Prepublication

NCS Linac QA report

Beam Parameters for Non-Wedge High-Energy Photon Beams

NEDERLANDSE COMMISSIE VOOR STRALINGSDOSIMETRIE

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Disclosure of Potential Conflicts of Interest

None

Preface

The Nederlandse Commissie voor Stralingsdosimetrie (NCS, Netherlands Commission on Radiation Dosimetry, http://www.radiationdosimetry.org) was officially established on 3rd September, 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, made up via recommendations from the supporting societies, including the Nederlandse Vereniging voor Radiotherapie en Oncologie (Dutch Society for Radiotherapy and Oncology), the Nederlandse Vereniging voor Nucleaire Geneeskunde (Dutch Society of Nuclear Medicine), the Nederlandse Vereniging voor Klinische Fysica (Society for Medical Physics of the Netherlands), the Nederlandse Vereniging voor Radiobiologie (Netherlands Radiobiological Society), the Nederlandse Vereniging voor Stralingshygiëne (Netherlands Society for Radiological Protection), the Nederlandse Vereniging voor Medische Beeldvorming en Radiotherapie (Dutch Society for Medical Imaging and Radiotherapy), the Nederlandse Vereniging van Klinisch Fysisch Medewerkers (Dutch Society for Medical Physics Engineers), the Nederlandse Vereniging voor Radiologie (Radiological Society of the Netherlands) and the Belgische Vereniging voor Ziekenhuisfysici/Société Belge des Physiciens des Hôpitaux (Belgian Hospital Physicists Association) and expanded with a representative from the Dutch Metrology Institute VSL. To achieve its aims, the NCS carries out the following tasks: participation in dosimetry standardisation, promotion of mutual comparisons of dosimetry, drafting of dosimetry protocols and the collection and evaluation of physical data related to dosimetry. Furthermore, the commission shall establish or maintain links with national and international organisations concerned with ionising radiation and promulgate information on new developments in the field of radiation dosimetry.

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Prepublication

NCS Linac QA Report

Beam Parameters for Non-Wedge High-Energy Photon Beams

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Prelude

This document regarding beam parameters is a prepublication of a chapter in the future NCS report 33: Linac QA, which is currently in preparation. This part is published ahead of the full report to make the proposed new framework for beam parameters available for implementation in commercial and 'in-house developed' analysis software without further delay. The final version of the report may deviate somewhat and changes in de accompanying text may occur on the instigation of other readers. The method, however, shall not change.

Contents

Introduction

In 1995 and 1996, the Netherlands Commission on Radiation Dosimetry (NCS) issued its reports 8 [1] and 9 [2]. These NCS reports were intended to serve as a model for good clinical practice for linac quality control (QC), and cover a large number of topics, including an extensive description of test methods, test frequencies and tolerance levels. Since the issue of these reports, many new techniques have been introduced into clinics worldwide. These techniques call for new types of tests and new tolerances and frequencies. Therefore, in 2017, the NCS constituted a new subcommittee, which was assigned the task to update and improve the existing reports to modern standards. This update will be published as NCS report 33.

The application of FFF beams is expanding rapidly, urgently calling for a new paradigm for beam parameters that extends beyond the realm of flattened beams.

Therefore, it was decided to publish the chapter concerning beam parameters ahead of the full report to make the proposed new framework for beam parameters available for implementation in commercial and 'in-house developed' analysis software without further delay.

The aim of this prepublication is to make the user acquainted with the relevant beam parameters and to facilitate clinical introduction ahead of the publication of the full report. This publication proposes a framework to facilitate QA and trend-analysis of the beam profile shape and ascertain its stability

Users and vendors are encouraged to implement the presented concepts and parameters in order to get familiar with the new concepts, to compare these with their QA history and to start building new QA datasets, facilitating a smooth and quick implementation of the methods that will be recommended in report 33.

