TECHNICAL REPORT

ISO/TR 24422

First edition
2022-12

Development of a water equivalent phantom to measure the physical characteristics of specific radiosurgery treatment devices

Développement d'un fantôme équivalent eau pour le mesurage des caractéristiques physiques de modèles spécifiques de dispositif de traitement de radio-chirurgie

Reference number
ISO/TR 24422:2022(E)

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Published in Switzerland

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Foreword

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

Development of a water equivalent phantom to measure the physical characteristics of specific radiosurgery treatment devices

1 Scope

A water phantom is used to ensure the accurate measurement of absorbed dose delivered by a radiation therapy machine as well as standardizing the dose distribution produced by the radiation therapy device.

This document describes a detailed procedure for the construction and calibration of a polystyrene phantom and the results of its use in measuring the absorbed dose profile around the mechanical centre of a radiosurgery medical device, the full width at half maximum (FWHM) of the field and the physical penumbra at the mechanical centre, as well as the associated uncertainties.

According to IAEA TRS-483 document, the most common design recommended in Gamma Knife® system is a hemisphere atop a water filled or compact polystyrene cylinder, and when using a polystyrene phantom, the measurement depth of the absorbed dose to water is reported to be the centre of the hemisphere with the radius of 8 cm.

This document mainly describes the procedure for measuring the absorbed dose distribution around the mechanical centre of Gamma Knife® and obtaining the FWHM and penumbra from it. The developed phantom is made of polystyrene and has a hemispherical shape in accordance with the design suggested in IAEA TRS-483.

This type of phantom is specific and adapted only for the Gamma Knife® radiosurgery facilities (Perfexion™ and Icon™ models) and does not apply to general dosimetry protocols in radiotherapy facilities that use a small radiation field to treat a disease such as LINAC or Cyberknife.

Considering that the type of medical device corresponds to treatment using external beam radiotherapy following small static fields, this technical report follows the recommendations published in the IAEA TRS-483.

2 Normative references

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

IAEA TRS-483, *Dosimetry of Small Static Fields Used in External Beam Radiotherapy: An International Code of Practice for Reference and Relative Dose Determination*

AAPM TG-178, *Recommendations on the Practice of Calibration, Dosimetry, and Quality Assurance for Gamma Stereotactic Radiosurgery*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IAEA TRS-483 and AAPM TG-178 apply.

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

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

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

3.1
radiosurgery
medical procedure using a high single dose of radiation, directed to a stereotactically defined intracranial volume allowing minimally invasive treatment of benign and malignant tumors and other pathologies

Note 1 to entry: The term “radiosurgery” is also used for treatments comprising up to several fractions.

3.2
Gamma Knife®
device used to treat benign and malignant tumors and other pathologies by delivering high-intensity ^{60}Co external beam radiation therapy in a manner that focuses the radiation over a small volume[1)]

Note 1 to entry: Gamma Knife® therapy, like all radiosurgery, uses doses of radiation sufficient to kill cancer cells or shrink tumors, delivered precisely to avoid damaging healthy brain tissue. The device aims gamma radiation to a target point in the patient's brain. Gamma Knife® radiosurgery is able to accurately and precisely focus many beams of gamma radiation to converge on one or more tumors. The Gamma Knife® type C and its predecessors consist of a heavily shielded assembly in the internal collimator containing 201 ^{60}Co sources of approximately 1,1 TBq, each placed in a hemispherical array and interchangeable collimator located in hemispherical external helmet. On the other hands, Gamma Knife® Perfexion™ and Icon™ (later model) has no such external helmet but 192 ^{60}Co sources are arranged internally with 3 different collimator sizes on 8 independent sectors of 24 elements. Each individual beam is of relatively low intensity, so the radiation has little effect on intervening brain tissue and is concentrated only at the lesion itself. An ablative dose of radiation is thereby delivered to the tumor in one treatment session, while surrounding brain tissues are relatively spared.

3.3
calibration
operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indication with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

3.4
machine specific reference field
field used when the absolute value of the absorbed dose to water is measured in a small field external beam radiotherapy facility

Note 1 to entry: According to the IAEA TRS-483, 16 mm collimator field for Perfexion™ and Icon™ is a machine specific reference field.

