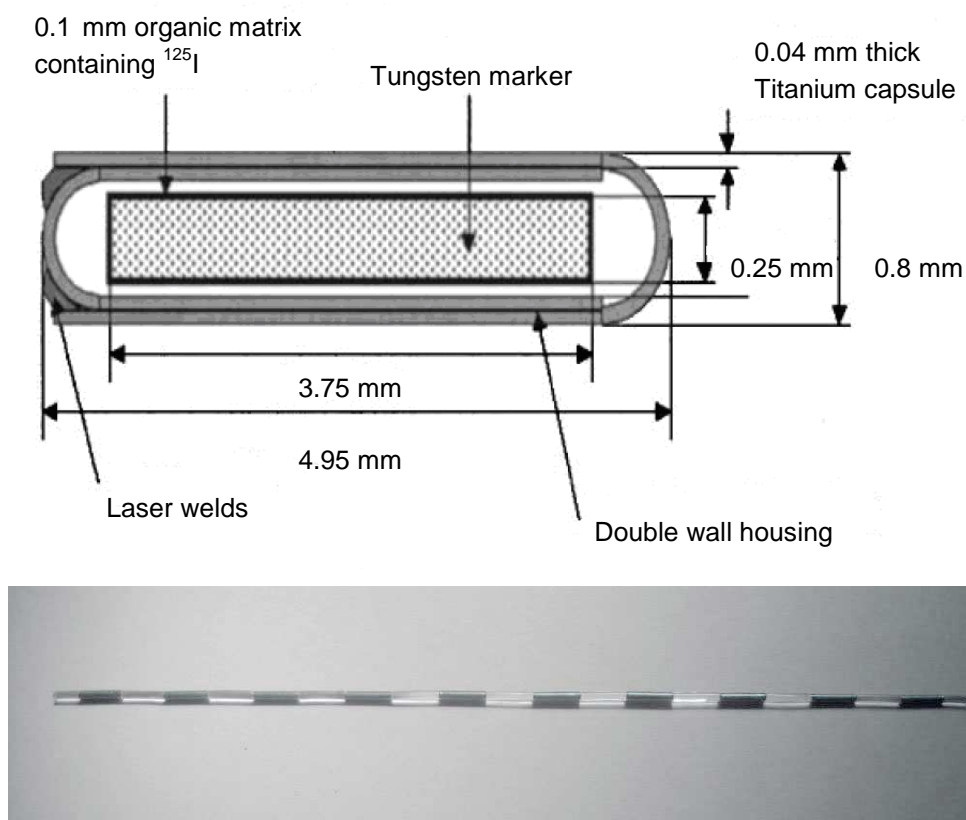
Figure 6: Schematic diagram of the Best ^{125}I model 2301 (top) and an example of a strand configuration (bottom).

2.1.5 IBt InterSource model 1251L

The InterSource model 1251L seeds manufactured by IBt (IBt s.a., Seneffe, Belgium)[2] are composed of two concentric titanium tubes of 0.04 mm wall thickness, laser welded at the edges. All body tissue contacting surfaces inside and outside the hollow seeds are made from medical grade titanium. The sources have a physical length of 4.5 mm and an outer dimension of 0.8 mm (see Figure 7).

On the outer surface of the inner tube a platinum-iridium alloy opaque marker is placed in the central part of the seed. The radioactive ^{125}I solution is deposited onto the outer surface of

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[2] IBt has terminated the production of model 1251L in 2008

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the inner tube as three printed bands (thickness of 0.009 mm for the central band and 0.015 mm for the others). The active length was determined from the distance between the outer edges of the two outer active bands. As there is no silver in the InterSource seed, there are no Ag characteristic x-rays [16,17].

The product Interstrand consists of 10 InterSource hollow seeds threaded onto a monofilament degradable suture. The seeds are spaced 10 mm apart measured centre to centre.
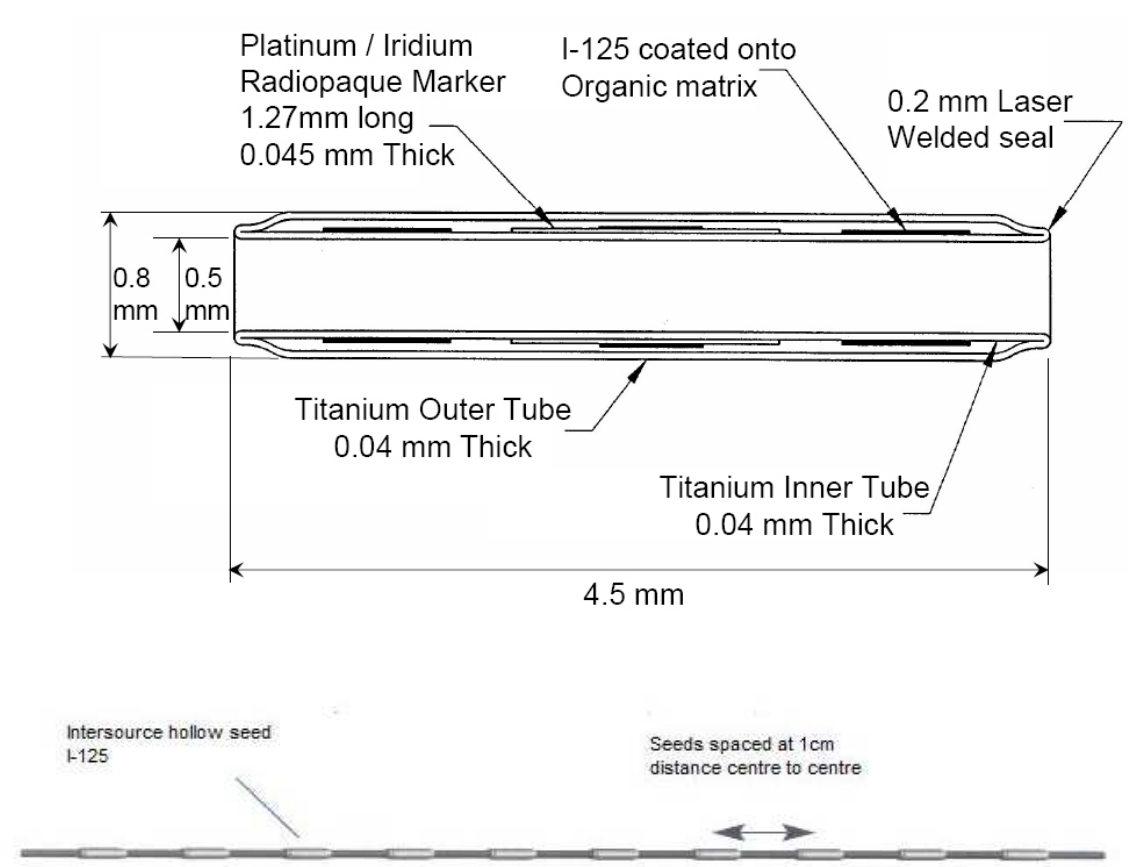
Figure 7: Schematic diagram of the InterSource seed model 1251L (top) and an example of a strand configuration (bottom).

2.1.6 Isotron selectSeed model 130.002

The selectSeed prostate seed (model 130.002) manufactured by Isotron (Isotron Isotopentechnik GmbH, Berlin, Germany) is shown in Figure 8. The core consists of a cylindrical silver rod, 3.4 mm long and 0.5 mm in diameter, coated with a radioactive silver halide layer. This active element is encapsulated in a hollow titanium tube that is sealed by laser welding using hemispherical shaped end welds. The seeds are 4.5 mm long with an external diameter of 0.8 mm [18,19,20].

SelectSeed sources are not available as strands. They are supplied as loose seeds stored in cartridges of maximum 100 seeds and are to be used in an implant procedure with the Nucletron seedSelectron afterloading device [21].
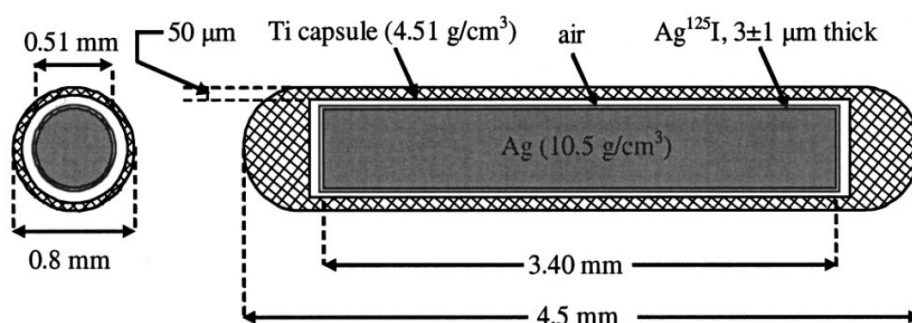
Figure 8: Schematic diagram of the selectSeed model 130.002

2.1.7 Oncura Oncoseed model 6711

The loose seed Oncoseed model 6711 supplied by Oncura Inc. (U.S.) consists of a welded titanium capsule, 0.06 mm wall thickness, whose ends are sealed by arc welding. The seed length is 4.5 mm and the outer diameter 0.8 mm. The titanium tube contains ^{125}I in the form of silver halide adsorbed onto the surface (including the ends) of a radio-opaque silver wire 0.5 mm in diameter and 3 mm long. The internal construction and dimensions of model 6711 are shown in Figure 9.

Beside the photons emitted from the radionuclide itself, fluorescence x-rays (Ag K-edge characteristic) of energies 22.1 and 25.2 keV are emitted from the silver rod [1,2,8,22].

The strand product RAPID Strand is composed of 10 seeds model 6711 alternated by 9 degradable spacers within a bio-degradable braided carrier. The spacers maintain the seed centres at a fixed distance of 10 mm.
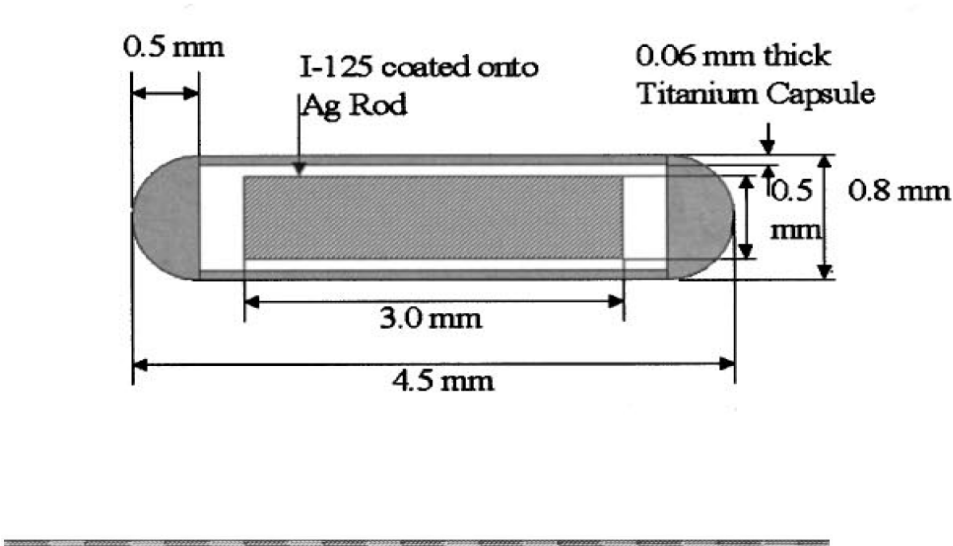
Figure 9: Schematic diagram of the Oncoseed model 6711 (top) and an example of a strand configuration (bottom).

2.2 Dose calculation methods

At present the most commonly used dose calculation algorithm in commercially available treatment planning systems (TPS) is the AAPM TG-43 formalism.

This dosimetry protocol was first published in 1995 by the American Association of Physicists in Medicine (AAPM) Task Group No. 43 [1], introducing a new brachytherapy dose calculation formalism based largely on findings of the Interstitial Collaborative Working Group (ICWG) [23].

The calculation algorithms that were used up to that moment (such as the Sievert integral) provided acceptable dose calculation accuracy for high energy photon sources, but could result in errors of up to 17% for low-energy photon sources such as ^{125}I. The reason is that these older formalisms did not account for variations in source type for encapsulation or internal construction because the input parameters to these algorithms only depended on the radionuclide itself [24]. For more details, see also the TG-43 report and its appendices [1] and the ESTRO booklet No. 8 [25].

The approach of TG-43 was to provide a comprehensive system by:

- formulating an algorithm that generates the dose distribution around a BT source with sufficient accuracy, based on source specific parameters which are derived from a set of measured and calculated dose rate values,
- defining consensus dosimetry data sets of these parameters for a number of commonly used sources,
- providing guidance for researchers on how to determine the dosimetric characteristics of new or existing sources, by combining experimental methods (LiF TLD dose measurements) and Monte Carlo calculations.

It should be noted that the concept of the algorithm was not to formulate the dose calculation based on specific strict physical parameters and principles, but rather to provide a system that allows the calculation of dose distributions around a source (previously determined with measurements and Monte Carlo calculations) starting from a limited number of tabulated parameter values.

For most sources several publications are available presenting TG-43 parameters derived from measured and/or calculated dose rate tables. Slight differences however exist between data on identical sources due to uncertainties introduced by the measuring and calculation

methodology used. Therefore, in order to obtain a better uniformity, it is desirable that an official body collects all data and advises on the use of a unique dataset for each source type and model.

The report published in 1995 presented such recommended dosimetry data for four low-energy photon emitting BT sources (seeds). In the 2004 update (TG-43U1) [2], the AAPM Low Energy interstitial Brachytherapy Dosimetry working group (LEBD, a working group under the AAPM Brachytherapy Subcommittee, BTSC) reviewed the protocol and source data, and included consensus data on six other interstitial BT sources. In the meantime several additional seed sources had become available, and in 2007 consensus datasets for a number of these newer sources were presented in a supplement (TG-43U1S1) [3].

A list of brachytherapy sources meeting the AAPM dosimetric prerequisites including references to the publications taken as evidence of compliance is published on the website of the Radiological Physics Centre [26] in direct collaboration with BTSC.

At the European level, the GEC-ESTRO BRAPHYQS group has published recommended TG-43 data sets on the ESTRO website for most of the high and low-energy sources [27]. The recommended parameters for the seven sources used in clinical practice in Belgium and the Netherlands are also listed in appendix 1 of this report.

2.2.1 AAPM TG-43 Dose calculation formalism

In the TG-43 protocol, both 2D (cylindrically symmetric line-source) and 1D (point-source) dose-calculation formalisms are given, ignoring the true 3-dimensional nature of a source. However this simplification is not likely to introduce additional uncertainties in the dose calculations. An in-depth discussion on this can be found in a paper by Kouwenhoven et al. [28].

2.2.1.1 General 2D formalism

The formalism assumes the dose to be distributed symmetrically with respect to the longitudinal axis of the source. A polar coordinate system is used with its origin located at the centre of the active source and zero angle coinciding with the longitudinal axis of the source. The reference point $P(r_0, \theta_0)$ is taken on the source transverse plane ($\theta_0 = 90°$) at the reference distance of 1 cm (Figure 10).
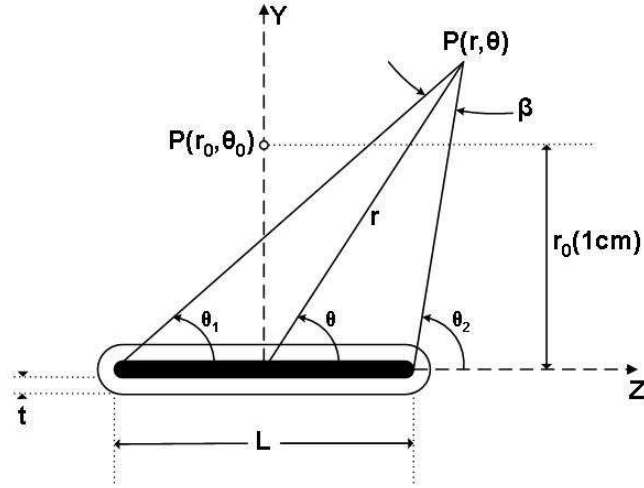
Figure 10: Illustration of geometry assumed in the dose calculation formalism. β is the angle subtended by the active length L at point P. The reference point is represented by $P(r_0, \theta_0)$

The dose rate to water at a point $P(r,\theta)$ can be expressed as

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} \cdot g_L(r) \cdot F(r,\theta) \tag{1}$$

where

$\dot{D}(r,\theta)$ is the absorbed dose rate to water at (r,θ) (in units of cGy h^{-1}),

r is the radial distance from the source centre to the point of interest,

θ is the polar angle,

S_K is the air kerma strength of the source (in units of $U = \mu Gy\ m^2\ h^{-1} = cGy\ cm^2\ h^{-1}$),

Λ is the dose rate constant (in units of $cGy\ h^{-1}\ U^{-1}$ which reduces to cm^{-2}),

$G_L(r,\theta)$ is the geometry function,

$g_L(r)$ is the radial dose function,

$F(r,\theta)$ is the 2D anisotropy function.

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Air kerma strength[3], S_K, is a measure of brachytherapy source strength, which is specified in terms of air kerma rate, $\dot{K}_\delta(d)$, in vacuum and due to photons of energy greater than δ, at distance d, multiplied by the square of this distance, d^2 :

$$S_K = \dot{K}_\delta(d)d^2 \tag{2}$$

In standard dosimetry laboratory conditions, $\dot{K}_\delta(d)$ is usually inferred from transverse plane air kerma rate measurements performed in a free-air geometry at distances large in relation to the maximum linear dimensions of the detector and source, typically of the order of 1 meter.

The dose rate constant, Λ, is defined as ratio of the dose rate to water at the reference point (r_0 = 1 cm on the transverse axis) and the source strength in a water phantom. Mathematically, the dose rate constant, Λ, is

$$\Lambda = \frac{\dot{D}(r_0,\theta_0)}{S_K} \tag{3}$$

The dose-rate constant depends on the radionuclide as well as on the source model and internal design (geometry, encapsulation and self-filtration within the source), and is thus specific for a given source type. As it converts source strength into dose to water, the dose rate constant will also be influenced by the experimental methodology used by the primary standards laboratory (ie NIST) to determine S_K.

The geometry function, $G_X(r,\theta)$, serves to account for the inverse square-law based upon an *approximate model* of the spatial distribution of radioactivity within the source. Photon absorption and scattering in the source or the surrounding medium are taken into account in the radial dose function and anisotropy function.

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[3] The recommended quantity defined by the ICRU is reference air kerma rate (RAKR), due to photons of an energy greater than δ, at a point located at a distance of 1 m from the source centre, in vacuum. By multiplying the reference air kerma rate at a point in free space with the square of the distance to this point the need to specify a reference distance is eliminated.

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The distribution of radioactivity can be approximated as either a point source P or a line source of size L, resulting in the following expressions:

$$G_P(r,\theta) = r^{-2} \qquad \text{point-source approximation} \qquad (4)$$

$$G_L(r,\theta) = \begin{cases} \dfrac{\beta}{Lr\sin\theta} & \theta \neq 0° \\ \left(r^2 - L^2/4\right)^{-1} & \theta = 0° \end{cases} \quad \text{if} \qquad \text{line-source approximation,} \qquad (5)$$

where β is the angle, in radians, subtended by the tips of the hypothetical line source with respect to the calculation point, $P(r, \theta)$.

The geometry function represents the largest variation in dose as a function of distance. By introducing this function the remaining terms of the formalism are less varying with distance, allowing a linear interpolation between the discrete data points at which these parameters are tabulated.

Deviations introduced by representing the true 3D source shape dosimetrically with a 1D point - or 2D line model will be to a large extent taken into account when defining the other factors $g_X(r)$ and $F(r,\theta)$ in the formula. It is thus extremely important to be consistent in the use of data sets: the geometry function used in the patient dose calculation should be the same as the one that was used when determining the basic data for the radial dose function and anisotropy function from measured and calculated dose rate tables.

The radial dose function, $g_X(r)$, accounts for dose fall-off on the transverse-plane due to photon scattering and attenuation, i.e., excluding the inverse square-law correction accounted for by the geometry function. $g_X(r)$ is defined by Eq. (6), and is equal to unity at r_0 = 1 cm.

$$g_X(r) = \frac{\dot{D}(r,\theta_0)}{\dot{D}(r_0,\theta_0)} \frac{G_X(r_0,\theta_0)}{G_X(r,\theta_0)} \qquad (6)$$

The subscript "X" indicates whether a point-source P or line-source L geometry function was used in transforming the data.

The 2D anisotropy function, $F(r,\theta)$, is defined as

$$F(r,\theta) = \frac{\dot{D}(r,\theta)}{\dot{D}(r,\theta_0)} \frac{G_L(r,\theta_0)}{G_L(r,\theta)} \qquad (7)$$

The 2D anisotropy function accounts for the variation in dose as a function of polar angle θ relative to the transverse plane and distance r due to photon scattering and attenuation, i.e. excluding the inverse square law, and is equal to unity at the transverse plane (θ=90°).

2.2.1.2 General 1D formalism

When evaluating implants with a large number of seeds, it is often difficult to determine the exact orientation of the source longitudinal axis for each individual seed. Moreover, many TPS assume the seeds to be oriented parallel to the longitudinal axis of the image set, i.e. perpendicular to the transverse images. Using the 1D point-source approximation (Eq. 8) eliminates the need to determine the orientation of the sources, but as a consequence this model will only approximate the true 2D dose distribution as it will apply an average correction for the anisotropy effects and treat the source as being isotropic.

$$\dot{D}(r) = S_K \cdot \Lambda \cdot \frac{G_X(r,\theta_0)}{G_X(r_0,\theta_0)} \cdot g_X(r) \cdot \phi_{an}(r) \qquad (8)$$

One of the following implementations of Eq. (8) should be used for dose calculation:

$$\dot{D}(r) = S_K \cdot \Lambda \cdot \left(\frac{r_0}{r}\right)^2 \cdot g_P(r) \cdot \phi_{an}(r) \qquad (9)$$

or

$$\dot{D}(r) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta_0)}{G_L(r_0,\theta_0)} \cdot g_L(r) \cdot \phi_{an}(r) \qquad (10)$$

TG-43U1 recommends the use of Eq. (10) because of an improved accuracy at small distances ($r < 1$ cm).

The 1D anisotropy function, $\phi_{an}(r)$ can be seen as an average anisotropy correction as a function of the distance from the source, without considering the exact orientation of the

source. It is defined as the ratio of the solid angle-weighted dose rate, averaged over the 4π steradian space, to the dose rate at the same distance r on the transverse plane, see Eq. (11),

$$\phi_{an}(r) = \frac{\int_0^{\Pi} \dot{D}(r,\theta)\sin(\theta)d\theta}{2\,\dot{D}(r,\theta_0)} \tag{11}$$

Note that one should integrate the dose rate, not the values of the 2D anisotropy function to arrive at $\phi_{an}(r)$.

In the original TG-43 report the 1D anisotropy function was referred to as the anisotropy factor. The continued use of this terminology can create confusion and should be avoided.