1 Glossary

1.1 Summary and definitions of parameters for high energy photons

Note: in the final version the arrangement of these definitions will be altered

(All positions relative to the origin of measurement device)

Name	Code	Unit	Description	§
Origin			Origin of the coordinate system of measuring device	
Field centre			Mid-point between field edges obtained from a profile measurement (see below)	
Field size	FS	[cm]	Distance between the two field edges obtained from a profile measurement (see below)	
Nominal Field size	FS_{nom}	[cm]	Field size as set on the treatment machine	3.2.2
Field size FWHM	FS_{FWHM}	[cm]	Measured distance between field edges using the FWHM method	3.2.2
Field size INFL	FS_{Infl}	[cm]	Measured distance between field edges using the Inflection point method	3.2.2
Field Edge FWHM L/R	X_{FWHM}	[mm]	Field edge of the profile, left or right, defined as the 50% point or Full Width at Half maximum	3.2.2
Field Edge INFL L/R	X_{Infl}	[mm]	Field edge of the profile, left or right, defined as the point of inflection or maximum gradient	3.2.2
Height of Inflection Point	Y_{Infl}	[%]	Relative dose at position of the Inflection point	3.2.2
In-Field Area	IFA	[mm]	The analysis area which depends on the nominal field width	3.2.1
Area Ratio	Sym_{int}	[%]	Ratio of integrated areas of left and right part of the profile within the IFA	3.2.3
Top position	Top	[mm]	Position of the top of a flattening filter free profile	0
Profile evaluation points	PEPXX	[%]	In-Field ratio at XX% region of the nominal field size. (average of left and right side) Where XX can be 20, 50, 60 or 80%	3.2.5
Profile evaluation points	PEPXXcm	[%]	In-Field ratio at +/-XX cm (average of left and right side) where XX can be 5, 10 or 12 cm	3.2.5
Penumbra width FWHM	$PenWidth_{FWHM}$	[mm]	Width of the penumbra 20-80% using the FWHM method	3.2.6
Penumbra width INFL	$PenWidth_{INFL}$	[mm]	Width of the penumbra 20-80% using the INFL method	3.2.6

Penumbra Steepness	$PenSteep_{Infl}$	[%/mm]	Penumbra steepness at the Inflection point	3.2.6

3 Beam parameters

3.1 Introduction

Traditionally, only a few parameters, flatness, symmetry, field size and penumbra width, were sufficient to describe the profiles of beams with a flattening filter (WFF). For these parameters, tolerance levels can be set easily in a convenient manner, confining the allowed variation of the beam profile. These flattened beams were required in the era of manual dose calculations and simple treatment planning systems.

Over the years, however, radiotherapy techniques have advanced such that these traditional parameters do no longer suffice.

3.1.1 Using baseline reference profiles

The traditional parameters describing the radiation beam (for WFF beams) still leave quite some room for undetected deviation. As treatment techniques have become more complex and treatment planning systems have become more accurate, such errors are not desirable. Moreover, many multi-linac departments nowadays choose to commission only one single beam model for each beam energy to serve all linacs in the department.

Therefore, the linac beams should be tuned to a baseline reference profile, rather than to the traditional beam parameters, characterising one specific beam of one specific linac. This baseline reference profile should represent the beam data modelled in the treatment planning system (see also appendix 3.A).

Within this approach, beam parameters still serve as global indicators of how the beam deviates from the reference profile (symmetry, shape). A limited set of beam parameters that characterizes the beam adequately can be employed for trend analysis of beam data over time.

3.1.2 Beam parameters for WFF and FFF beams

A second argument for developing a new set of beam parameters is that traditional beam parameters, applied according to their definition, do not yield meaningful results for non-flattened (Flattening Filter Free, FFF) beams.

For instance, the parameter “field size” requires a definition of the position of the field edge. For WFF beams, the field edge is defined as the 50% or Full Width at Half Maximum (FWHM) of the profile. This definition clearly does not hold for FFF beams, and a revised definition of the field edge is needed to obtain a meaningful value of that parameter, for both WFF and FFF beams.

Similar to “field size”, also the traditional beam parameters “symmetry” and “penumbra width”, originally designed for WFF beams, are in principle useful for FFF beams, but may only be employed using revised definitions.

Flatness, obviously, has little meaning for an FFF beam. We will therefore introduce the concept of Profile Evaluation Points (PEPs) for the description of beam profile shape (both WFF and FFF).

