Reference dosimetry protocols and their application in radiotherapy environments with strong magnetic fields.

CIRMS 2018

Daniel O’Brien, PhD

Global Product Support, Elekta

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MRI-guided Radiotherapy

- New treatment modality that combines MR-imaging with radiotherapy linacs
- Introduces magnetic fields to the radiotherapy environment
- Current range from 0.35 T to 1.5 T

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Standard Reference Dosimetry Protocols

Formalism

Standard Reference Dosimetry Protocols

All major dosimetry protocols use some variation of the following formalisms

Direct Calibration $$D_w^Q = M \cdot N_{D,w}^Q$$ (e.g. NPL)

Corrected Calibration $$D_w^Q = M \cdot N_{D,w}^{^{60}Co} \cdot k_Q$$ (e.g. AAPM, IAEA)

Beam Quality

Standard Reference Dosimetry Protocols

- Some measurable metric (or beam quality specifier) must be used to determine the radiation quality of the beam.

- Two most common beam quality specifiers are:
  - $\%dd(10)_x$ Used by AAPM TG-51 protocol

    The percentage depth dose at 10 cm depth for a pure photon beam (*no electron contamination*). Must be measured at 100 cm SSD.

  - TPR_{10}^{20} Used by IAEA TRS-398 protocol

    Ratio of the dose at isocenter at a depth of 20 cm to the dose at isocenter at a depth of 10 cm. Independent of SSD. Potential for the relationship with k_Q to change for FFF beams.

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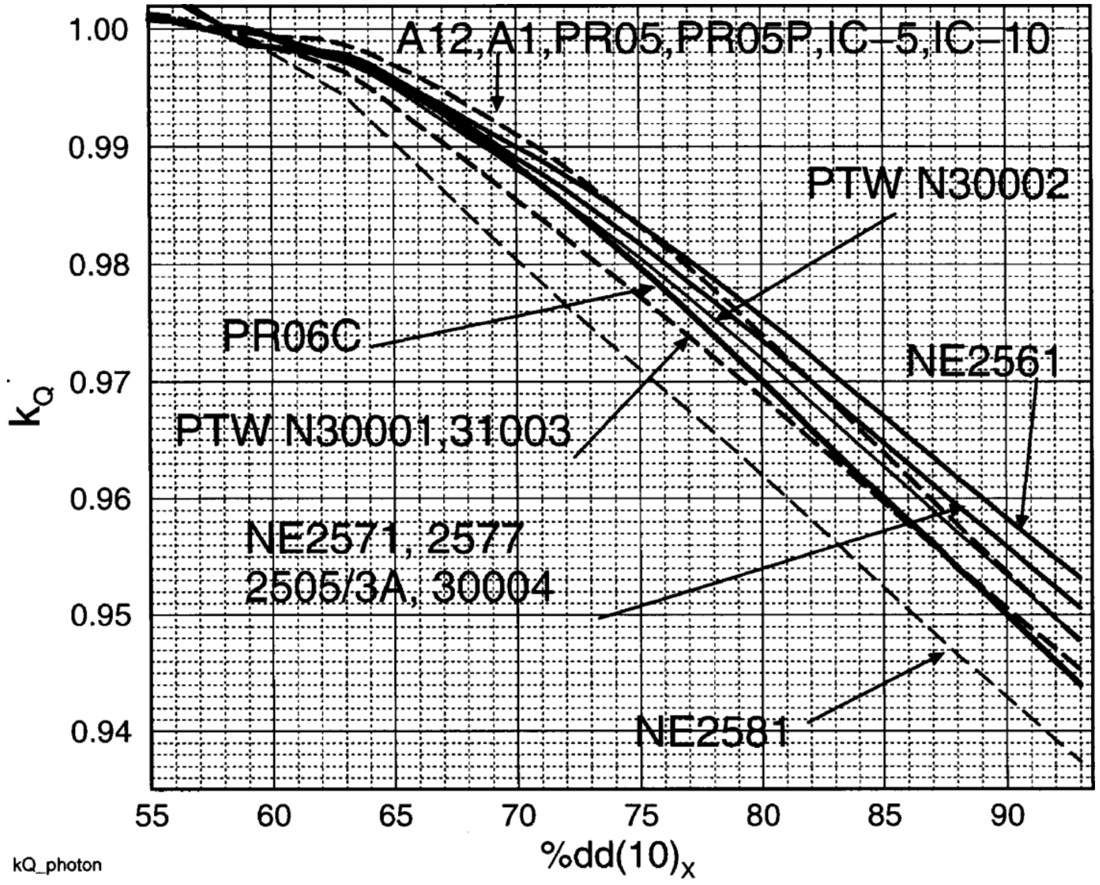
Beam Quality Correction

