Standards for nonstandard photon beams

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- Some brand names of commercial products are mentioned in this presentation. This does not represent any endorsement of one product or manufacturer over another

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Learning Objectives

- Review absorbed dose standards and discuss these suitable for small and nonstandard fields
- Discuss possible future standards for nonstandard fields

Overview

- Nonstandard fields and its problems
- AAPM-IAEA dosimetry formalism and *msr* fields
- Absorbed dose radiation standards
  - Principle
  - Nonstandard beams

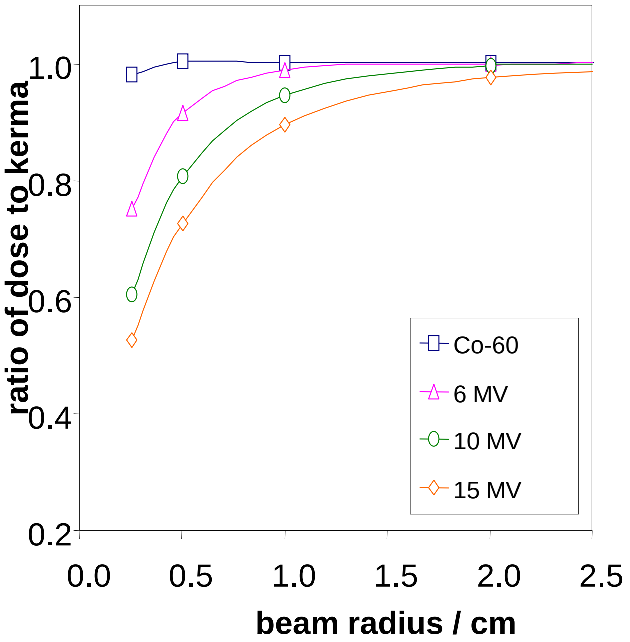
What constitutes small-field conditions?

- Beam-related small-field conditions
  - the existence of lateral charged particle disequilibrium
  - partial geometrical shielding of the primary photon source as seen from the point of measurement
- Detector-related small-field condition
  - detector size compared to field size

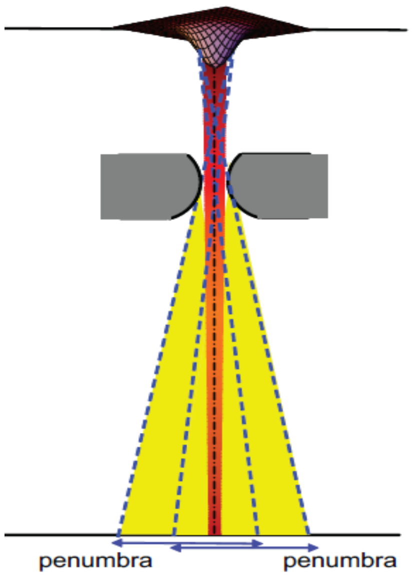
Ch. 2 - Physics of small fields

e.g. Small field conditions

LCPE

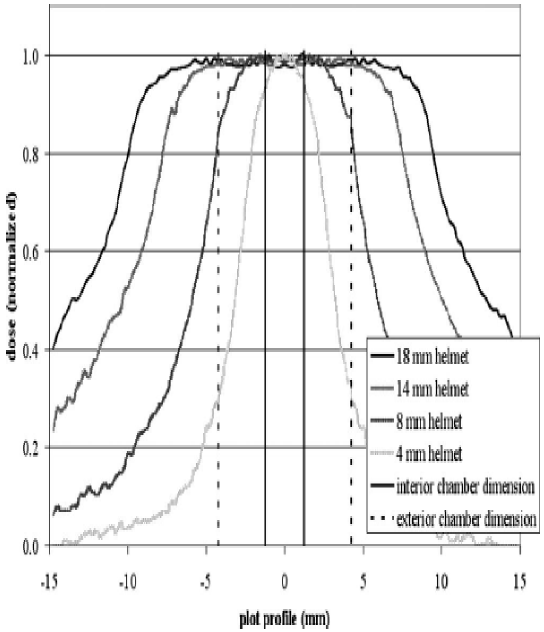


source occlusion



source occlusion with penumbra overlap and drop in output

detector size



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Aspradakis et al 2010
IPEM Report 103

Meltsner et al. 2009
Med Phys 36:339-50

Machine-specific reference fields Small Fields

REFERENCE DOSIMETRY

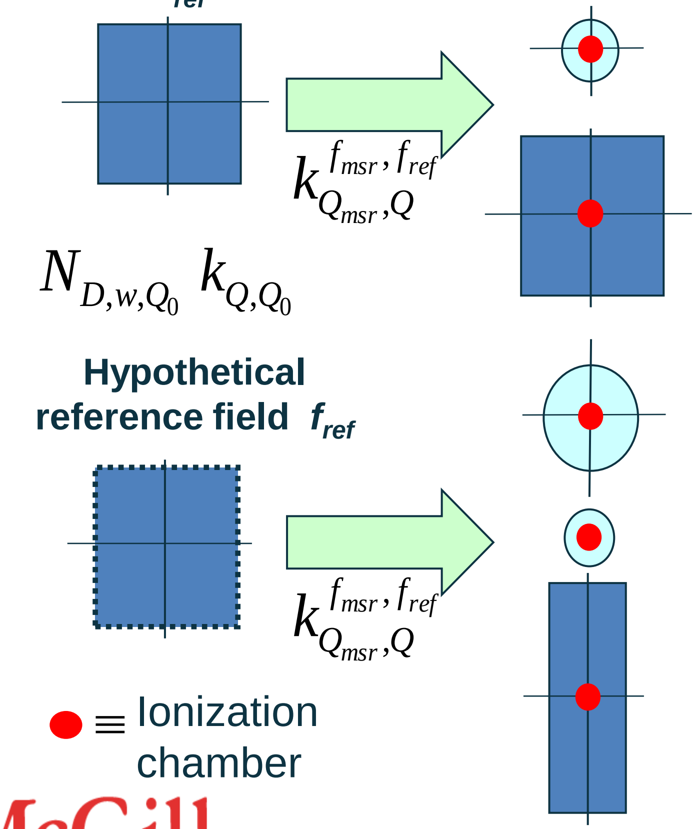
$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} N_{D,w,Q_0} k_{Q,Q_0} k_{Q_{msr},Q}^{f_{msr},f_{ref}}$$

RELATIVE DOSIMETRY

$$D_{w,Q_{clin}}^{f_{clin}} = D_{w,Q_{msr}}^{f_{msr}} \Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$$

Broad beam reference field f_{ref}

Machine specific reference field f_{msr}



$k_{Q_{msr},Q}^{f_{msr},f_{ref}}$

N_{D,w,Q_0} k_{Q,Q_0}

Hypothetical reference field f_{ref}

$k_{Q_{msr},Q}^{f_{msr},f_{ref}}$

● ≡ Ionization chamber

Radiosurgical collimators d = 1.8 cm

micro MLC **10 cm x 10 cm**

CyberKnife 6 cm

GammaKnife d = 1.6/1.8 cm

Tomotherapy 5 cm x 20 cm

Clinical field f_{clin}

$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$$

Ch3. – Formalism (Alfonso et al) / D_w in machine specific reference (msr) fields

- Chamber calibrated specifically for the msr field

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_{msr}}^{f_{msr}}$$

- Chamber calibrated for the conventional reference field and generic correction factors are available

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_0}^{f_{ref}} \cdot k_{Q_{msr},Q_0}^{f_{msr},f_{ref}}$$

- Chamber calibrated for the conventional reference field and generic correction factors not available

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_0}^{f_{ref}} \cdot k_{Q,Q_0}^{f_{ref}} \cdot k_{Q_{msr},Q}^{f_{msr},f_{ref}}$$

Ch3. – Formalism / determination of field output factors

- Field output factor relative to reference field (ref stands here for a conventional reference or msr field)

$$\Omega^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}} = \frac{M^{f_{clin}}_{Q_{clin}}}{M^{f_{ref}}_{Q_{ref}}} \cdot k^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}}$$

- Field output factor relative to reference field using intermediate field or ‘daisy chaining’ method

$$\Omega^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}} = \frac{M^{f_{clin}}_{Q_{clin}}(\mathrm{det})}{M^{f_{\mathrm{int}}}_{Q_{\mathrm{int}}}(\mathrm{det})} \cdot \frac{M^{f_{\mathrm{int}}}_{Q_{\mathrm{int}}}(IC)}{M^{f_{ref}}_{Q_{ref}}(IC)} \cdot K^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}}$$

where

$$K^{f_{clin},f_{ref}}_{Q_{clin},Q_{ref}} = k^{f_{clin},f_{\mathrm{int}}}_{Q_{clin},Q_{\mathrm{det}}}(\mathrm{det}) \cdot k^{f_{\mathrm{int}},f_{ref}}_{Q_{\mathrm{int}},Q_{ref}}(IC)$$

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msr dosimetry data $k_{Q_{msr},Q_{ref}}^{f_{msr},f_{ref}}$

Authors	Publication	Unit	Ref. Field	Chamber(s)	Ref. Dosimeter	$k_{Q_{msr},Q_{ref}}^{f_{msr},f_{ref}}$
Krauss et al. 2007	Phys Med Biol 52:6243-59	Philips SL 75-20	5 cm × 5 cm ($TPR_{20,10}$=0.716)	NE2561 NE2571	Water Calorimeter	0.999 (3) 0.999 (3)
			5 cm × 5 cm ($TPR_{20,10}$=0.762)	NE2561 NE2571		1.000 (3) 1.001 (3)
Pantelis et al. 2010	Med Phys 37:2369-2379	CyberKnife	6 cm diameter	PTW 30013	Alanine	0.999 (16)
Duane et al. 2006	Med Phys 33:2093-2094	TomoTherapy HiArt	5 cm × 10 cm	NE2611 Exradin A1SL	Alanine	1.000 (8) 0.996 (8)
Bailat et al. 2009	Med Phys 37:3891-6	TomoTherapy HiArt	5 cm × 10 cm	NE2611 NE2571 Exradin A1SL	Alanine	0.996 (12) 1.013 (14) 0.984 (11)
Somigliana et al. 1999	Phys Med Biol 44:887-97	GammaKnife	1.8 cm helmet	PTW 233642	MD-55	0.997 (19)

Standards for nonstandard fields

- Calorimeters
  - Water calorimeter
  - IMRT calorimeter
  - Graphite probe calorimeter
  - Dose-area product methodology
- Small field “transfer” standards
  - Chemical dosimetry
  - Ionization chambers
  - Alanine/ESR
  - High precision radiochromic film / TLD