Finally, FFF beams call for an additional parameter, the top position, which is only applied for FFF beams.

In the following paragraphs we will present the newly introduced beam parameters, as well as the updated definitions of the retained traditional beam parameters.

The proposed definitions meet the following requirements:

1. They are applicable to both WFF and FFF beams (except top position);
2. For WFF beams they yield numerical values comparable to those of the beam parameters obtained using the traditional definitions. This warrants continuity of QA measurement series for WFF beams.

The new framework of QA parameters hence makes no distinction between the descriptions of WFF and FFF beams with one exception, the Top position (Top), which is applied exclusively for FFF beams.

3.1.3 Measurements and interpolation

Water phantom measurements are the gold standard for accurate profile measurements, but these measurements are relatively time consuming. The introduction of modern (array) profilers has reduced the workload for measuring beam profiles, facilitating (much) more frequent accurate beam QA relative to reference data.

The detector spacing of these arrays is typically larger (range 3 - 10 mm) than the resolution of a water phantom (minimal spacing ranging from 0.1 mm to 1 mm).

Beam parameters, such as field size, need to be assessed with an accuracy that is higher than array measurements provide, inevitably leading to interpolation. Straightforward linear interpolation improves the accuracy, but results may vary significantly depending on the positioning of the array (see appendix 3.B). Hence, linear interpolation does not provide stable values of the required beam parameters.

For the definition of the beam parameters we therefore propose more sophisticated interpolation models for the penumbra and the FFF beam top. These models have shown to be very robust to detector placement, even for low (3 – 10 mm) resolution measurements of the profile (see Appendix 3.C), eliminating the need of regular elaborate water tank measurements.

For all profile measurements, the measuring device should be set up such that the origin of its coordinate system is intersected by the mechanical collimator axis of the linac. This alignment should be within 0.5 mm, preferably within 0.2 mm. The deviation in this alignment directly translates to errors in the determination of the field edges and the Top Position.

3.1.4 Alternative proposals for beam parameter definitions that include FFF beams

Based on traditional QA protocols on beam profiles, Fogliata and IPEM have proposed alternative solutions for defining the field edge and symmetry[3–6]. Most of these solutions relate the FFF beam to a WFF beam with a similar energy on the same device. In addition, these methods require elaborate procedures, involving renormalisation of the profile and the use of a predefined set of table values linked to WFF beams. In addition, the methods described by others have an implicit assumption of the beam shape and therefore of the filters provided by the vendor. What's more, recently new types of linear accelerators have been introduced to the market that exclusively provide flattening filter free beams[7–9], rendering such solutions inadequate.

To account for these drawbacks, this NCS subcommittee proposes a new framework providing a comprehensive set of parameters to describe the beam profile. This method does not rely on the presence of WFF beams and is applicable to both conventional WFF and FFF beams. In addition, the proposed procedures are (relatively) insensitive to noise and/or the resolution of the measurement device, facilitating the use of detector arrays besides scanning water phantoms to acquire the profile of the radiation beam whilst still obtaining the beam parameters with a sufficiently high resolution.

3.2 Parameter definitions for high energy photon beams

In this section we describe the parameters that comprehensively describe the main characteristics of the beam. Clearly, the values of these parameters depend on measurement conditions such as the nominal field size, depth, Source to Surface Distance (SSD) and phantom material. These conditions should be clearly stated when reporting the obtained values.

3.2.1 In-Field Area

Traditionally the flatness and symmetry for WFF fields are evaluated over a "flattened area". Various definitions for this flattened area exist, but for all definitions the flattened area roughly encompasses the high dose area or plateau within the penumbra. Generalizing this concept to FFF beams, we propose the name 'In-Field Area' (*IFA*) as a replacement for 'Flattened Area'.

The *IFA* dimensions depend on the nominal field size (F_{nom}). The centre of the IFA coincides with the origin of the coordinate system of the measuring device. The IFA is used to calculate the symmetry of a beam.