3.5
beam quality correction factor
ratio of the calibration coefficient, which is used to convert the measured electric charge to the absorbed dose to water in the machine specific reference field to the absorbed dose to water calibration factor obtained in the reference calibration condition

Note 1 to entry: This factor corresponds to the beam quality correction factor, $k_{Q_{msr},Q_0}^{f_{msr},f_{ref}}$, of IAEA TRS-483.

3.6
ionization chamber
ionization detector consisting of a chamber filled with a suitable gas, typical air, in which an electric field applied between two electrodes, that is insufficient to induce gas multiplication, is provided for the collection at the electrodes of charges associated with the ions and the electrons produced in the sensitive volume of the detector by the ionizing radiation

1) Gamma Knife® type C, Perfexion™ and Icon™ are the three different models of Gamma Knife® radiosurgery facilities supplied by Elekta Ltd., Sweden. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named.

3.7
radiochromic film
colourless transparent films that give permanent coloured images on exposure to ionizing radiation

3.8
mechanical centre
point on which multiple ^{60}Co gamma radiation beams converge, supposed to coincide with a radiological centre which was determined by the measured dose distribution

3.9
physical penumbra
spatial region surrounding the centre point of the lateral dose profile, characterized by the lateral distance between two specified isodose curves (80 % and 20 %) at a specified depth[1]

Note 1 to entry: This definition generally applies to a broad beam, but it is also useful for the case of the small beam whose value of the physical penumbra is 3 mm to 10 mm, determined by the dose distribution obtained using the 16 mm collimator of Gamma Knife® Perfexion™ and Icon™.

Note 2 to entry: Isodose curve is a line that joins data points of the same dose value in a dose plot such as a 2D contour plot.

Note 3 to entry: An 80 % isodose curve indicates the data points where the dose values dropped to 80 % of the maximum dose value at the centre of the radiation field.

4 Phantom manufacturing

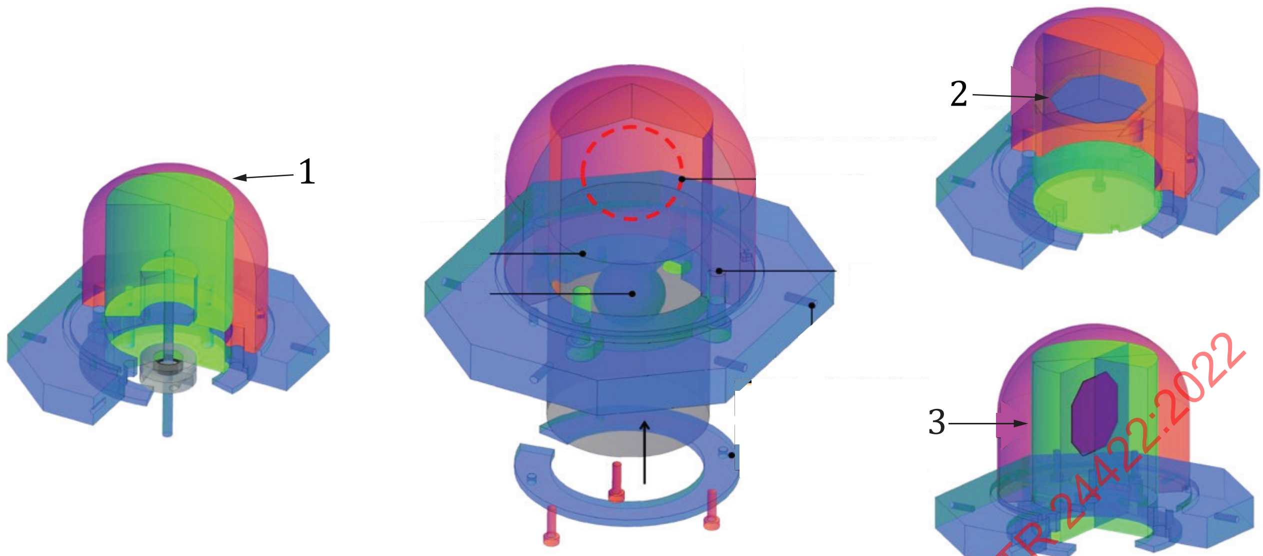
4.1 Phantom description

A water equivalent plastic phantom was build according to IAEA TRS-483 recommendations.