Calorimeter-based absorbed dose standards

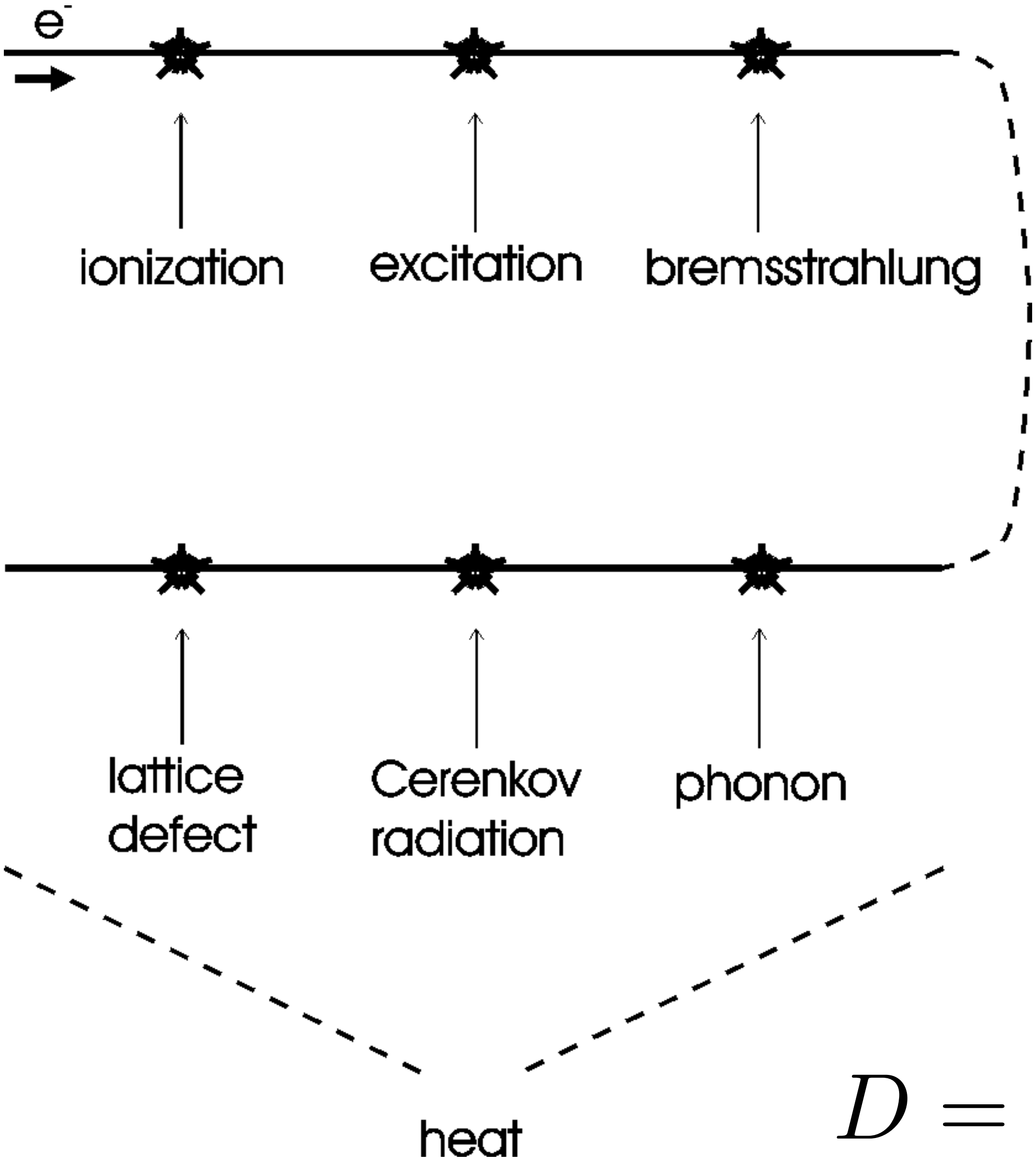
- An absolute technique to measure absorbed dose

$$D = \frac{d\epsilon}{dm}$$

ϵ: energy imparted

m: mass of medium

Calibration does not require a beam of ionizing radiation



e^-

ionization

excitation

bremsstrahlung

lattice defect

Cerenkov radiation

phonon

heat

$$D = c\,\Delta T$$

Absorbed dose water calorimetry

- Dose to water is determined directly, *at a point*, by measuring the temperature increase:

$$D_w = c_w \; \Delta T_w \; k_c \; k_p \; k_r \; k_\rho \; \frac{1}{1-h}$$

c_w: specific heat capacity of water (4180 $\mathrm{Jkg^{-1}K^{-1}}$)

ΔT_w : temperature increase (0.25 mK/Gy)

k_c: heat loss correction factor

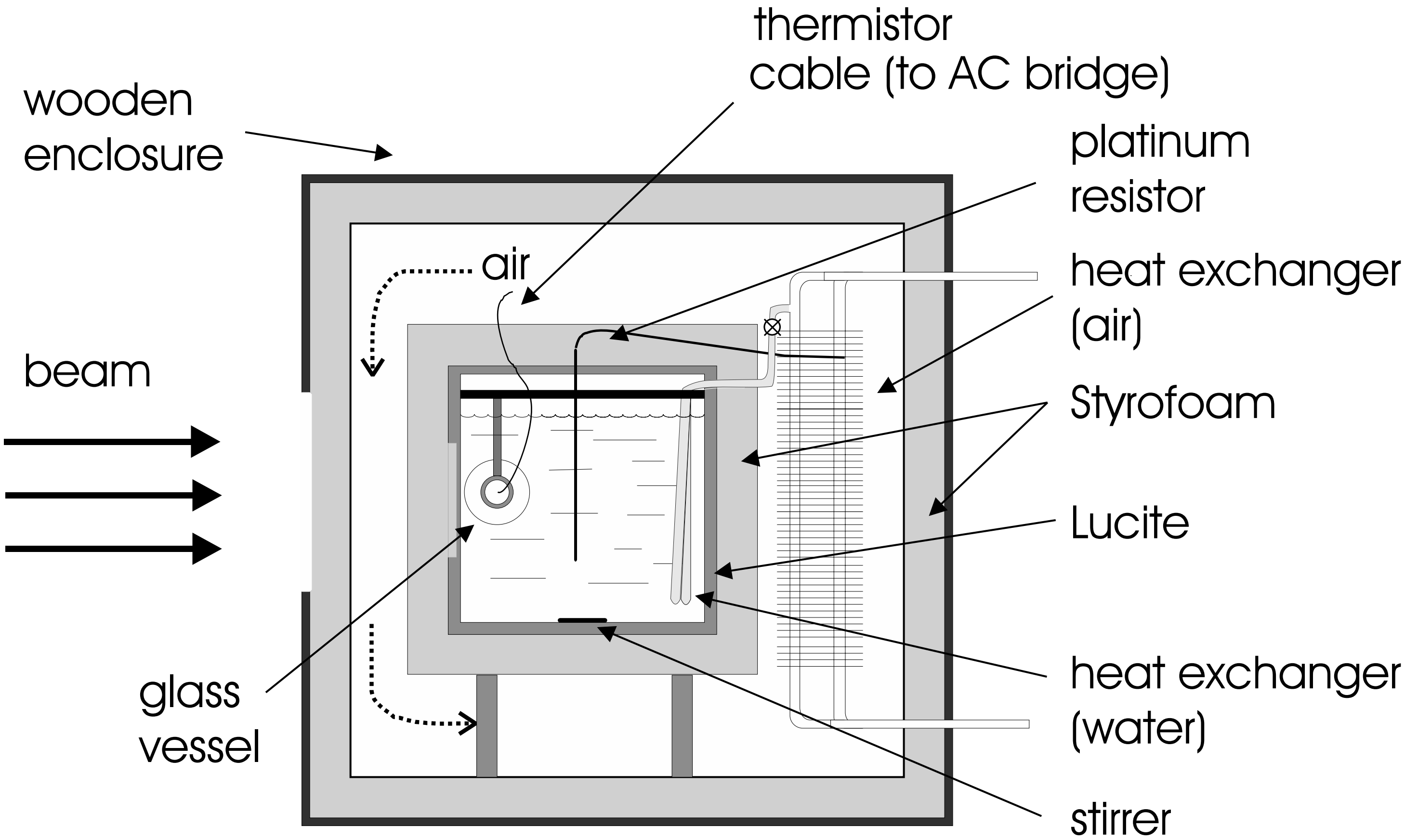
k_p: perturbation of radiation field correction factor

k_{dd}: non-uniformity of lateral dose profile corr. Factor

k_ρ : water density difference correction factor

h: heat defect

Practical realisation



The NRC water calorimeter, Ottawa, Canada

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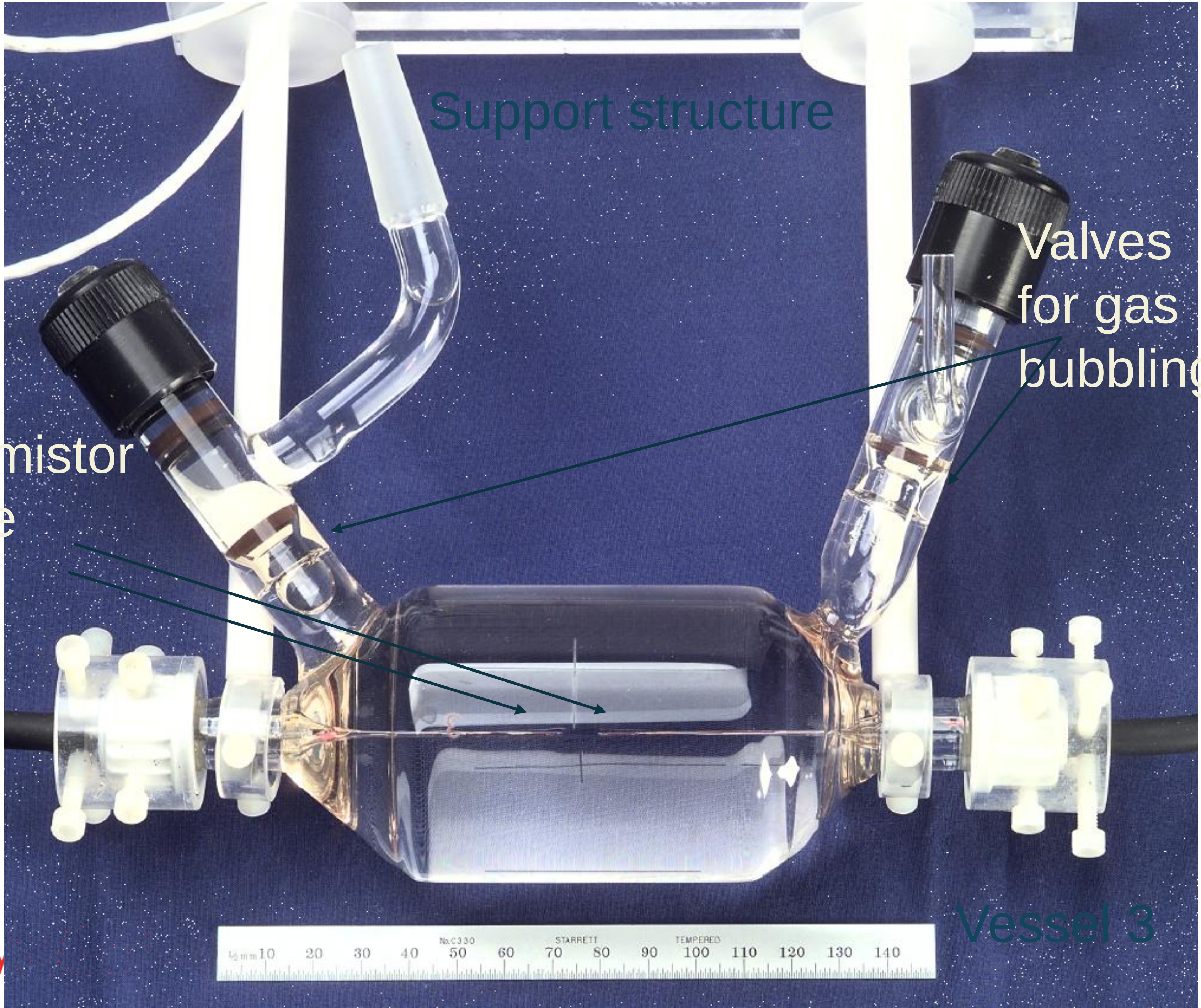


Support structure

Valves for gas bubbling

Thermistor probe ends

Vessel 3

Water calorimetry applied to small and nonstandard fields

$$D_w = c_w \, \Delta T_w \, k_c \, k_p \, k_r \, k_\rho \, \frac{1}{1-h}$$

Heat loss correction is field size dependent

Is field size dependent!