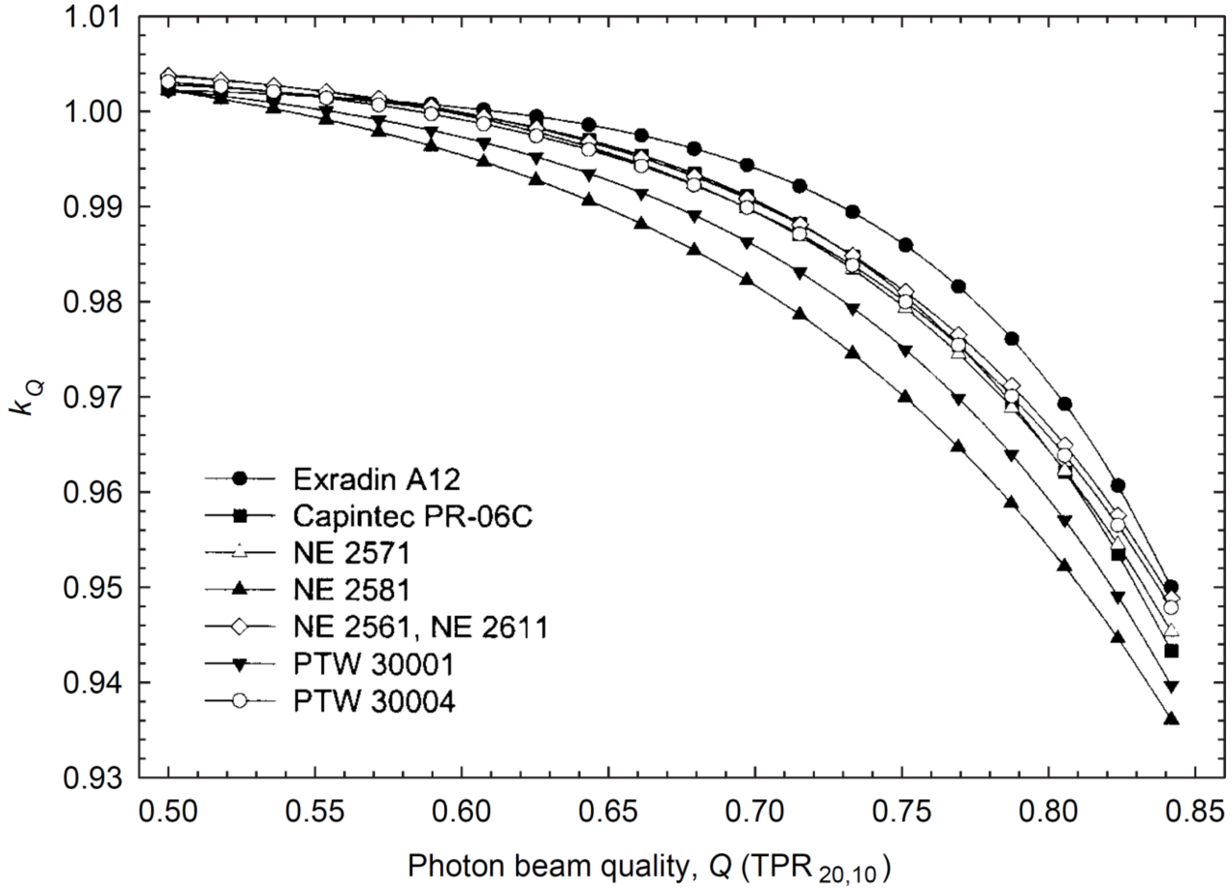
Standard Reference Dosimetry Protocols

AAPM TG-51



kQ_photon

IAEA TRS-398



Complications in Magnetic Fields

Lorentz Force

No Magnetic Field

1.5 T Magnetic Field

Electrons (in red) continue to scatter.

However, their trajectory in water/tissue is heavily influenced by the Lorentz force.

Note: Positrons (in blue) are deflected in the opposite direction

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Electron Return Effect

No Magnetic Field

1.5 T Magnetic Field

Beam Quality Determination

Complications in Magnetic Fields

Source to surface distance (SSD) restrictions due to the cryostat

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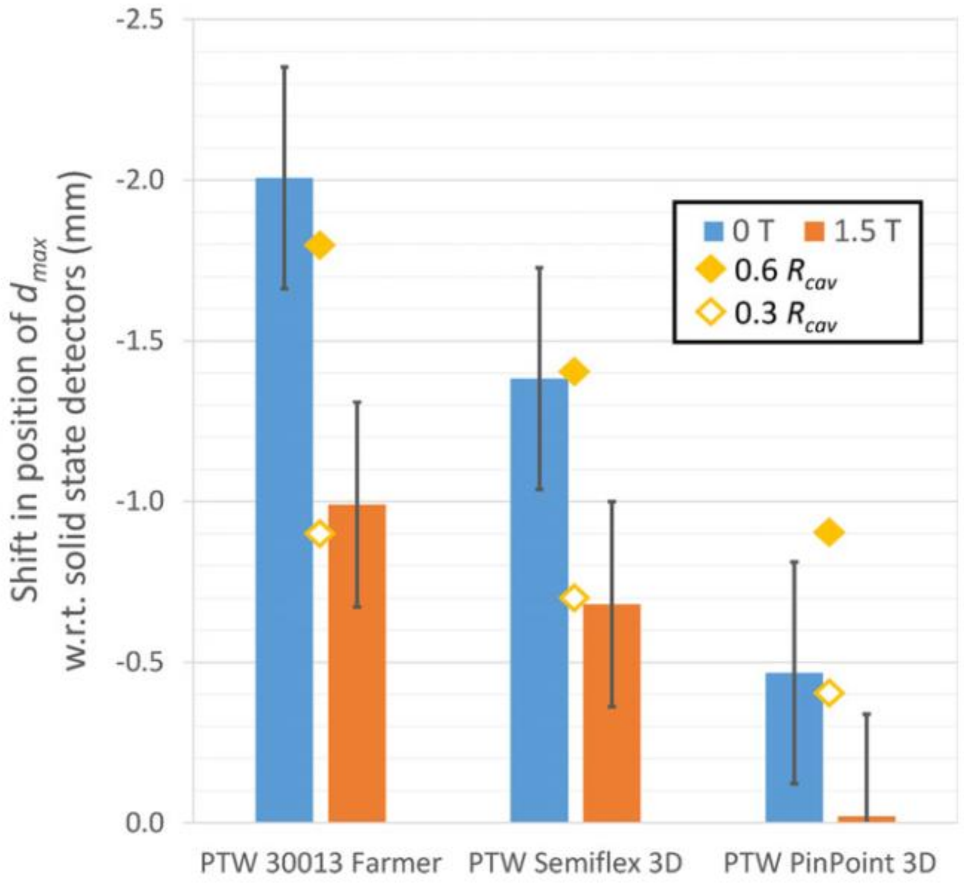
Beam Quality Determination

Complications in Magnetic Fields

- Magnetic field alters the effective point of measurement of ionization chambers.