The *IFA* limits are defined as

for main axis : $$IFA = F_{nom} - (2 * D_m) \quad (1)$$

for diagonal axis : $$IFA = \left(F_{nom} \cdot \sqrt{2}\right) - (2 * D_q) \quad (2)$$

D_m and D_q are parameters that depend on the nominal field size (F_{nom}) as outlined in Table 1. As the IFA size is defined relative to the nominal field size the IFA size does not vary with the actual (measured) field size.

Table 1: **Parameters D_m and D_q for different values of F_{nom} for square fields**.

Square Field size *F*	**D_m for main axis**	**D_q for diagonal**
5 cm ≤ F_{nom} ≤ 10 cm	1 cm	2 cm
10 cm ≤ F_{nom} ≤ 30 cm	0.1 · F_{nom}	0.2 · F_{nom}
30 cm ≤ F_{nom}	3 cm	6 cm

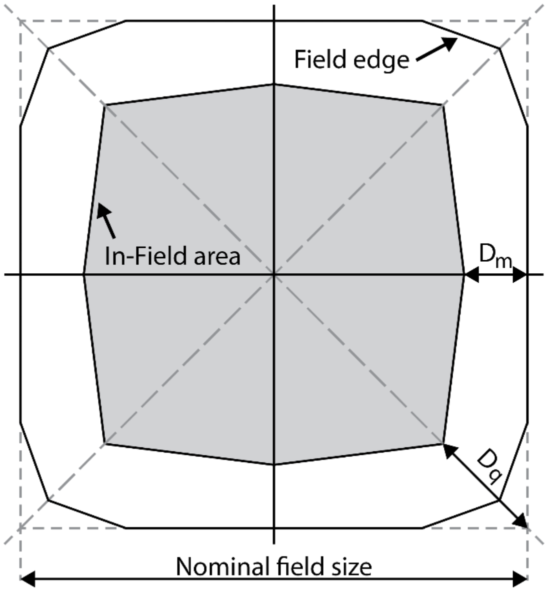

Figure 1: Graphical representation of the In-Field area.

3.2.2 Field edge and field size

Traditionally, the field edges are defined by the 50% dose points in the penumbra (or Full Width at Half Maximum, FWHM). This definition does not hold for FFF beams as the 50% dose points in FFF profiles may even be located outside the penumbra region. In addition, as the traditional derivation of the field edges for WFF generally relies on (linear) interpolation of the measurement points, a model-based approach is also preferential for WFF beams as it yields much more accurate and stable results (see appendix 3.B).

Because of the reproducibility, especially for low-resolution measuring devices, we recommend adapting to the model-based approach for obtaining the field edges, both for WFF and FFF beams. The field edges and field size are determined as follows:

1) Fit the penumbras to an equation around the nominal field edge. We propose the fit function presented in equation (3).
2) The location of the maximum gradient in this fit, also called the inflection point (INFL), defines the field edge.
3) The field size is the distance between the two field edges.

This approach can be applied to both WFF and FFF beams. Please note that the location of the (traditional) FWHM points may not coincide with the field edge as derived above. The user may choose to keep to the FWHM for WFF beams until recommissioning of the TPS is scheduled.

For the fit of the penumbra a four parameter non-linear regression model, given in equation (3), is proposed, although alternative models may be considered.

$$F(x) = \frac{a}{\left(1 + \left(\frac{x}{b}\right)^{c}\right)} + d \tag{3}$$

Where:

a. = Asymptote (+ d) for small values of x;

b. = Scaling parameter; location on x-axis between the extremes, close to the inflection point;

c. = Hill's slope; steepness of the curve (can be positive or negative);

d. = Asymptote for large values of x

Prior to fitting, the profiles should be normalised to the value at the origin. Examples of the fit for various types of profiles are shown in Appendix 3.C along with the corresponding fit parameters.

3.2.3 Symmetry

The symmetry is defined as the difference between the integral, or summated measured values, on the left and right side of the profile, divided by the average of these values, within the IFA.

$$\text{Symmetry } = 2 * \frac{(Sum_{left} - Sum_{right})}{(Sum_{left} + Sum_{right})} \cdot 100\% \tag{4}$$

This definition of symmetry results in a signed value indicating the direction of the asymmetry.