Field size dependence

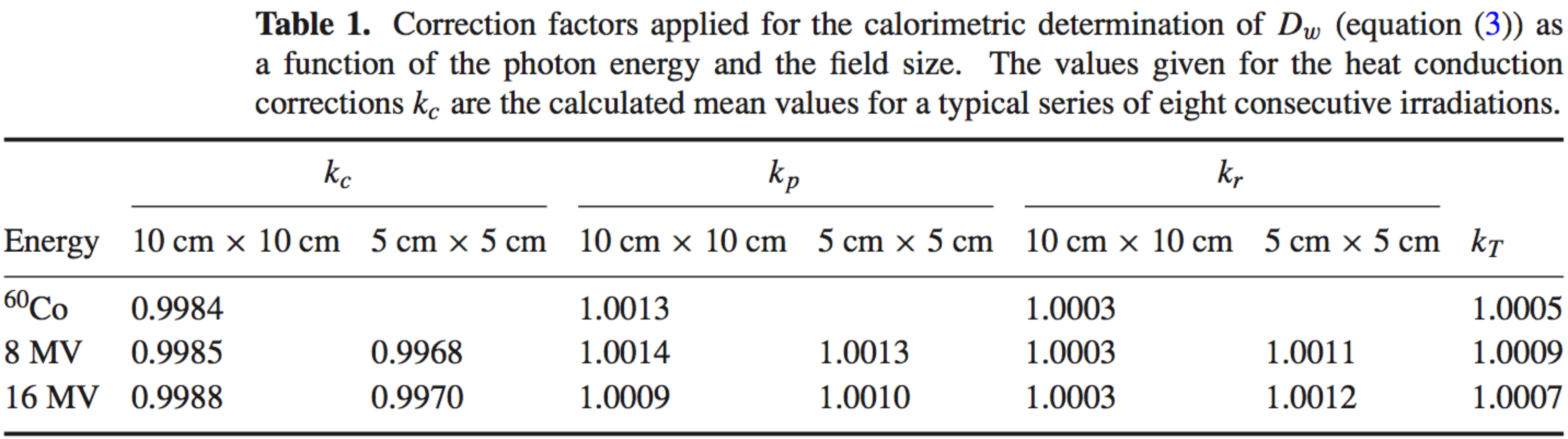


Table 1. Correction factors applied for the calorimetric determination of D_w (equation (3)) as a function of the photon energy and the field size. The values given for the heat conduction corrections k_c are the calculated mean values for a typical series of eight consecutive irradiations.

	k_c		k_p		k_r		
Energy	10 cm × 10 cm	5 cm × 5 cm	10 cm × 10 cm	5 cm × 5 cm	10 cm × 10 cm	5 cm × 5 cm	k_T
^{60}Co	0.9984		1.0013		1.0003		1.0005
8 MV	0.9985	0.9968	1.0014	1.0013	1.0003	1.0011	1.0009
16 MV	0.9988	0.9970	1.0009	1.0010	1.0003	1.0012	1.0007

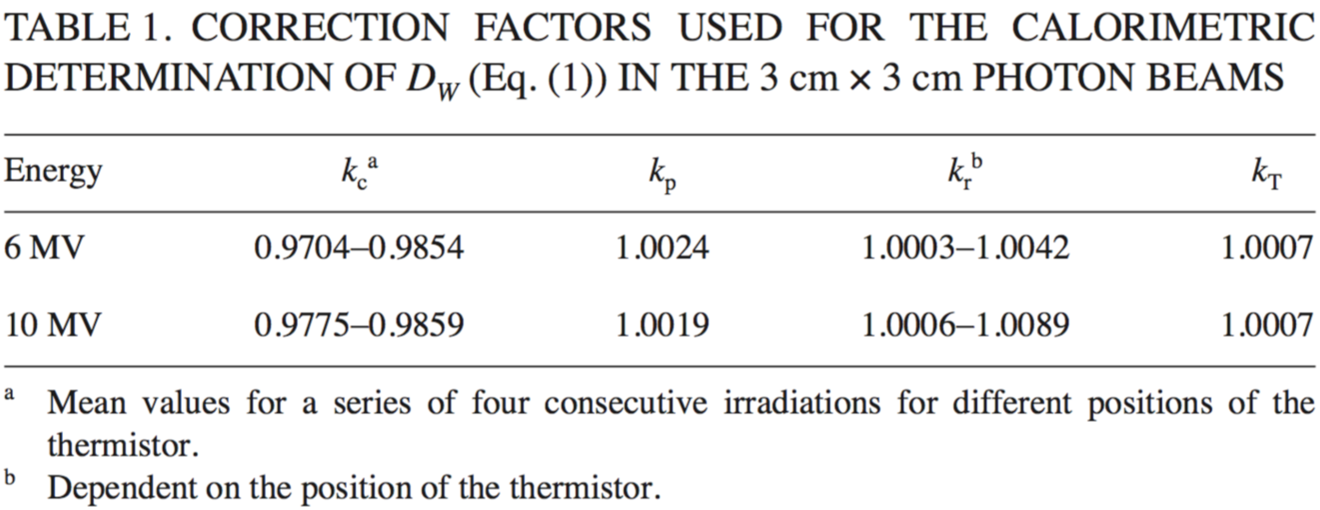


TABLE 1. CORRECTION FACTORS USED FOR THE CALORIMETRIC DETERMINATION OF D_W (Eq. (1)) IN THE 3 cm × 3 cm PHOTON BEAMS

Energy	k_c[a]	k_p	k_r[b]	k_T
6 MV	0.9704–0.9854	1.0024	1.0003–1.0042	1.0007
10 MV	0.9775–0.9859	1.0019	1.0006–1.0089	1.0007

[a] Mean values for a series of four consecutive irradiations for different positions of the thermistor.

[b] Dependent on the position of the thermistor.

Krauss and Kapsch 2007 Phys Med Biol, 52: 6243; Krauss et al 2010 IDOS (IAEA) Proc. 209

Beam quality correction factors

$$k_{Q_{\mathrm{msr}},Q_{\mathrm{ref}}}^{f_{\mathrm{msr}},f_{\mathrm{ref}}}$$

5 x 5 cm^2 field size		
TPR$_{20,10}$	NE 2611	NE 2571
0.716 (8 MV)	0.999 (0.004)	0.999 (0.004)
0.762 (16 MV)	1.000 (0.004)	1.001 (0.004)

Krauss and Kapsch 2007 Phys Med Biol, 52: 6243

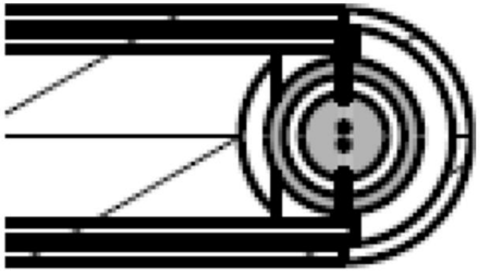
3 x 3 cm^2 field size	
TPR$_{20,10}$	NE 2561
0.683 (6 MV)	0.999 (0.004)
0.733 (10 MV)	1.003 (0.004)

Krauss et al 2010 IDOS (IAEA) Proc.Vol1, pp 209

Limitations of water calorimetry in small fields (< 3 x 3 cm^2)

- Temperature gradients lead to large heat loss corrections
- Heat loss corrections are a function of the irradiation time
- High dose / short radiation time is favorable to reduce the correction factors

IMRT calorimeter


(a)


(b)

Duane et al (2012) Metrologia 49: S168

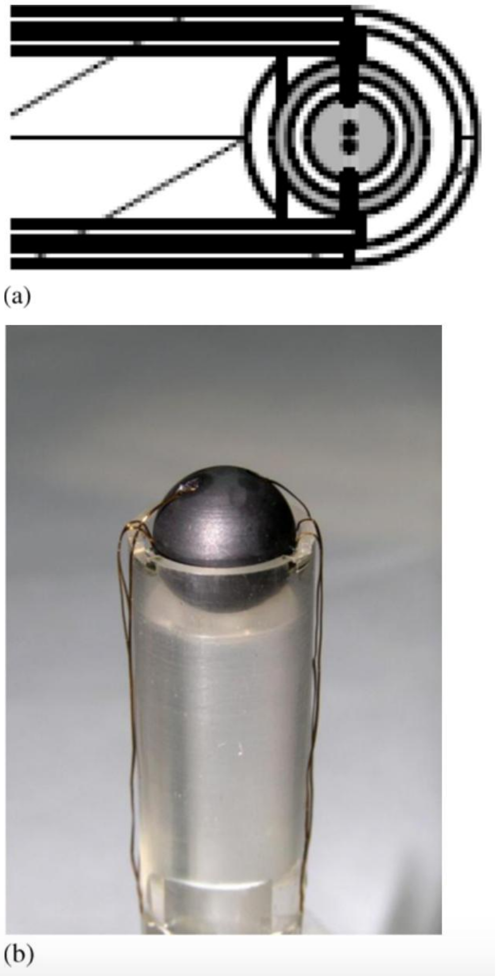
$$D^{\mathrm{std}}_{\mathrm{w},Q_{\mathrm{ref}}} = N^{\mathrm{calor}}_{D,\mathrm{w},Q_{\mathrm{ref}}} M^{\mathrm{calor}}_{Q_{\mathrm{ref}}} P_{\mathrm{vol},Q_{\mathrm{ref}}} \tag{4}$$

$$D_{\mathrm{w},Q} = \left(\frac{D_{\mathrm{w}}}{D_{\mathrm{g},0}}\right)_{\mathrm{MC},Q} M^{\mathrm{calor}}_{Q} \tag{5}$$

$$D_{\mathrm{w},\mathrm{Q}_{\mathrm{IMRT}}} = N^{\mathrm{calor}}_{D,\mathrm{w},Q_{\mathrm{ref}}} k_{Q_{\mathrm{IMRT}},Q_{\mathrm{ref}}} M^{\mathrm{calor}}_{Q_{\mathrm{IMRT}}} \tag{6}$$

$$k_{Q_{\mathrm{IMRT}},Q_{\mathrm{ref}}} = \left(\frac{D_{\mathrm{w}}}{D_{\mathrm{g},0}}\right)_{\mathrm{MC},Q_{\mathrm{IMRT}}} \Bigg/ \left(\frac{D_{\mathrm{w}}}{D_{\mathrm{g},0}}\right)_{\mathrm{MC},Q_{\mathrm{ref}}} . \tag{7}$$