- Must be accounted for when measuring percentage depth doses (PDDs)



* O'Brien et al. (2018). "Relative dosimetry with an MR-linac: Response of ion chambers, diamond, and diode detectors for off-axis, depth dose, and output factor measurements" Med. Phys. 45(2), 884–897

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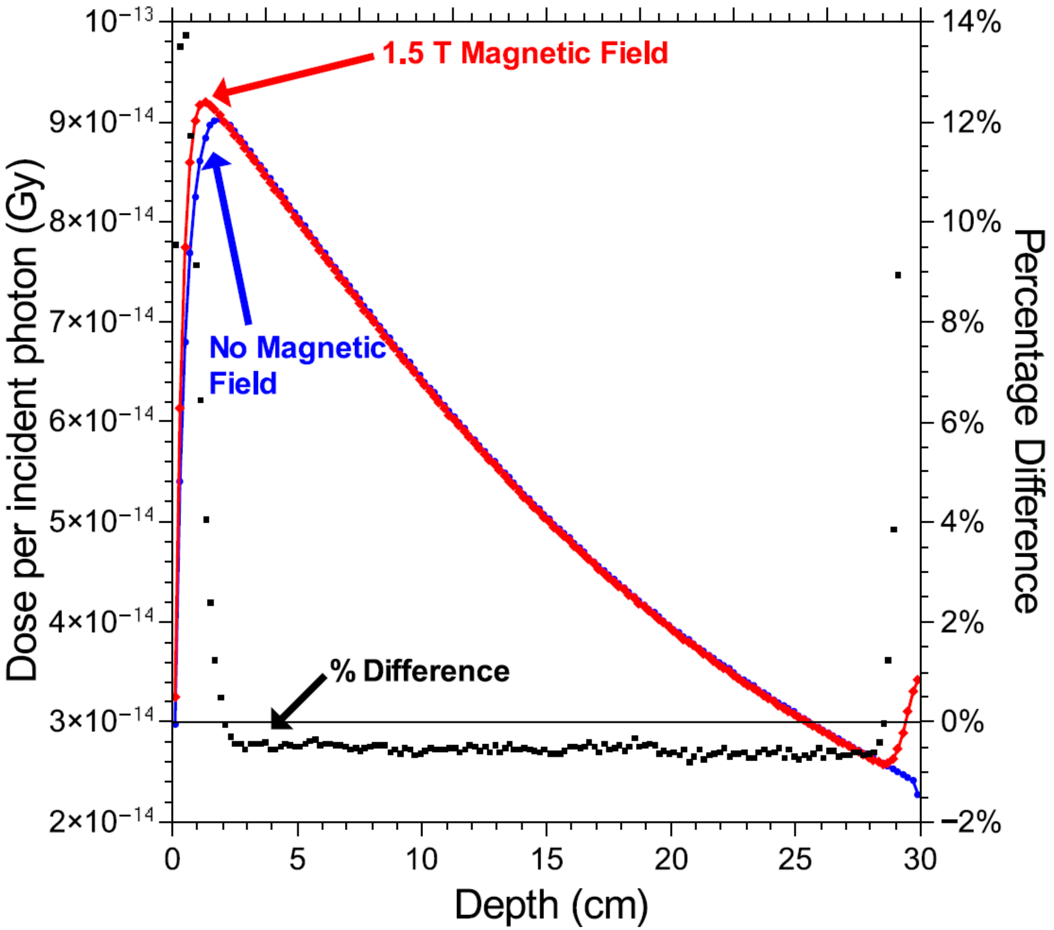
Beam Quality Determination

Complications in Magnetic Fields

Magnetic field alters the depth dose distribution.

- **Changes the value of the %dd(10)$_x$ beam quality specifier**
- **TPR_{10}^{20} effectively independent of magnetic field strength**

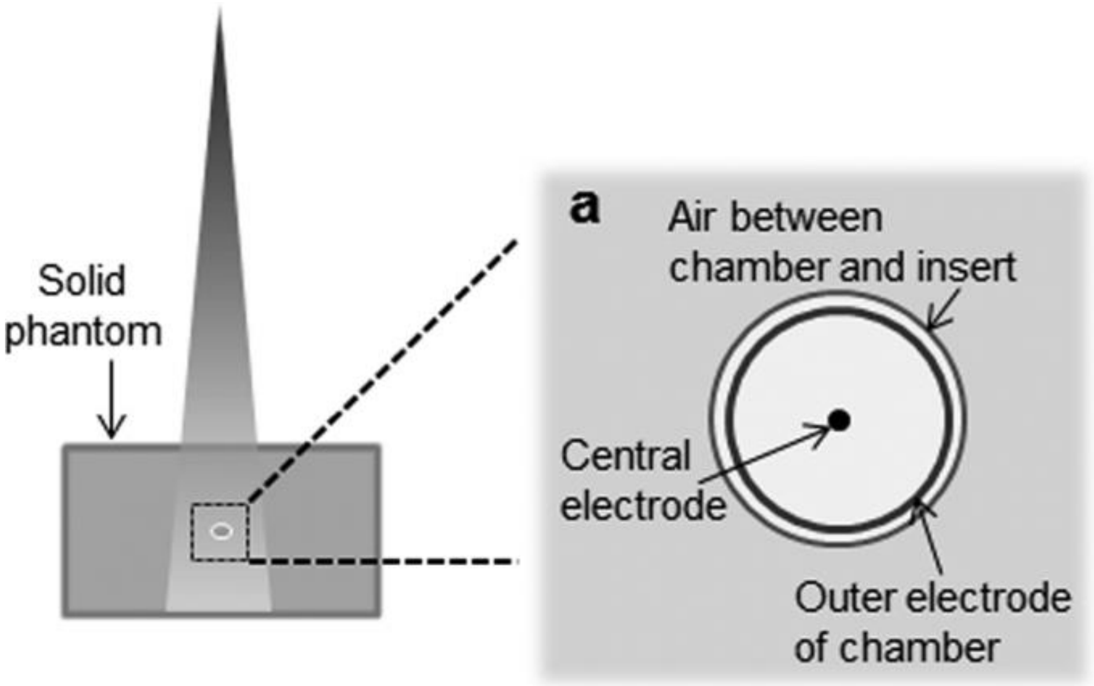
Pure Photon Beam	d_{max}	$\%dd(10)_x$	TPR_{10}^{20}
No magnetic field	1.85	71.4	0.697
1.5 T magnetic field	1.30	69.7	0.695