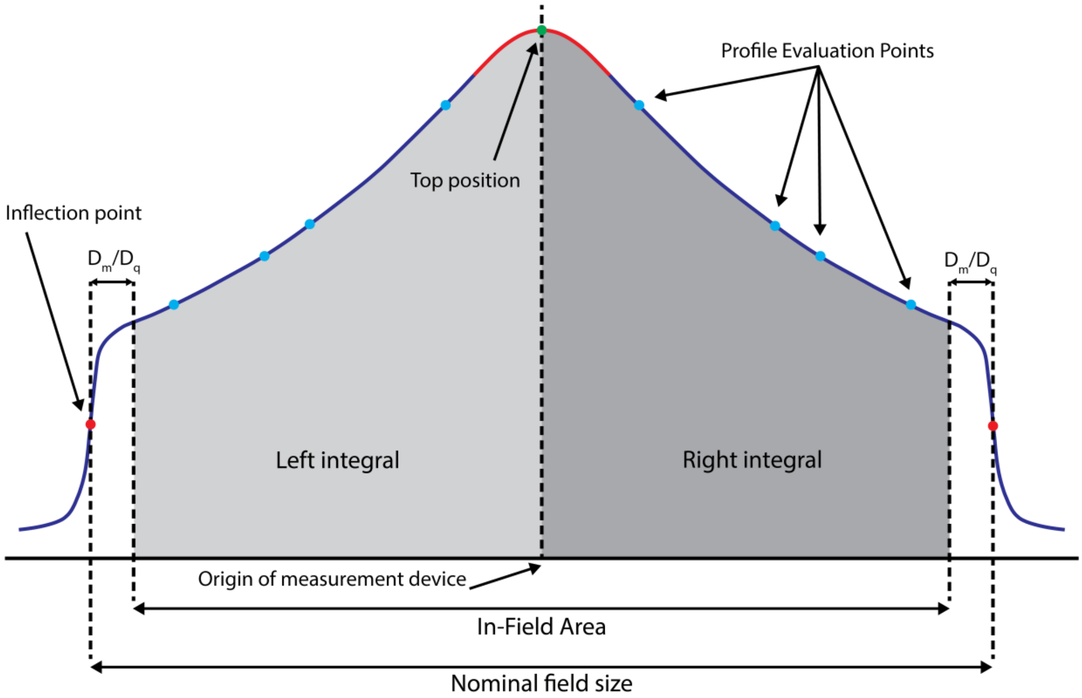

Figure 2: Graphical representation of field parameters for an ideal profile.

3.2.4 Top position (FFF specific)

For WFF beams, the presence of the flattening filter causes the symmetry parameter to depend strongly on various beam alignment parameters and thereby provides a sensitive way to check and adjust the position and shape of the focal spot. This dependency is much less pronounced for FFF beams and consequently the symmetry parameter does not suffice for monitoring beam steering. Therefore, we define a new parameter, the "Top position", representing the location of the maximum of the FFF profile. This position can be accurately determined by fitting the profile to a 2nd order polynomial over the central 5 cm around the origin. For beam adjustment, the Top position should not be used for fields smaller than 15x15 cm^2. In addition, in a succeeding version criteria will be formulated to judge if a profile can considered WFF or FFF.

3.2.5 Profile evaluation points

The traditional flatness parameter has no meaning for FFF beams. FFF beams require more parameters and measurement points to capture its profile than WFF beams. For practical purposes, this subcommittee defines a set of points that can be used to describe the shape of the profile within the IFA. This approach is suitable for both FFF and WFF beams. The profile is reduced to a set of dose values, normalized to the value at the origin, at designated Profile Evaluation Points (PEPs). For field sizes of 5 cm x 5 cm and larger the following points are to be evaluated.

- Major axis: Points at the 20%, 50%, and 80% distance from the origin to the nominal field edges. Extra points are optional[1]
- Diagonals: Points at the same distance from the origin as on the major axis, or at the 20%, 50% and 60% distance from the origin to the corner of the nominal field edges of a square field.

A graphical representation is given in Figure 2 and Figure 3.