IMRT calorimeter



Duane et al (2012) Metrologia 49: S168

$$J_0^{\mathrm{rad}} = m_0 c_p \frac{\mathrm{d}T_0}{\mathrm{d}t} - J_0^{\mathrm{elec}} + h_{01}(T_0 - T_1) \qquad (1)$$

$$m_0 D_{\mathrm{g},0}(t) = m_0 c_p \Delta T_0 - \int_0^t \left(J_0^{\mathrm{elec}} + h_{01}(T_1 - T_0)\right) \mathrm{d}t \qquad (2)$$

Effective specific heat capacity

Heat transfer

IMRT calorimeter foreign mass effect

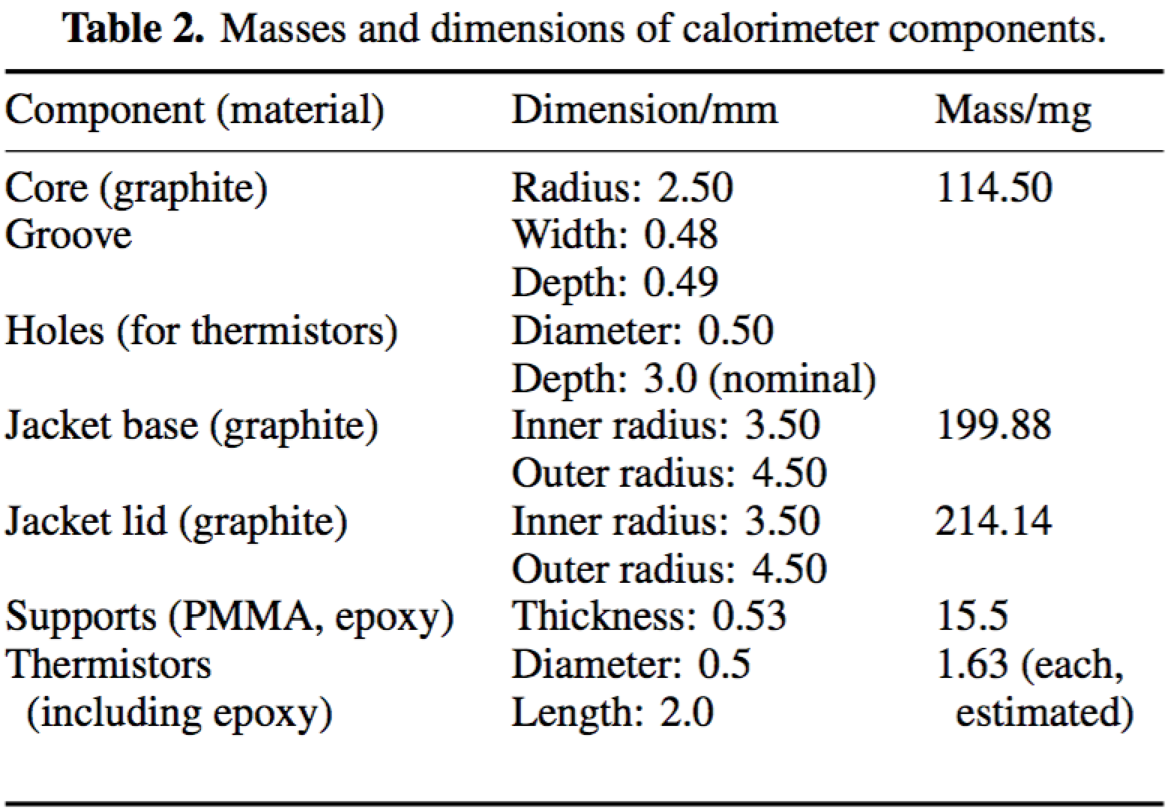
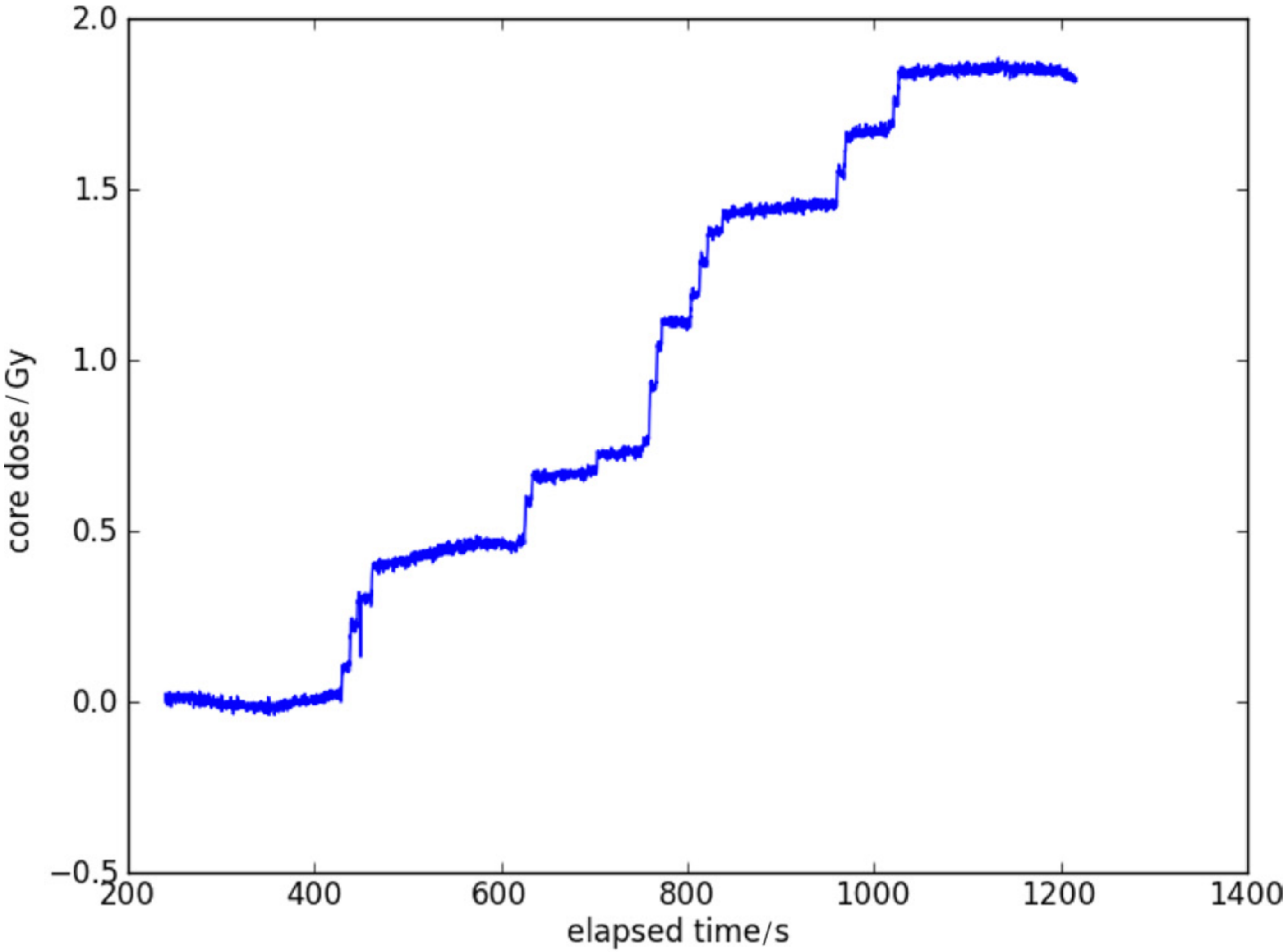


Table 2. Masses and dimensions of calorimeter components.

Component (material)	Dimension/mm	Mass/mg
Core (graphite)	Radius: 2.50	114.50
Groove	Width: 0.48 Depth: 0.49	
Holes (for thermistors)	Diameter: 0.50 Depth: 3.0 (nominal)	
Jacket base (graphite)	Inner radius: 3.50 Outer radius: 4.50	199.88
Jacket lid (graphite)	Inner radius: 3.50 Outer radius: 4.50	214.14
Supports (PMMA, epoxy)	Thickness: 0.53	15.5
Thermistors (including epoxy)	Diameter: 0.5 Length: 2.0	1.63 (each, estimated)