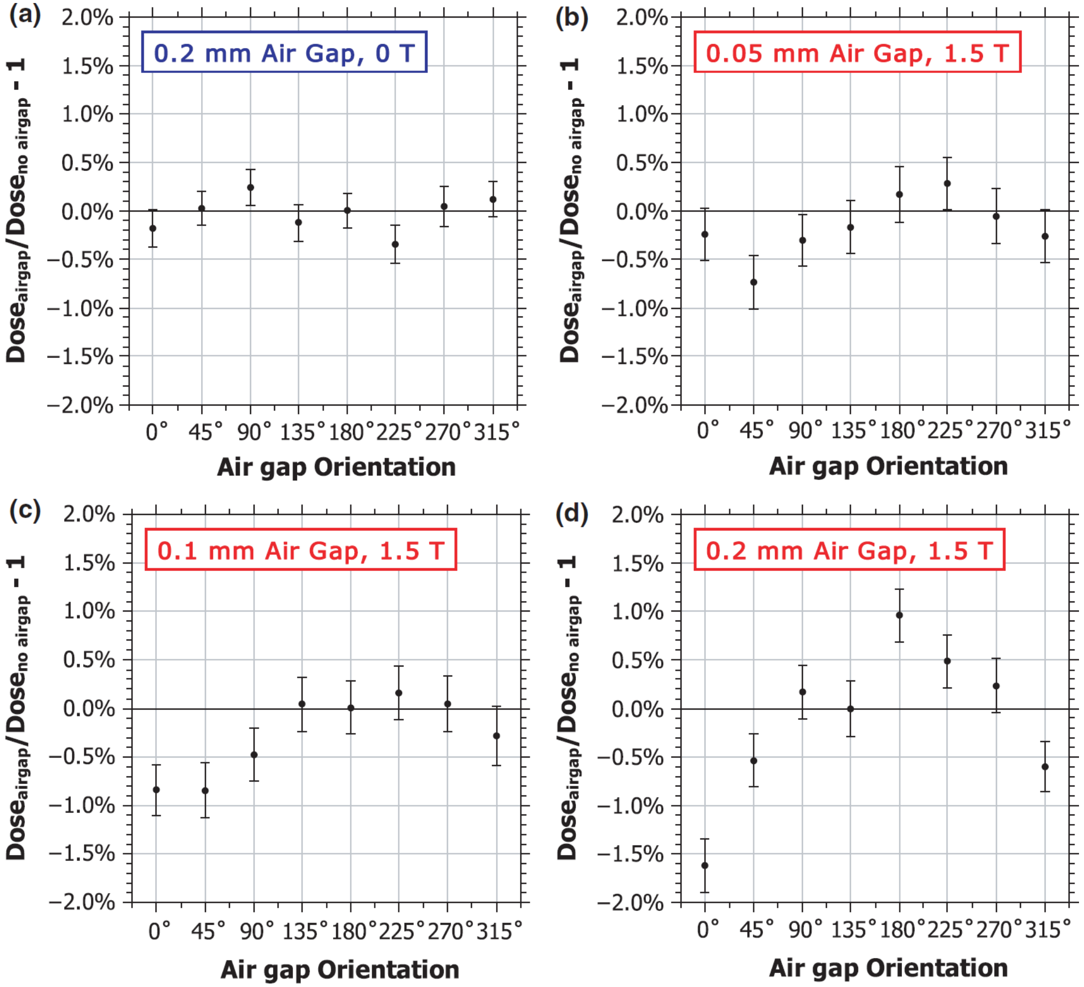
* O'Brien et al. (2016). "Reference dosimetry in magnetic fields: formalism and ionization chamber correction factors." Med. Phys. 43(8), 4915–4927