The anisotropy constant, $\bar{\phi}_{an}$, was introduced in the original TG-43 report, but its use is no longer recommended in TG-43U1. It represents an even more simplified correction for the anisotropy effects as it is a single average correction factor that is applied at all distances and angles. It is derived from the inverse-square law weighted average of $\phi_{an}(r)$ for $r>1$ cm and constant increments of $r,$

$$\bar{\phi}_{an} = \frac{\sum_{r \geq 1cm}^{r_{max}} \phi_{an}(r).r^{-2}}{\sum_{r \geq 1cm}^{r_{max}} r^{-2}} \tag{12}$$

Some brachytherapy treatment planning systems do not permit the entry of $\phi_{an}(r)$, only the use of the anisotropy constant is possible in the 1D formalism. In this case the following workaround can be applied to implement the more accurate function $\phi_{an}(r)$: in equation (8) $g_X(r)$ and $\phi_{an}(r)$ are replaced by two modified dosimetry parameters, $g'(r)$ and $\bar{\phi}'_{an}$, defined as

$$g'(r) = g_X(r).\phi_{an}(r),$$
$$\bar{\phi}'_{an} = 1. \tag{13}$$

However, this is not a favourable situation, care should be taken to document such a modified data entry properly, in order to prevent possible mistakes or errors later (e.g. when entering data for a new source or updating data).

2.2.2 Limitations and drawbacks of the currently used algorithm

The TG-43 algorithm aims at providing an accurate and consistent dose calculation in reference conditions. The dosimetry parameters used in the formalism are determined in well defined conditions (water-equivalent phantom with fixed dimensions) and the dose distribution in the patient is calculated under the assumption of the same conditions. However, several aspects that influence the clinical dose distribution cannot be accounted for by the TG-43 formalism [25, 29].

Source modelling

In the TG-43 formalism, sources are modelled as lines, rather than as true 3D cylindrical objects. Although it could be possible to extend the formalism to take the 3D shape of the source into account, doing so would have a major impact on the existing treatment planning systems, as the internal structure of all programs would need to be adapted. As mentioned earlier, the uncertainty introduced by this simplification is expected to be very limited, as the effect is corrected for in the determination of $g(r)$ and $F(r,\theta)$.

Tissue density and composition

The TG-43 formalism does not provide for tissue heterogeneity and composition correction. The dose is calculated for the medium that was used when determining the reference dose rate tables and TG-43 parameters, and this is recommended to be water. For interstitial implants and high energy sources the dose calculated with water as reference medium should not deviate significantly from the dose in the patient as the high energy photons will show a similar behaviour in tissue as in water. For low-energy sources the effect can be more pronounced, as the importance of the photo-electric effect increases with decreasing energy. Certainly, when using these sources in tissues of density deviating strongly from water care should be taken to evaluate the importance of this uncertainty e.g. by comparison with Monte Carlo calculations. The impact of tissue composition compared to water can amount up to 4% for the D90 parameter in prostate brachytherapy [30].

Lack of full scatter

Most TPS assume infinite and full scatter conditions, similar to the conditions of the TG-43 formalism. For the use of seeds in permanent prostate brachytherapy this assumption is valid, given the large distance to the body surface. However when calculating the dose for

implants close to the skin it should be taken into account that the dose close to the skin is overestimated by the TPS.

Intersource effects

If several sources are implanted at close distance, each source will influence the dose distribution from the neighbouring sources and absorb to some extent the radiation emitted by these sources. The size of this effect will depend on the number of sources, their composition, the photon energy emitted and the geometry. In situations where a large number of sources is implanted such as a typical prostate implant using ^{125}I, the peripheral dose might be reduced by up to 6% by this effect [5]. Carrier et al [30] reported differences up to 3% on the D90 value when the intersource effect was taken into account.

Abboud et al. [31] compared the dose distribution calculated with Monte Carlo to the standard clinical dose calculation using a TG-43-based commercial system for 10 patients. Large differences were observed close to the seeds which are known to be due to the limitations of the TG-43 formalism at close distance to the source. In this evaluation differences due to the intersource effect approaching 10% were observed, however dependent on the seed arrangement.

3. Calibration methods and standards

3.1 Primary standards for low-energy photon sources

Until recently only the National Institute of Standards and Technology (NIST, U.S.) could provide calibrations for ^{125}I and [103]Pd in terms of the quantity reference air kerma rate (RAKR) or air kerma strength. Before 1999 the Ritz free-air chamber was used for the calibration of seeds. Single seed measurements were not possible, due to its relatively small collecting volume and the low signal produced by LEP sources. Since 1999, the measurement of source strength for low-energy photon sources is based on a new primary standard, the wide angle free air chamber (WAFAC) developed by Loevinger [32]. The WAFAC has a variable volume with an entrance aperture located 30 cm from the seed defining a conical beam with a half angle of about 8°. The x-rays emitted by the source pass through aluminized Mylar electrodes and collected charge is measured at two different volumes to account for interface effects. An aluminium filter is placed between the seed and the free-air chamber to remove the 4.5 keV Ti x-rays from the seed. The much larger solid angle of the WAFAC compared to the Ritz chamber results in an improved sensitivity and signal-to-background ratio for the WAFAC. Its characteristics allowed the measurement of single sources with source strengths at levels suitable for clinical applications. In 2003 a computer controlled version of the WAFAC was introduced [33]. A photograph of the WAFAC is shown in Figure 11.

The WAFAC standard is used to establish calibrations for many ^{125}I and [103]Pd sources introduced to the market. Calibrated standard sources are transferred to secondary standard dosimetry laboratories (SSDLs) in order to calibrate sources and well-type ionisation chambers for users [34].

The combined relative standard uncertainty of a calibration of a single seed performed with the WAFAC is estimated to vary between 0.8 and 2.1% (k=1) [33, 35]. This measurement uncertainty includes the Type B uncertainties of several correction factors, most of which are fixed for the different seed types. The variation in the combined relative standard uncertainty is depending on the reproducibility (Type A contribution) of the net ionisation current, produced by different seed models.

It should be noted that the reported combined relative standard uncertainty for the WAFAC includes the up-down variability of the seed measurement and the effect on S_K of azimuthal anisotropy of the seed.

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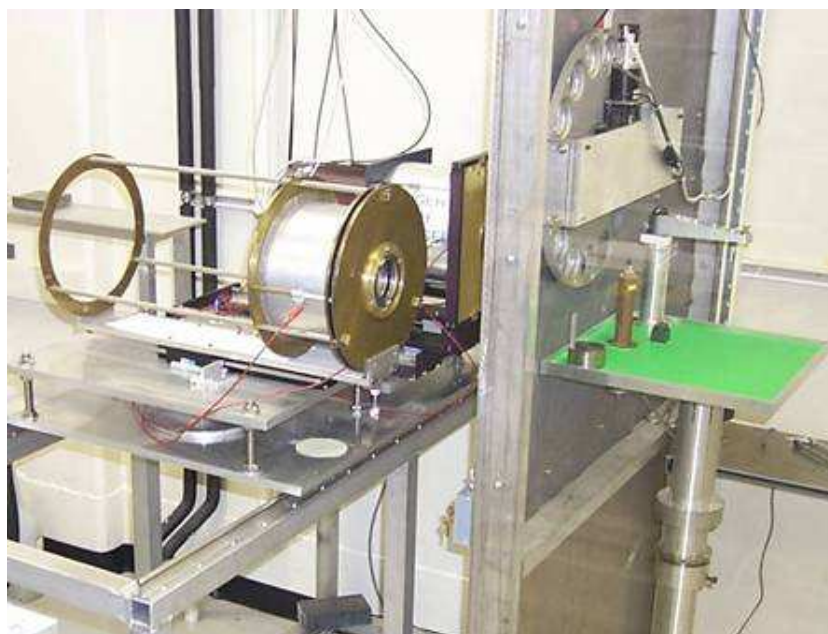
Figure 11: The Wide Angle Free Air chamber (WAFAC) maintained at NIST

In Europe the first operational primary standard to measure the reference air kerma rate of low-energy photon sources was developed at the Physikalisch Technische Bundesanstalt (PTB). The standard is a large air-filled parallel-plate extrapolation chamber with thin graphite front and back electrodes, named the Grossvolumen Extrapolationskammer (GROVEX). The distance between the electrodes is adjustable from $0 - 20$ cm. The source to be measured is mounted vertically on the tip of a thin PMMA rod and is rotated during measurement to eliminate the influence of any anisotropy perpendicular to the source axis. A 5 mm lead shutter is inserted for background and leakage measurements, which can be removed for normal ionisation measurements. Similar to the WAFAC a 0.1 mm thick aluminium filter is installed between the source and the chamber to eliminate the characteristic Ti x-rays. The expanded relative uncertainty for the calibration of a single seed with the GROVEX is 1.8% (k=2). This value is exclusive uncertainty contributions for decay correction and anisotropy. Estimates given by PTB for the uncertainty contribution of (polar) anisotropy based on a study of four different seeds amount to 1.2% (k=2). Note that the uncertainty associated with the azimuthal anisotropy is included in the relative expanded uncertainty of 1.8%, due to the rotation of the source during calibration. If these latter contributions are added, the total uncertainty for the calibration of a specific source is estimated to be less than 3% (k=2). A

detailed description of the GROVEX is given in reference [36]. A picture of the GROVEX is shown in Figure 12.

Figure 12: The GROVEX extrapolation chamber maintained at PTB

Also the Laboratoire National Henri Becquerel (LNHB, France) has designed a novel, circular free-air chamber for future air kerma source strength measurements of ^{125}I and ^{103}Pd sources. The chamber has the shape of a torus and therefore rotation of the source during measurement, to compensate for the anisotropy of the emitted radiation along its axis, is no longer a necessity. The chamber will have a fixed volume and no moving parts. However, the chamber is still under development [37].

Several European national metrology institutes (NMIs) are developing primary standards based on absorbed dose to water for HDR and LDR brachytherapy sources within the framework of a EURAMET co-ordinated research project, but the discussion of these standards is outside the scope of this report [38].

3.2 Calibration services in Europe

Traceable calibration services for low-energy photon sources are offered by a limited number of NMIs. All services are based on measurement standards realising the quantity reference air kerma rate. As already mentioned the PTB (Germany) operates the only available primary standard for these sources in Europe. PTB provides direct calibration of well chambers, ^{125}I and ^{103}Pd sources.

The National Physical Laboratory (NPL, UK) offers air kerma rate calibrations for ^{125}I seeds using a secondary standard radionuclide calibrator [39]. The calibration coefficient of the radionuclide calibrator (well-type chamber) is made traceable to the NPL primary standard for air kerma using a spherical ionisation chamber with a thin, graphite-coated carbon fibre wall. The spherical transfer chamber has a volume of 3000 cm^3. The primary air kerma measurement is performed at 1 m from the ^{125}I seed using the spherical transfer chamber. The transfer chamber is calibrated with ISO/IEC 4037 Narrow Spectrum Series beams, and the calibration coefficient for ^{125}I is taken as the average of the calibration coefficients at beam energies of 25 keV and 33 keV respectively. To account for the anisotropy of the emitted radiation from the source, the seed is rotated at 45° intervals around its long axis during the measurements. As the source is at 1 m from the chamber in air, no filter is needed to eliminate the 4.5 keV Ti x-rays from the spectrum emitted by the source. The expanded relative uncertainty (k=2) for an air kerma rate calibration of ^{125}I seeds is 5.6%.

The vast majority of European countries, like Belgium and The Netherlands have no measurement services available nor under development to calibrate ^{125}I and ^{103}Pd sources in terms of reference air kerma rate. The current situation is very undesirable and not likely to change in the near future.

An alternative method is offered by the seed manufacturers. Several manufacturers offer the user the possibility to order seeds which have been individually measured, and which come with a traceable calibration certificate issued by the manufacturer stating the source strength of each seed individually. Such seeds can then be used to calibrate the measurement equipment used in the hospital. The disadvantage of this method is that the measurements performed by the manufacturer and the user are not fully independent. This is due to the fact that all measurements are traceable to the same NIST calibration coefficients for the particular seed model.

Also vendors of measurement equipment for quality control of brachytherapy LEP sources can offer calibration services termed as factory based calibrations. Often these services,

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delivered by seed manufacturers or by suppliers of measurement equipment, do not comply fully with the requirements for traceability and accreditation, and are therefore not recommended. If a user has no access to a traceable calibration service, factory calibrated measuring equipment may be preferred over non-calibrated equipment.

3.3 Calibration and QC performed by the manufacturer

3.3.1 NIST traceability

To ensure accurate clinical dosimetry a precisely known value of the air kerma strength for LEP sources is of utmost importance. The AAPM has recommended that calibrations in terms of air kerma of all brachytherapy sources should be directly traceable to NIST or to an Accredited Dosimetry Calibration Laboratory (ADCL).

In 2004, the Calibration Laboratory Accreditation Subcommittee (CLA) of the AAPM issued procedures to establish and maintain the dosimetric traceability of LEP sources to air kerma strength standards [40]. Source manufacturers have to comply with these procedures when introducing new sources to the U.S. market and for sources previously introduced in the market. An important aspect of the CLA procedures is the periodic verification of the air kerma strength value assigned by NIST to each particular source model produced by a manufacturer. Therefore all seed manufacturers (re-)calibrate their equipment with seeds that are directly traceable to NIST. Once or twice per year, depending on the manufacturer's policy, three high-activity standard production seeds are sent to NIST for measurement in the WAFAC standard. Based on the measured air kerma strength stated on the NIST certificate, the manufacturers use the calibration results as a consistency check on the value of the established air kerma strength for their sources and on the calibration coefficients of their measurement equipment. For every periodic re-calibration of a source model the calibration coefficient should deviate less than ± 2.0% from prior values of the calibration coefficient determined by NIST. If the deviation is equal to or greater than ± 2.0% from the initially measured value by NIST the cause has to be investigated.

As most SSDL's, manufacturers and users utilise well chambers to maintain traceability to NIST, it is important to understand the relationship between the WAFAC and well chamber calibrations. The response of the well chamber relative to the WAFAC has been shown to depend on the emitted spectral distribution of the source and on anisotropy variations in seed emissions [41]. Therefore additional measurements in well chambers and angular x-ray

spectrometry are conducted at NIST during the periodic re-calibrations of every seed model. The NIST data including those from the ADCLs and data from the manufacturers are compiled and monitored over time to ensure the validity of the calibrations and to reveal any unexpected changes in seed characteristics during production.

3.3.2 Source strength determination performed by the manufacturers

The information discussed in this section was retrieved from a questionnaire sent to vendors of the seed models discussed in section 2.1 and from documents, which accompanied purchased batches of seeds or strands for clinical use. It has to be noted that most of information presented in this section was compiled in the period 2005-2007. In general manufacturers base their reference measurements on calibrated well-type ionisation chambers used for source strength measurements and the quality control of sources during various production stages. All seed manufacturers have at least one reference chamber that is periodically calibrated with a seed of which the source strength was measured directly at NIST. The number and types of available instruments and the applied calibration uncertainties differ between various seed suppliers.

Seeds are sold by the manufacturer in ranges (bins) based on source strength measurements. The seeds are divided into several classes with a certain nominal value, and a source strength range varying from $\pm$ 2 to $\pm$ 5%. Generally the nominal values of these bins are based on the 7 day decay of ^{125}I, which is 0.9216 or approximately 8%. For a bin range of $\pm$ 4%, this implies that each class covers the source strength values of approximately one week. Therefore, seeds are ordered with a nominal source strength value which is associated with a fixed calibration day. Below some manufacturer specific conditions are described.

A. Bard Source Tech Medical model STM1251
Seeds are sold in 21 activity ranges (0.18 – 0.995 mCi), based on the apparent activity of the source. Each range is characterised by a low, upper and midpoint value expressed in mCi. The seeds are supplied loose or loaded in shielded disposable Mick magazines (cartridges). Special calibration seeds may be ordered from Bard, which are calibrated in a re-entrant ionisation chamber with a measured calibration coefficient traceable to NIST. The relative uncertainty in the source strength of calibrated seeds or in assayed sources is estimated to be ± 5%. No coverage factor, nor level of confidence is stated. Bard uses a ^{125}I half-life value of 59.6 days to correct for decay.

B. Bebig IsoSeed models I25.S06 and I25.S17

Sources are delivered as single seeds or as strands. Seeds are divided into several activity classes by measuring the apparent activity of each seed. Every single seed is positioned in the centre of a cylindrical detector array consisting of eight silicon detectors. This detector array is calibrated periodically (every 6 months) with NIST certified seeds. Based on the mean value of the apparent activities measured with these eight detectors, the production seeds are classified into activity classes with a bin range of $\pm$ 4%. The seed classes correspond approximately to the weekly decay rate of ^{125}I.

The total uncertainty of the individual seed measurements during division in classes is stated to be < 3.0% by the manufacturer. However, no information with respect to the coverage factor is stated. The uncertainty includes the uncertainty contributions associated with the NIST calibration, Type A and B contributions related to the measurement set-up and the detector device. Each class of sources is characterized by a minimum, maximum and midpoint activity level.

For each order of a customer, a random sample of 10 percent of the number of ordered seeds is re-measured in a CAPINTEC CRC7BT well chamber for final proof of the source strength. This well chamber is calibrated directly with the same NIST certified seeds as the silicon detector array. The stability of the calibration coefficients of the measurement instruments are maintained by daily checks using NIST traceable calibrated IsoSeeds. Calibration coefficients are adjusted if the test results deviate from previously obtained calibration coefficients by more than 1%.

Special calibration seeds can be ordered, of which the source strength is measured in two orientations (up and down position by reversing the seed in the adapter). In total 10 measurement runs are performed, 5 runs with the seed in the up position and 5 runs in the down position. The 10 measurements are averaged to give a mean value for the air kerma strength ($\mu Gy\ m^2\ h^{-1}$). However, no uncertainty is stated on the calibration certificate. A half-life value of 59.46 days was used by Bebig to correct for decay. Currently Bebig uses a half-life value of 59.40 days.

C. IBt InterSource model 1251L[4]

The source strength of the seeds in the production process is determined with a double CZT (Cadmium Zinc Telluride) solid state x-ray detector. This CZT detector is calibrated with respect to a reference well chamber (CAPINTEC) by means of standard production seeds.

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[4] IBt has terminated the production of model 1251L in 2008.

Several CAPINTEC well chambers are available which are calibrated with seeds that are directly certified at NIST. The calibration coefficients of the well chambers are adjusted, if subsequent re-calibrations with seeds measured at NIST show deviations of more than 1.5%. Daily checks to verify the response stability of the well-type chambers are performed with barium-133 and cesium-137 sources. The half life values for these radionuclides are respectively 10.5 years and 30.2 years. Deviations between stability test results are kept below 1%.

The CZT detector is daily checked with the reference chamber using standard production seeds. Based on individual seed measurements in the CZT detector, the seeds are sorted in source strength classes. The bins have a range of ± 2%. A sample of each bin undergoes an independent re-assay of the source strength in the well chamber. Any deviation of more than 1.5% between the measurement in the CZT detector and the well chamber results in a re-assay of the entire bin of the lot. During the production process spectra of sample seeds from each run are measured with a high purity germanium detector system to look for impurities. With the CZT detector the equatorial anisotropy is measured for every individual seed. A half-life value of 59.4 days is used by IBt to correct for decay.

D. Isotron selectSeed model 130.002

To determine the strength of the seeds, eight detectors are available each with a sensor head consisting of a Si-pin diode. These detectors are calibrated on a regular basis (every six months) with seeds directly traceable to NIST. The response stability of the detector is daily checked with production seeds that are cross-checked against the NIST certified seeds with an acceptance tolerance of ± 0.8%.

The source strength of each seed is measured in all eight detectors through an automated procedure. According to the mean source strength calculated from these measurements, the seeds are assigned to the appropriate classes. These classes have a bin range of ± 4%. Hence, the nominal source strength values of successive classes correspond approximately with the weekly decay rate of ^{125}I.

Calibrated seeds ordered from Isotron are also measured in two orientations. According to the manufacturer in total 20 measurement runs are performed, 10 runs in either orientation. The results are averaged to give a mean value for the source strength. A half-life value of 59.46 days is used by Isotron to correct for decay.

E. Oncura Oncoseed model 6711

Individual Oncoseeds model 6711 can be loaded in Mick cartridges and are also available as strands (Model 7000 RAPID Strand).

The NIST certified seeds are used bi-annually to calibrate the "Metrology" Well Chamber (Capintec CRC127R). This chamber is used as the local reference standard to which the other production well chambers (Capintec CRC127R) are calibrated by means of standard production seeds. In between two NIST calibrations, the stability of all chambers is controlled on a daily basis using a ^{241}Am check source (half-life of 432 years). The daily readings with the check source should remain constant to within ± 0.5%.

Based on source strength measurements, the seeds are divided into several classes with a certain nominal value, and a source strength range of ± 4%. The nominal values of these bins are based on the 7 day decay rate of ^{125}I. The relative expanded uncertainty on reported seed strength measurements of purchased seeds is stated to be ± 7.0% (k=2).

Individually calibrated seeds can be provided for use as equipment reference sources. The relative expanded uncertainty in the determination of the source strength of these special calibrated seeds is estimated to be ± 3.5% (k=2). Oncura uses a half-life value of 59.43 days to correct for decay.

3.3.3 Additional quality assurance tests performed by the seed manufacturers

After seed assembly, all manufacturers perform some tests to ensure the quality of the seeds. Before measurement of the source strength, each radioactive seed undergoes a leakage test. In addition, each seed is subjected to an optical inspection of the dimensions and welding, either automated or manually, in order to intercept irregularities in shape. Tests are performed on each seed to ensure that the anisotropic dose distribution falls within the specific tolerance limits of the manufacturers. Seeds that do not meet all requirements are removed from the lot.

3.4 Notes on the use of well-type chambers for QC measurements

Well-type ionisation chambers for brachytherapy source strength measurement should be of the type designed for radiotherapy applications and capable of measuring the (reference) air kerma rate of LEP sources [34]. Due to the nearly 4π geometry and the large detection volume, the ionisation signal is high and easy to measure with sufficient precision. The long

term stability is generally in the order of 0.5% over a period of several years. It is recommended to use well-type chambers open to the atmosphere. The use of sealed chambers is discouraged, because the gas is at a higher pressure than the ambient atmospheric pressure. These chambers may develop a problem of slow leakage of the gas. In such cases a change in the calibration coefficient of the chamber would result. Well chambers vented to the atmosphere need to be corrected for temperature and pressure[5] since the calibration coefficient is based upon the density of air corresponding to standard ambient conditions.

Pressurized well-type chambers used for Nuclear Medicine applications are not recommended for brachytherapy measurements due to the following reasons:

- The chambers have settings for given radionuclides, but not for brachytherapy sources.

- The chambers measure only in units of activity.

- Without close control, the general use of the chamber may result in contamination from nuclear medicine procedures.

- Since the gas may leak from the pressurized volume, the response may change over time.

- The thick walls required for the pressurization may absorb a significant part of the radiation to be measured. This may result in a high energy dependence, which is particularly emphasized when measuring LEP sources, such as ^{125}I and ^{103}Pd seeds.

Constancy tests should be performed to check for possible drift in the response of the chamber at regular intervals with a long-lived radioactive source, e.g. ^{137}Cs or ^{241}Am. The check sources should be inserted into the chamber in a reproducible way using an appropriate spacer and/or holder. Readings using the check sources, corrected for temperature, pressure and decay of the source, should remain constant to within ± 0.5%.

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[5] Griffin et.al. [42] pointed out that for LEP sources the response of Standard Imaging well chambers may be affected by changes in low atmospheric pressure conditions. For low atmospheric pressure conditions the authors provide an additional factor to correct the well chamber response appropriately to standard temperature and pressure. For the ambient pressure conditions prevailing during the NCS on-site visits this additional correction factor could be neglected. The NCS subcommittee is not aware of any publication reporting such effect for other types of well chambers available for QC measurements of LEP brachytherapy sources.