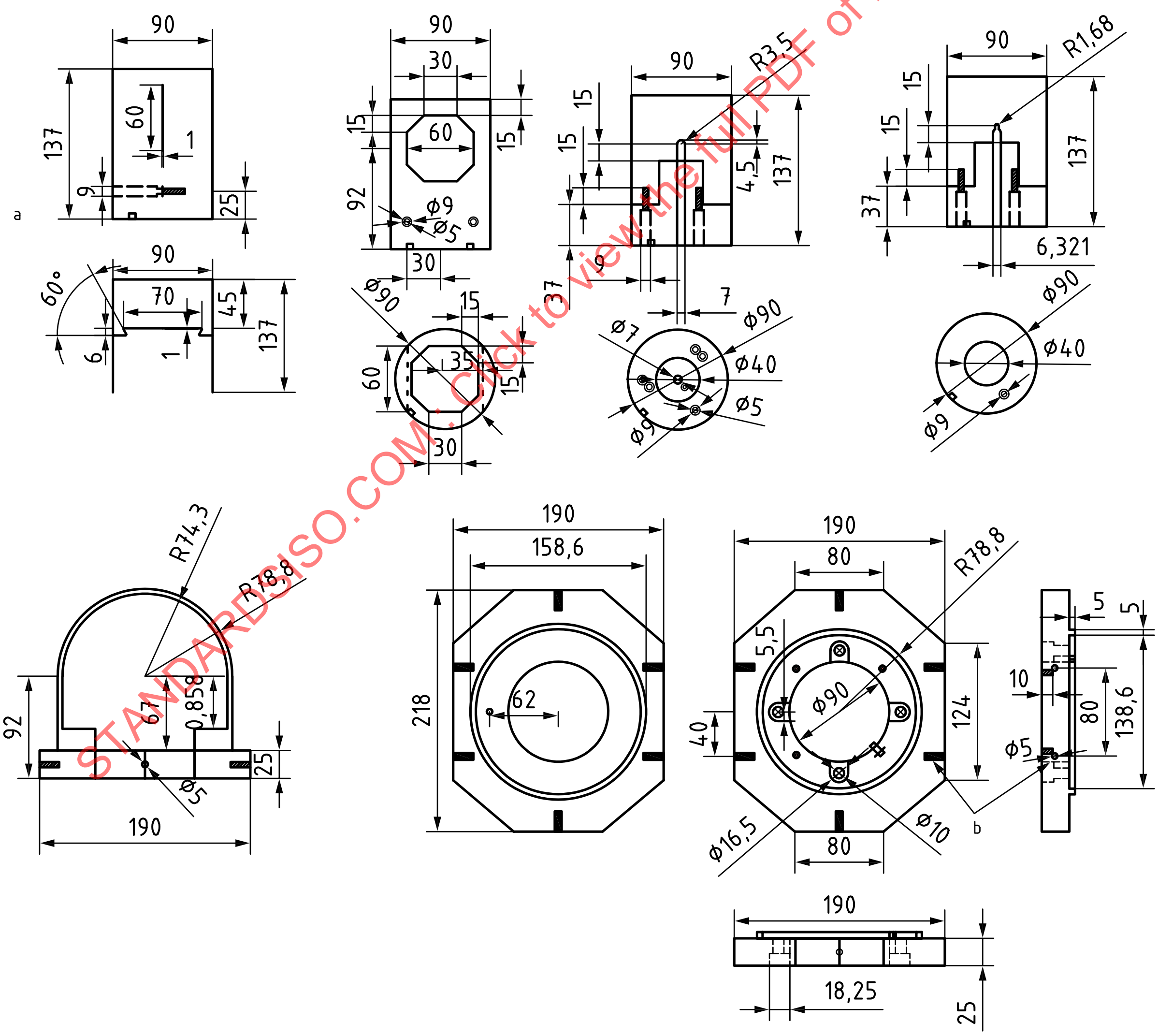
The phantom is constructed from polystyrene water equivalent material and is customized for two models of Gamma Knife® radiosurgery devices (Perfexion™ and Icon™) for the measurement of absorbed dose to water and several associated physical characteristics.

As described in the scope, the polystyrene phantom is designed and constructed according to the reference conditions for determining absorbed dose to water of Gamma Knife®, so this phantom has a limitation that it can only be applied to the Gamma Knife®.