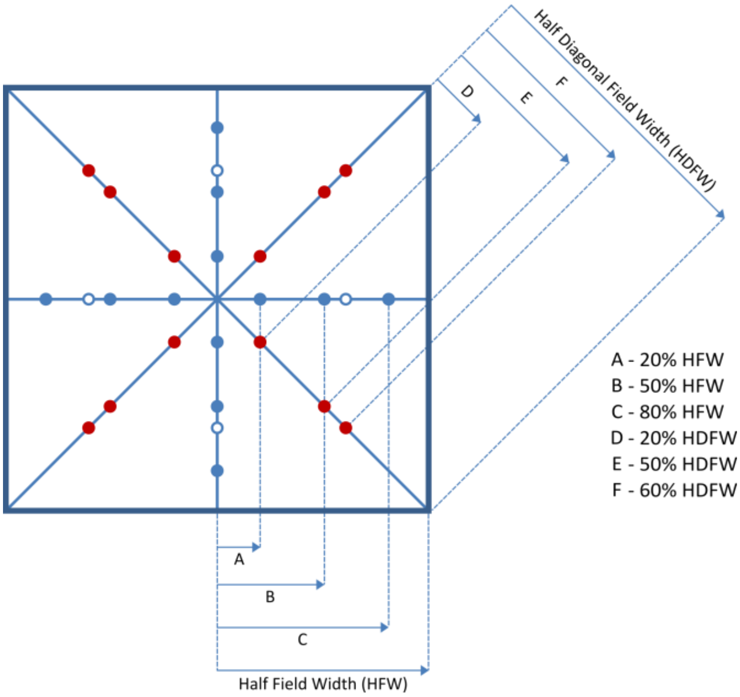

Figure 3: Graphical representation of the position of the In-Field Points for beam profile shape and symmetry. Blue points indicate major axis evaluation points and the red points indicate the diagonal axis evaluation points.

[1] In common linear accelerators, the evaluation of the beam in the monitor chamber is performed at a certain off-axis (projection in ISOC at 100 cm), for a max field size of 40 x 40 cm^2. Therefore, an additional in-field evaluation point, which coincides at this projection, is advisable.

3.2.6 Penumbra width

Conventionally, the penumbra width ($\text{PenWidth}_{\text{FWHM}}$) is used to indicate the dose fall-off between 80% and 20%. For FFF beams, this approach makes less sense. Therefore, we propose an alternative definition of the penumbra width: the maximum slope at the inflection point [%/mm] ($\text{PenSteep}_{\text{Infl}}$).

A similar definition for the penumbra for FFF beams can be given by the Penumbra width using the inflection point as the field edge ($\text{PenWidth}_{\text{INFL}}$). This width is defined as the distance between the locations where the dose equals 0.4 times the dose at the inflection point and 1.6 times that dose. This normalization defines the inflection point to the 50% since 0.4*50% and 1.6*50% yield the 20% and 80% respectively.

$$\text{PenWidthINFL}(mm) = \left|\text{Position}\left(0.4 \cdot Y_{InflY}\right) - \text{Position}\left(1.6 \cdot Y_{Infl}\right)\right| \quad (5)$$

These positions can be obtained using formula (7).

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Appendix

3.A **Implementation of beam data comparison to baseline data**

The beam parameters that have been described can be used to report the long-term stability of the linac. Adjusting the beam to optimise the linac performance requires a more dynamic insight into the parameters with respect to the values of the reference beam.
To evaluate and adjust the beam, a dynamic, high-resolution view of the measured profile compared to the commissioned (reference) profile in combination with a difference or ratio profile should be available. For a good assessment of the differences, it should be possible to zoom in a part of the profile. Note that to quantify potential deviations from the baseline profile, the tolerance levels need to be compared to the baseline data (e.g. max deviation).

For an optimal workflow, the baseline datasets and export directories should be selected automatically, from a predefined library, based on the machine and beam parameters set on the linac. After adjustment, it should be easy to export the profile to an alternative (homemade) evaluation program, for example using the clipboard functionality, along with all relevant metadata. For this, a vendor neutral well-defined data format is desirable.