Air Gap Effect

Complications in Magnetic Fields



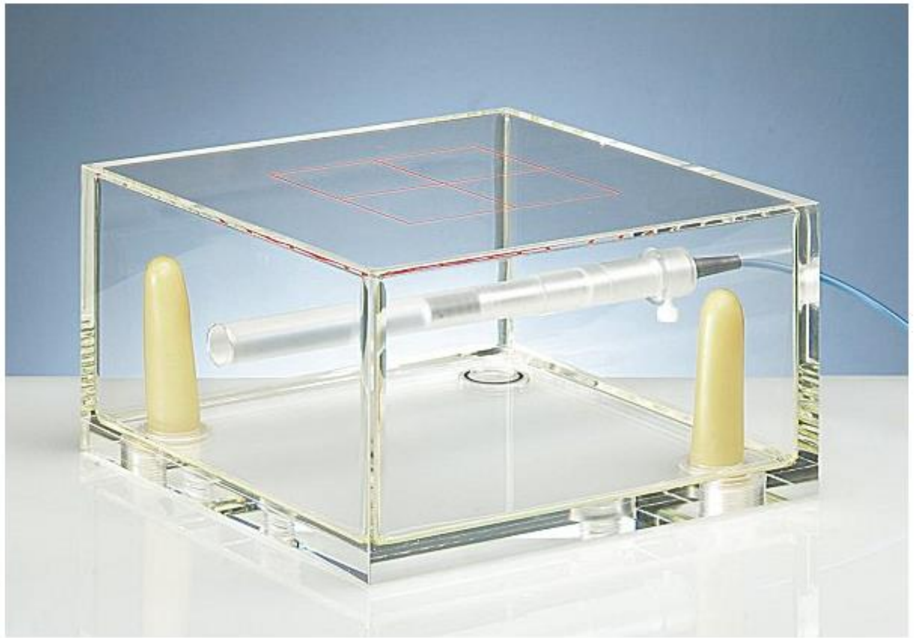
* (Adapted) Hackett et al. (2016). "Consequences of air around an ionization chamber : Are existing solid phantoms suitable for reference dosimetry on an MR-linac?" Med. Phys. 43(7), 3961–3968



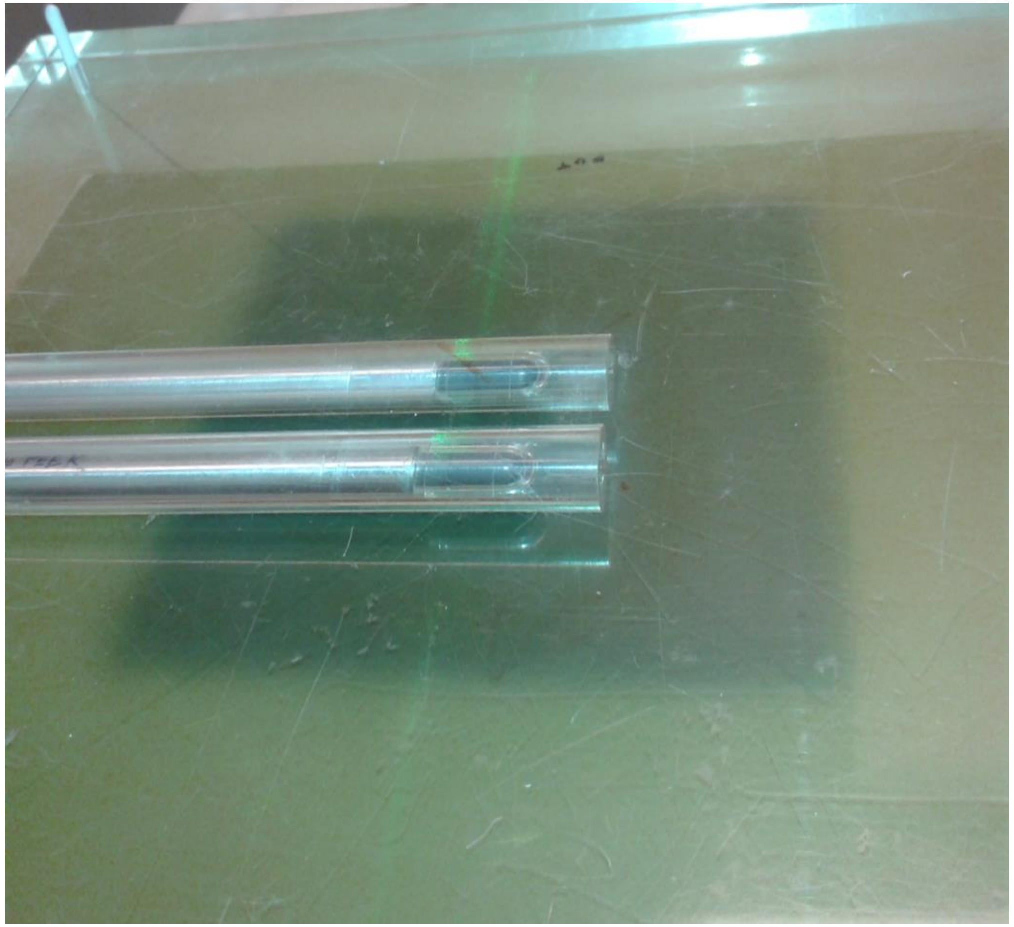
* O'Brien et al. (2017). "Monte Carlo study of the chamber-phantom air gap effect in a magnetic field." Med. Phys. 44(7), 3830–3838