Duane et al (2012) Metrologia 49: S168

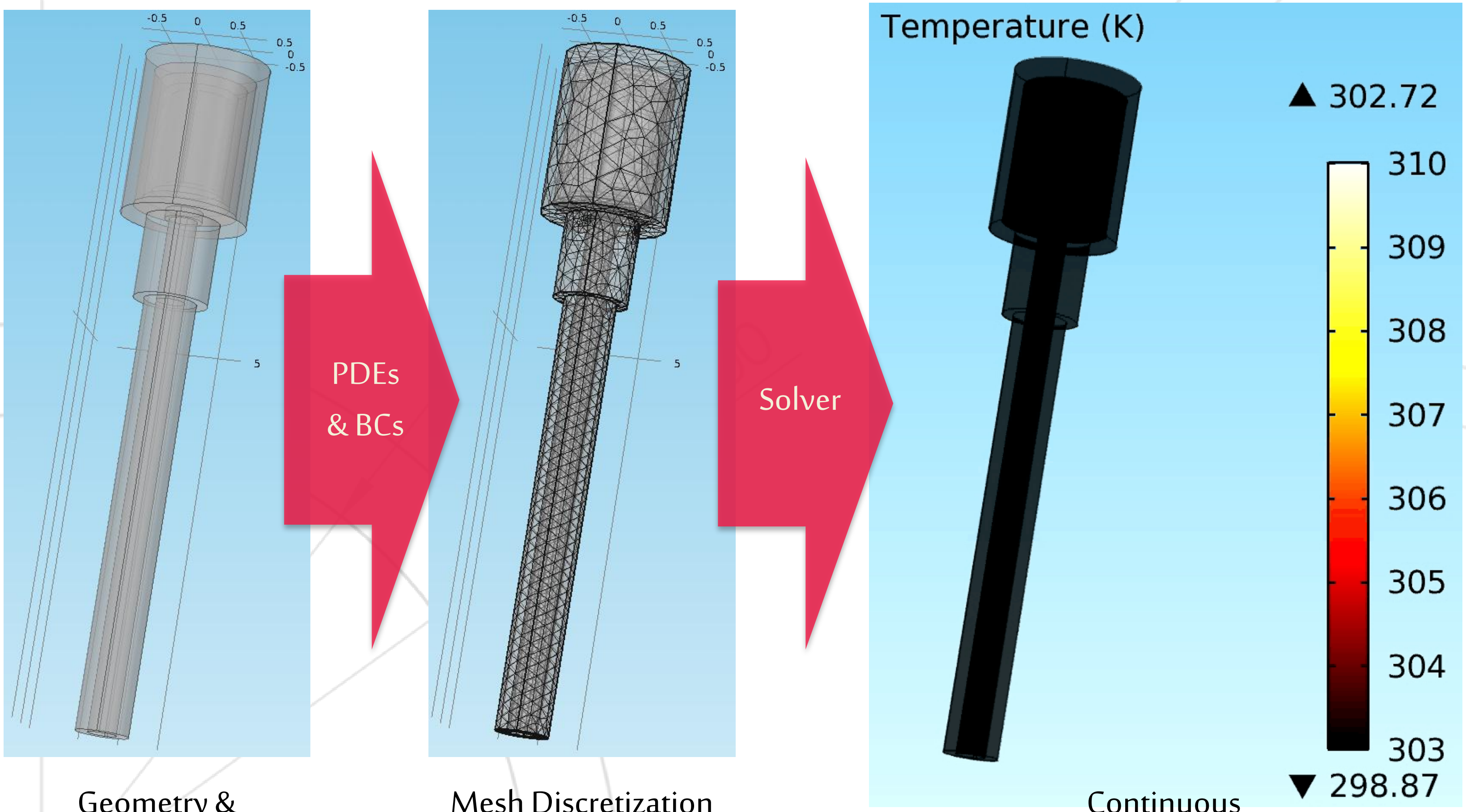
IMRT calorimeter signal



Patent no. WO/2013/177677

Renaud et al 2013-2015

Preamble



PDEs
& BCs

Solver

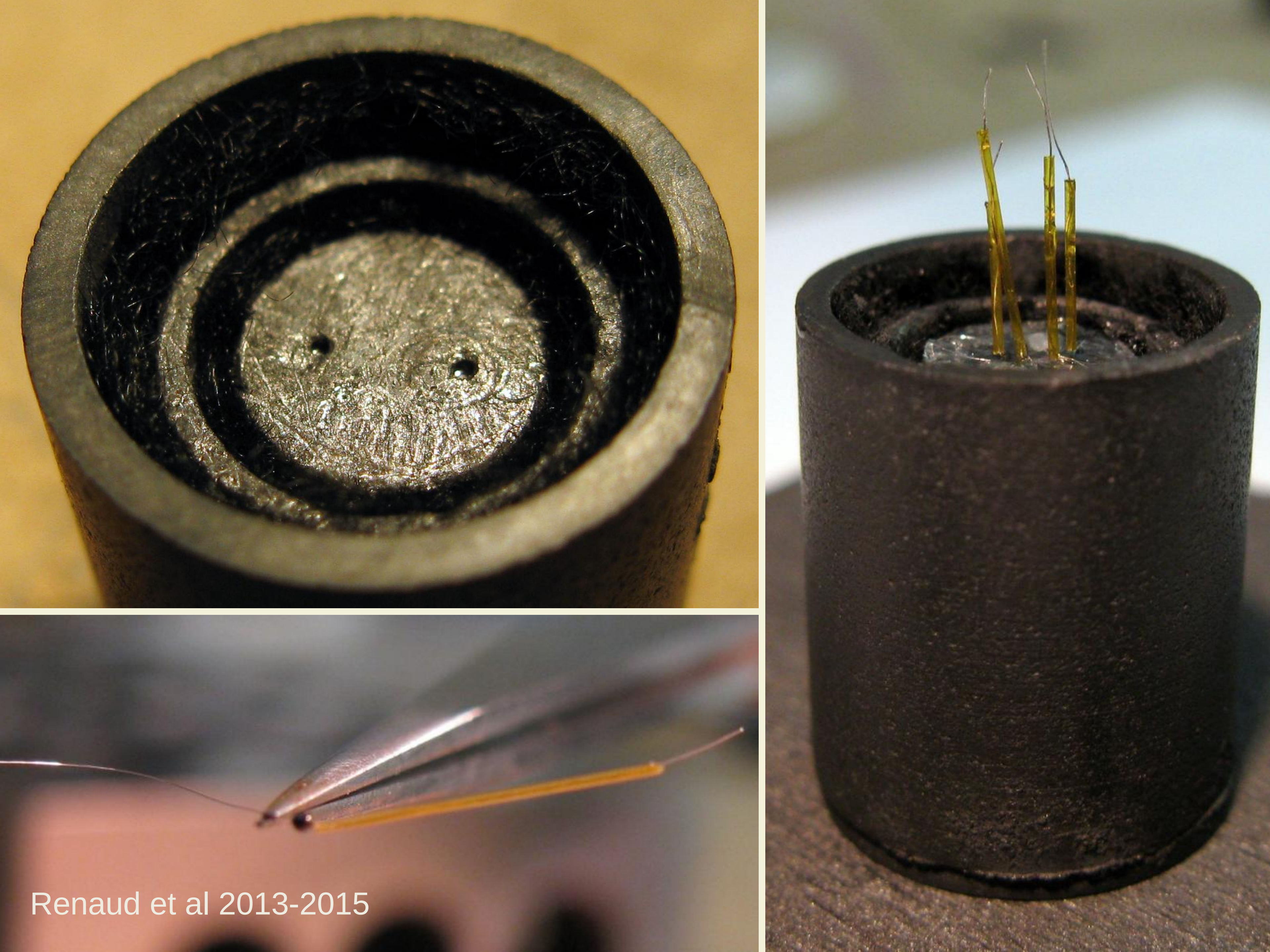
Geometry &
Materials

Mesh Discretization

Continuous
Solution

Renaud et al 2013-2015

Comsol Multiphysics®



Renaud et al 2013-2015

76.5 cGy

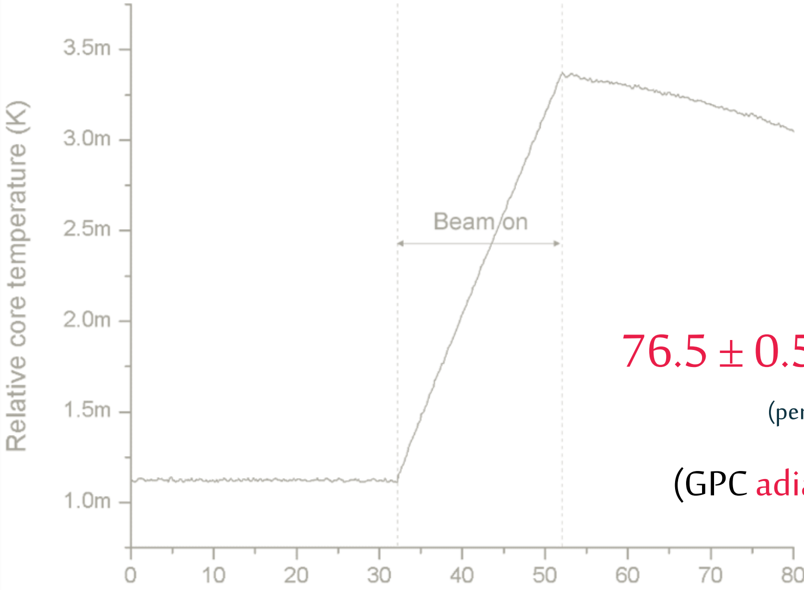
(per 100 MU)

(TG-51)

76.9 ± 0.5 cGy

(per 100 MU)

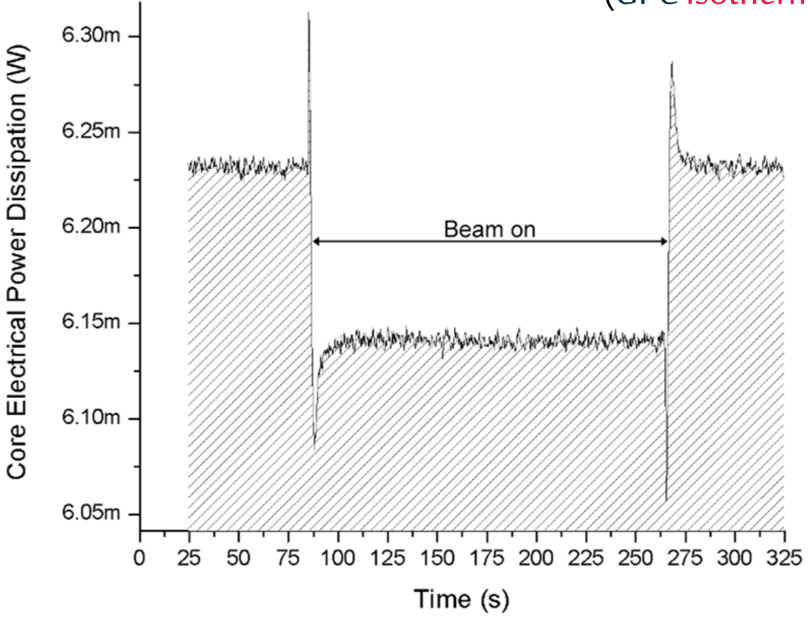
(GPC isothermal)



76.5 ± 0.5 cGy

(per 100 MU)

(GPC adiabatic)