The users should note that quality assurance is severely hampered if the software and equipment used precludes a smooth workflow due to lacking functionality.

There are some challenges that should be acknowledged:

- The calculation of a ratio enhances noise effects significantly. Both pre-filtering and post-filtering should be available.
- The setup, notably the origin, might be prone to variations. The software should be able to shift the baseline data set if needed. Therefore, a reliable field edge detection should be available (see 3.2.2). Preferably, the user should have multiple choices for the definition of the "centre of field".

3.B Penumbra interpolation accuracy

Current commercial linear arrays have a resolution between 3 and 5 mm. This resolution is too coarse to accurately determine the field edge using a linear interpolation.

To illustrate this, a StarCheck array (L981389, PTW Freiburg, Germany), with a 3 mm chamber spacing, was placed on an accurate translation stage (SLA48 PTW Freiburg, Germany). A 10x10 cm field from an Elekta linear accelerator was measured with this array multiple times shifting the 0.3 mm between each measurement.

Figure 4 shows two measurements of the same penumbra with a shift of 1.5 mm of the array between the measurements. The linear interpolation between the points surrounding the 50% are separated by 0.2 mm.
Figure 5 shows the calculated field size for multiple array shifts. This shows a difference in field size of up to 0.4 mm depending on the location of the penumbra on the array, when using a linear interpolation. When using a fit through the penumbra this difference is negligible.

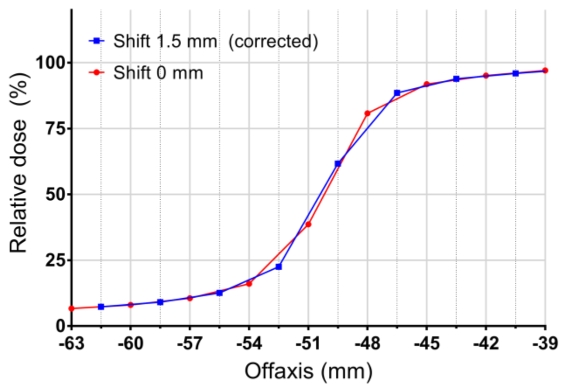


Figure 4: An example of 2 measurements of the same penumbra but with a shift of 1.5 mm of the measurement array. The insert is a magnification of the 50% area. Here it can be clearly seen that the 2 linear lines are shifted.

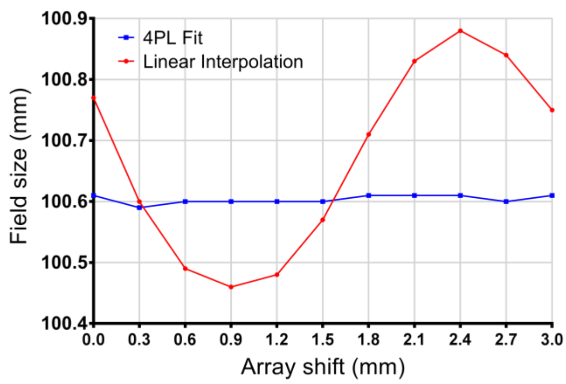


Figure 5: Field sizes of the same field measured by shifting the array between each measurement. The red line is calculated using a linear interpolation, the blue lines are calculated using formula 1 to fit the penumbra.

3.C Examples of four parameter non-linear regression model

The X-value of the inflection point can be calculated by the following formula:

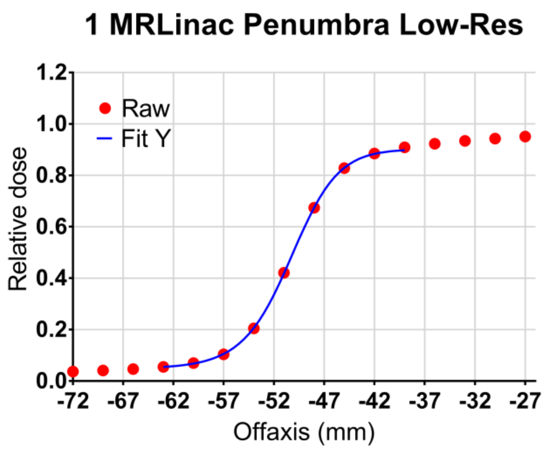
$$Infl = b \cdot \left(\frac{c-1}{c+1}\right)^{\frac{1}{c}} \tag{6}$$