4 Survey of clinical practice

In order to study the clinically applied QC procedures with respect to the use of LEP sources, the subcommission decided to start by conducting a survey in the radiotherapy institutes in Belgium and the Netherlands. The questionnaire was first sent in 2004 and updated in January 2006. All centres performing PPBT responded: 22 RT departments in Belgium and 12 RT departments in the Netherlands.

4.1 Applications and patient load

Only the use of ^{125}I sources was reported, most often for PPBT, but also for eye and breast treatments (each in 1 institute). Estimated patient load is presented in chapter 1.4 (Figure 1).

4.2 Type of sources

The different seed models/brands used are presented in Table 1.

Table 1: Number of users of different source models in Belgium (Be) and the Netherlands (Nl) at the time of the survey (January 2006).

		BE	NL	TOT
Oncura	**6711** (RAPID Strand)	10	5	15
IBt	**1251L** (InterSource)	7	1	8
	1251L (Interstrand)	4	6	10
Bebig	**I25.S06** (IsoSeed)	1	-	1
	I25.S17 (IsoCord)	1	-	1
Bard	**STM1251**	1	-	1
Isotron	**130.002** (selectSeed)	-	1	1

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[125]I sources are used as single seeds and in prostate BT also as seeds packed in Mick cartridges or linked together in strands. Most manufacturers can supply their seeds in any of these different forms. Which form is used by an institute will be related to the application technique that it applies, each having specific advantages and possible shortcomings.

4.3 Source Calibration

Table 2: QC instruments used in the different institutes in Belgium and the Netherlands. Number of instruments of each brand is indicated on the graph.

	BE	NL	TOT
None	5	1	6
PTW SourceCheck	9	1	10
SI (HDR1000/IVB1000)	4	4	8
NA 34-070	3	3	6
Capintec (CRC-10/CRC-15R)	2	1	3
Veenstra VDC-303	-	1	1
Sun Nuclear 100840	-	1	1

There is a large variety in QC instruments and methods for verifying the source strength of the seeds (Table 2). In total 6 out of the 34 institutes reported not having a specific instrument to verify the source strength of the seeds used for PPBT. Of the 29 instruments available in the hospitals only 3 were calibrated at SSDL-level (all at an Accredited Dosimetry Calibration Laboratory), 4 were calibrated by the manufacturer (the PTW instruments).

Figure 13 gives an overview of the number of hospitals performing clinical routine measurements to check the source strength of purchased seeds or strands. Eighteen institutes reported not performing any measurement in clinical routine. Of the remaining centres some measured all seeds/strands before use, some took a sample of a few seeds, while others measured some of the remaining seeds after the implantation. Major reasons mentioned for not measuring were: (1) handling of seeds/strands in sterile conditions, (2) inappropriate measurement equipment to handle stranded seeds or seeds in cartridges. Four

hospitals performed routine checks using calibrated instruments and 12 hospitals performed measurements without calibrated equipment. It should be noted that in this graph "factory calibrated" instruments are counted as calibrated equipment.
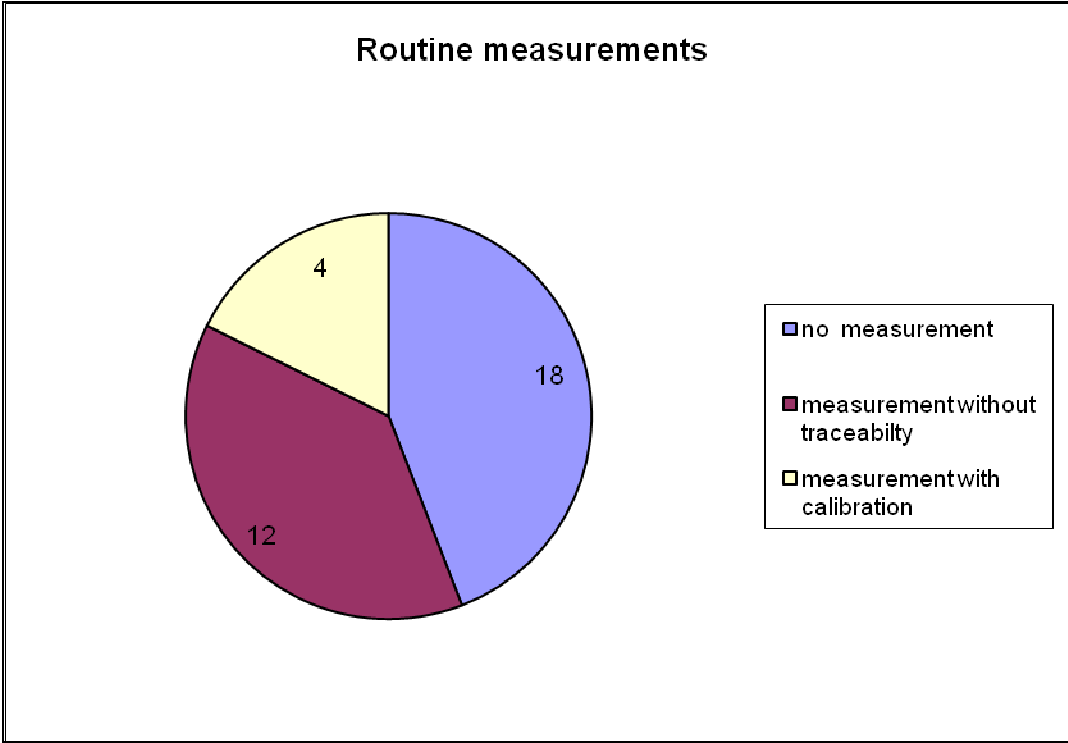
Figure 13: Routine measurements performed by the participating institutes in the period 2005-2007.

Thirty institutes participated in the NCS source strength measurements during the on-site visits and in 15 institutes the local medical physicist performed in-house measurements during the visits. The in-house measurements performed by participating institutes in the period 2005-2007 will be discussed further in section 5.1.8.

4.4 Treatment planning systems

Table 3: Treatment planning systems used for dose calculation in PPBT.

	BE	NL	TOT
Variseed	21	9	30
Prowess	1	1	2
PSID	1	1	2
SPOTpro	-	1	1

Four different TPS systems were encountered, of which VariSeed (Varian) was most frequently used (Table 3). In all TPS systems, AAPM TG-43 based dose formalism and algorithms are implemented. A large variability was observed in the calculation model applied by the institute (point-source or line-source approximation), and anisotropy correction (constant, 1D function or 2D function). Nine centres still applied the anisotropy constant as correction factor, while this is no longer recommended by AAPM TG-43U1 since 2004.

5 Dosimetry comparisons by visiting team

5.1 Seed strength determination

5.1.1 Introduction

An independent and periodic verification of the source strength of delivered seeds in Belgian and Dutch radiotherapy institutes is not common practice and is even lacking in many hospitals. Therefore data on the agreement between the source strength as stated by the manufacturer and actually measured values is hardly available. In order to gain insight in the practice in Belgium and the Netherlands on-site visits were organized. The dosimetric part of an on-site visit consisted of a measurement of the source strength and investigation of the local verification procedure, if available. The verification measurements were performed by the visiting team with a well-type ionisation chamber and a device specifically designed for the source strength measurement of seeds. Both instruments were calibrated directly traceable to NIST for all seed types in use at the radiotherapy institutes in Belgium and the Netherlands during the on-site visits. The results of the measurements were compared with the values for the air kerma strength stated by the supplier or manufacturer for the seeds used in the investigation.

5.1.2 Measurement equipment

The measurement equipment for the source strength measurements of seeds consisted of a well-type ionisation chamber type IVB1000 manufactured by Standard Imaging and a flat ionisation chamber device from PTW (SourceCheck, type 34051). Both instruments are specially designed for source strength measurement of brachytherapy sources and have vent holes for maintaining the internal air at ambient atmospheric pressure. Each instrument is equipped with various adapters or inserts to accommodate for commercially available seed types. Ancillary equipment was available to measure the ambient air conditions, i.e. temperature, pressure and relative humidity on location. The IVB1000 chamber and the SourceCheck device were used with high sensitive PTW electrometers of type Unidos E and Unidos respectively. These electrometers have a reading in current or charge, a wide dynamic range and an interval time function.

The IVB1000 well-type chamber of Standard Imaging has an active volume of 475 cm^3, a height of 25.9 cm and an outer diameter of 10.2 cm. The height and diameter of the well are 22.4 cm and 3.5 cm respectively. The device was specifically designed for measurement of intravascular brachytherapy sources, but its characteristics are also suitable for measurement of low-energy photon sources, e.g. ^{125}I and ^{103}Pd. The chamber has a very stable axial response: typically ± 0.3% for an LDR ^{192}Ir source over 100 mm around the centre of the cylindrical axis ("sweet spot"). The IVB1000 is operated at + 300 V. The voltage polarity effect is expected to be less than 0.1%. For ^{125}I sources the current to air kerma strength sensitivity is typically 4.3 pA/U (1U = 1 $\mu Gy\ m^2\ h^{-1}$). In Figure 14a the device is shown connected to a PTW Unidos E electrometer. In Figure 14b the adapter is shown, which is used for single seeds.
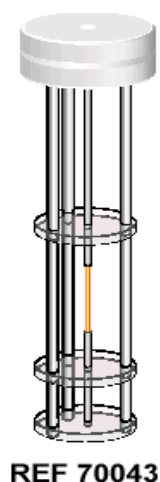
(a)   (b)

Figure 14: Measuring device used for the on-site visits: well-type chamber (IVB1000, Standard Imaging) connected to an electrometer PTW Unidos E (a), together with the insert for seeds (b).

The PTW SourceCheck device has a guide tube located at the centre of the chamber allowing the radioactive seeds to be introduced from either side (See Figure 15a). The device has a sensitive volume of 55 cm^3, outer dimensions of 220 mm x 60 mm x 14 mm and is operated at a chamber voltage of + 400 V. The SourceCheck device should be handled with care, because it showed to be sensitive to physical contact. For all measurements of seeds located inside the chamber, the device is placed between two PMMA backscatter phantoms

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to define backscatter and shielding conditions. Special adapters for inserting single seeds in the guide tube are available (see Figure 15b). Note that these adapters can be placed in the left or right entry of the guide tube. When source trains (e.g. segmented or complete strands) are measured the backscatter phantom is removed from the upper side of the chamber and replaced by an appropriate strand adapter. Note that the sources are placed in the adapter on the flat top side of the device.

(a)   (b)
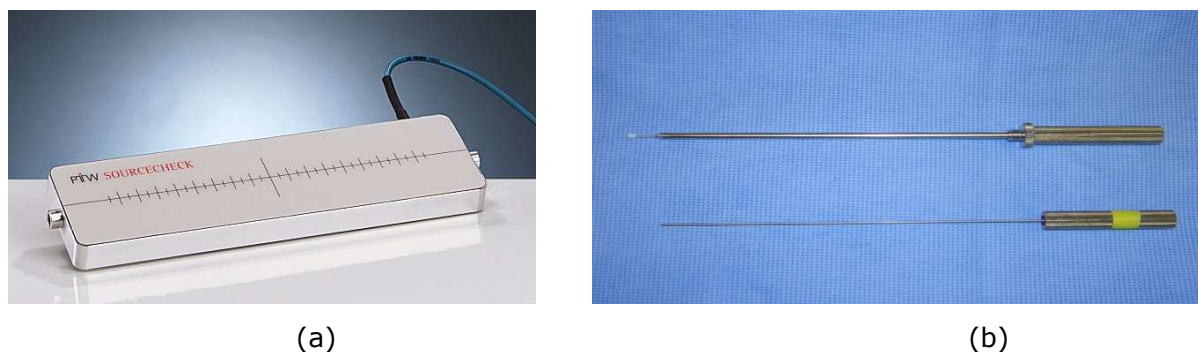
Figure 15: Measuring device used for the on-site visits: the PTW SourceCheck device (a), together with special adaptors for single seed measurement (b). The SourceCheck was connected to a PTW Unidos E electrometer.

5.1.3 Pre-measurement tests

Test measurements were performed to check the characteristics of the equipment, (e.g. background signal, leakage, stability of response, linearity) and to define measurement settings for single seed and strand measurements. A difference in sensitivity was noted depending on the entry of the PTW SourceCheck guide tube, chosen to insert the seed adapter. Therefore all calibration and on-site measurements for single seeds were carried out using the same entry of the guide tube. To check the long term stability regular measurements were performed using a constancy check source. A ^{226}Ra source and a ^{90}Sr-^{90}Y source were used for the IVB1000 and the SourceCheck 34051 respectively.

5.1.4 Calibration of instruments

The IVB1000 well-type chamber and the PTW SourceCheck device were calibrated for the seed types in use in Belgian and Dutch radiotherapy centres during the on-site visits. As a first step individual seeds were directly calibrated in terms of air kerma strength ($\mu Gy\ m^2\ h^{-1}$)

against the WAFAC primary standard at NIST for all vendors involved. The individual seeds were provided by the vendors and after calibration at NIST the seeds were transferred to the Van Swinden Laboratorium (VSL, Delft). However the seeds provided by Bebig GmbH were calibrated at PTB, using the GROVEX primary standard. At VSL the seeds were measured in the secondary standard well chamber facility of VSL and in the Standard Imaging IVB1000 and PTW SourceCheck equipment respectively using appropriate adapter/inserts. From these measurements calibration coefficients were obtained for all seed types examined during the on-site measurements. The calibration coefficients for the various seeds obtained with the VSL secondary standard facility were used for reference purposes. It should be emphasized that for every seed type the geometrical conditions for the measurement equipment, the position of the seed in the sensitive area (or well) of the detector and the insert applied were the same during the calibration and the on-site measurement. All individual seeds were measured twice by reversing the orientation of the seed in the insert before placing it in the well or tube guide ("up" and "down" position). Every measurement cycle started with a zero adjustment of the electrometer and at least 5 charge readings were taken. Each charge reading was accumulated during a timed run of 60 s. During the calibration measurements of the various single seeds the readings were corrected for background, temperature and pressure. No corrections for recombination effects were applied. The averaged charge reading of a measurement cycle was also corrected for decay according to the calibration date and time of the appropriate NIST (or PTB) calibration.

5.1.5 On-site measurements

The hospitals were grouped in regions based on the travelling distance for the team members to reach them. In this way the teams were able to visit on the average two hospitals per day. After visiting the participating hospitals in a region the measurement equipment was returned to VSL, Delft for consistency tests and maintenance. A visiting team consisted of two or three members of the committee, all being physicists with expertise in brachytherapy. Source measurements were performed by two team members, while the third member discussed the treatment planning results with the local physicist or brachytherapy technician (see paragraph 5.2).

During the visit a minimum of two individual seeds was selected and measured by the visiting team with the equipment described in paragraph 5.1.2. The source output data from the manufacturer were taken from the certificates related to the batches of seeds. The selected seeds were either loose seeds or were taken from one or several strands. Whenever an in-

house method or clinical procedure to verify the source strength was available the results of the local measurements were discussed with the visiting team. However, only in a limited number of cases were local measurements in terms of air kerma rate available of the same seeds as measured by the visiting team. In two hospitals the visiting team measured all 10 individual seeds from a strand. In most hospitals the number of measured seeds varied from 2 – 4. In all hospitals the seeds were selected from available lots, purchased for clinical applications. In about 50% of the participating hospitals the total source strength of a strand was measured.

The measurement procedure during the on-site visit was as follows. Firstly the measurement equipment was unpacked and set-up at a table in a room where the measurements were being performed. In order to minimise the contribution of room scatter the detectors were placed at a table preferably as far as feasible from the nearest wall, floor and ceiling. The detector systems and electrometers were connected and allowed to stabilise for at least 30 minutes and the leakage was monitored. In some cases the measurements were performed in the presence of additional sources, which added to the leakage current of the dosimetry systems. With portable devices the temperature, pressure and relative humidity were monitored close to the location of the dosimetry systems.

Each seed was placed in one of the detector systems using the appropriate insert. All seeds were measured twice by reversing its (longitudinal) position in the insert. A measurement cycle included a zero check, a background measurement and the measurement of the selected seed. Every reading of the background or signal of the seed was corrected to standard temperature (22 $^{\circ}$C)[6] and pressure (1013.25 hPa). All seed measurements during the on-site visits were performed on the same ranges of the electrometers as were used during the calibration of the equipment at VSL, Delft. The net current signal was calculated after subtraction of the averaged background signal from the averaged ionisation current of the seed. By applying the appropriate calibration coefficient for the measured seed type the value of air kerma strength for the corresponding seed was determined. It should be noted that during the on-site measurements the same geometry, comprising the appropriate seed type, insert and detector, was used as applied during calibration. As the detectors were calibrated together with their respective electrometers as a dosimetry system, no separate correction factor for the electrical calibration of the electrometer was required. During the on-site visits the long term stability of the dosimetry systems was monitored with the radioactive check sources as mentioned earlier.

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[6] The reference temperature in North America is 22 ^{0}C and in Europe 20 ^{0}C

5.1.6 Results of source strength measurements during the on-site visits

The measurements were analysed per seed type and presented as the ratio of value stated by the manufacturer to the measurement value by the visiting team. All but two radiotherapy centres participating in the on-site visits used either IBt InterSource I1251L or Oncura 6711 seeds. Seeds of type Bard STM 1251, Bebig 125 S17 and Isotron selectSeed I125 were each used in one hospital. Therefore the results for IBt seeds and Oncura seeds were grouped per source type and per measuring device of the visiting team and presented in histograms.

To calculate the ratio manufacturer/visiting team in the participating hospitals values for the source strength stated by the manufacturer were taken from the certificates accompanying the seeds or strands purchased for clinical application. In the IBt and Oncura certificates the source strength of the seeds or strands is described in terms of nominal kerma strength and air kerma strength respectively. Both quantities are expressed in units of $\mu Gy\ m^2\ h^{-1}$. The value for this quantity, as stated by the manufacturer, was used in the calculations of the ratios shown in Figure 16 and Figure 17. From the description given in the certificates it is not clear what these quantities represent. Is the quantity the mean measured source strength of the number of delivered seeds or strands, or is it taken as the median value of the bin, from which the ordered seeds or strands are selected?

IBt does not assign an uncertainty to the stated nominal air kerma, but gives a minimum and maximum value to indicate the air kerma range (± 2% of the nominal air kerma) of the delivered seeds or strands. Oncura assigns an expanded uncertainty of ± 7% (k=2, corresponding to a level of confidence of about 95%) to the air kerma strength stated on the certificates. This uncertainty value is also used as the bin range for the Oncura seeds or strands.

In Figure 16 the results are shown for the IBt seeds measured with the Standard Imaging IVB1000 and the PTW SourceCheck respectively. In total 51 seeds in 13 institutes were measured with the IVB1000 and 47 seeds with the PTW SourceCheck. The lowest ratio measured with the IVB1000 is 0.951 and the highest ratio is 1.031. For the PTW SourceCheck the values are 0.965 and 1.047 respectively. The mean values for the ratios are 0.993 ± 3.7% and 1.002 ± 3.7% (2 SD) respectively.

In Figure 17 similar results are presented for Oncura Oncoseed 6711. In total 46 individual seeds were measured in 15 institutes both with the IVB1000 and PTW SourceCheck. The lowest ratio measured with the IVB1000 is 0.959 and the highest ratio is 1.046. For the PTW SourceCheck these values are 0.943 and 1.045 respectively. The mean values are 1.006 ±

4.0% (2 SD) and 0.998 ± 4.6% (2 SD) respectively. There were no statistically significant differences between the source models, ionisation chambers, or their uncertainties.
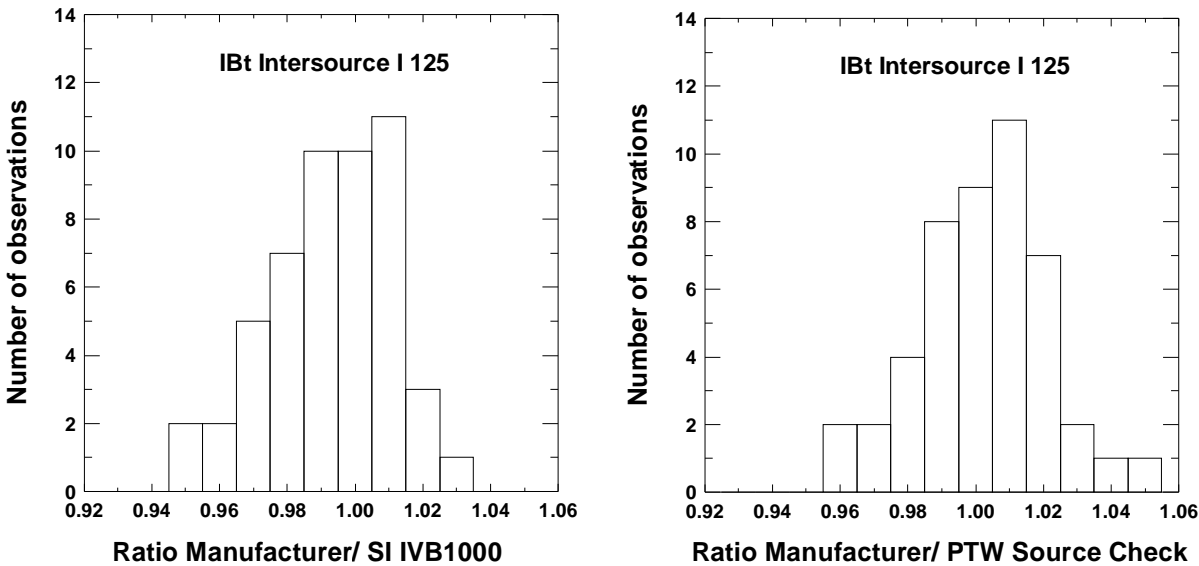
Figure 16: ratio of measured source strength to manufacturer's certificate for IBt InterSource 1251L determined with the Standard Imaging (SI) IVB1000 (left) and the PTW SourceCheck (right).
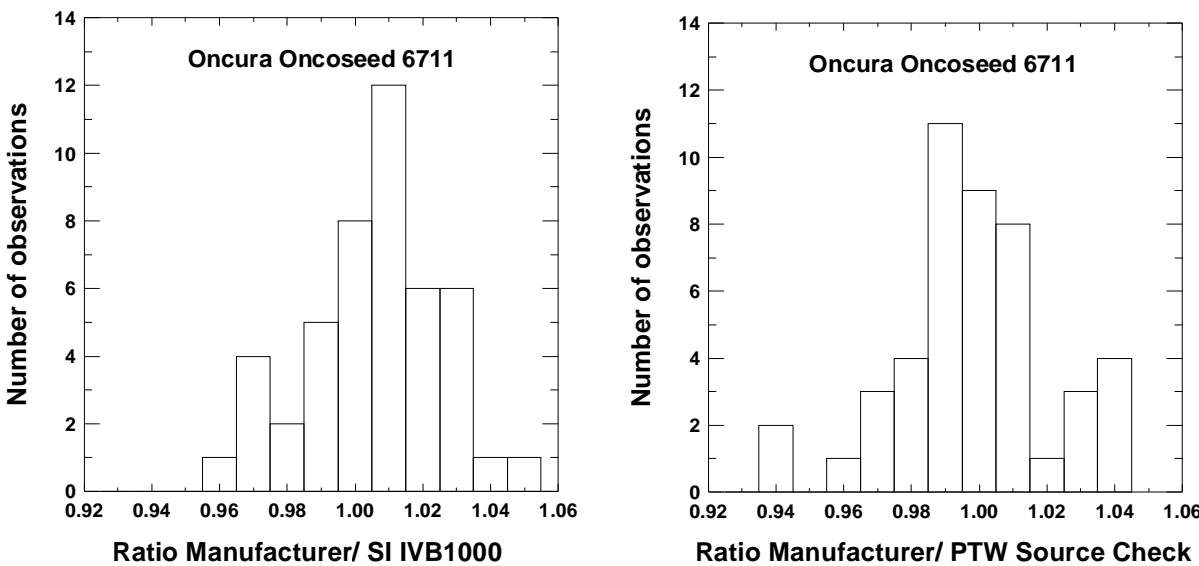
Figure 17: ratio of measured source strength to manufacturer's certificate for Oncura Oncoseed 6711 determined with the Standard Imaging (SI) IVB1000 (left) and PTW SourceCheck (right).