Renaud et al 2013-2015

Accuracy & Precision

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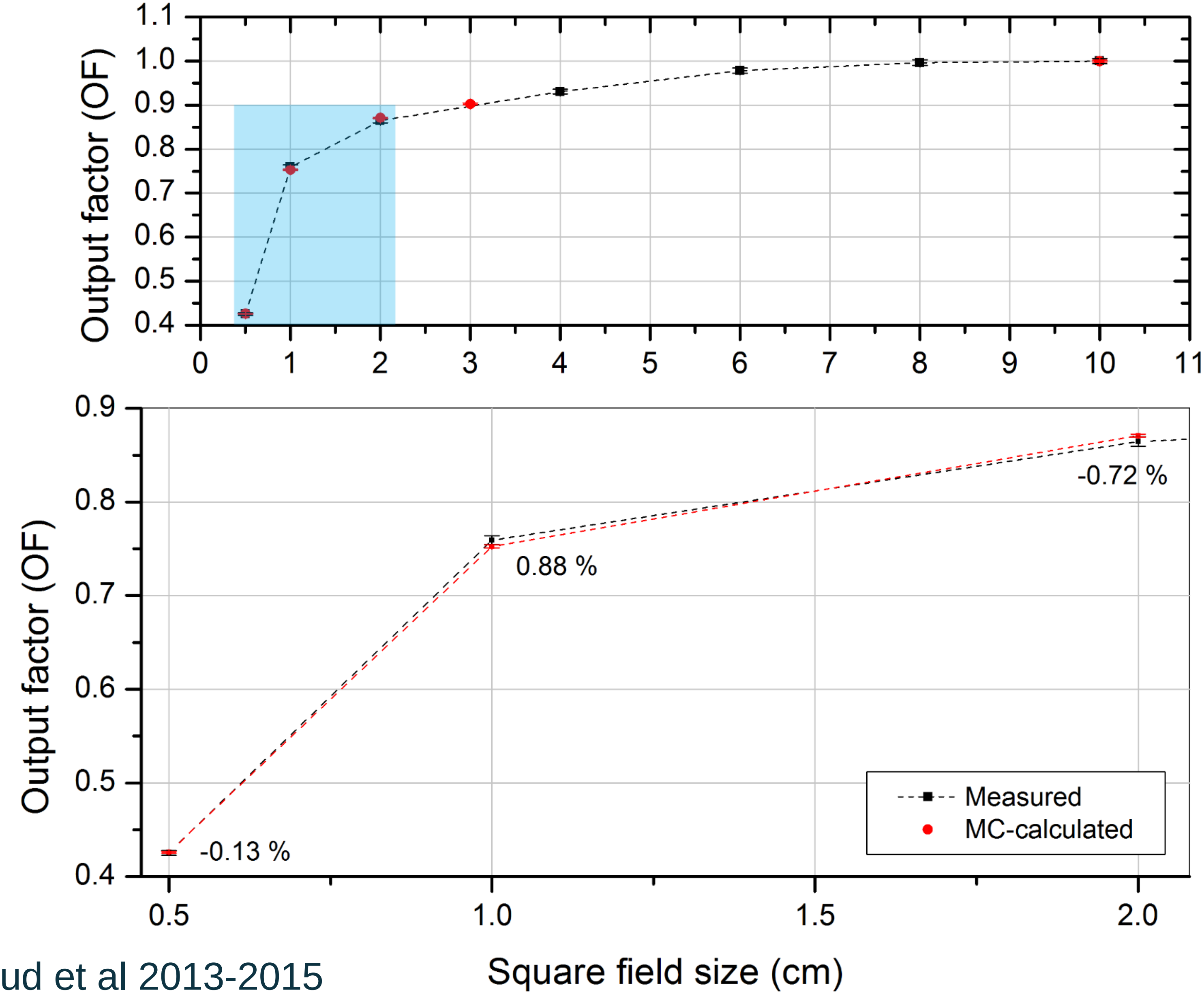
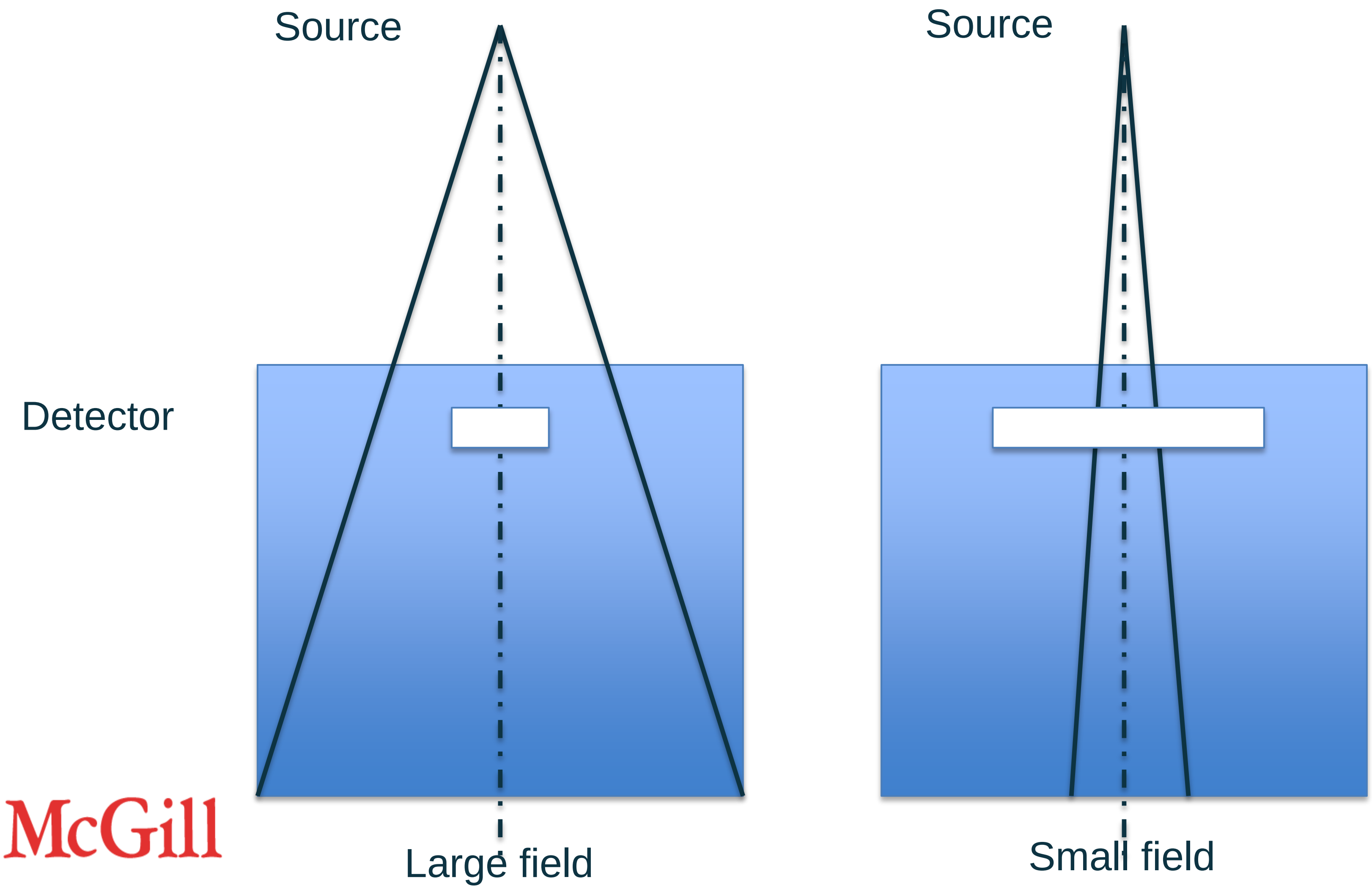
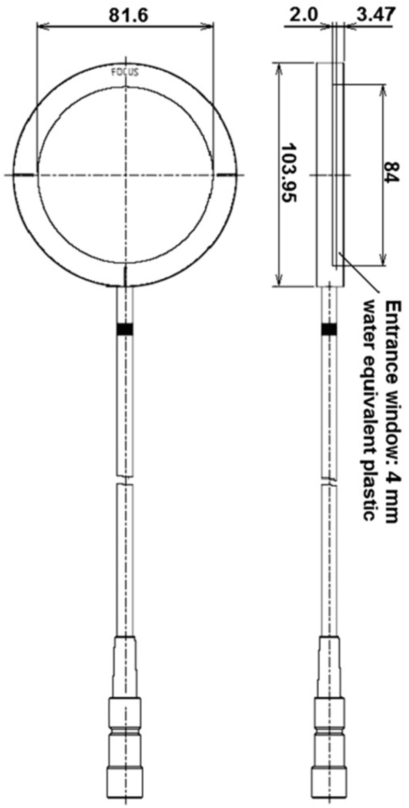