Calibration Phantoms

Complications in Magnetic Fields



* PTW Stationary Water Phantom



* Photo courtesy of Nikolas Marinos, Elekta

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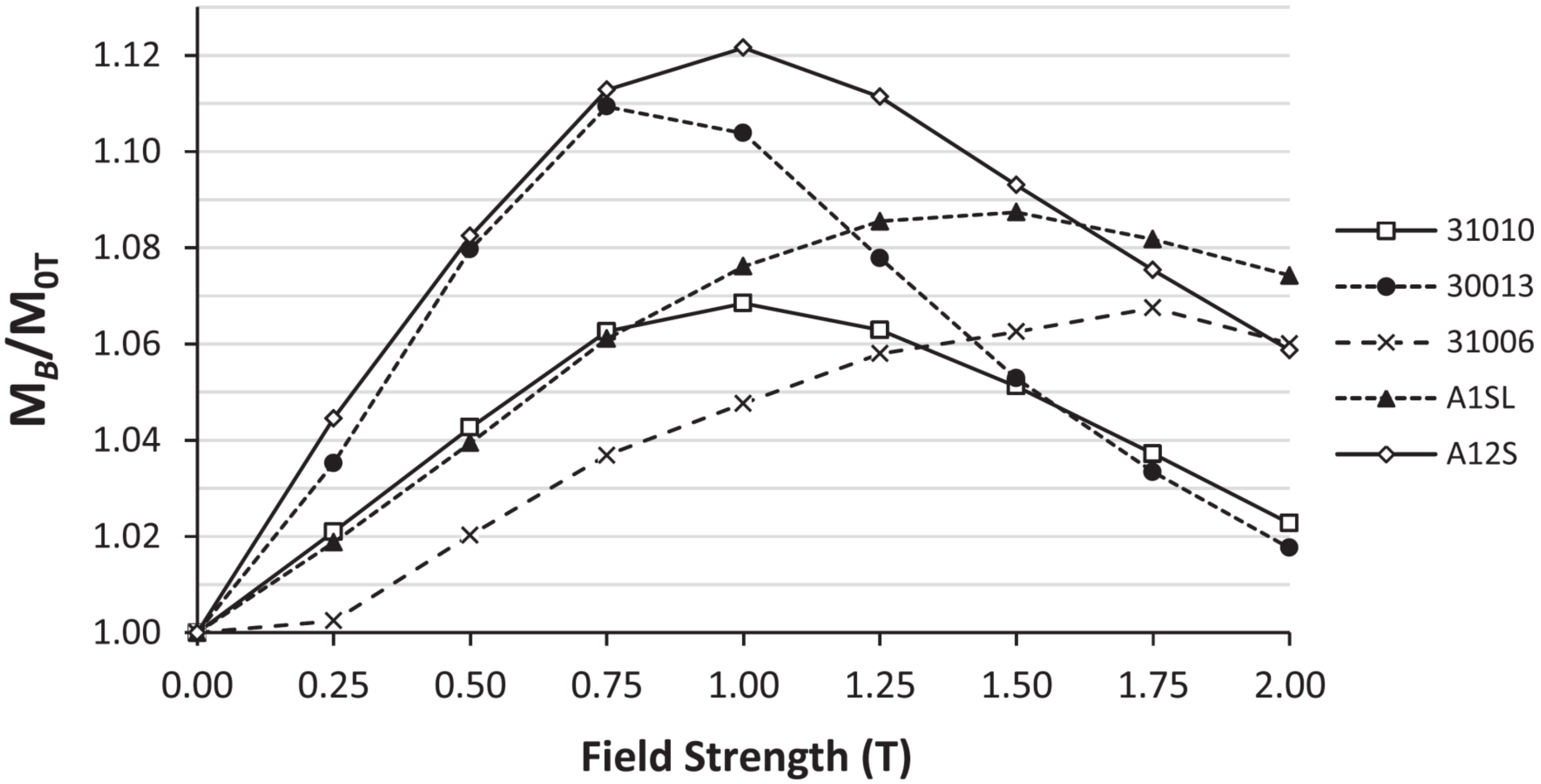
Ion Chamber Response

Complications in Magnetic Fields



* Agnew et al. (2017). "Quantification of static magnetic field effects on radiotherapy ionization chambers" Phys. Med. Biol. 62(5), 1731-1743

Adaptation Strategies

Code of Practices?

Adaptation Strategies

NPL

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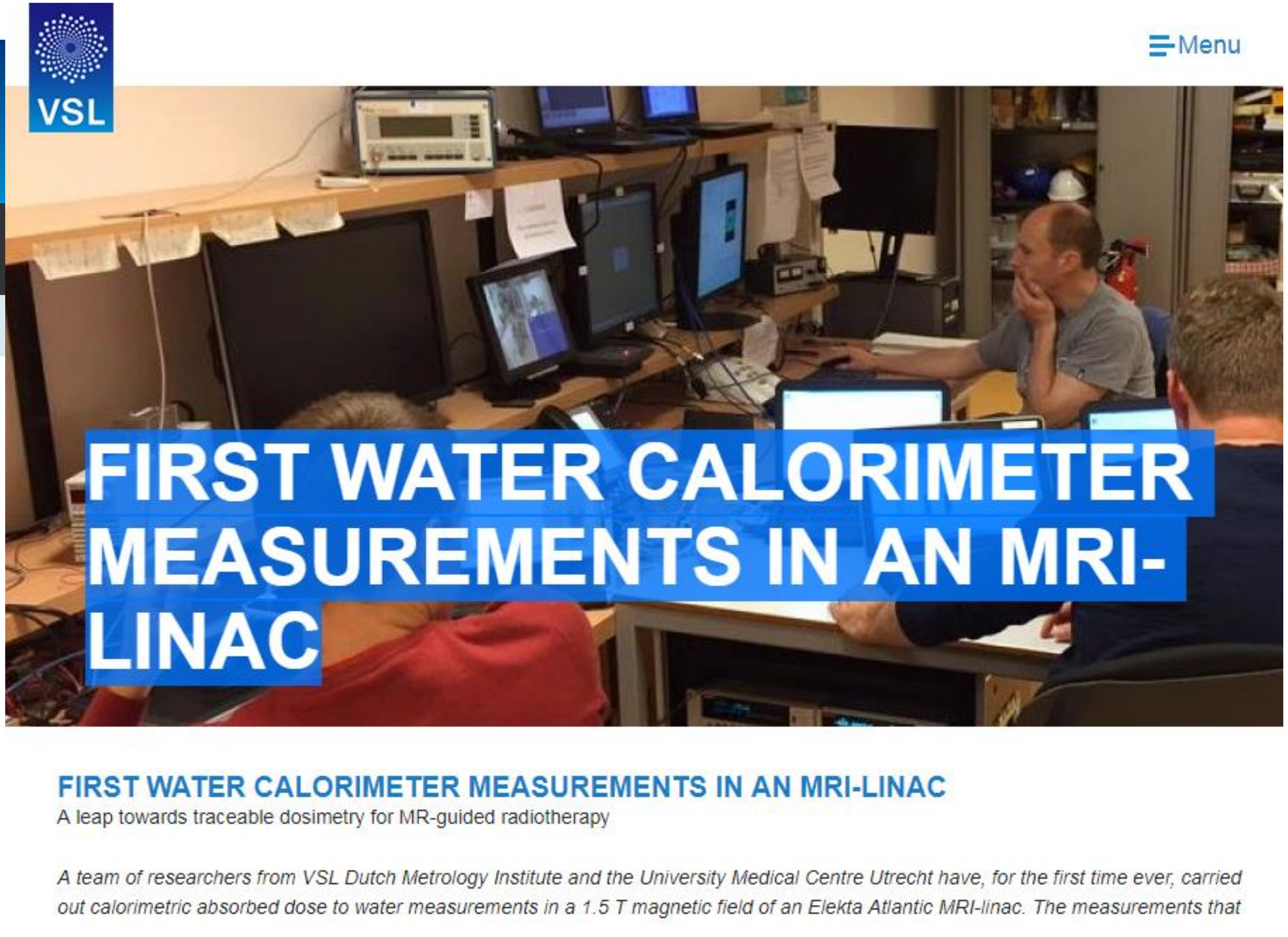
New facility supports development of MRI-guided radiotherapy