The phantom has a hemi-spherical shape. The whole phantom consists of an outer and an inner part. While the outer part is firmly attached to the Leksell Gamma frame (Elekta AB, Stockholm, Sweden), the inner part can accommodate three different cylindrical inserts, one for hosting an ionization chamber and the two others for film-hosting. These three inserts are easily interchangeable depending on the type of measurement. The inner part is well fitted to the outer part so that the whole phantom is approximated to be homogenous. One of the film-hosting inner insert was designed to set a film in the xy-plane (axial plane) of the Leksell stereotaxic coordinate system, and the other can set a film in the xz-plane (sagittal plane). The thickness of the outer part is 5 mm, and the equivalent water depth (EWD) corresponding to this value is 5,08 mm. The cylindrical insert is constructed to have a EWD of 8 cm from the surface of the outer part to the centre of the insert, including the EWD of the outer part. The schematic drawings of the polystyrene phantom with the ionization chamber insert and the film inserts for the measurement of absorbed dose and dose profile are shown in Figure 1. In Figure 2 are given photographs of the inner inserts.



a) Film XY, YZ, ZX – Direction **b) PTW 31010** **c) Exradin A16**



d) Phantom dimension **e) Hexagonal plate for attaching the outer part of the phantom to Leksell Gamma Knife frame**

Key

1 ionometric measurement of absorbed dose to water

2 radiochromic film measurement of dose distribution

3 radiochromic film measurement of dose distribution

a M5 Volt.

b 5 pi Screw.

Figure 1 — Schematic diagram of the polystyrene phantom with different dosimeter inserts and its technical drawings (the unit of the length is mm)

a) Photographs of the ionization chamber insert of the Gamma Knife® polystyrene phantom

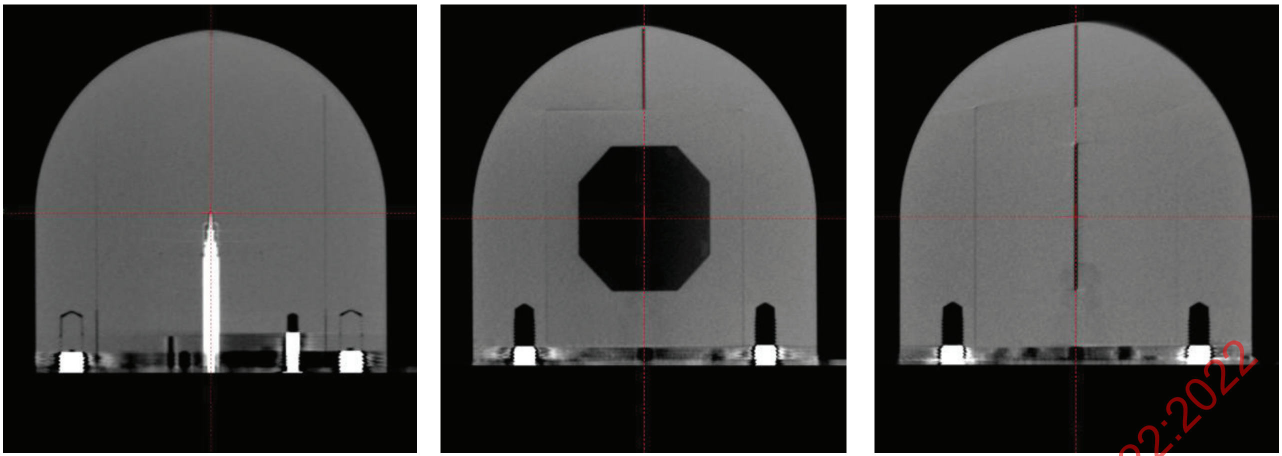
b) Photographs of the film inserts of the Gamma Knife® polystyrene phantom

Figure 2 — Photographs of the inner inserts

4.2 Positioning of the inner inserts with respect to the mechanical centre

Considering the absorbed dose profile of Gamma Knife®, it was important to verify the location of the measurement point with care and to modify displacements larger than 0,3 mm[2].