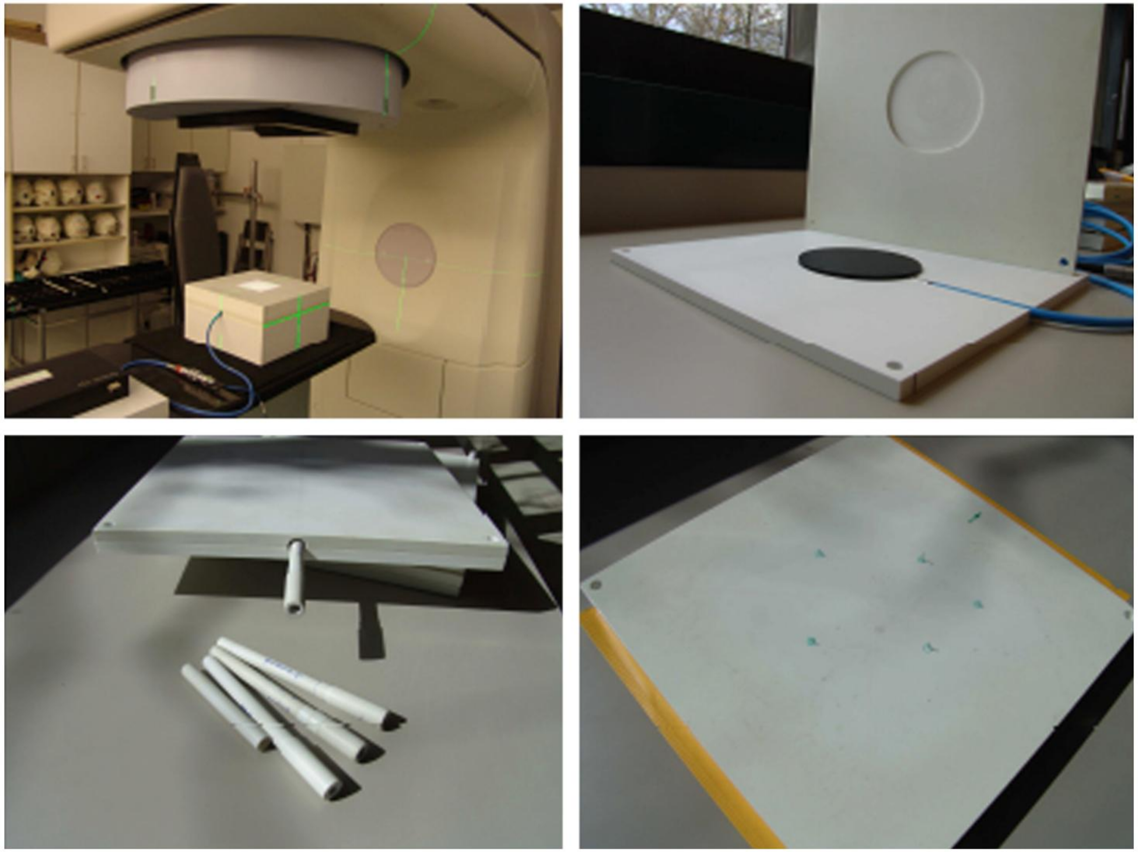
Renaud et al 2013-2015

Dose area product methodologies



Dose area product methodologies





Sanchez-Doblado et al 2007

Dose area product methodologies

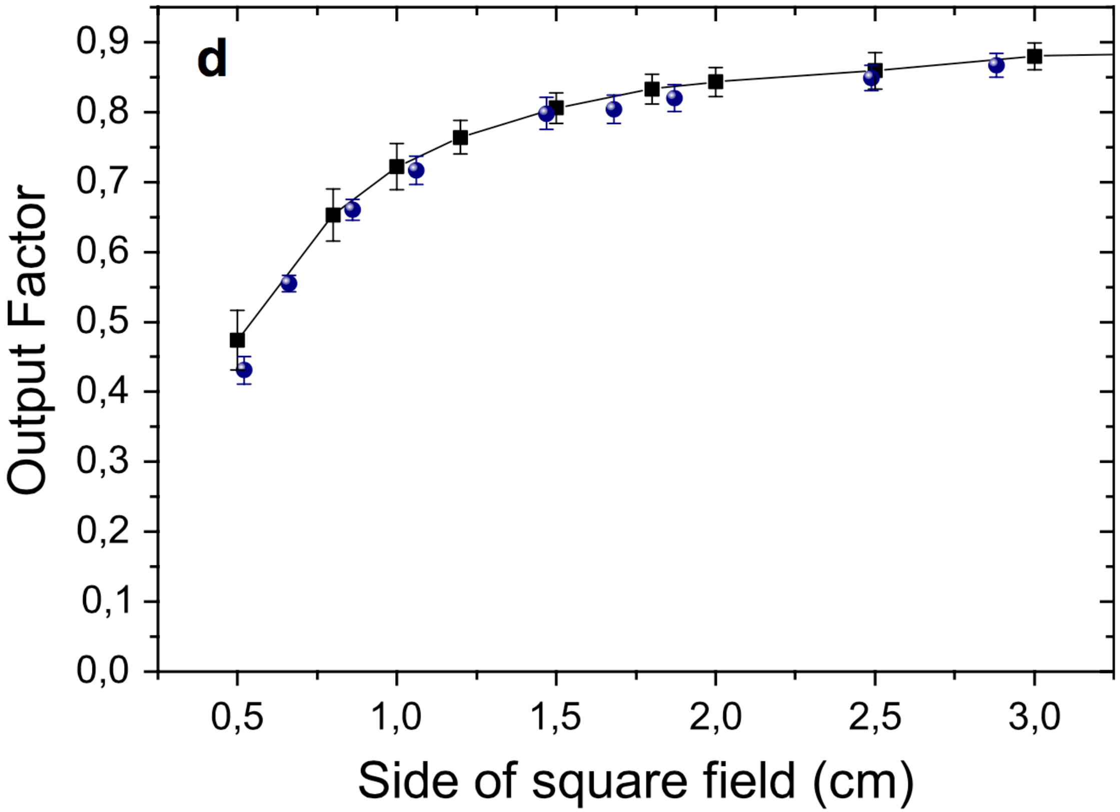
$$D_{\mathrm{ROI}} = D_{\mathrm{Ch}} \cdot F$$

Dose collected by entire pp chamber

$$F = \frac{\int_{\mathrm{ROI}} \rho(x,y)\,dA}{\int_{\mathrm{Ch}} \rho(x,y)\,dA}$$

Relative distribution measured with radiochromic film

Dose area product methodologies



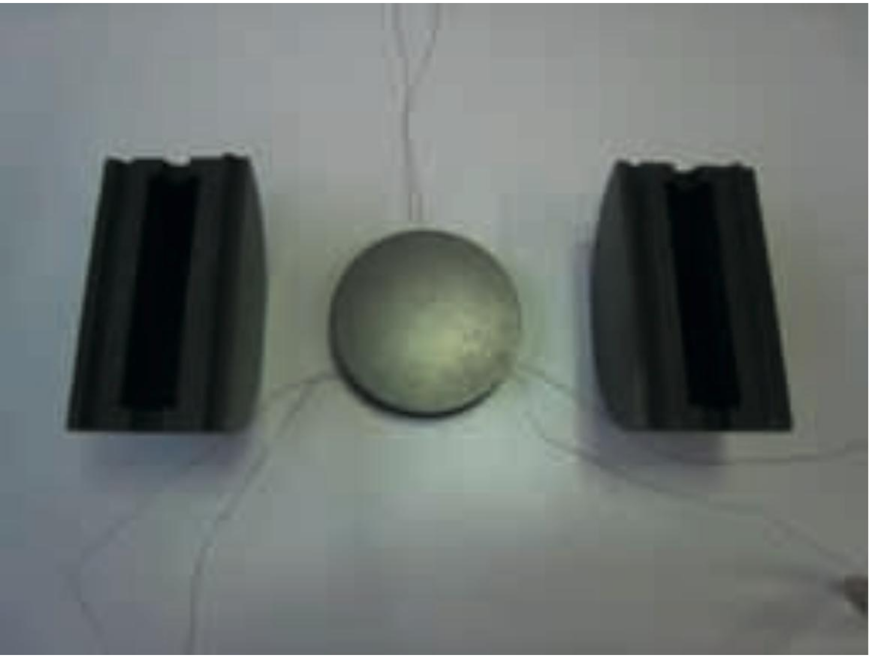
Blue data points, DAP measurement
Black data points: Monte Carlo

Sanchez-Doblado et al 2007

Dose area product methodologies

- Assumption: the sensitivity of the detector is uniform over its cavity – this may be a problem for ionization chambers
- But: Methodology could be applied with graphite calorimeters!

Dose area product methodologies



Picard et al 2011

BIPM graphite calorimeter

Transfer standards

- A detector that can be used to “transfer” absorbed dose established in a large field to a small field
- Thus a transfer standard must:
  - Be water-equivalent and perturbation free or the changes must be well-characterized between large field conditions and small field conditions

Ionization based absorbed-dose standard

- Based on the measurement of ionization in a cavity chamber inserted in water:

$$D_w = \frac{M}{\rho V}\frac{W_{\rm air}}{e}\boxed{s_{w,air}p_Q}$$

from a MC calculation

Issues:

1. effective volume must be known
2. cavity theory or MC needed for dose conversion
3. W_{air}/e needed (and assumed to be constant)

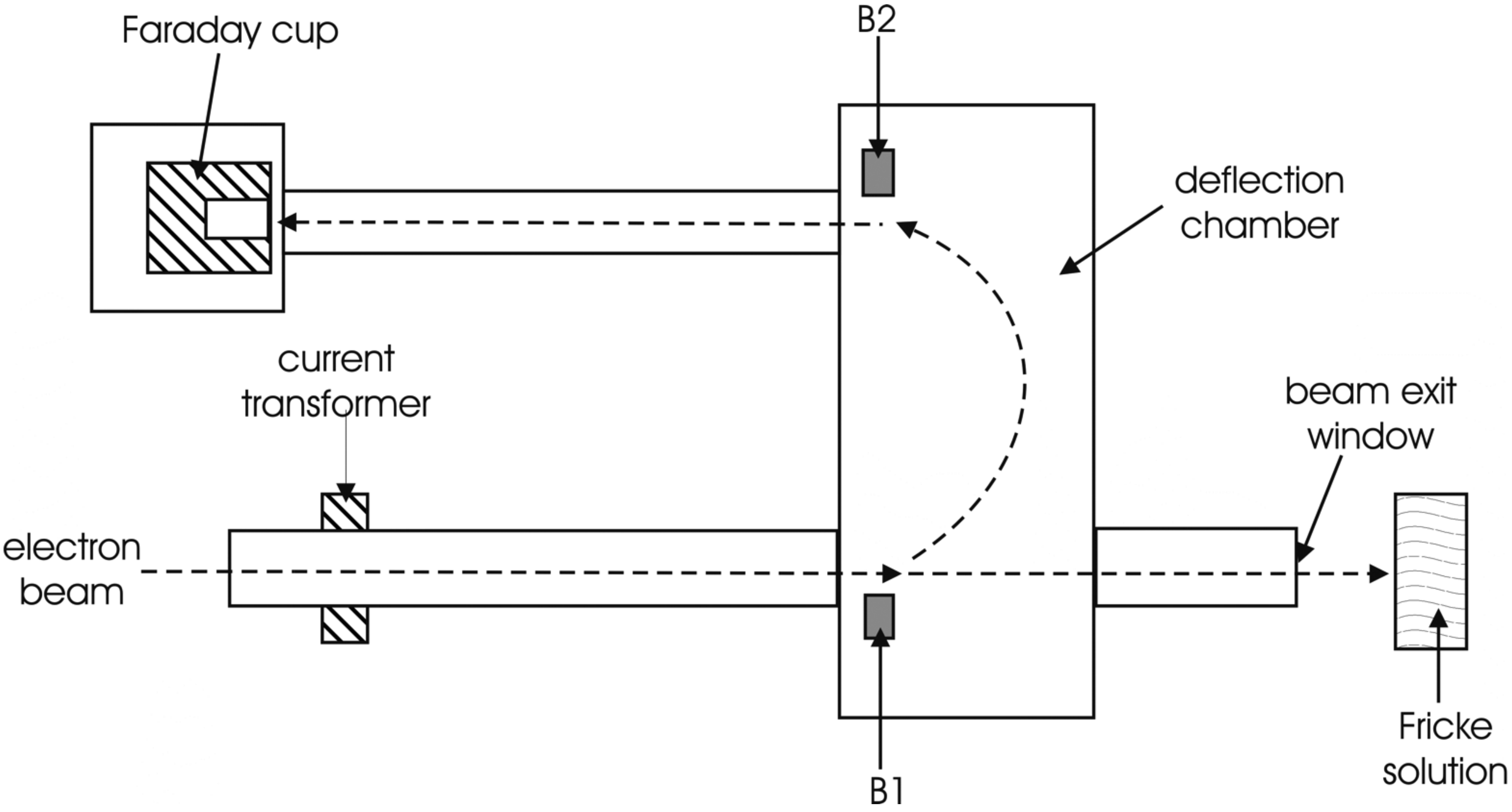
Total absorption-based absorbed-dose standard

- Known beam energy *E*, known particle fluence, known absorber mass *m*:

$$\overline{D}_{med} = \frac{E}{m}$$

Issues:

1. Absorbed dose is average over a volume and needs to be transferred to a point
2. Corrections required to back up assumption of total absorption


Faraday cup
B2
deflection chamber
current transformer
beam exit window
electron beam
Fricke solution
B1

Total absorption to determine Fricke radiation chemical yield

$$\overline{D}_{\mathrm{F}} = \frac{E_e N}{m} f_{\mathrm{T}}$$ via the total absorption method

$$\overline{D}_{\mathrm{F}} = \frac{\Delta A_{\mathrm{T}}}{\epsilon \cdot G(Fe^{3+}) \cdot \rho \cdot l_{\mathrm{T}}}$$ -> solve for $\epsilon \cdot G(Fe^{3+})$

Then use the Fricke solution in a small vial in a water phantom to get D_w at a point in a small field:

$$D_w = \overline{D}_{\mathrm{F}} \boxed{s_{\mathrm{w,F}} p_{\mathrm{wall}}} \longrightarrow$$ from a MC calculation

Cojocaru et al 2010 – wall-less Fricke system

Other transfer standards suitable for small fields

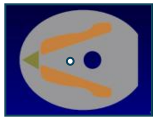
- Alanine /ESR
- Liquid ionization chamber
- Plastic scintillator
- CVD diamond detectors
- High-precision radiochromic film
- High-precision TLD

GORTEC
Groupe Oncologie Radiothérapie
Tête Et Cou
Radiotherapy oncology group for head & neck

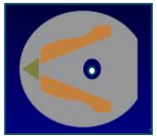
Gortec IMRT Test Phantom

TLDs are placed at seven locations.