In three hospitals other seed types as mentioned in Figures 16 and 17 were used. The results of the source strength measurements performed by the NCS team for these source types are summarized per hospital in Table 4 below. In institutes A and B the seeds were selected from a batch of seeds, whereas in institute C the seeds were selected from a batch of strands. The source strength values in terms of air kerma strength taken from the manufacturer in the ratio's of hospital A and C are based on midpoint values defined by (Min+Max)/2, where Min and Max are the minimum and maximum value of the air kerma strength range stated in the respective certificates. For the Bebig seeds differences up to 8% were observed between the air kerma strengths measured by the NCS and the stated values from the manufacturer. The certificates of Bard and Bebig contained no uncertainty estimates. However Bard performed an assay on 10 seeds selected from the total number of ordered seeds and quotes an uncertainty in the averaged assay activity of ± 5%. Isotron quotes an air kerma strength value with an uncertainty of ± 4%. In both cases the uncertainty is given without a coverage factor (k) or a statement on the level of confidence (e.g. k=2 or level of confidence about 95%).

Table 4: Ratio of stated to measured source strength for other source types.

Hospital	Source type	Seed number	Man/ SI IVB1000	Man/ PTW SourceCheck
A	Bard STM1251	seed 1	1.002	0.999
		seed 2	0.983	0.990
		seed 3	0.961	0.950
B	Isotron 130.002	seed 1	0.976	0.954
		seed 2	1.043	1.013
C	Bebig IsoCord I25.S17	seed 1	0.949	0.932
		seed 2	0.945	0.924
		seed 3	0.970	0.944

5.1.7 Uncertainty estimation for source strength measurements by on-site visit teams

The source strength data for individual seeds or strands as stated on the manufacturer's certificate and as measured by the medical physicists lacked sufficient information in order to estimate the uncertainty in their source strength determinations. However, for individual seeds this uncertainty is estimated for the measurements performed by the NCS teams

during the on-site visits. The uncertainty is determined in two steps. Firstly the uncertainty contributions related to the calibration of the NCS measurement equipment with NIST calibrated sources are assessed. This step involves the determination of the calibration coefficient for the measurement devices by measuring the current of the sources assigned with air kerma strengths by NIST. The measured current is corrected for background, temperature, pressure and decay. The total uncertainty estimated in the determination of the calibration coefficient is stated in terms of the relative standard uncertainty (Type B). In Table 5(a) this uncertainty component is given for the Standard Imaging well chamber (step1: calibration coefficient). Secondly the uncertainty of the source strength measurement during the on-site visits using the calibrated NCS equipment is determined. In Table 5(a) the uncertainties in the air kerma rate measurements performed with the Standard Imaging IVB1000 well chamber are presented. In the last line of Table 5 under heading (b) the relative expanded uncertainty is given for the results obtained with the PTW SourceCheck assembly. Note that no uncertainty contributions are assumed for the recombination effect, positioning of the source in the adapter and the determination of measurement time. The largest contribution in the relative combined standard uncertainty presented in Table 5a and 5b is related to the calibration coefficient for IVB1000 well chamber and for the PTW SourceCheck device. In general the reproducibility of current measurements was slightly better for the Standard Imaging device compared with the PTW SourceCheck. In appropriate cases this resulted in a higher estimated uncertainty for the net current in the SourceCheck measurements.

The relative expanded uncertainties stated in Table 5 differ slightly from the previous values derived for the NCS on-site visit measurements and quoted in reference 43 This is mainly due to a re-evaluation of the uncertainty contribution related to the correction for source decay in the determination of the calibration coefficients for the measurement equipment (Table 5: step 1). Recently the AAPM Taskgroup No. 138 and CEG-ESTRO issued a report on the dosimetric uncertainty analysis for photon-emitting brachytherapy sources [44]. For the uncertainty contributions considered in Table 5 the TG138 report estimates an expanded uncertainty of 2.6%, provided care is taken in all aspects of the measurement procedure ("best practice"). The estimates for the expanded uncertainty given in Table 5 are in reasonable agreement with the corresponding value for LEP sources stated in the TG138 Report.

Table 5: The estimated uncertainty (%) in the air kerma rate measurements performed by the NCS audit teams during the on-site visits for the various seeds discussed in this report.

Uncertainty Component		Bard STM1251	Bebig I25.S17	IBt 1251L	Isotron 130.002	Oncura 6711
(a) SI IVB1000 well chamber						
Step 1: Calibration coefficient	Type B	1.04	1.51	1.19	1.05	0.89
Step 2: Current measurement [a]	Type A	0.22	0.23	0.30	0.20	0.20
Correction for T and p [b]	Type B	0.11	0.11	0.11	0.11	0.11
Relative combined standard uncertainty		1.07	1.53	1.23	1.07	0.92
Relative expanded uncertainty (k=2)		2.1	3.1	2.5	2.1	1.8
(b) PTW SourceCheck						
Relative expanded uncertainty (k=2)		2.1	3.2	2.8	2.2	2.5

[a] determined as the standard deviation of the mean current (corrected for background)

[b] correction for temperature and pressure

5.1.8 In-house measurements

In this section a brief overview will be given on the in-house measurements performed by local physicists during the period of on-site visits. The majority of the in-house measurements were based on baseline values in the unit mCi derived from source strength data obtained from the source supplier or manufacturer. The most common method in the group of non-traceable measurements was to average source strength data supplied by the manufacturer for a number of purchased seeds or strands over a period of time. From the averaged data a conversion factor is retrieved, which is applied to the well chamber reading. Another approach is the use of a seed individually calibrated by the manufacturer. In general the quality control history of the equipment involved was often not documented or made available to the on-site visit teams. It is obvious that these non-traceable in-house

measurements cannot be considered as independent measurements to verify the source strength, but may only serve as a consistency check. Moreover the definition of the quantity activity may vary from manufacturer to manufacturer. Certificates issued by suppliers or manufacturers contain insufficient information on the determination of the stated source strength quantity and the related uncertainty. It should be emphasized, that the quantities (nominal) activity and apparent activity are considered obsolete and not recommended to specify the source strength of LEP sources [25].

Only in five[7] institutes were the in-house measurements corroborated by either documented traceable calibration or by calibration coefficients obtained from the manufacturer of the QC equipment. Of these five, only one had an NMI-traceable calibration.

Figure 18 gives the results for the in-house measurements performed with traceable or factory calibrated equipment. Institutes 1, 2 and 4 measured complete strands and institutes 3 and 5 individual seeds. When strands were measured by the local medical physicist, a factory based calibration coefficient for the strand was available for his equipment, and the results could be reported in terms of air kerma strength. For the strands involved, the NCS team measured the current of the complete strand and from the individual seeds. From these measurements conversion factors were experimentally determined, in order to achieve an averaged kerma strength value for the seeds in the strand.

The data are presented in the form of ratios: in-house measurements divided by the source strength values measured by the NCS audit team (+) and the ratios of the manufacturer's values divided by the NCS values (o). The measurements of the institutes were in good agreement with the results found by the NCS on-site visit team. However, only institute 3 used traceably calibrated equipment (ADCL UW Wisconsin, U.S.), the other institutes obtained results using factory calibrated equipment. No general conclusions can be drawn from the findings presented in figure 18, because the sample of participants is rather small.

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[7] One institute performed in-house measurements with two different QC measurement systems for two different source types applied in two different LEP brachytherapy applications. This institute is noted as institute 4 and institute 5 in figure 18
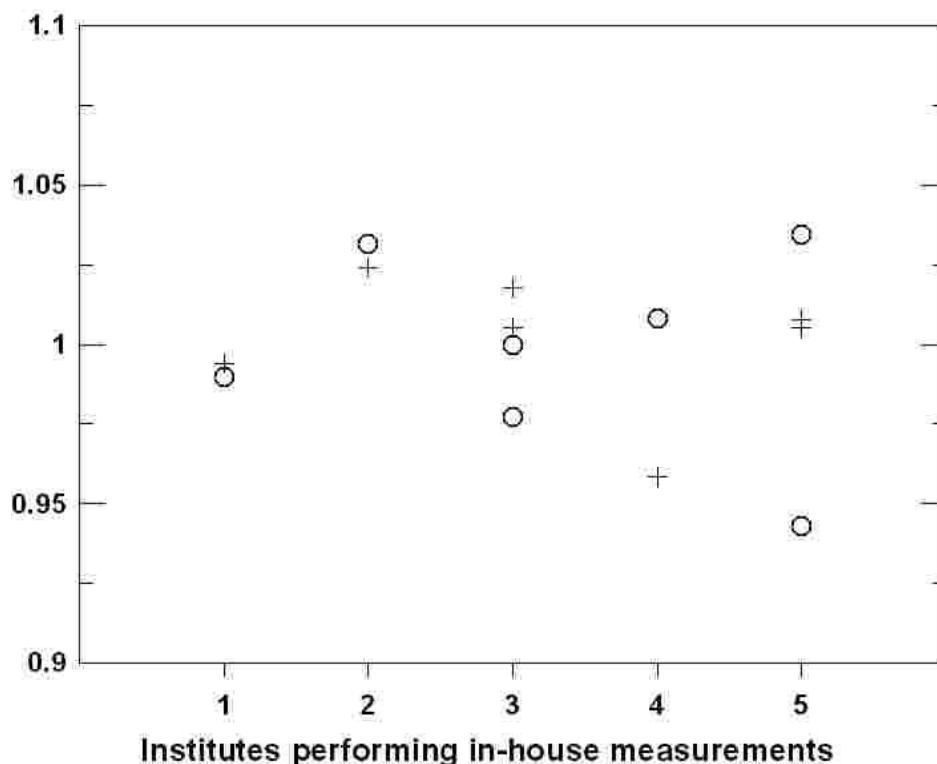
Figure 18: results of in-house measurements performed with traceable or factory calibrated equipment. The results are presented as ratios of the in-house source strength normalised to the value measured by the NCS team (+). Also shown are the ratios of the source strength values for the same sources as stated by the manufacturer normalised to the NCS values (○).

5.1.9 A note on the source strength measurement of strands

In a number of Belgian and Dutch institutes LEP brachytherapy sources are used in the form of strands. Multiple seed trains (strands) can be measured in well chambers provided the axial region of approximate uniform response[8] is long enough to contain the strand or part of the strand. Manufacturers of QC equipment can provide for various source types specific adapters to measure the complete strand. A common procedure employed by some Belgian and Dutch medical physicists is based on the use of an adapter which has a lead shield covering part of the strand. The strand would be first measured in one direction, while half of the strand length is shielded. Then the strand is rotated 180 degrees in order to measure the

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[8] The point of maximum response is called the "sweet spot"

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other half. For some source types inserts are available, which are not shielded. The strand may then be measured directly in the unshielded insert or holder. However source strength measurements are based on the calibration of single seeds. Therefore a conversion factor has to be determined to obtain an air kerma (rate) value for the strand. The determination of the conversion factor for each source type involves an adapter to measure the strand and an adapter for measuring the individual seeds of the strand. The latter adapter should be the same as used during the calibration of QC device. It should be emphasized that the adapters are <u>specific</u> for each source type. Firstly the whole strand is measured using an adapter supplied by the manufacturer or employing a home-made adapter. The total net current for the strand is recorded. After completion of the measurement of the whole strand the strand is cut in 10 individual seeds. Each individual seed is measured using the appropriate insert or holder. The current readings are all corrected for background, ambient conditions, etc. The conversion factor (CF) is the ratio of the corrected net current of the total strand and the sum of the corrected net currents of the individual seeds. If the CF is multiplied by the calibration coefficient N_k for a single seed an "equivalent" calibration coefficient for a strand is obtained.

5.1.10 Conclusions

Source strength measurements were performed by NCS teams during on-site visits in 30 out of 34 institutes. The results of individual seeds from IBt and Oncura measured by the NCS visiting teams in terms of air kerma (strength) agree with the results stated by the manufacturer within ± 5%. It should be noted that the air kerma (strength) values stated by the manufacturers are averaged over a large number of seeds or strands.

Table 4 presents data for three institutes each using different source types: from Bard, Isotron and Bebig respectively. In general, the deviation between the results obtained by the NCS team and the manufacturer is within 5%, except for the Bebig seeds. The maximum deviation was about 8% for one Bebig seed. All calibration coefficients for the NCS measurement devices were directly traceable to NIST, only for the Bebig seeds the calibration coefficients were traceable to PTB. However the measurements were limited to one institute and additional measurements would be needed before general conclusions can be drawn.

Averaging procedures for the determination of air kerma strength by the various manufacturers may differ and the methods used are not always clearly described in the certificates. Furthermore it is often unclear whether the stated air kerma strength values by

the manufacturer are directly determined from the periodic NIST calibrations or derived from activity quantities, which may be in use during the production process of the seeds or strands.

The majority of institute measurements performed by local medical physicists are performed without calibrated equipment. Very often the in-house results are based on source strength data from the manufacturer. Such measurements cannot be considered as an independent quality control check, which is the desired requirement.

Most source strength measurements in radiotherapy institutes are currently not expressed in terms of air kerma strength (or reference air kerma rate). However, the traceability of source strength measurements and the calibration of QC measurement equipment are directly related to this quantity.

Until recently all source strength measurements were relying on one primary standard (*i.e.* NIST). The development of primary standards in Germany, France and other countries in Europe will foster the dissemination of the quantity reference air kerma rate to (secondary) calibration laboratories.

Due to the lack of available calibration services for LEP sources operated by National Metrology Institutes in Belgium, The Netherlands and most countries in Europe, medical physicists have to rely on ADCL calibrations and on calibrations provided by manufacturers (e.g. PTW). This is a very undesirable situation and it is strongly recommended that sufficient traceable calibration services will be established on a national or regional scale in Europe. Another approach could be the development of fully accredited[9] calibration laboratories operated by manufacturers of QC equipment for LEP sources in Europe.

5.2 Quality control of treatment planning systems

5.2.1 Introduction

In the period 2005-2006, radiotherapy departments in Belgium (n=22) and the Netherlands (n=12) were visited and asked to perform dose calculations for relatively simple source

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[9] In general NMIs and calibration laboratories (e.g. SSDLs) are accredited for their calibration services by internationally recognized (national) accreditation bodies to comply with the requirements of ISO/IEC standard 17025. In the United States ADCLs are accredited by the AAPM. However to obtain traceable calibrations from an ADCL, the laboratory has also to be accredited by the A2LA (American Association for Laboratory Accreditation).

configurations using the available TPS. Stated values were compared with values calculated by this NCS subcommittee using the dose formalism as proposed by the AAPM in the TG-43 update manuscript [2] and consensus data [2,3] or otherwise published data on the source dosimetry parameters.

5.2.2 Materials and methods

Participants performed five tests:

- Test 1, point-source calculation: calculation of the dose from a single seed in a number of points at different distances perpendicular to the seed axis using the point-source approximation
- Test 2, dose summation: summation of the dose from two seeds in a number of points at different distances perpendicular to the seed axes using the point-source approximation
- Test 3, isodose representation: representation of the isodose lines around a single source using the point-source approximation
- Test 4, dose-volume histogram: calculation of the DVH from a single source using the point-source approximation
- Test 5, line-source calculation: calculation of the dose from a single seed in a number of points at different distances along the transverse and longitudinal axis of the seed and in three points at angles in between using the line-source approximation

The dose was calculated for a source strength of 100U (1U = 1 µGy m^2 h^{-1}) to minimize rounding of dose values at distances between 0.5 and 6 cm from the source. For more details on the test conditions see Appendix 2. The total delivered dose was calculated as:

$$D(r) = \dot{D}_i(r) \cdot T_{1/2} \, / \, ln(2) \qquad (14)$$

where:

$$D(r) = \text{total dose}$$
$$\dot{D}_i(r) = \text{ initial dose rate}$$
$$r = \text{distance to source}$$
$$T_{1/2} = \text{half life}$$

5.2.3 Results

At the time of our survey the most commonly used treatment planning system was Variseed, used in combination with Oncura 6711 or IBt 1251L ^{125}I seeds (Fig. 19). A total of 36 combinations in 31 responding institutes were recorded.
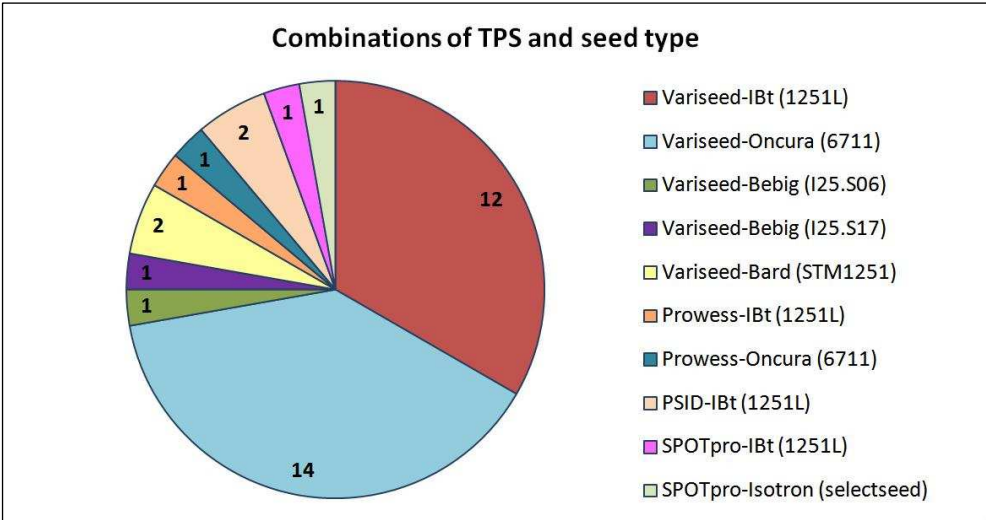
Figure 19: Distribution of different combinations of treatment planning system and seed type encountered in the survey period.

1D calculations

The figures in the following subsections present 2 types of curves. The black curves denote the total dose in cGy (left Y-axis) due to a source with a source strength of 100 U, the blue curves denote the dose deviations in percentage of the local dose (right Y-axis) as a function of distance to the seed for all combinations of seed types, treatment planning systems and institutes.

In the majority of institutes using the Variseed treatment planning system and the Oncura 6711 seed (n=14) the deviations in the 1D calculations are smaller than 2% over the range of 0.5 to 6 cm (Figure 20). At the institutes 3, 5, 8, 18 and 21 the results deviate from the reference results probably due to the use of TG-43 parameter values instead of the TG-43 update parameter values. Furthermore the institutes 8 and 18 reported the same dose values for 1D and 2D calculations suggesting that the tests were not properly interpreted. The institutes 3 and 8 have a correct calculated dose at 1 cm due to a 1.5% too high dose rate constant (0.98 instead of 0.965) which is compensated by a 1.5% too low anisotropy factor

(0.93 instead of 0.944 anisotropy function value at 1 cm), but at smaller and larger distances the dose deviates more.
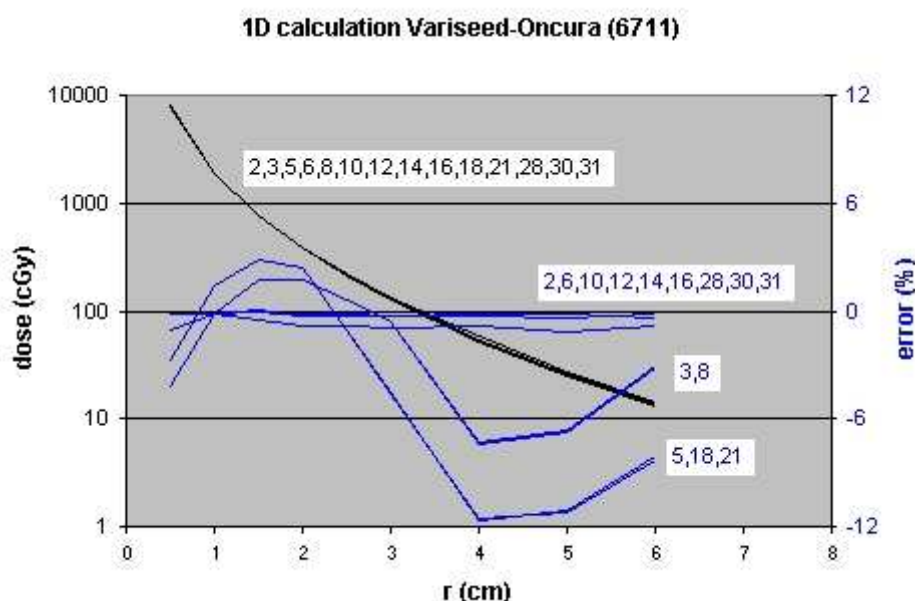
Figure 20: The dose deviations encountered for the combinations of Oncura 6711 seed and the Variseed treatment planning system at different institutes (n=14) as a function of distance to the seed in the 1D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis).

In all institutes using the Variseed TPS in combination with the IBt 1251L seed (n=12) the 1D calculations deviate from the reference results (Figure 21). This predominantly stems from the fact that institutes at the time of the survey used early data from literature [16,17], whereas the reference result was based on the data from the Supplement to the 2004 update of the AAPM task group 43 [3]. Institute 11 calculated higher dose values compared to the reference results and also compared to other institutes, probably due to the use of the 2D anisotropy function $F(r,\theta)$ for this test instead of the 1D anisotropy function $\varphi_{an}(r)$.
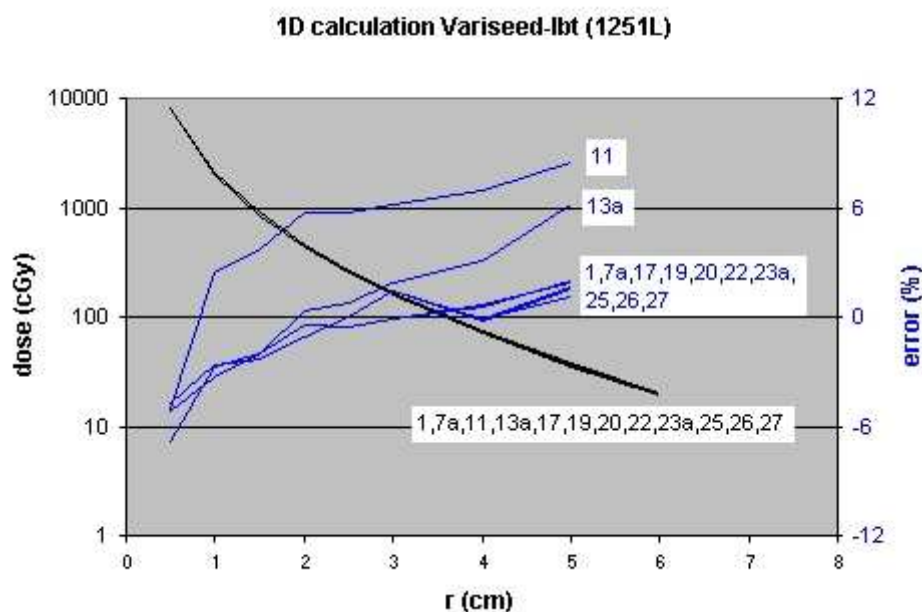
Figure 21: The dose deviations encountered for the combinations of IBt 1251L seed and the Variseed treatment planning system at different institutes (n=12) as a function of distance to the seed in the 1D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis).