The alignment of the centre of the active volume of a PTW TN31010 ionization chamber to the PPS (patient positioning system) calibration centre was investigated by cone beam computed tomography (CBCT) images taken using the CBCT of a Gamma Knife® Icon™ (see Figure 3 a). The image slices were 0,5 mm thick, and the pixel size was 0,5 mm × 0,5 mm in an image. The operating peak voltage was 90 kVp and current was 1,0 mA/projection. In this figure, the cross point of the two red dashed lines denotes the radiation centre of a Gamma Knife®, and its location was compared with the active point of the ionization chamber and centre point of the film inserts, respectively. The measured coordinate values of the effective point of the Exradin A16 ionization chamber deviated by 0,2 mm along the x-axis only. The deviations of the film-holding inner phantoms were less than or equal to 0,1 mm along a direction perpendicular to the dose profile measuring plane (see Figures 3 b, 3 c). More details about the CBCT images of the Gamma Knife® ICON™ are provided in one of the research papers published in 2018[3].



a) Effective point of the PTW TN31010 ionization chamber is 0,2 mm off in the x-direction

b) xy-plane film position is well-matched with the xy-plane

c) xz-plane film position is well-matched with the xz-plane

Figure 3 — Reconstructed coronal computed tomography images of the polystyrene phantoms

4.3 Electron density calculation and determination of polystyrene phantom radius

The plastics such as polystyrene, solid water, acrylonitrile butadiene styrene (ABS), and others were used as phantom material to substitute a water sphere. The radius of the polystyrene phantom was determined to be the same as the reference depth of water, 8 g/cm^2, recommended in IAEA TRS-483. In the range of photon energy from 1,25 MeV of ^{60}Co, main interaction of photons is Compton scattering so that the equivalent water depth (EWD) of a material was determined by multiplying the ratio of its electron density to that of water by the reference depth of water[4]. To this end, the electron density of polystyrene was calculated.

IAEA TRS-483 advised that the phantom density always be determined experimentally due to the significant discrepancies in density quoted by the manufacturer.

The effective atomic number Z_{eff} of the polystyrene (C_8H_8) for the 0,5 to 1,5 MeV photon energy has a constant value of 3,51 while water has a constant value of 3,35[5].

Bulk density of polystyrene was measured from 1 cm^3 cubic pieces by weighing method and the composition of polystyrene was analysed by elementary analysis (EA). From the results of analysis and the density measurement, the electron density could be calculated by the Formula (1).

$$\rho_{\text{polystyrene}}^{\text{el}} = \rho_{\text{polystyrene}}^{\text{mass}} \times \left[\Sigma_i f_i \left(\frac{Z}{A} \right)_i \right] \quad (1)$$

, where $\rho_{\text{polystyrene}}^{\text{mass}}$ is the bulk density of polystyrene, f_i is the fraction by the atom i. The atomic number weight ratio, $\left(\frac{Z}{A} \right)_i$ is the ratio of atomic number to atomic weight for an atom i.

The electron density of the polystyrene obtained through the process described above is 0,562 6 N_A e/cm^3, where N_A is Avogadro constant.

The density of water at 24,15 °C is 0,997 3 g/cm^3 and the corresponding electron density of water is 0,553 9 N_A e/cm^3 at the same temperature. Using these results, the radius of polystyrene corresponding to 8 cm water depth is determined to be 7,87 cm from Formula (2), which is the radius of the polystyrene phantom.

$$r_{polystyrene} = r_{EWD} \frac{\rho^{el}_{H_2O}}{\rho^{el}_{polystyrene}} \tag{2}$$

, where $r_{polystyrene}$ is the physical radius of the polystyrene phantom, r_{EWD} is the equivalent water depth, $\rho^{el}_{H_2O}$ is the electron density of water, and $\rho^{el}_{polystyrene}$ is the electron density of polystyrene.

5 Measurement methods and results

As described in Clause 4, the developed polystyrene phantom was constructed in a hemispherical shape based on the ^{60}Co source configuration of the Gamma Knife® and the suggestions provided in IAEA TRS-483. The characteristics of this phantom is that it is designed for multiple purposes to measure the absorbed dose to water using the inner part equipped with the ionization chamber and easily replace it with the inner part equipped with the radiochromic film to measure the Gamma Knife® beam profile.