A new electromagnet at the National Physical Laboratory's (NPL) Theratron radiation facility will enable research supporting MRI-guided radiotherapy - a state-of-the-art cancer treatment.

Radiotherapy treats cancer by focusing beams of ionising radiation on a tumour, killing cancerous cells by damaging their DNA. Radiation delivery must be tightly controlled to minimise damage to the surrounding healthy tissue. Typically, X-ray based techniques are used to image a patient immediately before treatment to direct the radiation. But tumours move and deform inside a patient's body with bodily functions such as breathing, and can shift and change in size over the course of treatment.

MRI-guided radiotherapy provides real-time images during a patient's treatment, and offers more detailed and higher contrast images for the identification of tumours and soft tissues. This boosts tumour targeting accuracy, reducing side-effects and increasing survival rates. Currently untreatable cancers, such as kidney and pancreatic tumours, which can't be accurately tracked during treatment, may become treatable.



VSL

Menu

FIRST WATER CALORIMETER MEASUREMENTS IN AN MRI-LINAC

FIRST WATER CALORIMETER MEASUREMENTS IN AN MRI-LINAC

A leap towards traceable dosimetry for MR-guided radiotherapy

A team of researchers from VSL Dutch Metrology Institute and the University Medical Centre Utrecht have, for the first time ever, carried out calorimetric absorbed dose to water measurements in a 1.5 T magnetic field of an Elekta Atlantic MRI-linac. The measurements that

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Formalism

Adaptation Strategies

Current dosimetry formalisms do not account for the effect of the magnet field on the ionization chamber response:

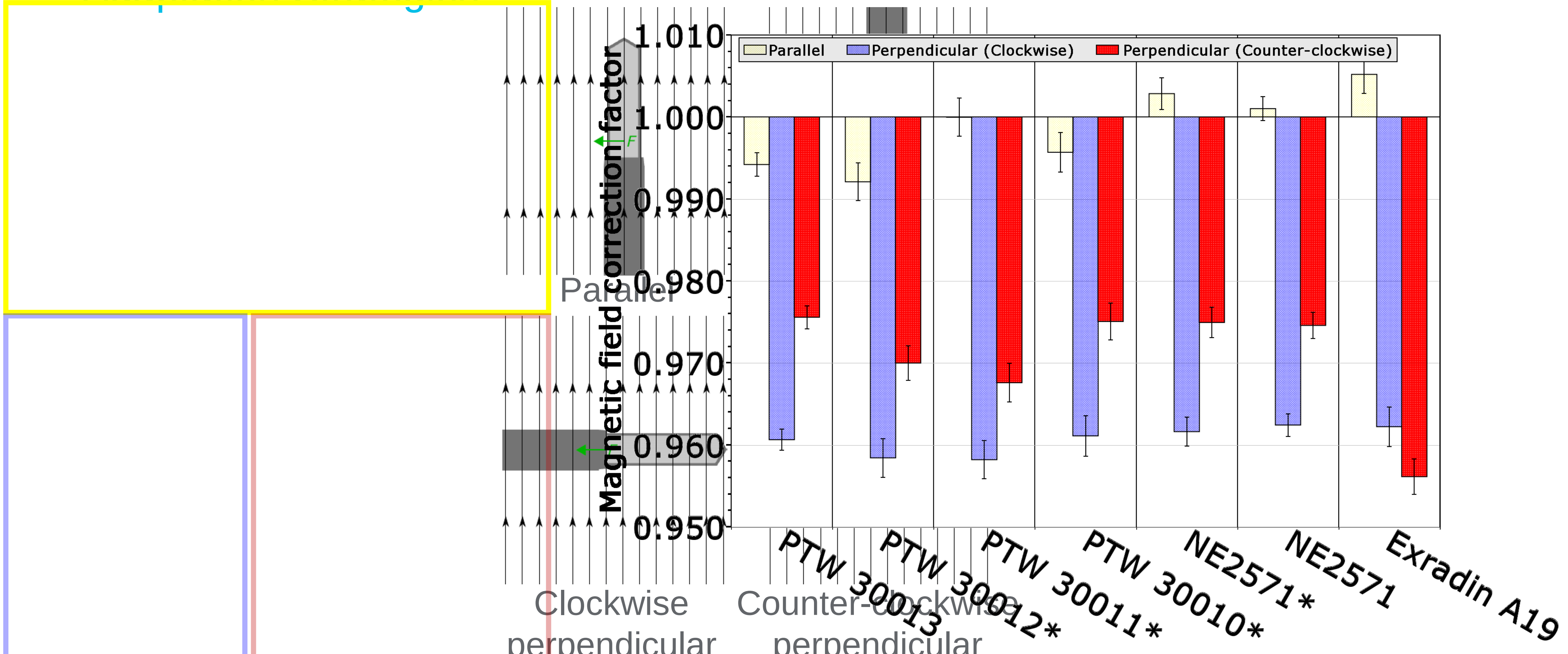
Original Formalism $$D_w^Q = M \cdot N_{D,w}^{^{60}Co} \cdot k_Q$$