The institute using the Variseed TPS in combination with the Bebig I25.S17 seed reported calculated dose values within 0.5% to the reference values which were based on data in literature [12]. Deviations were larger for the combination with the Bebig I25.S06 seed in institute 13 (Figure 22). Institute calculations and reference values were both based on the TG-43 update data [2], but $g_L(r)$ values reported by the institute differed for unknown reason from the $g_L(r)$ values in the TG-43 update report. Dose calculations in the institutes 4 and 7 for the combination of Variseed TPS and the Source Tech STM1251 seed were about 5% too low due to the use of early data from literature [6], whereas the reference values were based on the data from the Supplement to the 2004 update of TG-43 [3], e.g. the dose rate constant was 0.98 cGy/h/U as determined by Kirov and Williamson and 1.018 cGy/h/U for the Supplement.

Figure 22: The dose deviations encountered for the combinations of Bebig and Source Tech seeds and the Variseed treatment planning system at different institutes (n=4) as a function of distance to the seed in the 1D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis). 4,7b: Variseed-SourceTech STM1251; 9: Variseed-Bebig I25.S17; 13b: Variseed-Bebig I25.S06.

In the 3 institutes using Prowess, PSID or SPOTpro treatment planning system in combination with the IBt 1251L seed the 1D calculations deviate from the reference results (Figure 23). This predominantly stems from the fact that institutes at the time of the survey used early data from literature [16,17], whereas the reference results were based on the data from the Supplement to the 2004 update of the AAPM task group 43 [3]. Deviations are larger for these combinations compared to the Variseed-IBt 1251L calculations (Figure 21) suggesting differences in implementation of the TG-43 dose calculation formalism between planning systems. Calculations with SPOTpro for the Isotron selectSeed were in agreement with the reference results. For graph 23b (Prowess-Oncura 6711) the results deviate from the reference results probably due to the use of TG-43 parameter values instead of the TG-43 update parameter values. The calculated dose at 1 cm is correct due to a 1.5% too high dose rate constant (0.98 instead of 0.965) which is compensated by a 1.5% too low anisotropy factor (0.93 instead of 0.944 anisotropy function value at 1 cm), but at smaller and larger distance the dose deviates more (no data given beyond 3 cm).

1D calculation Prowess, PSID, SPOTpro, Variseed and Ibt(1251L), Isotron (selectSeed), Oncura (6711)
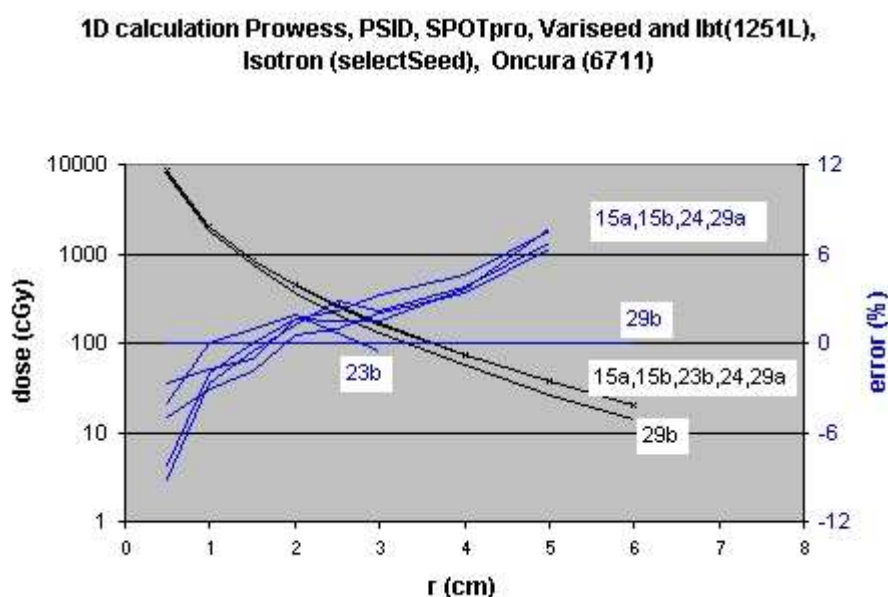
Figure 23: The dose deviations encountered for the combinations of IBt 1251L, Oncura 6711 and Isotron selectSeeds and the Prowess, PSID and SPOTpro treatment planning systems at different institutes (n=6) as a function of distance to the seed in the 1D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis). 15a: Prowess-IBt; 15b, 24: PSID-IBt; 23b: Prowess-Oncura 6711; 29a: SPOTpro-IBt; 29b: SPOTpro-selectSeed.

Dose summation

Using the point-source approximation, summation of the dose from two seeds at a number of points at different distances was implemented correctly in all TPS encountered in this survey.

Representation of isodose lines

Not all institutes delivered isodose line plots, but all treatment planning systems showed correct representations of the isodose lines around a single source using the point-source approximation in a dose calculation grid size of 1 to 2 mm.

2D calculations

In the majority of institutes using the Variseed treatment planning system and the Oncura 6711 seed (n=14) the deviations in the 2D calculations along the perpendicular axis are smaller than 0.3% over the range of 0.5 to 6 cm (Figure 24). At the institutes 3 and 21 the results deviate from the reference results probably due to the use of TG-43 parameter values instead of the TG-43 update parameter values. The institutes 3, 8 and 18 did not interpret the test properly since they reported the same dose values for the 1D and 2D calculations or same values along the perpendicular and longitudinal axes. Figure 25 shows that the deviations in the 2D calculations along the longitudinal axis are smaller than 0.3% over the range of 0.5 to 6 cm in most centres. At the institutes 5 and 21 the results deviate from the reference results probably due to the use of TG-43 parameter values instead of the TG-43 update parameter values. The institutes 3, 8 and 18 did not interpret the test properly since they reported the same dose values along the perpendicular and longitudinal axes resulting in deviations beyond the scale of Figure 25.
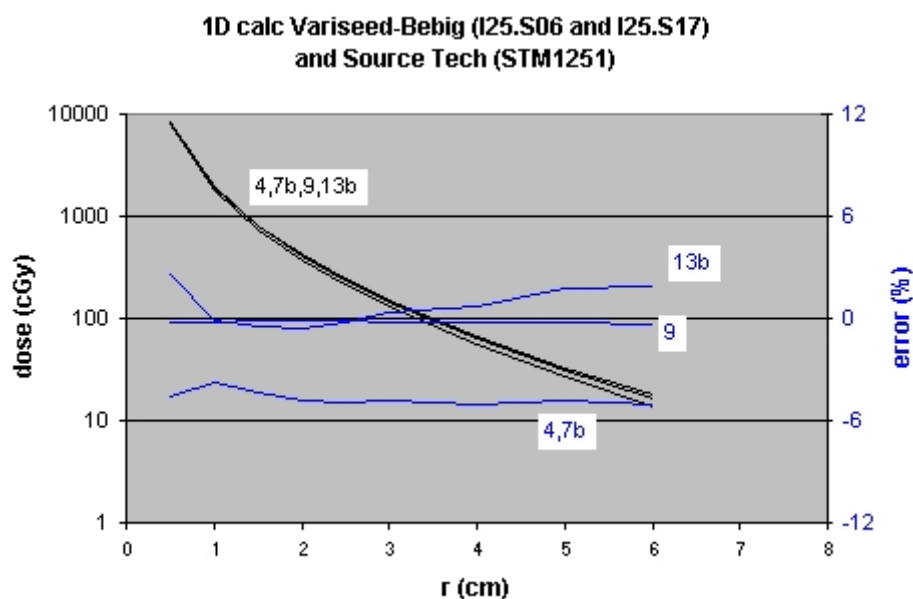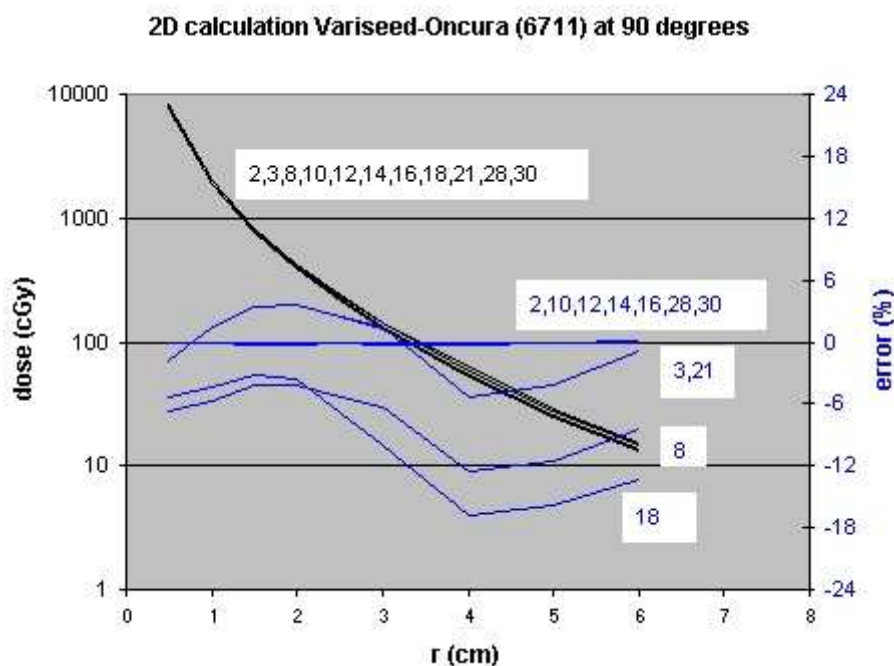

Figure 24: The dose deviations encountered for the combinations of Oncura 6711 seed and the Variseed treatment planning system at different institutes (n=14, missing data for 3 institutes: 5,6,31) in a number of points at different distances perpendicular to the seed axis in the 2D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis).
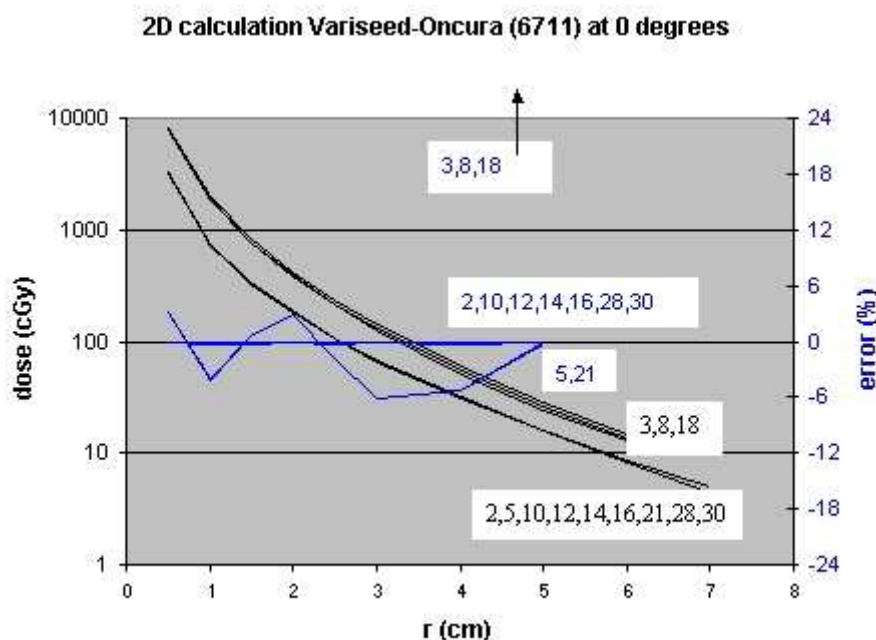
Figure 25: The dose deviations encountered for the combinations of Oncura 6711 seed and the Variseed treatment planning system at different institutes (n=14, missing data for 2 institutes: 6,31) in a number of points at different distances along the longitudinal seed axis in the 2D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis).

In the majority of institutes using the Variseed treatment planning system and the IBt 1251L seed (n=12) the deviations in the 2D calculations along the perpendicular axis range from -3% to 4% at distances between 0.5 and 6 cm (Figure 26). This predominantly stems from the fact that institutes at the time of the survey used early data from literature [16,17], whereas the reference results were based on the data from the Supplement to the 2004 update of the AAPM task group 43 [2]. The institutes 17 and 26 did not interpret the test properly since they reported the same dose values along the perpendicular and longitudinal axes. Institute 1 reported dose values only along the perpendicular axis, which were comparable to the erroneous values reported by the institutes 17 and 26. Figure 27 shows that the deviations in the 2D calculations along the longitudinal axis range from –2% to 3% at distances between 0.5 and 6 cm. The results from institutes 17 and 26 are beyond the scale of Figure 27.

2D calculation Variseed-Ibt (1251L) at 90 degrees
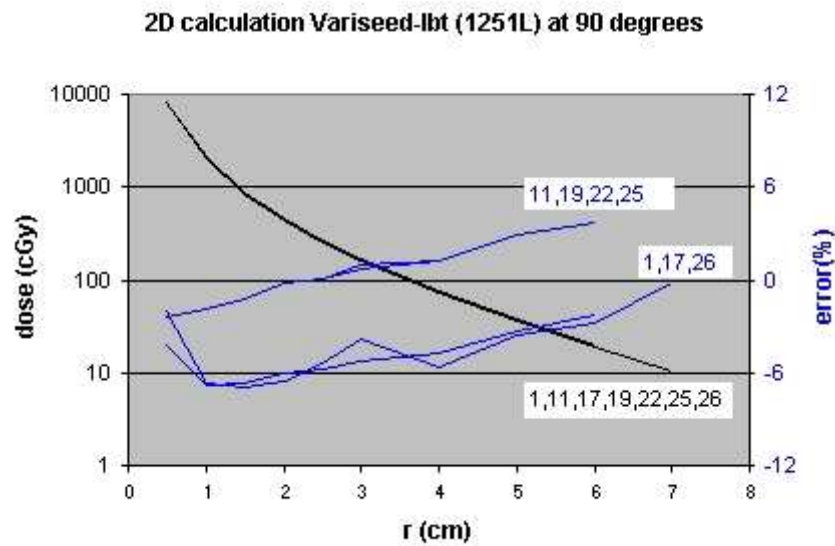
Figure 26: The dose deviations encountered for the combinations of IBt 1251L seed and the Variseed treatment planning system at different institutes (n=12, missing data for 5 institutes: 7a,13a,20,23,27) in a number of points at different distances perpendicular to the seed axis in the 2D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis).

2D calculation Variseed-Ibt (1251I) at 0 degrees
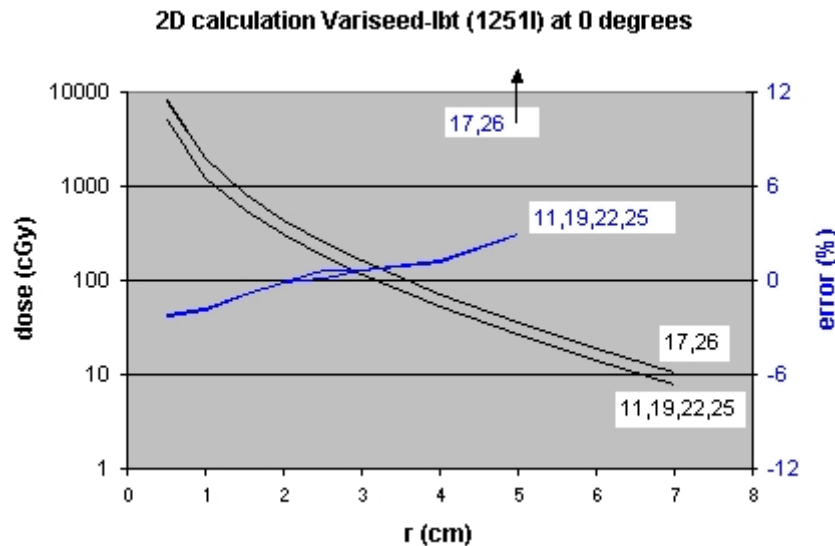
Figure 27: The dose deviations encountered for the combinations of IBt 1251L seed and the Variseed treatment planning system at different institutes (n=12, missing data for 6 institutes: 1,7a,13a,20,23,27) in a number of points at different distances along the longitudinal seed axis in the 2D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis).

The Figures 28 and 29 show that 2D dose calculations along the perpendicular and longitudinal axes are in good agreement with the reference results for combinations 9 (Variseed-Bebig I25.S17) and 29b (SPOTpro-Isotron selectSeed). Calculations for the IBt 1251L seed with different treatment planning systems showed deviations, which stem probably again from the fact that institutes at the time of the survey used early data from literature [16,17], whereas the reference result was based on the data from the Supplement to the 2004 update of the AAPM task group 43 [2]. The discrepancy for dose points on the longitudinal axis of the source for the PSID system (combinations 15b and 24) could be related to the implementation of an adapted anisotropy correction formula.
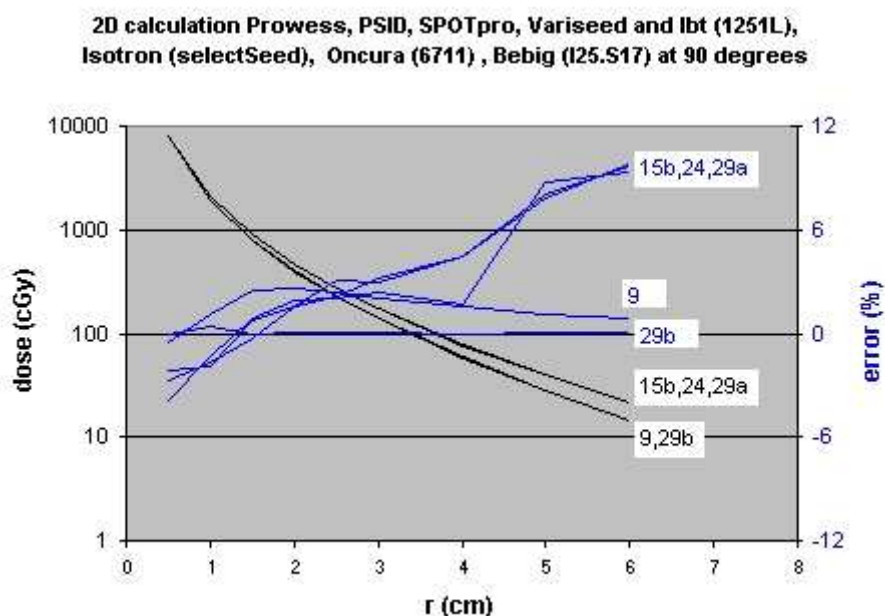
Figure 28: The dose deviations encountered for the combinations of IBt 1251L, Oncura 6711, Bebig I15.S17 and Isotron selectSeeds and the Prowess, PSID, Variseed and SPOTpro treatment planning systems at different institutes (n=7, missing data for the 2 combinations 15a and 23b) in a number of points at different distances perpendicular to the seed axis in the 2D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis). 9: Variseed-Bebig I25.S17; 15a: Prowess-IBt; 15b, 24: PSID-IBt; 23b: Prowess-Oncura 6711; 29a: SPOTpro-IBt; 29b: SPOTpro-selectSeed.

2D calculation Prowess, PSID, SPOTpro, Variseed and Ibt(1251L), Isotron (selectSeed), Oncura (6711), Bebig (I25.S17) at 0 degrees
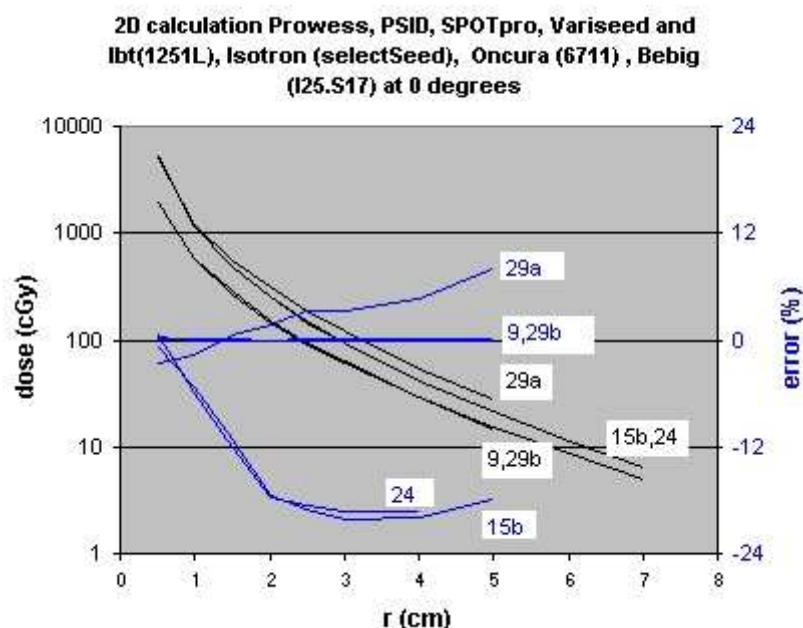
Figure 29: The dose deviations encountered for the combinations of IBt 1251L, Oncura 6711, Bebig I25.S17 and Isotron selectSeeds and the Prowess, PSID, Variseed and SPOTpro treatment planning systems at different institutes (n=7, missing data for the 2 combinations 15a and 23b) in a number of points at different distances along the longitudinal seed axis in the 2D calculation test. Total dose delivered (black lines and left y-axis) and deviations from reference values (blue lines and right y-axis). 9: Variseed-Bebig I25.S17; 15a: Prowess-IBt; 15b, 24: PSID-IBt; 23b: Prowess-Oncura 6711; 29a: SPOTpro-IBt; 29b: SPOTpro-selectSeed.

Dose-volume histogram calculations

Volume errors in dose-volume calculations ranged from –17% to 2% for spheres with radius 1 cm (volume= 4.19 cm^3), from –10% to 0% for spheres with radius 2 cm (volume= 33.51 cm^3), and from –11% to 0% for spheres with radius 3 cm (volume= 113.10 cm^3). The error depends strongly on the resolution (in the Z-direction) that is used for the DVH calculation. In one TPS (Variseed) the result is also influenced by a specific setting defining the DVH calculation range: DVH's can be calculated for a particular structure, or over the entire dose calculation matrix. This setting influences the way the dose-volume is interpolated near the

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upper and lower edge of the volume. In general the treatment planning systems tend to underestimate the volumes in dose-volume histogram calculations (Figure 30).
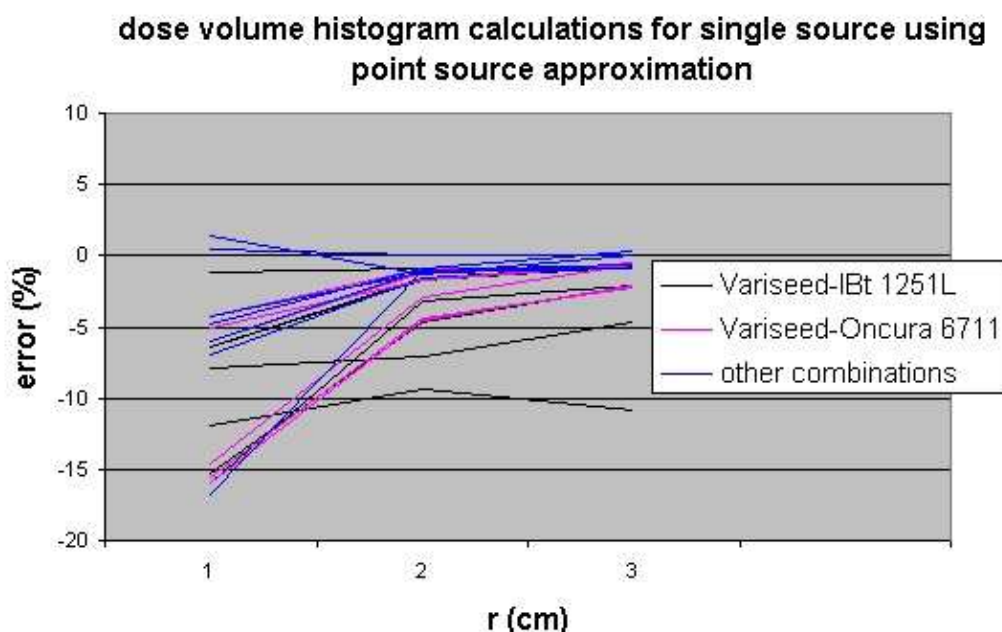
Figure 30: The errors in volumes encountered for different seeds, treatment planning systems and institutes for a number of dose levels at different distances from the seed centre in the 1D calculation test.