For the determination of the 50 % point the following formula can be used:

$$Position\ (y = 50\%) = b\left(\frac{-a}{d-y} - 1\right)^{\frac{1}{c}}, \text{with } y = 0.5 \tag{7}$$

Depending on the resolution of the measurement device the amount of measurement points to include in the fit may vary. For example, a high-resolution water phantom measurement (0.5 mm) may require a range of 8 mm around the nominal field edge, whereas an ionisation chamber array with a resolution of 3 mm may need a range of 24 mm or higher to produce accurate results. A minimum of 8 measurement points in the fit should suffice. The user should check these guidelines with their equipment and data.

- **Low resolution MR-Linac array profile**



4PL fit parameters

A = 0.85379505

B = -50.36722565

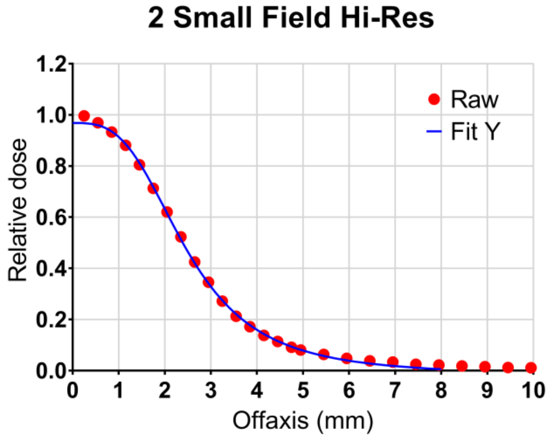
C = 21.16204453

D = 0.04768321

Infl = -50.1426 mm

FWHM = -50.0842 mm

- **Small field**



4PL fit parameters

A = 0.96819723

B = 2.44875288

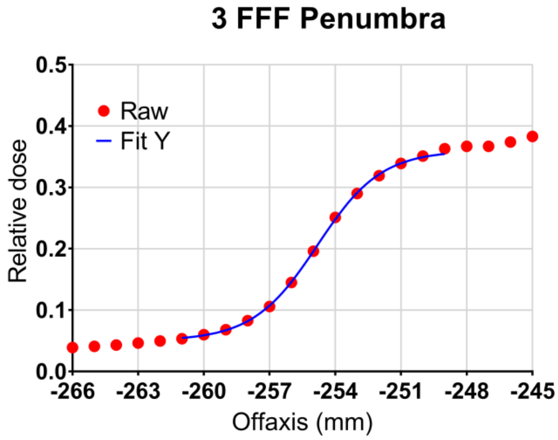
C = 3.24485326

D = -0.00386275

Infl = 2.0122 mm

FWHM = -2.3879 mm

- **FFF**



4PL fit parameters

A = 0.32143772

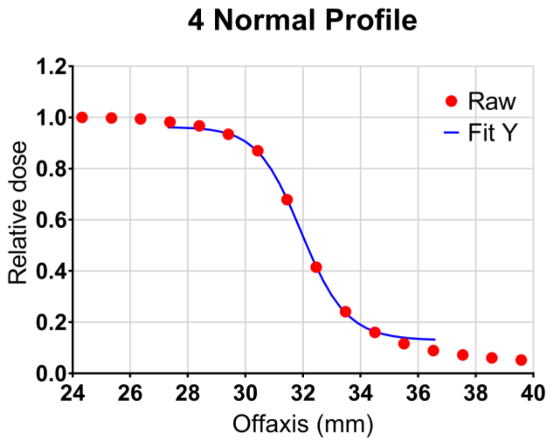
B = -254.7692871

C = 163.2085266

D = 0.04649442

Infl = -254.7502 mm

- **Normal penumbra**



4PL fit parameters

A = 0.91508591

B = 32.03378677

C = 34.12318802

D = 0.07582804

Infl = 31.9788 mm

FWHM = -32.1713 mm