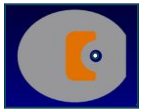
- Point 1: Isocenter



- Point 2: Spinal cord isocenter

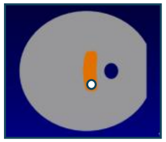


- Point 3: Spinal cord cranial

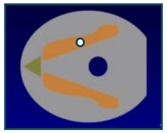


- Point 4: PTV T R

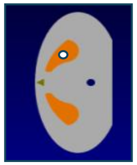
- Point 5: PTV T R cranial



- Point 6: PTV N L



- Point 7: PTV N L caudal



**Courtesy M. Tomsej,
St. Luc, Brussels**

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Sample Tomotherapy Results

TLD loc.	Calc (Gy)	Meas (Gy)	Meas/Calc
Point 1	1.920	1.922	1.001
Point 2	1.191	1.198	1.005
Point 3	1.214	1.213	1.000
Point 4	2.035	2.017	0.991
Point 5	2.017	2.001	0.992
Point 6	2.023	1.985	0.981
Point 7	2.012	1.970	0.979

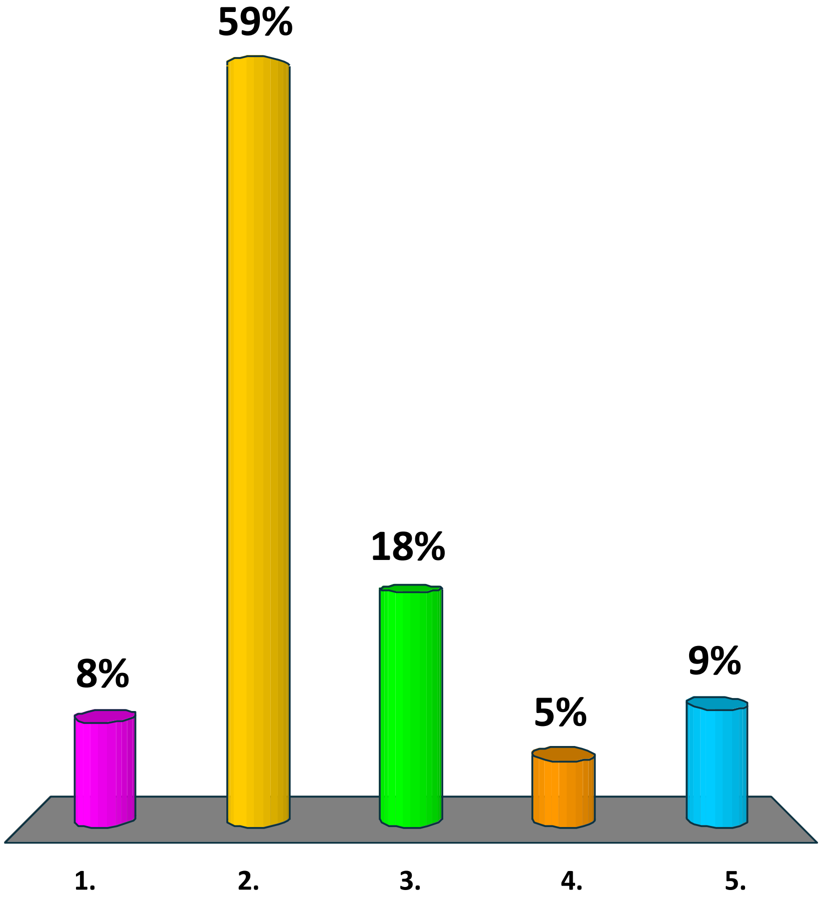
2.5 cm mode

Conclusions

- Absorbed dose standards for nonstandard fields are being developed and characterized
- The operating principle in nonstandard fields is the same as in standard fields
- Each device or methodology has its own issues that require full characterization before these new standards can be declared

Which of the following absorbed dose standards for photon beams do not require a field of ionizing radiation for their characterization?

1. Air-filled Ionization chambers with known effective volume
2. Calorimeters
3. Ferrous sulphate dosimeters
4. Film dosimeter with an absolute calibration
5. Alanine/ESR dosimeters



- Correct answer: 2.

- Discussion: Calorimeters can be characterized by temperature calibration and thus do not require ionizing radiation for their characterization. All the other options, require, at some stage, the use of ionizing radiation for their characterization.

- References: Seuntjens and Duane (2009) Metrologia 46, S39-S58

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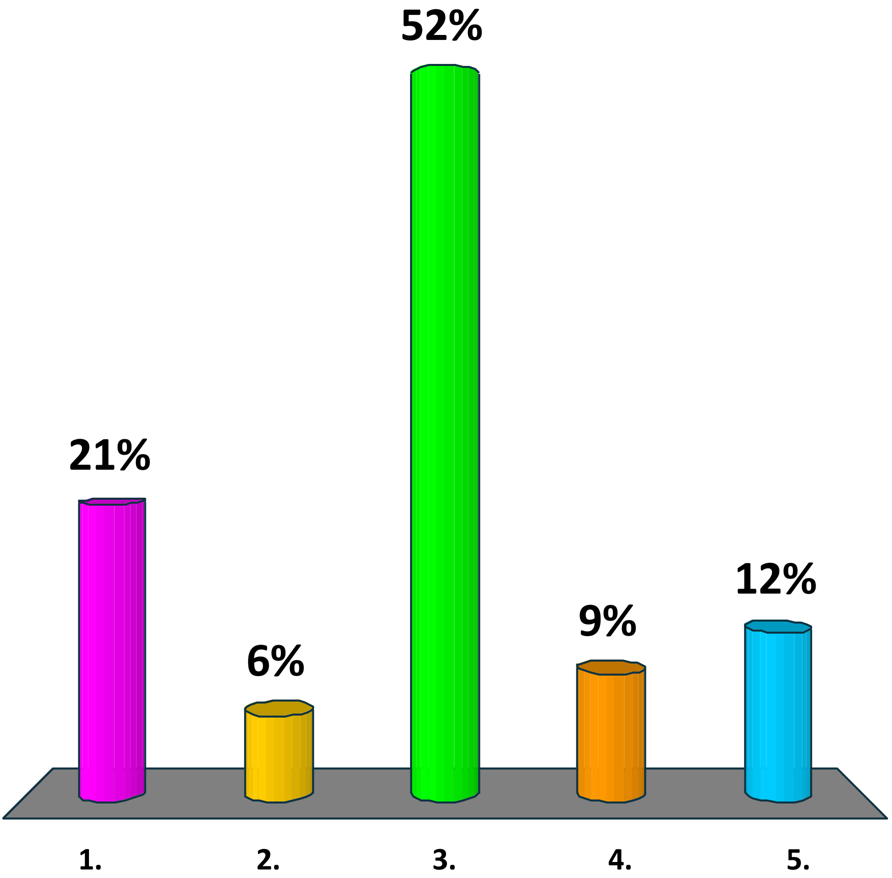
Water calorimeters are currently not suitable for the standardization of absorbed dose to water in small fields because of the following reason

1. The chemical heat defect is field size and beam quality dependent
2. The dose rate for small fields is too low and leads to reproducibility problems
3. The heat loss in water becomes too significant and heat transfer corrections become unmanageably large
4. The thermistors (temperature sensors) cannot be well-positioned in small fields
5. Water calorimeters are too bulky for small field measurements



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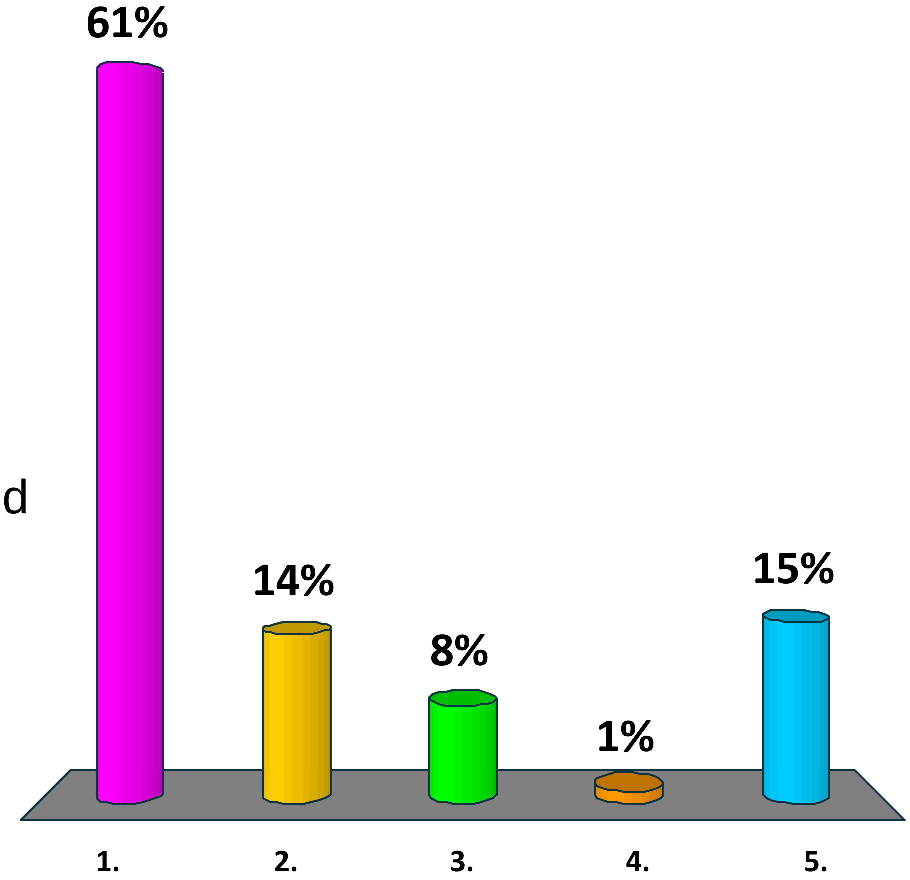
- Correct answer: 3.

- Discussion: Heat loss corrections become on the order of several percent for field sizes of 3 x 3 cm^2 and larger below that. The uncertainty on the correction becomes unmanageably large.

- Reference: Palmans H (2010) Small And Composite Field Dosimetry: The Problems And Recent Progress. IDOS: Standards, Applications and Quality Assurance in Medical Radiation Dosimetry. Proceedings of an international Symposium. IAEA 9-12 November 2010. Pp 161-180

Transfer standards are used by standards laboratories to provide traceable calibrations in nonstandard fields. The most important characteristic of transfer standards is

1. Must be water equivalent and perturbation free in reference field and small field and be practical
2. Must have air-filled detection cavity that is small compared to the field size
3. Must have outer dimensions that are small compared to the field size
4. Must have a stem that is small compared to the field size
5. Must not depend on the use of ionizing radiation for their full characterization



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- Correct answer: 1

- Discussion: The relative correction involved in transferring a calibration from a standard field to a non-standard field must be small and its uncertainty well understood. Suitable transfer standards are: alanine/ESR dosimeter, ferrous sulphate dosimeter, etc.

- Reference: Palmans H (2010) Small And Composite Field Dosimetry: The Problems And Recent Progress. IDOS: Standards, Applications and Quality Assurance in Medical Radiation Dosimetry. Proceedings of an international Symposium. IAEA 9-12 November 2010. Pp 161-180