5.2.4 Discussion

Only for a small number of combinations of TPS, institute and seed type the 1D dose calculation errors were smaller than ±1% in the calculation points at distances between 0.5 and 6 cm. Deviations in the dose calculation stem from the use of incorrect TG-43 dosimetry parameters for a particular seed type or incorrect implementation of the TG-43 dose formalism in the TPS. For example, for the IBt InterSource 1251L seed this NCS committee calculated reference values according to the most recent dosimetry data in the Supplement to the 2004 update of the AAPM task group 43 [2], whereas users referred to the dosimetry parameters as determined by Meigooni et al 2002 and Reniers et al 2001 [16,17], which were available at the time of survey. For one TPS e.g. we found that equation 11 of the TG-43 update was not correctly implemented. Errors in 1D calculations at the reference point may stem from an incorrect value for the dose rate constant, which can be easily checked or an incorrect implementation of the geometry function in the TPS. Some users did not

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interpret the TPS tests correctly and applied for the 1D calculation test the 2D anisotropy function $F(r,\theta)$ instead of the 1D anisotropy function $\varphi_{an}(r)$. Misinterpretation of the TPS test and/or misunderstanding of the TG-43 dose calculation formalism caused lager errors and more missing data for the 2D calculation tests. Probably, the 2D calculation modes and parameters of the TPS were not thoroughly tested by the users, since most of them use the 1D calculations for planning of the prostate brachy dose distributions.

It should be noted that the observed errors for the 1D and 2D point dose calculations at large distance (more than 2 cm) have little influence on the clinical dosimetry for a typical prostate implant, since the inverse square law is the predominant factor in the calculation of the dose distribution.

Most TPS proved to underestimate the volumes in dose-volume histogram calculations. Users should pay attention to the accuracy of DVH calculation and its dependency on dose grid and number of sampling points.

Dose summation and representation of isodose lines proved to be correct in all reports.

6 Quality control in ^{125}I brachytherapy

6.1 Measurement of source strength

6.1.1 Introduction

Several organisations have published recommendations on quality control of brachytherapy sources and measuring equipment: the IAEA report 1274 [34], the AAPM reports 46, 56 and 64 [5,45,46], the ICRU report 72 [35] and the IPEM report 81 [47]. Most of the recommendations apply to non-permanently implanted high-energy photon emitting sources. However some recommendations, although scarce, can be applied to or are specifically given for low-energy photon emitting sources used for permanent implantation, like ^{125}I or ^{103}Pd. For this type of sources, the AAPM Low Energy Brachytherapy Source Calibration Working Group recently summarized and updated the AAPM recommendations [48].

A problem may arise with modern implantation techniques using online treatment planning of the seed configuration. Seeds, delivered under sterile conditions are in this procedure unpacked and configured in theatre. Measurement then demands equipment being under sterile conditions as well. When the user wants to avoid repeated sterilization of calibration equipment, a possible although expensive solution is to purchase extra seeds originating from the same batch and measure these outside the operating room before application. AAPM, ICRU and IAEA give recommendations regarding the limitation of the number of sources to be measured, as it is obviously unpractical to check every individual source in a purchased batch.

In the following sections recommendations published in literature on dosimetric verification of source strength and on the number of seeds to be assayed are briefly reviewed and in section 6.1.5 NCS considerations on these topics are discussed.

6.1.2 Review of literature recommendations

The results of the source strength measurements performed by the local medical physicist will generally not agree with the stated value from the supplier. Criteria for tolerance levels have to be set with respect to deviations, which may be considered acceptable in clinical practice. The different recommendations found in the literature for numbers of seeds to be assayed and the tolerance levels for deviations from manufacturer's stated values and for

deviations from the mean measured source strength are summarized in Table 6. A brief description found in publications of four different international authorities is given below.

IAEA report 1274

Report 1274 of the IAEA gives detailed recommendations on measurement equipment, e.g. well chambers. Only appendix G, however, specifies that all or a random sample of seeds, but minimally 10% of clinically used sources should be measured. No recommendations are given for tolerance levels.

AAPM reports

The AAPM report 64 refers regularly to recommendations in reports 46 and 56 and gives recommendations both for numbers of seeds to be assayed and for deviations in source strength. In case of loose seeds, a random sample of 10% or 10 seeds, whichever is greater is recommended. In case of strands, the largest of 10% or two strands should be measured. With regard to deviations in source strength, report 64 [46] recommends that in case the mean of the institute's measured source strength disagrees with the vendor's data by more than 3%, the source of the disagreement should be investigated. Differences of more than 5% should be reported to the manufacturer. In AAPM report 56 a tolerance level is given for differences between the institute's measured source strength of an individual seed and the manufacturer's stated value of the delivered batch. AAPM recommends a maximum deviation of 5% from the manufacturer's stated value for individual seeds. The responsibility of the medical physicist to perform an independent verification of the source strength of procured seeds assigned by the manufacturer is additionally emphasised by the AAPM LEBSC working group [48]. These verification measurements have to be performed with dosimetric equipment with traceable calibration to national standards (e.g. through the services of ADCLs in the U.S.).

ICRU Report 72

The recommended quantity for specifying the source strength of low-energy photon sources is reference air kerma rate. However, older source specifications as activity and milligram-radium equivalent are still discussed. Only dosimetric QC aspects for checking photon emitting seeds are discussed. In ICRU 72 the following guidelines are given:
A random sample of standard photon seeds (activity <100 MBq), consisting of ≥10% of the shipment or 10 seeds, whichever is greater, should be checked for reference air kerma rate.

For sources of short half-life nuclides, spot checks should be made with each batch delivered.

The results of local check measurements generally will not agree exactly with the supplier's stated values. The following agreement can be considered reasonable: 5% for reference air kerma rate for photon sources (^{125}I and ^{103}Pd) when using a well-type ionisation chamber. If agreement is within this limit, either the measured or the stated value can be used for treatment, and the choice should be recorded. If the discrepancy is >5%, the first step is to check the measuring equipment and technique for problems. If none are found, additional measurements should be made. An irresolvable discrepancy >5% should be reported to the supplier and the locally measured value should be used clinically. Discrepancies >10%, or discrepancies >5% that occur routinely, suggest measurement problems that should be carefully investigated and resolved.

IPEM Report 81

The report *Physics Aspects of Quality Control in Radiotherapy* is very brief with respect to QC aspects of ^{125}I seeds and refers to the source strength of the seeds in terms of the quantity activity. The report recommends only that on receipt of ^{125}I seeds, the activity must be measured in a calibrator, and this activity checked with that stated on the certificate of the vendor. IPEM recommends a maximum deviation of 5% from the manufacturer's stated value for brachytherapy sources in general (^{192}Ir wires and coils), but does not specify a tolerance level for ^{125}I seeds.

Table 6: Recommendations from literature for the number of seeds to be assayed and tolerance levels for deviations.

Reference	Quantity		Tolerance	
	Loose seeds	Strands	Mean	Deviation
IAEA	minimally 10%	not specified	not specified	not specified
AAPM	max (10 seeds, 10%)	max (2 strands, 10%)	3%	5%
ICRU 72	max (10 seeds, 10%)	not specified	5%	not specified
IPEM 81	not specified	not specified	not specified	not specified

6.1.3 Statistical considerations of the assay process

IAEA, ICRU and AAPM give recommendations for numbers of seeds to be assayed in order to be confident about the source strength of the batch of seeds as delivered by the manufacturer, albeit without a statistical justification. Yue [49] however published the statistical aspects of the assay process under the assumptions that

a) the seeds within an ordered batch come from a normally distributed population with expected mean source strength S;
b) the consecutive measurements are statistically independent.

Yue's statistical considerations imply that, instead of measuring a predefined number or percentage of seeds, the assay process can be tailored to an individual case encountered in clinical practice by continuously monitoring the obtained variation in measured source strength during the assay process. This offers the possibility of measuring less seeds in cases where the variation is small and more seeds in cases where this variation is larger. The described procedure results in the 95% confidence interval (CI) for the difference between expected mean (S) and estimated mean source strength (S_n). This interval can be calculated during the assay process from the number n (≥ 2) of assayed seeds and the percent standard deviation σ_n/S_n (%) of the n measured values, because the stochastic quantity $(S - S_n)/(\sigma_n/\sqrt{n})$ is distributed according to a Student-T distribution with n-1 degrees of freedom. The procedure is illustrated by a series of measurements in one of the visited institutes, where ^{125}I seeds are used for treatments using eye plaques. Table 7 shows three series of measurements of batches of 40 seeds. Of each series the running average and standard deviation after n measurements and the 95% confidence interval for the percent difference S_n-S between the measured average and the population (or "expected") average are given. The relative difference $(S_n-S)/S_n$ is taken from Yue's published table, based on calculated tabulated values of the T(n-1) distribution. The table shows that, if the user aims at a confidence interval of ±1%, this is not always accomplished with the same number of measured seeds because of the dependence of the confidence interval on the standard deviation obtained so far. For the first batch (columns 1-5) the user could have stopped measuring only after 25 seeds, for the second batch (columns 6-10) already after 7 seeds. Besides, the confidence interval does not always show a continuously decreasing behaviour. Analogous reasoning applies to a confidence interval of e.g. 2% or 5%.

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Applying Yue's theory to the AAPM recommendations, S_n must be replaced by the vendor's stated source strength S_v to obtain a 95% confidence level for the difference between S_v and S. In case the measured mean strength S_n differs from S_v by a certain percentage, the 95% CI for S-S_v will be broadened relative to the above described 95% CI for S-S_n. For instance, when σ_n/S_n is 5% after measuring 14 sources, $CI_{95\%}(S$-$S_n)$ is ± 2.9%. When S_n equals S_v, i.e. no difference is found between measurement and vendor's stated value, then $CI_{95\%}(S$-$S_v)$ also equals ± 2.9%. When S_n differs from S_v however, by 3%, $CI_{95\%}(S$-$S_v)$ increases to ± 5.4%. The method to calculate the decrease in confidence when a difference between measured and vendor's stated value is obtained, is considered beyond the scope of this report.

Table 7: Source strength measurement results for 3 batches of 40 I-125 seeds, used for the treatment of ocular melanoma.

n	Meas. value (u)	running mean (S_n)	running stdev (σ_n)	relative stdev σ_n/S_n (%)	95% CI (%) for $(S-S_n)/S_n$ from table 1 Yue	Meas. value (u)	running mean (S_n)	running stdev (σ_n)	relative stdev σ_n/S_n (%)	95% CI (%) for $(S-S_n)/S_n$ from table 1 Yue	Meas. value (u)	running mean (S_n)	running stdev (σ_n)	relative stdev σ_n/S_n (%)	95% CI (%) for $(S-S_n)/S_n$ from table 1 Yue
1	7,859	7,859				7,577	7,577				7,690	7,690			
2	8,430	8,145	0,404	4,96	[-44.90 ; +44.90]	7,534	7,555	0,031	0,40	[-2.97 ; +2.97]	7,652	7,671	0,027	0,35	[-2.97 ; +2.97]
3	7,790	8,026	0,351	4,38	[-11.18 ; +11.18]	7,375	7,495	0,106	1,42	[-3.73 ; +3.73]	7,987	7,776	0,184	2,36	[-6.21 ; +6.21]
4	8,009	8,022	0,287	3,58	[-5.57 ; +5.57]	7,529	7,503	0,088	1,18	[-1.59 ; +1.59]	8,178	7,877	0,250	3,18	[-4.77 ; +4.77]
5	7,917	8,001	0,253	3,16	[-3.72 ; +3.72]	7,456	7,494	0,079	1,06	[-1.24 ; +1.24]	7,884	7,878	0,217	2,75	[-3.72 ; +3.72]
6	8,358	8,060	0,269	3,34	[-3.67 ; +3.67]	7,490	7,493	0,071	0,95	[-1.05 ; +1.05]	8,048	7,906	0,206	2,61	[-2.62 ; +2.62]
7	8,235	8,085	0,254	3,15	[-2.78 ; +2.78]	7,506	7,495	0,065	0,87	[-0.93 ; +0.93]	7,949	7,912	0,189	2,39	[-2.31 ; +2.31]
8	8,512	8,139	0,280	3,44	[-2.93 ; +2.93]	7,473	7,492	0,061	0,81	[-0.84 ; +0.84]	7,860	7,906	0,176	2,22	[-1.67 ; +1.67]
9	8,311	8,158	0,268	3,28	[-2.69 ; +2.69]	7,664	7,511	0,081	1,07	[-0.77 ; +0.77]	7,925	7,908	0,165	2,08	[-1.54 ; +1.54]
10	8,161	8,158	0,252	3,09	[-2.15 ; +2.15]	7,228	7,483	0,118	1,57	[-1.07 ; +1.07]	7,934	7,911	0,155	1,96	[-1.43 ; +1.43]
11	8,310	8,172	0,244	2,98		7,278	7,464	0,128	1,71		7,865	7,906	0,148	1,87	[-1.34 ; +1.34]
12	8,023	8,159	0,236	2,90		7,301	7,451	0,130	1,75		7,827	7,900	0,143	1,81	[-1.27 ; +1.27]
13	8,056	8,151	0,228	2,80		7,275	7,437	0,134	1,80		8,019	7,909	0,141	1,78	[-1.21 ; +1.21]
14	8,183	8,154	0,219	2,69		7,276	7,426	0,136	1,83		7,709	7,895	0,145	1,84	[-1.16 ; +1.16]
15	7,949	8,140	0,218	2,68	[-1.39 ; +1.39]	7,174	7,409	0,146	1,97	[-1.11 ; +1.11]	8,012	7,903	0,143	1,81	[-1.11 ; +1.11]
16	8,048	8,134	0,212	2,60		7,534	7,417	0,145	1,95		7,874	7,901	0,139	1,76	[-1.07 ; +1.07]
17	8,270	8,142	0,208	2,55		7,523	7,423	0,142	1,92		7,945	7,903	0,135	1,71	[-0.77 ; +0.77]
18	8,141	8,142	0,201	2,47		7,576	7,432	0,143	1,92		7,938	7,905	0,131	1,66	
19	8,160	8,143	0,196	2,41		7,548	7,438	0,141	1,90		7,943	7,907	0,128	1,61	
20	8,365	8,154	0,197	2,42	[-1.17 ; +1.17]	7,334	7,432	0,139	1,88	[-0.94 ; +0.94]	8,058	7,915	0,129	1,63	[-0.70 ; +0.70]
21	7,945	8,144	0,197	2,42		7,376	7,430	0,136	1,84		7,908	7,914	0,125	1,58	
22	8,114	8,143	0,193	2,37		7,451	7,431	0,133	1,79		7,779	7,908	0,126	1,59	
23	8,198	8,145	0,189	2,32		7,480	7,433	0,131	1,76		8,128	7,918	0,131	1,66	
24	8,259	8,150	0,186	2,28		7,154	7,421	0,140	1,88		8,080	7,925	0,132	1,67	
25	8,117	8,149	0,182	2,24	[-0.83 ; +0.83]	7,140	7,410	0,148	2,00	[-0.83 ; +0.83]	7,786	7,919	0,133	1,67	[-0.62 ; +0.62]
26	7,945	8,141	0,183	2,25		7,466	7,412	0,145	1,96		8,001	7,922	0,131	1,65	
27	8,059	8,138	0,180	2,21		7,576	7,418	0,146	1,97		7,941	7,923	0,128	1,62	
28	8,374	8,146	0,182	2,24		7,338	7,415	0,144	1,94		8,108	7,930	0,131	1,65	
29	8,045	8,143	0,180	2,21		7,211	7,408	0,147	1,98		8,038	7,933	0,130	1,64	
30	8,204	8,145	0,177	2,17	[-0.75 ; +0.75]	7,301	7,405	0,145	1,96	[-0.75 ; +0.75]	7,750	7,927	0,132	1,67	[-0.56 ; +0.56]
31	7,932	8,138	0,178	2,19	[-0.73 ; +0.73]	7,325	7,402	0,144	1,94	[-0.73 ; +0.73]	7,635	7,918	0,140	1,77	[-0.73 ; +0.73]
32	8,204	8,140	0,176	2,16		7,374	7,401	0,141	1,91		8,094	7,923	0,141	1,78	
33	7,901	8,133	0,178	2,19		7,135	7,393	0,147	1,98		7,915	7,923	0,139	1,75	
34	8,396	8,141	0,181	2,22		7,497	7,396	0,145	1,97		7,851	7,921	0,137	1,73	
35	7,871	8,133	0,184	2,26		7,319	7,394	0,144	1,95		8,082	7,925	0,138	1,74	
36	7,953	8,128	0,184	2,26		7,254	7,390	0,144	1,94		7,640	7,918	0,144	1,82	
37	8,043	8,126	0,182	2,24		7,126	7,383	0,148	2,01		7,629	7,910	0,150	1,89	
38	8,372	8,132	0,184	2,26		7,202	7,378	0,149	2,02		7,766	7,906	0,150	1,89	
39	7,916	8,127	0,185	2,27		7,493	7,381	0,148	2,01		7,951	7,907	0,148	1,87	
40	8,115	8,126	0,182	2,24		7,431	7,382	0,147	1,99		7,734	7,903	0,148	1,88	

6.1.4 Notes on the quality control of equipment for the measurement of source strength

Verification of source strength for seed brachytherapy should preferably be performed with equipment calibrated against a primary or secondary standard. We strongly recommend the quantity reference air kerma rate (RAKR) to specify the source strength of LEP sources for brachytherapy. The use of obsolete quantities as nominal or apparent activity and milligram radium-equivalent is discouraged and shall not be used. Moreover TPS systems currently in use for brachytherapy applications in Belgium and The Netherlands don't require the activity quantities as input data. We extend these recommendations to vendors of LEP sources for brachytherapy and encourage them to implement these recommendations in the certificates, source ordering/delivery processes with clinics, and their internal assay practices. We endorse the recommendation stated in TG-56, that every radiotherapy institute practising brachytherapy with low-energy photon sources shall have a system for measuring source strength in place with a traceable calibration for all source types used in its practice.

The most practical method for checking the source strength of LEP sources is the use of a well chamber. Details on the experimental determination of the source strength in terms of reference air kerma rate are given in section 5.1 of this report. Well-type chambers or other types of source strength measuring devices should be calibrated at regular intervals and checked for long term constancy. For low-energy sources, like ^{125}I or ^{103}Pd, a calibration interval of two years is recommended [34, 50]. Statements on the air kerma strength of sources based on the measurement of a sample of sources from a delivered batch determined by a local medical physicist as well as the stated source strength in the manufacturer's certificate accompanying the batch of sources should include an uncertainty estimate according to the GUM or publication EA--4/02 (1999) [51,52].

Recommendations for frequency of stability checks with a control source vary in the literature from prior to each assay of brachytherapy source strength to once per three months [5,34]. Constancy is considered acceptable when a reference source reading remains within ± 0.5% of the average of the 4 previous readings [34]. A recalibration of the chamber is recommended whenever this limit is exceeded. To perform constancy checks, a long half-life source should be available, such as ^{137}Cs, ^{90}Sr/^{90}Y, or ^{241}Am. However, ^{241}Am sources are preferred when considering the low-energy range of ^{125}I or ^{103}Pd and potential variations in detector energy response. Care must be taken to assure that the stability checks are performed under reproducible conditions.

6.1.5 NCS considerations

To our knowledge, Yue's method is the only reference providing for a statistical foundation for recommended numbers of seeds to be assayed. The results shown in Table 7 indicate that a 95% confidence interval for a difference between measured and expected source strength to be smaller than 2% is obtained after measuring about 10 seeds. Still, the number of seeds one has to measure is unpredictable to a certain extent, which can be a drawback in practice. We therefore do not impose Yue's statistical method as a recommendation, but instead adopt the AAPM 10 seeds/10% procedure and recommend that the mean of either 10 or 10% of the delivered seeds will be verified. This recommendation is also in line with today's practice of using stranded seeds, mostly delivered as strands containing 10 seeds. One or two strands can be measured as a whole, or as 2 times 5 seeds by using a simple measurement device enabling the shielding of half of the strand.

It has to be stressed that whichever assay recommendation is followed, including Yue's method, the use of traceably calibrated measuring equipment is essential. To assess for multi-source implants the difference between the measured mean source strength of an institute and the strength indicated by the manufacturer's certificate we will adopt the 2008 AAPM recommendations [48] and distinguish three action levels, i.e. less than 3% is acceptable, between 3% and 5% is acceptable but shall be registered and above 5% has to be investigated and should be taken into account.

It should be noted that the source strength of individual seeds may differ by more than 5% from the value stated on the manufacturers certificate. However, we will not follow the AAPM tolerance level of a 5% deviation of individual seeds from the manufacturers source strength, as long as the above stated tolerances on the mean value are not violated. In our opinion variations in individual seed strength have a limited influence on the dose distribution of a ^{125}I prostate implant.

It should be noted, that until recently all source strength measurements were relying on one primary standard (NIST). Due to the lack of available calibration services for LDR (LEP) sources operated by National Metrology Institutes in Belgium, The Netherlands and most countries in Europe medical physicists have to rely on ADCL calibrations and on calibrations provided by manufacturers (e.g. PTW). This is a very undesirable situation and it is strongly recommended that sufficient traceable calibration services will be established on a national or regional scale in Europe. However, the recent establishment of a primary air kerma standard (GROVEX) in Germany via PTB, and the development of new standards in France and other countries in Europe may foster in the future the dissemination of the quantity air kerma (rate) for LEP sources to (secondary) calibration Laboratories in the European region.

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Another approach could be the development of fully accredited calibration laboratories operated by manufacturers of QC equipment for LEP brachytherapy sources in Europe.

6.2 Calibration of the ultrasound system and perineal needle template

6.2.1 Introduction

In current practice of permanent prostate implants, the needles are inserted into the prostate through a perineal template guided by transrectal ultrasound. Most ultrasound prostate scanners superimpose the grid of template coordinates on the real-time axial ultrasound image to provide a reference between needle position in the template and in the image. Adequate ultrasound image quality and alignment of the needle template to the electronic grid of template coordinates are mandatory for accurate placement of needles and consequently seeds.

Although quality assurance of the ultrasound system and template calibration were not topics of our survey in Belgium and the Netherlands, we give a brief discussion and list some references.

6.2.2 NCS considerations

Quality assurance of the ultrasound system regards image quality on the one hand and image accuracy on the other. For objective testing of image quality it is important to have reproducible settings for the monitor.