However, since the procedure of measuring the absorbed dose to water in the Gamma knife® is well described in IAEA TRS-483, this document mainly focus on the measurement of the beam profile using radiochromic film as a technical report related to Gamma Knife® and describes the procedure for determining FWHM and penumbra.

5.1 Beam quality correction factor

The beam quality correction factor defined in both IAEA TRS-483 and AAPM TG-178 is the ratio of the calibration coefficient, which is used to convert the measured electric charge to the absorbed dose to water in the machine specific reference field to the calibration coefficient obtained in the reference calibration field. For Gamma Knife®, the factor is given in IAEA TRS-483 for various combinations of ionization chambers and phantoms. Because Perfexion™ and Icon™ use the same irradiation device, they share the same radio-physical characteristics such as the beam quality correction factors[6]. The factors were obtained through Monte Carlo simulations. According to the machine specific reference conditions of Gamma Knife® Perfexion™/Icon™ of IAEA TRS-483, these correction factors were calculated at the centre of spherical plastic phantoms of radius 8 cm, which was not 8 g/cm^2 of water equivalent depth so that additional phantom correction factors are already included in the given factors.

These factors were not given in the IAEA TRS-483 for the polystyrene phantoms, but were given by Mirzakhanian et. al.[7] for the Perfexion™ model. The beam quality correction factor proposed by Mirzakhanian et. al. for a polystyrene phantom is 1,014 for a PTW 31010 and 1,024 for an Exradin A16 ionization chamber.

5.2 Measurement of the beam profile

For Gamma Knife®, the beam size varies depends on the collimator size. Though the FWHM of the field is larger than the specified collimator size (i.e. collimator size varies from 4-mm to 16-mm for Perfexion™ and Icon™) as it is shown in the dose distribution, it is a convention to define the beam size of the Gamma Knife® at approximately 40 cm from the sources where the individual beams intersect.

The beam profiles using the 16-mm collimator of one Gamma Knife® Icon™ unit and five Gamma Knife® Perfexion™ units were measured using GafChromic™ EBT3 films (Ashalnd, Covington, KY and Wayne, NJ, USA). Full width half maximum (FWHM) values and the physical penumbra, which is defined as the distance from the dose level of 80 % to the dose level of 20 %, were measured[1]. The films were cut into (6 × 6) cm^2 octagonal pieces to be fitted into the film-hosting inner phantom. The films were calibrated by irradiating 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60 Gy at the maximum using the 16-mm collimator.

The analysis of the irradiated films followed standard procedures of radiochromic film dosimetry[8]. The films were scanned using an EPSON Expression 10000XL scanner with a transparency unit

(Seiko-Epson Co, Nagano, Japan). The scanned images were analysed with Image J and homemade LabVIEW software. More detailed film handling procedures are described in a previous report[6]. In brief, the films were scanned with 300 DPI resolution and the red channel values were converted to optical densities. Absorbed doses profile were obtained by fitting the calibration data points with a third-order polynomial using the commercial software package such as Origin 2015 (OriginLab Corp, Northhampton, MA, USA) and TableCurve 2D (SYSTAT Software Inc., San Jose, CA, USA). One-dimensional dose distributions along the x-axis (right to left), y-axis (posterior to anterior), and z-axis (head to feet) were analysed and compared with Leksell Gamma Plan.

The radiochromic film measurements were performed with polystyrene phantom and the Elekta solid water (SW) phantom at six Gamma Knife® (one Icon™ and five Perfexion™) sites.

In this study the EPSON 10000XL flatbed scanner and GafChromic™ EBT3 radiochromic films were used for obtaining the Gamma Knife® beam profile. Other types of flatbed scanner such as UltraScan XL, V SCAN GS-670, CMR-604/608, VXR-12, Arcus II and Lumiscan 75/150 and various types of radiochromic films such as GafChromic™HD-810, GafChromic™ DM-1260, GafChromic™ DM-100, GafChromic™ MD-55 and GafChromic™ MD-V3 are also currently available[9] for the radiochromic film dosimetry.

5.3 Measurement of FWHM – physical penumbra and sharpness

The images of the irradiated radiochromic films were analysed with a high resolution flatbed scanner to produce the absorbed dose distributions. Figure 4 shows the photograph of one of the radiochromic films that was irradiated at the mechanical centre of Gamma Knife® and the measured dose profiles for the x-, y- and z-directions.