AAPM TG-128 [53] recommends setup and defining the monitor in terms of greyscale visibility. Image quality also depends on depth of penetration and axial and lateral resolution, which can be measured in a phantom with a distribution of single targets. This type of phantom can also be used to measure image accuracy. If locations of single targets are known, axial and lateral distance accuracy can be checked. Volume measurement accuracy can be measured with a phantom with a 3D target of known size. The above mentioned tests on phantoms must assure that ultrasound images are geometrically accurate and should be part of the acceptance testing of an ultrasound machine and after that repeated annually.

In brachytherapy applications the grid superimposed on the ultrasound image and the perineal template also provide a useful means to measure ultrasound image accuracy. Needles are inserted at known locations and the distances between the needles are verified on the images. Mutic et al [54] describes a technique for alignment of the needle template to

the ultrasound image grid. The ultrasound probe with the template attached is placed vertically in a water tank. Needles are placed at each corner of the template and one at the centre. Needle reflections in the image should correspond to the locations on the electronic grid. AAPM TG-128 recommends a tolerance limit of 3 mm.

To the experience of this NCS committee, 2 mm accuracy is achievable and may be recommended as limit. The water tank may be filled with water at room temperature (sound speed approximately 1480 m/s), although increasing the water temperature [53] or adding ethylene glycol [55] improves tissue equivalence (sound speed 1540 m/s). The use of a stand-off balloon may influence template alignment depending on the acoustic properties of the materials. AAPM TG-128 recommends verifying template alignment prior to each case if a pre-plan technique without intra-operative needle adjustment is used. For intra-operatively planned cases, template alignment may be verified less frequently since needle placement can be adjusted and is therefore less dependent on absolute coordinates.

6.3 Quality control of the TPS

6.3.1 Introduction

Treatment planning is an important step in the overall radiotherapy process, and this is also the case in brachytherapy. There are a number of international and national reports available that give recommendations and guidelines for acceptance testing and commissioning (initial verification), and for periodic quality control of treatment planning systems, such as ESTRO booklet No.8 [25], report of AAPM task group 53 [56], IAEA Technical Report Series No. 430 [57], NCS Report 15 [58] and IAEA TECDOC 1540 [59]. Except for the ESTRO booklet No.8 and IAEA Technical Report No. 430, these reports focus on external beam treatment planning systems. Although the general recommendations from these reports also apply to a large extent to the QA of systems that are designed to perform treatment planning for low-energy photon sources, a number of points deserves specific attention.

6.3.2 Basic data

Very often treatment planning systems come with preloaded TG-43 data for most source models/brands. As mentioned previously it is recommended to apply whenever available the consensus data from professional societies for the seeds in clinical use. Furthermore it was

noted in chapter 2.2 that several variations of the TG-43 dose calculation algorithm are possible, and the user should be well aware which version of the algorithm is used by the TPS for all procedures used in clinic (preplanning, on-line planning and/or post-planning).

It should be verified that the proper TG-43 data are introduced in the TPS, for the seed model(s) used in clinical routine and in correspondence with the calculation algorithm being used.

6.3.3 Reconstruction accuracy of images and source positions

Different image modalities (US, CT, MRI) can be used for treatment planning in brachytherapy. As tissue densities are not used by the TG-43 algorithm, Hounsfield number calibration is not an issue. Geometrical accuracy however should be verified for each image modality used. For details we refer the reader to NCS report 15 [58] or any of the other reports mentioned above. The geometrical accuracy for the US images can be tested after the superimposed grid of the US has been calibrated as mentioned in the previous chapter.

At the time of the NCS survey, 4 different treatment planning systems were used. In three systems, transversal US images are acquired by moving the US probe stepwise through the rectum using a stepper and in 1 TPS the 3D US image set is reconstructed from longitudinal images, which are acquired during a motorised rotation of a bi-plane US probe through the rectum. In case of stepwise acquisition of transversal images, it is important to verify the step size of the stepper, since errors in step size would result in inaccurate distances and volumes determined on the US images in the TPS. To the experience of this NCS committee, 0.5 mm accuracy over a range of 5 cm (about prostate length) is readily achievable and is recommended as a tolerance. Distances and volumes should also be verified in the TPS on US images of a phantom with a 3D target of known size. Also, in case of acquisition of longitudinal images, it is recommended to verify distances and volumes in the TPS based on the reconstructed 3D US image of a phantom with known size. Since basic US inaccuracy is recommended to be less than 2 mm, US based reconstruction inaccuracy of needles and seeds is also recommended to be less than 2 mm.

For US, calibration phantoms are not readily available. For x-ray and CT images ESTRO-EQUAL is offering a mailed audit procedure for testing the geometrical reconstruction technique in brachytherapy [60]. A phantom containing 25 stainless steel marker points must be reconstructed by the user employing the standard imaging and treatment planning procedure. From the stated marker coordinates, 300 different inter-marker distances are calculated and compared to the reference distances. Two quantities are used as a measure

for the accuracy of the geometrical reconstruction method: the mean deviation and the confidence limit Δ, where Δ is taken equal to |mean| + 2SD. Results are considered optimal when the mean deviation is ≤ ± 0.5 mm and when Δ ≤ 1.0 mm, and within the tolerance level when the mean deviation is > ± 0.5 mm and ≤ ± 1.0 mm, or when Δ > 1.0 mm and ≤ 2.0 mm. Studies with dedicated seed phantoms suggest that on CT a reconstruction accuracy <1mm (2 SD) can be achieved in the axial directions, whereas errors in the longitudinal direction can be larger depending on slice thickness or pitch in case of spiral scanning [61,62]. The NCS recommends to apply a CT slice thickness of 2 mm or smaller.

Reconstructions of seeds on MRI are reported to be less accurate than on CT, with mean errors in the order of 2 mm [61, 63]. The signal void of a seed on MR images depends on seed type, magnetic field strength and MR imaging sequences [63-65]. In clinical cases the signal voids of seeds and blood vessels are difficult to discriminate and also seeds close to the rectum may be difficult to identify. Therefore some authors recommend to use a combination of CT and MRI to localise the seeds in relation to the prostate and other structures [67-71].

6.3.4 Dose calculation from a single source including decay

In principle the TG-43 algorithm should reproduce for a given seed exactly the dose rate table from which its basic data have been derived. However, small differences can be observed in practice, due to interpolation and rounding errors and depending on how basic data are entered in the system. AAPM TG-43U1 [2] states that the dose rate calculated by the TPS should agree with the values from the published dose rate tables to within ± 2% over all angles and over the range of radial distances commissioned.

The user should verify the dose calculation in a number of points on the longitudinal and transverse axis of the source, and in points at arbitrary angle and distance, and compare the calculated dose with reference data for all sources that are used clinically. The reference data can be read directly from the published consensus dose rate tables, or when not available in these tables, by calculating the dose according to the TG-43 algorithm using hand calculations. If deviations between the TPS-calculated results and the reference data exceed ± 2%, the deficiencies of the TPS should be further investigated.

For improved test accuracy, it is recommended to do this verification by defining dose points, i.e. calculation points with well known coordinates or linked to the needle implantation grid, in order to eliminate point positioning uncertainty.

The verification should be done for all calculation settings that are used clinically (line or point-source model, different modes of anisotropy handling).

A point of consideration are the different calculation modules that a TPS can offer (preplanning, dynamic dose calculation, live planning, post-planning, 3D-calculation), as the TPS could be using different implementations of the algorithm in the different modules, depending on the architecture of the system. In some of these modules it might not be possible to create dose points. In those cases, at least a visual inspection of the dose calculated at some relevant distances should be performed for all calculation modules.

6.3.5 Dose summation from multiple sources

Typical implantations of LEP sources involve several (up to 100 or more) seeds. The TPS calculates the dose distribution from each individual seed, and sums up these distributions to determine the total dose. In this procedure, the source-to-source shielding effects are neglected by the system, so the summation of doses should be numerically accurate.

The user can test the dose summation for a simple geometry involving only a few sources. After having calculated the dose in a point from each individual source, the dose in the same point can be calculated while placing all the sources. This dose should be equal to the sum of the doses from the individual sources.

6.3.6 Isodose representation

The isodose line representation should be verified in the different calculation modules that the system offers. For this, the dose points determined earlier can be used: an isodose line of a value equal to the dose in a certain point should cross this dose point exactly. The dose line representation can be verified visually on the computer screen.

6.3.7 Dose-volume histograms and planning evaluation parameters

It is not straightforward to verify the accuracy of dose-volume histogram (DVH) calculations and planning evaluation parameters based on DVH's. DVH calculation accuracy is known to depend on the method that is used to generate the dose calculation points within the volume (e.g. random versus fixed points, resolution) and on how the TPS is handling slice thickness effects, especially at the cranial and caudal edges of the volume [72].

To our knowledge, no reference data are available enabling a test that mimics the clinical application, i.e. a target encompassing a number of sources and volumes of interest in the near vicinity of these sources. However, two aspects with respect to dose-volume calculations can be addressed by the test procedure described below:

Verification of the volume calculation of a geometrical object

A CT scan of an object of known dimensions is imported in the treatment planning system. After delineation of the object, the volume determined by the TPS is compared with the real volume. Alternatively, an object of given dimensions can be embedded in a series of CT images using a software tool such as Matlab.

The way 3D objects are reconstructed from discrete 2D slices, especially at the cranial and caudal edges, is a major factor influencing the accuracy of the volume calculation. This modelling is TPS dependent, and in general more accurate, for image sets with smaller slice thickness. The influence of TPS and of slice thickness was investigated in Kirisits et al. [72], where four phantom image sets with varying slice thickness were imported in seven different treatment planning systems developed for brachytherapy. Contours were defined for three scanned structures: a small cylinder, a large cylinder, and a large cone. The difference between the real and the calculated volumes averaged over the TPSs varied, depending on the used imaging modality and slice thickness, between -3.1% and 8.3% for a small cylindrical volume of about 4 cm^3 (urethra), and 0.5 to 8.3% for larger objects of about 60 cm^3.

An independent, approximate verification of the volume calculation can be obtained by comparing the volume of an organ (prostate) outlined on the ultrasound machine with the volume obtained by copying this outline on the TPS.

Verification of the dose-volume calculation

The accuracy of the volume calculation of a 3D isodose shape can be verified for the setup of a single point source assuming isotropic dose fall off. For this special case, the generated isodose levels are represented by spheres and the corresponding dose volumes calculated by the TPS should equal the volumes of the spheres. By adjusting the source strength, a certain isodose level (e.g. 1 Gy) can be set at a certain distance from the source (e.g. r = 1 cm). The isodose volumes in the DVH as calculated by the TPS can then be compared to the mathematical volume. This can be repeated for spheres with different radii over a relevant range (description in Appendix A.3 (test 4), see results in paragraph 5.2.3).

In these test conditions, accuracy of calculations <5% can be achieved (Figure 30 in 5.2.3), on the condition that the dose calculation resolution is sufficiently high (< 2 mm). However, deviations may be larger in clinical cases depending on how the slice thickness interferes with the volume calculation, in the case of high dose values relevant for prostate implants (up to 200%) or in case of low resolution voxels [72,73].

6.3.8 Program output

As for other TPS's, the printed and graphical output should be verified, with attention to clearness and completeness of data, units and scaling. Should the TPS have a direct link to another system such as a seed preparation tool or an automatic seed afterloader, then this link should also be thoroughly tested.

6.3.9 Implications of upgrades/ improvements

In the case of major system upgrades or improvements in the basic TG-43 data, it is good practice to study the influence of these changes for a number of clinical cases by comparing results of previous calculations with the new ones, and discuss possible differences with the radiation oncology team.

The treatment planning system should be tested at time of commissioning, at every software upgrade, when basic TG-43 data are modified or updated or when a new source model is being used. As an example, the test procedures used during the survey by this NCS subcommittee are given in appendix 2

6.4 Post-planning

Real implants never match the planned implantation scheme, no matter how skilled and experienced the physician and how ideal the patient. Post-implant planning provides the necessary information to evaluate the 'real' implant dosimetry. The European organisations ESTRO, EAU and EORTC, as well as the ABS and AAPM formulated recommendations and guidelines for post-implant dosimetry on permanent prostate brachytherapy implants [46,74 - 77]. Although uncertainty in post-implant dosimetry is reported because of interobserver variation and because of dependence on image modality applied, there is evidence that clinical outcome is related to dosimetric post-planning indices [78-83]. Besides, post-implant

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dosimetry allows evaluation of the implant procedure (the adequacy of the implant design, skill of the operating room staff and appropriateness of equipment used) and can hence act as a valuable learning tool.

The European as well as the American organisations recommend to perform post-implant dosimetry on all patients 4 to 6 weeks after implantation, when oedema has settled. At that moment, it is usually not possible anymore to take away or add seeds to correct for a non optimal realised implant. For this reason, the implant technique has shifted over the past years from pre-planning to intra-operative planning. Various evaluation techniques using different imaging modalities are under development to check the implant dosimetry in the operating theatre, allowing for corrections.

Although a description of post-planning techniques falls beyond the scope of this report, we endorse the importance of post-implant dosimetry evaluation as described by the ESTRO/EAU/EORTC, ABS, and AAPM recommendations.

7 Summary of NCS recommendations

This chapter provides for the reader a quick scan of the recommendations discussed in this report, which are endorsed by the NCS.

7.1 Measurement of source strength

- Specification or measurement of source strength of LEP sources in terms of activity, nominal activity, or apparent activity is strongly discouraged.

- Certificates of a manufacturer or vendor should state the source strength of a batch of sources in terms of reference air kerma rate or air kerma strength.

- The specification of the source strength should include the relative expanded uncertainty (k=2), taking into account the bin size of purchased batches.

- The local medical physicist should perform source strength measurements in terms of reference air kerma rate with traceably-calibrated equipment on a sample of sources taken from every batch of sources prior to clinical use.

- Data of source strength measurements determined by the local medical physicist should be assigned a relative expanded uncertainty (k=2).

- A minimum number of 10 seeds or 10% from a batch should be measured for seed strength verification, whichever is greater.

- A tolerance level of 3% between measured mean value and the value stated on the certificate is recommended. Deviations between 3 to 5% may be accepted, but should be registered. Deviations above 5% should be investigated.

7.2 Use and calibration of measurement equipment

- Traceable calibration of the measurement equipment should be performed at a 2 year interval.

- Instruments should be calibrated for all source types, inserts (or adapters) and geometrical conditions applied in local clinical procedures and practice.

- The stability should be checked every 3 months with a long half-life source such as ^{137}Cs, ^{241}Am, or ^{90}Sr/^{90}Y.

- Results of constancy (or stability) checks should be within ± 0.5% of the average of the 4 previous readings. If the limit of ± 0.5% is exceeded the measurement device should be recalibrated.

7.3 Calibration of US machine and template

- US grid and template alignment should be verified at a 3 months interval or whenever misalignment is suspected during an implant procedure.
- A tolerance limit of 2 mm should be adopted to the accuracy of the alignment between US grid and the template.

7.4 QC of the TPS

- Commissioning of the TPS should include verification of the dose calculation algorithm and source data according to TG-43 (and updates). This should be repeated after every (major) software update.
- The accuracy of source position reconstruction on CT and MRI should be verified at the commissioning of TPS and for (major) updates using a dedicated phantom (accuracy < 2 mm).
- The geometrical accuracy for the US images should be tested after the superimposed grid of the US has been calibrated as mentioned in §7.3 (accuracy < 2 mm).
- The accuracy of dose calculation should be tested at the commissioning of the TPS and for (major) updates and should be $< \pm 2\%$ for the clinically used source models.
- This test should be performed for a single source, but also for the summed dose distribution from multiple sources.
- The accuracy of isodose lines around a single source should be verified at the commissioning of the TPS and for (major) updates.
- Volume calculation of contoured objects should be tested at the commissioning of the TPS and for (major) updates.
- Dose-volume calculation should be tested at the commissioning of the TPS and for (major) updates.
- Data output and connectivity with other programs or systems should be tested at commissioning of TPS and after (major) updates.

Appendices

A.1 TG-43 data for commonly used sources

Table A.1.1

Point-source approximation							
Manufacturer / Model name	Oncura Oncoseed	Bebig IsoSeed	Bebig IsoSeed	IBt InterSource	Bard Source Tech Medical	Isotron selectSeed	Best ^{125}I
Model reference	6711	I25.S06	I25.S17	1251L	STM1251	130.002	2301
Half Life (days)	59.4	59.4	59.4	59.4	59.4	59.4	59.4
Conversion U/mCi	1.27	1.27	1.27	1.27	1.27	1.27	1.27
Active Length (mm)	2.8	3.5	3.4	4.35	3.81	3.4	4.0
Reference	TG-43U1	TG-43U1	[12]	TG-43U1S1	TG-43U1S1	[18,19]	TG-43U1
Λ (cGy.h^{-1}.U^{-1})	0.965	1.012	0.94	1.038	1.017	0.946	1.018
	r (cm)						
$g_p(r)$ 0.1	0.696	0.613	0.655	0.403	0.544		0.579
0.15	0.853	0.76	0.812	0.569	0.7		0.725
0.2			0.912				
0.25	0.982	0.908	0.973	0.805	0.876		0.878
0.3			1.008				
0.4			1.041				
0.5	1.048	1.001	1.05	0.978	0.999		0.991
0.6			1.048				
0.7			1.041				
0.75	1.036	1.012		1.012	1.013		1.02
0.8			1.029				
0.9			1.015				
1	1	1	1	1	1		1
1.5	0.912	0.942	0.913	0.945	0.943		0.945
2	0.819	0.863	0.818	0.869	0.864		0.875
2.5			0.723				
3	0.636	0.695	0.636	0.71	0.698		0.715
3.5			0.557				
4	0.499	0.543	0.484	0.562	0.546		0.562
4.5			0.42				
5	0.367	0.413	0.363	0.432	0.42		0.432
6	0.272	0.316	0.271	0.328	0.318		0.324
7	0.2	0.234	0.199	0.244	0.239		0.251
8	0.149	0.178	0.148	0.183	0.178		0.189
9	0.11	0.135	0.108	0.141	0.133		0.144
10	0.0809	0.0967	0.08	0.102	0.098		0.104

[12] Lymperopoulou 2005   [18]Anagnostopoulos 2002   [19]Karaiskos 2001

The data in this appendix are consensus data collected from the TG-43 reports, updates and other references and were used for the calculation of the reference results in the tests of the

treatment planning systems. For treatment planning purposes, it is advised to get source data directly from the TG-43 reports and updates regarding the consensus data.

Table A.1.2

Line-source approximation								
Manufacturer / Model name		**Oncura** **Oncoseed**	**Bebig** **IsoSeed**	**Bebig** **IsoSeed**	**IBt** **InterSource**	**Bard Source** **Tech Medical**	**Isotron** **selectSeed**	**Best** **[125]I**
Model Reference		6711	I25.S06	I25.S17	1251L	STM1251	130.002	2301
Half Life (days)		59.4	59.4	59.4	59.4	59.4	59.4	59.4
Conversion U/mCi		1.27	1.27	1.27	1.27	1.27	1.27	1.27
Active Length (mm)		3	3.5	3.4	4.35	3.81	3.4	4
Reference		TG-43U1	TG-43U1	[12]	TG-43U1S1	TG-43U1S1	[18,19]	TG-43U1[10]
Λ (cGy.h^{-1}.U^{-1})		0.965	1.012	0.94	1.038	1.017	0.946	1.018
	r (cm)							
$g_L(r)$	0.1	1.055	1.01	1.062	0.757	0.941	1.042	1.033
	0.15	1.078	1.018	1.079	0.841	0.972		1.029
	0.2			1.09			1.082	
	0.25	1.082	1.03	1.097	0.963	1.013		1.027
	0.3			1.098			1.087	
	0.4			1.09			1.085	
	0.5	1.071	1.03	1.079	1.021	1.033	1.078	1.028
	0.6			1.065			1.066	
	0.7			1.051			1.052	
	0.75	1.042	1.02		1.024	1.022		1.03
	0.8			1.035			1.035	
	0.9			1.018			1.019	
	1	1	1	1	1	1	1	1
	1.5	0.908	0.937	0.908	0.937	0.937	0.907	0.938
	2	0.814	0.857	0.812	0.859	0.856	0.808	0.866
	2.5			0.717			0.713	
	3	0.632	0.689	0.631	0.7	0.691	0.627	0.707
	3.5			0.552			0.548	
	4	0.496	0.538	0.48	0.554	0.54	0.477	0.555
	4.5			0.416			0.414	
	5	0.364	0.409	0.36	0.425	0.415	0.357	0.427
	6	0.27	0.313	0.269	0.323	0.314	0.265	0.32
	7	0.199	0.232	0.197	0.24	0.236	0.196	0.248
	8	0.148	0.176	0.146	0.18	0.176	0.144	0.187
	9	0.109	0.134	0.107	0.138	0.131	0.106	0.142
	10	0.0803	0.0957	0.079	0.101	0.0969	0.078	0.103

[12] Lymperopoulou 2005   [18]Anagnostopoulos 2002   [19]Karaiskos 2001

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[10] The values for $\Phi_{an}(1)$ and $\Phi_{an}(2)$ in the last column Table A.1.3 and for F(1,0) and F(2,0) in Table A.1.10 are taken from the Erratum to Reference 2. This Erratum is published in Med.Phys. 31:3532-3533, 2004.

Table A.1.3

1D Anisotropy Function							
Manufacturer / Model name		Oncura Oncoseed	Bebig IsoSeed	Bebig IsoSeed	IBt InterSource	Bard Source Tech Medical	Isotron selectSeed	Best [125]I
Model Reference		6711	I25.S06	I25.S17	1251L	STM1251	130.002	2301
	r (cm)							
$\Phi_{an}(r)$	0.25		1.122			1.21		
	0.3						1.051	
	0.5	0.973	0.968	0.975	1.028	0.982	0.959	
	0.7						0.938	
	1	0.944	0.939	0.949	0.958	0.942	0.933	0.986
	1.5			0.947			0.932	
	2	0.941	0.939	0.949	0.945	0.937	0.936	0.976
	3	0.942	0.938	0.951	0.948	0.947	0.941	0.968
	4	0.943	0.94				0.943	0.971
	5	0.944	0.941	0.95	0.945	0.938	0.945	0.969
	6						0.946	0.991
	7		0.949	0.948		0.944		0.969
	8						0.950	
	10						0.951	
Constant Φ_{an}		0.943	0.939	0.949	0.954	0.941	0.936	0.9565

Table A.1.4

2D Anisotropy function F(r,θ)						
Oncura Oncoseed 6711						
r (cm) / θ (°)	0.5	1	2	3	4	5
0	0.333	0.370	0.442	0.488	0.520	0.550
5	0.400	0.429	0.497	0.535	0.561	0.587
10	0.519	0.537	0.580	0.609	0.630	0.645
20	0.716	0.705	0.727	0.743	0.752	0.760
30	0.846	0.834	0.842	0.846	0.848	0.852
40	0.926	0.925	0.926	0.926	0.928	0.928
50	0.972	0.972	0.970	0.969	0.969	0.969
60	0.991	0.991	0.987	0.987	0.987	0.987
70	0.996	0.996	0.996	0.995	0.995	0.995
80	1	1	1	0.999	0.999	0.999

Table A.1.5

Anisotropy function F(r,θ)								
Bebig IsoSeed I25.S06								
r (cm) θ (°)	0.25	0.5	1	2	3	4	5	7
0	0.302	0.429	0.512	0.579	0.610	0.631	0.649	0.684
5	0.352	0.436	0.509	0.576	0.610	0.635	0.651	0.689
10	0.440	0.476	0.557	0.622	0.651	0.672	0.689	0.721
20	0.746	0.686	0.721	0.757	0.771	0.785	0.790	0.807
30	0.886	0.82	0.828	0.846	0.857	0.862	0.867	0.874
40	0.943	0.897	0.898	0.907	0.908	0.913	0.918	0.912
50	0.969	0.946	0.942	0.947	0.944	0.947	0.949	0.946
60	0.984	0.974	0.97	0.974	0.967	0.966	0.967	0.976
70	0.994	0.989	0.988	0.990	0.984	0.985	0.987	0.994
80	0.998	0.998	0.998	1	0.994	1	0.993	0.999

Table A.1.6

Anisotropy function F(r,θ)							
Bebig IsoSeed I25.S17							
r (cm) θ (°)	0.5	1	1.5	2	3	5	7
1	0.205	0.290	0.357	0.383	0.458	0.538	0.641
2	0.207	0.291	0.361	0.399	0.473	0.572	0.618
3	0.208	0.316	0.414	0.468	0.542	0.587	0.632
4	0.214	0.379	0.457	0.491	0.551	0.606	0.627
5	0.261	0.408	0.465	0.497	0.550	0.613	0.631
6	0.323	0.416	0.466	0.503	0.556	0.613	0.636
7	0.350	0.423	0.479	0.521	0.571	0.625	0.655
10	0.393	0.480	0.532	0.568	0.613	0.662	0.693
12	0.446	0.523	0.569	0.602	0.642	0.690	0.716
15	0.527	0.587	0.631	0.659	0.693	0.727	0.750
18	0.599	0.649	0.681	0.705	0.730	0.762	0.776
20	0.643	0.681	0.708	0.732	0.758	0.777	0.796
25	0.735	0.753	0.773	0.790	0.808	0.831	0.829
30	0.808	0.813	0.823	0.834	0.845	0.858	0.863
31	0.819	0.822	0.833	0.845	0.854	0.868	0.866
35	0.866	0.858	0.865	0.873	0.885	0.888	0.893
40	0.914	0.900	0.903	0.908	0.915	0.916	0.913
45	0.954	0.932	0.933	0.933	0.937	0.937	0.936
50	0.985	0.960	0.957	0.956	0.958	0.952	0.955
60	1.022	1.003	0.995	0.992	0.989	0.981	0.976
70	1.003	1.029	1.022	1.021	1.016	1.005	1.001
80	0.997	1.013	1.027	1.028	1.022	1.013	1.007

Table A.1.7

Anisotropy function F(r,θ)					
IBt InterSource 1251L					
r (cm) / θ (°)	0.5	1	2	3	5
0	0.476	0.544	0.653	0.680	0.703
5	0.645	0.626	0.656	0.713	0.718
10	0.725	0.699	0.709	0.736	0.751
20	0.810	0.783	0.789	0.810	0.817
30	0.867	0.849	0.849	0.859	0.854
40	0.923	0.900	0.910	0.911	0.911
50	0.966	0.946	0.946	0.949	0.954
60	0.991	0.979	0.971	0.976	0.968
70	0.998	0.988	0.991	0.996	0.988
80	1.002	0.996	0.997	0.995	0.988

Table A.1.8

Anisotropy function F(r,θ)							
Bard STM1251							
r (cm) / θ (°)	0.25	0.5	1	2	3	5	7
0	0.863	0.524	0.423	0.453	0.500	0.564	0.607
2	0.865	0.489	0.616	0.701	0.702	0.706	0.720
5	0.784	0.668	0.599	0.611	0.637	0.657	0.682
7	0.861	0.588	0.575	0.603	0.632	0.655	0.682
10	0.778	0.562	0.579	0.617	0.649	0.672	0.700
20	0.889	0.688	0.698	0.722	0.750	0.761	0.781
30	0.949	0.816	0.808	0.819	0.841	0.838	0.845
40	0.979	0.898	0.888	0.891	0.903	0.901	0.912
50	0.959	0.956	0.943	0.941	0.950	0.941	0.945
60	0.980	0.988	0.982	0.980	0.985	0.973	0.982
70	0.989	0.973	1.005	1.002	1.011	0.995	0.998
80	0.994	0.994	0.989	1.015	1.018	1.003	1.011

Table A.1.9

Anisotropy function F(r,θ)									
Isotron selectSeed 130.002									
r (cm) θ (°)	0.3	0.5	0.7	1	1.5	2	3	4	6	8
0.5	0.197	0.205	0.248	0.291	0.344	0.388	0.464	0.515	0.569	0.615
1.5	0.200	0.211	0.251	0.297	0.382	0.441	0.519	0.553	0.620	0.648
2.5	0.201	0.218	0.268	0.354	0.441	0.483	0.552	0.580	0.635	0.655
3.5	0.202	0.246	0.333	0.406	0.463	0.499	0.557	0.591	0.639	0.658
4.5	0.213	0.309	0.373	0.420	0.467	0.508	0.559	0.594	0.641	0.667
5.5	0.240	0.351	0.384	0.425	0.471	0.511	0.562	0.599	0.644	0.671
7.5	0.353	0.371	0.401	0.442	0.495	0.535	0.581	0.616	0.668	0.685
10.5	0.410	0.425	0.460	0.499	0.546	0.580	0.631	0.654	0.699	0.719
12.5	0.469	0.473	0.502	0.540	0.582	0.617	0.657	0.680	0.716	0.731
15.5	0.565	0.543	0.567	0.595	0.633	0.661	0.695	0.715	0.745	0.762
17.5	0.623	0.588	0.602	0.631	0.663	0.689	0.723	0.739	0.763	0.788
20.5	0.700	0.646	0.659	0.679	0.706	0.728	0.754	0.769	0.792	0.810
25.5	0.803	0.728	0.729	0.747	0.766	0.783	0.799	0.814	0.836	0.840
30.5	0.880	0.797	0.790	0.799	0.815	0.828	0.844	0.852	0.867	0.871
35.5	0.937	0.854	0.841	0.844	0.853	0.866	0.879	0.882	0.892	0.903
40.5	0.970	0.902	0.886	0.886	0.889	0.898	0.907	0.908	0.918	0.926
50.5	0.988	0.973	0.955	0.952	0.951	0.956	0.955	0.955	0.958	0.959
60.5	0.966	1.003	1.002	0.998	0.991	0.991	0.993	0.991	0.986	0.987
70.5	0.987	0.981	1.013	1.017	1.016	1.019	1.014	1.008	1.011	1.006
80.5	0.996	0.995	0.995	0.994	1.013	1.019	1.018	1.019	1.018	1.014

Table A.1.10

Anisotropy function F(r,θ)							
Best ^{125}I 2301							
r (cm) θ (°)	1	2	3	4	5	6	7
0	0.867	0.854	0.922	0.902	0.894	0.893	0.858
5	0.724	0.720	0.726	0.738	0.753	0.771	0.800
10	0.653	0.671	0.699	0.727	0.732	0.764	0.782
20	0.785	0.794	0.809	0.814	0.825	0.852	0.821
30	0.900	0.890	0.885	0.892	0.899	0.915	0.873
40	0.982	0.954	0.947	0.939	0.943	0.976	0.937
50	1.014	0.992	0.985	0.991	0.997	0.989	0.961
60	1.030	1.010	1.009	1.007	1.010	1.019	1.002
70	1.036	1.026	1.016	1.023	1.011	1.035	1.010
80	1.010	1.030	1.019	1.017	1.010	1.020	1.005

A.2 Procedures used by the NCS subcommittee during their survey

The tests described in this appendix were used as part of the NCS on-site visit. These tests were intended only to be used in the framework of the on-site visits, and typically do not replace any acceptance testing that should be performed by the hospital physicist prior to using a new treatment planning system or new version of it for patient treatments. In no respect, the NCS subcommittee or members of it can be held responsible for any errors that could result from misinterpretation of the results of these tests. It should be noted that the tests described in this appendix do not cover all verifications that are recommended by this subcommittee as described in chapter 6 and 7.

Where available consensus source data published by the AAPM TG-43U1 are to be used as reference.

The following tests are described:
- Test 1: Point-source calculation test
- Test 2: Dose summation test
- Test 3: Isodose representation test
- Test 4: Dose-volume histogram test
- Test 5: Line-source calculation / 2D anisotropy function test

Tests 1-4 are done using a 1D anisotropy calculation model. If only a 2D anisotropy calculation is used in clinical routine, we still recommend these tests use the 1D calculation model. Standard settings as used in clinical routine should be used.

A.2.1 Test 1: Point-source calculation test (1D Anisotropy)

In this test the dose calculation in a number of points at different distances perpendicular to the seed axis of a single seed using the point-source approximation is verified.
Test procedure:
1. Create a test patient with a test study on the TPS.
2. Create a "phantom" of about 10x10x10 cm^3.
3. Place 1 source of strength 100U at image 5 (z=2 cm), at the left most column, middle row.
4. Add dose points to this image, on grid points on the right of the source, at distances of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0 and 6.0 cm (and 7.0 cm if possible).

5. Check the doses to these points against the reference values.

A.2.2 Test 2: Dose summation test

In this test the dose calculation using 2 seeds in a number of points (dose points) at different distances perpendicular to the seed axis is verified.

Test procedure:

1. Use the plan from Test 1.

2. Add a source of strength 100U at the image at z=2 cm, at 1 cm right from the first source.

3. Verify that the dose calculated in the dose points as defined in Test 1 equals the sum of the doses from the 2 sources as calculated in Test 1.

A.2.3 Test 3: Isodose representation test

In this test the isodose representation around a single source is verified using the point-source dose calculation approximation.

Test procedure:

1. Use the plan from Test 1, clear all sources.

2. Add a source of strength 100U at the central image (z=5 cm), at the centre of the grid.

3. Select isodose levels equal to the doses calculated in Test 1 in the dose points at 1.0, 2.0 and 3.0 cm.

4. Verify visually that these isodoses pass through the grid points at the respective distances, and show up as circles. If possible verify also the isodoses in a sagital plane through the source axis: using the 1D anisotropy correction function isodoses should be circular.

A.2.4 Test 4: Dose-volume histogram test

In this test the dose-volume calculation of the treatment planning system is verified by using simple geometrical DVH values. This test only applies for a point source model, 1D anisotropy correction function, where the isodoses should represent a sphere.

Test procedure:

1. Create a new test study for the test patient.

2. Create a volume ("prostate") of 7x7x7 cm^3.

3. Place a source at the central image (z=3.5 cm), at the centre of the grid.

4. Recalculate the source strength using the results from Test 1 as to obtain a dose of 100 Gy in points at respectively 1.0, 2.0 and 3.0 cm. Adapt the source strength to

these values and record the respective volumes covered by the 100 Gy dose from the DVH calculated by the TPS.

5. Compare the calculated volume of the 100 Gy dose with the mathematical volume of the sphere.

A.2.5 Test 5: 2D anisotropy function and line-source calculation model

This test only applies to dose calculations using the 2D anisotropy function data.

Part A: Dose in points along the transverse and longitudinal axis of the seed (at 90 and 0 degree angle):

1. Use the plan from Test 1.
2. Place 1 source of strength 100U at the image at z=2 cm, at the left most column, middle row.
3. Add additional dose points on this grid position to the other images at distances of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0 cm and 7.0 cm of the image containing the source. These points are aligned with the source axis (angle 0°).
4. Compare the calculated doses to the dose points in the plane of the source (90°) and in the other images (0°) with the reference values.

Part B: Dose in points at arbitrary distances and angles:

1. Use the plan from part A.
2. Place 1 source of strength 100U at image 5 (at z=2 cm), at the centre of the image.
3. Add dose points on other images and grid points, making sure to create dose points at different angles and distances.
4. Compare the computed dose to these points with values obtained by hand calculation using the TG-43 algorithm.

A.3 Safety aspects

The use of radioactive ^{125}I seeds implanted for patient treatment involves radiation safety issues: 1) rupture of a seed can cause contamination and 2) people approaching an implanted patient are exposed to ionising radiation.

Although the risk of contamination is small, it should be noted that free iodine coming from a ruptured seed is accumulated in the thyroid gland. In such a situation, one has to pay attention to the dose to that gland.

In estimating dose to people approaching implanted patients, the actual air kerma rate at some distance from the patient has to be known. Published data from direct dose measurements from patients differ by more than a factor of 10 and show a large variation. In this report data from MSKCC [84] demonstrating a dose rate of 40 µGy h^{-1} at the surface of the patient, 6 µGy h^{-1} at a distance of 30 cm, and 1 µGy h^{-1} at a distance of 1 m from the surface of the patient is applied for dose estimation of persons approaching patients implanted for prostate carcinoma. Assuming 1.6 GBq per patient, an air kerma factor of 0.034 µGy m^2 MBq^{-1} h^{-1} and attenuation by 12 cm surrounding tissue (HVL of 2 cm tissue), these figures roughly agree with theoretical values. To calculate the effective dose equivalent of a person present in the isotropic beam of radiation at some distance from the patient, a conversion factor of 0.05 Sv/Gy is handled [85].

A.3.1 In the hospital

Preparing the sources

In case of stranded seeds, strands are cut manually into pieces of two or more seeds that are loaded in implant needles. Seeds are handled with a pair of tweezers with a length of at least 15 cm and strands are cut with a scalpel which also has a length of at least 15 cm. Assuming 10 seeds of 20 MBq handled without attenuation at a distance of 7.5 cm, during 15 minutes per patient results in a calculated dose to the fingertip of 0.3 mSv. In case of four employees involved in source preparation and 300 patients treated each year, an annual dose of about 20 mSv is estimated for the fingertip. In practice, part of a strand will be shielded by steel during source preparation, reducing the dose to the fingertip considerably and resulting in a dose to the fingertip well below the annual legal limit of 500 mSv as stated for exposed workers [86,87].

Inserting the sources

If we assume that the radiation oncologist who performs the implant is at an average distance of 30 cm from the sources during the insertion of the loaded needles, and that the loading process takes one hour, then a dose level of 6 µGy is reached which corresponds to an effective dose of 0.3 µSv to the radiation oncologist. In case of a workload of 300 patients a year and two radiation oncologists, each implanting 150 patients per year, an annual effective dose of 45 µSv per radiation oncologist is estimated. Other persons involved in the implant procedure and present in the operating theatre during the implant, receive even a lower effective dose because of a larger distance to the patient. Thus, one may conclude to an annual effective dose far below the legal limits of 1 mSv per year applied to not-exposed employees.

The exposure of the finger of the treating physician ranges from 1 – 2 mSv per procedure. In case of hundreds of implants a year, the annual dose limit of 500 mSv can be reached [88].

For implants guided by C-arm control, the dose level in the operating room mainly is caused by fluoroscopy and a lead apron should be worn.

Nursing the patients

Following the implant procedure, patients mostly stay just for short time in the hospital and generally do not need extensive care. Often the brachytherapy is a one day procedure. The patient is implanted in the morning and leaves the hospital in the afternoon. In some situations the patient stays over for one night. Assuming a distance of 1 m to the patient corresponding to a dose rate of 1 µGy h^{-1}, a nurse taking care of the patient during one hour receives an effective dose of 0.05 µSv. This low dose level justifies the common practice in most hospitals to qualify nurses taking care of implanted patients as non-exposed workers, and to decide not to provide them with personal dosimeters.

Pregnant employees

Although for all activities around the brachytherapy treatment a low effective dose is estimated, in most departments pregnant employees are exempt from any task related to the implant procedure. Especially in circumstances where x-ray control is applied for source placement, pregnant employees should not take part in activities inside the operating theatre.

Control of the working area

To prevent seeds from getting lost within the hospital, control is needed during implantation in theatre, during the patients stay in nursing environments as well as during transportation between different locations. Different methods exist, from simple to more complex, some being partly complimentary. Simple methods are based on counting seeds entering and leaving the operating room. More complex methods use x-ray images, where film has been replaced by digital techniques over the past years. All methods, however, are applied in combination with radiation monitoring of the room itself, clothing of personnel and all technical equipment used during the implantation procedure.

Regarding the nursing environment, loss of seeds can be checked by collecting and monitoring urine and faeces during the nursing period. Finally the nursing room, including bed clothing, is thoroughly checked with a radiation monitor when the patient is released from the hospital.

Apart from losing whole seeds, a minor possibility exists of a seed leaking activity within the patient. In case of detecting activity in urine without detecting one or more seeds, additional measures should be taken to confirm leakage within the patient and to estimate, e.g. by monitoring the thyroid gland (only in case of ^{125}I), the amount of leaking activity.

As a worst case example, the dose to the thyroid is estimated assuming all activity from a 20 MBq seed leaking within the patient and assuming a metabolic process comparable to oral administration. From ICRU-32 appendix C [89] the fraction of administered activity after 24 hours in the thyroid is 30% and the absorbed dose in the thyroid is $2.6 \cdot 10^{-7}$ Gy/Bq. Ignoring the effect of non uniform distribution of radioiodine in the gland, these figures result in a mean absorbed dose to the thyroid gland of 0.3×20 MBq $\times 2.6 \cdot 10^{-7}$ Gy/Bq = 1.6 Gy.

In case of activity detected in the urine, oral administration of non-radioactive iodine can be considered.

Dose due to subsequent medical need

Occasionally subsequent medical care is needed for some time after the implant. In such a situation the team should be aware of the radioactivity in the patient

Post-implant TURP

In case of a post-implant trans-urethral resection of the prostate (TURP), removed tissue often contains some seeds. Processing of such a sample in the laboratory of pathology can cause contamination because of rupture of seeds and can damage the equipment in the laboratory. Before processing in the laboratory, the specimen should be verified on presence

of seeds. For example by taking an x-ray image of the sample. The hospital where the patient was implanted has to be contacted for information on how to handle these seeds.

Post-implant surgery

In case of post-implant surgery, the team has to be aware of the radioactivity in the patient. Because of the low dose level at some distance from the patient, there is no need for specific precautions. However, in pelvic or abdominal surgery one has to estimate the risk for removing seeds from the patient. It can be considered to monitor the operating room for radioactivity after surgery.

Post-implant physiotherapy or re-animation

In case of physiotherapy or re-animation, because of the low dose level at some distance from the patient, no specific precautions have to be taken.

Post-implant long-stay hospitalisation

In case, after implant, the patient has to stay for long time in the hospital, the patient should stay in a one-person nursing room. Because of the low dose level at some distance from the patient, no specific precautions have to be taken. It should be considered to excuse pregnant employees from taking care of the patient however.

A.3.2 At home

To estimate the dose to people approaching the patient after he is discharged from the hospital, the dose level during the lifetime exposure of the seeds is taken as starting-point. An initial dose rate (D_0) of 1 µGy h^{-1} at a distance of 1 m from the patient [84] results in a lifetime dose of 1.44 x T$_{1/2}$ x D_0 = 2080 µGy. Taking into account the conversion factor of 0.05 Sv/Gy [85], a lifetime effective dose of 104 µSv at a distance of 1 m is found.

Initial dose rates of 40 µGy h^{-1} at the surface of the patient and 6 µGy h^{-1} at a distance of 30 cm from the patient results in a lifetime effective dose of 4.2 mSv and 624 µSv respectively.

Dose to family, household members, comforters and carers.

From all the family or household members in the neighbourhood of a patient implanted, it can be stated that the partner will receive the highest dose. For the partner an occupancy factor per 24 hours in the vicinity of the patient as stated below is considered.

Out-of-doors (large distance) 3/24

Watching television (distance 0.5m) 3/24

Meals (distance 1m) 3/24

Sleeping (distance 0.7m) 9/24

Various (distance 3m) 6/24

Practising these time and distance factors results in an lifetime effective dose to the spouse of 150 μSv, corresponding well with the value of 100 μSv as reported from direct dose monitoring [90]. It seems reasonable to assume an even lower lifetime effective dose to other family, household members of the patient, comforters and carers. Since these lifetime dose levels are even below the annual 1 mSv limit as stated for not-exposed workers, no specific measures have to be taken.

Precautions with respect to children and pregnant relations

Young children related to the implanted patient concern generally grand children. For grand children it is stated that they stay 2 hours per week in the house of their grandfather at an averaged distance of 3m of him. Next to it, it is assumed that they stay each week during 15 minutes in the lap of their grandfather. Applying these figures results in a lifetime effective dose to the child of 16 μSv. Despite this low level of radiation, in the written instruction to the patient it is most often recommended not to nurse young children on their lap or sit close to them for long periods of time for the first two months after implantation.

Although the lifetime effective dose to a close family member (i.e. daughter) which is pregnant, is expected to be well below the 1 mSv limit, it is good practice to advice the patient to take care of distance and time. Extra precautions may be needed when the partner of the patient is pregnant.

Lost seeds found by the patient or a member of the family

The rate of expelled seeds is very low, especially when using stranded seeds. Seeds can be expelled in urine and in semen. Seeds expelled in urine cause negligible risk because they will be flushed away in the toilet. To remove the risk of seeds expelled in semen it is often recommended to wear a condom for the first five ejaculations after the implantation.

Lost seeds found by the patient should be stored in a small canister and returned to the hospital in charge. Although touching the seed for a very limited period of time is not harmful, it is recommended to use tweezers, a spoon etc.

A.3.3 Members of the public

As stated before, a person permanently staying at a distance of 1 m away from a patient implanted receives a lifetime effective dose of 104 µSv. Because of the distance and the actual small time-factor applicable to members of the public, this figure brings about an effective dose lower than the legal limit of 10 µSv per year for a general member of the public.

A.3.3.1 Cremation

In case of cremation one year after implantation of 10 patients per year in one crematorium the dose to the thyroïd of people living in the vicinity (at a distance of 175 m) of that crematorium is estimated to be 20 nSv/year. In case of a cremation short after implantation a thyroïd dose of 0.23 µSv is estimated [91]. In Belgium, the Hoge Gezondheidsraad [92] state that cremation can be allowed without any special precautions if about 2 years have elapsed since implantation.

A.3.4 Miscellaneous

A wallet card with all relevant information about the implant is useful to make employees aware of the radioactivity (i.e. in case of subsequent medical need, airport control, triggering of security radiation monitors etc.).
Minimum information on a wallet card, to be given to the patient at hospital discharge, should include [93,94]:
- patient's precise identification: surname, given names, date of birth
- type of implantation (i.e. ^{125}I)
- date of implantation/site of implantation (i.e. prostate gland)
- hospital in charge, with address and phone number where specific details can be obtained 24 h/day
- a short sentence should stress the need for showing this card in the event of an admission to any hospital, or in the event of any consultation with any doctor within 1 year of the date of implantation
- another sentence should stress the need for showing this card in the event of any anticipated surgical operation, particularly involving the abdomen and/or pelvis

- a final sentence must indicate to the patient that he has to carry his card with him at all times for a period of at least 1 year.

Consideration can be given to including a photo of the patient on the card, and a statement that the patient will in no case cause harm to persons in his vicinity. These recommendations should be reviewed if radionuclides other than ^{125}I are used.

The patient should receive rules of life after implantation [91,93]. These written recommendations, among others, include:

- no young children on your lap for long periods of time for the first two months after implantation
- specific precautions in case your partner or a close family member sharing your living accommodation is pregnant
- return a found seed to your physician in charge
- use of a condom for the first five ejaculations
- in case of death within 2 years after implantation, a burial is advised above cremation; in case of cremation within 2 years after implantation your prostate with seeds should be removed first and returned to the hospital in charge, and
- in case of medical need you should show your wallet card.

Acknowledgements

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