Adapted Formalism $$D_w^Q = M \cdot N_{D,w}^{^{60}Co} \cdot k_Q \boxed{\cdot\, k_B^Q}$$

k_B^Q (or k_B) is difficult to measure. Monte Carlo difficult to validate empirically.

Ion Chamber Orientation

Adaptation Strategies



* O'Brien et al. (2016). "Reference dosimetry in magnetic fields: formalism and ionization chamber correction factors." Med. Phys. 43(8), 4915–4927

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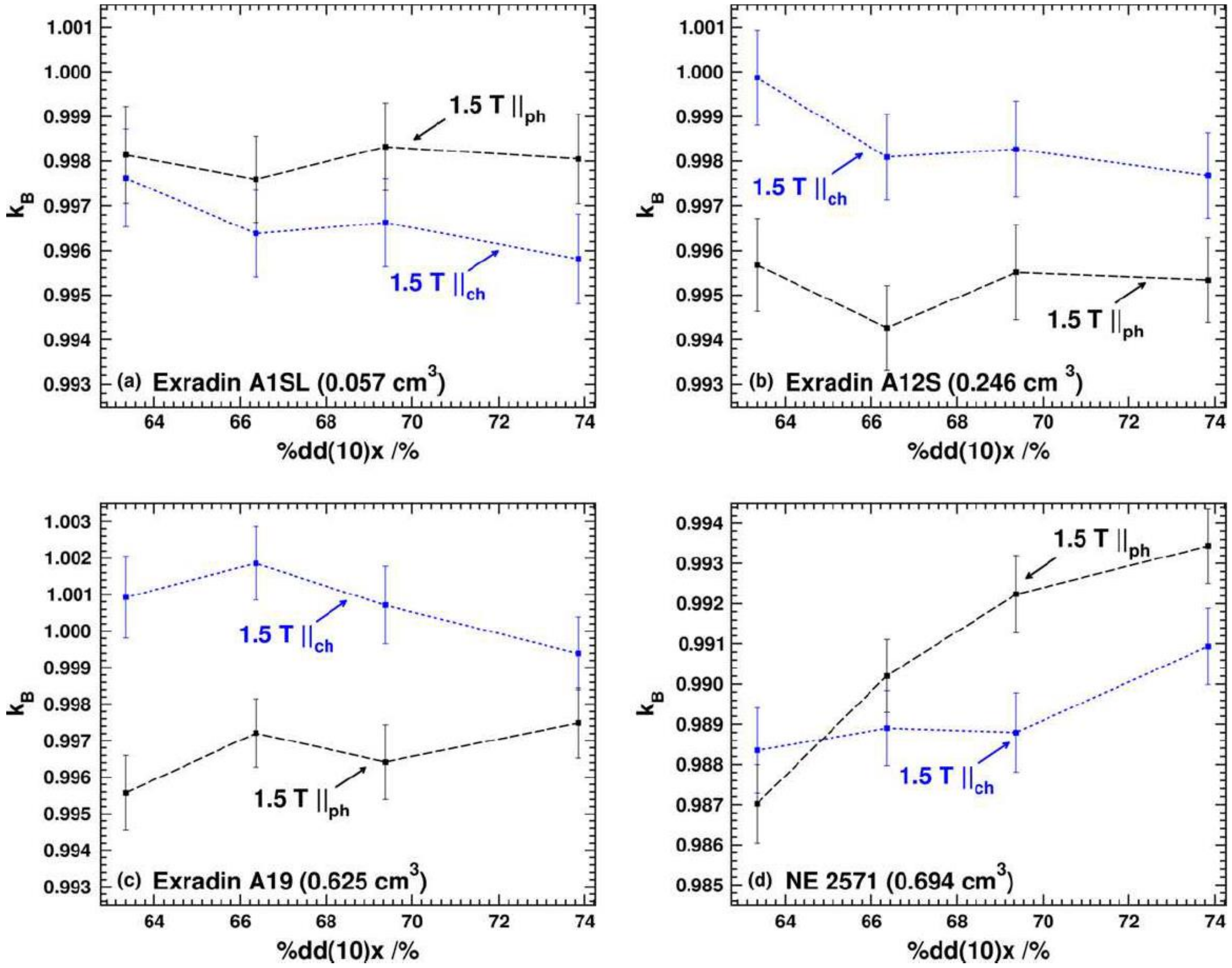
k_B vs Beam Quality

Adaptation Strategies

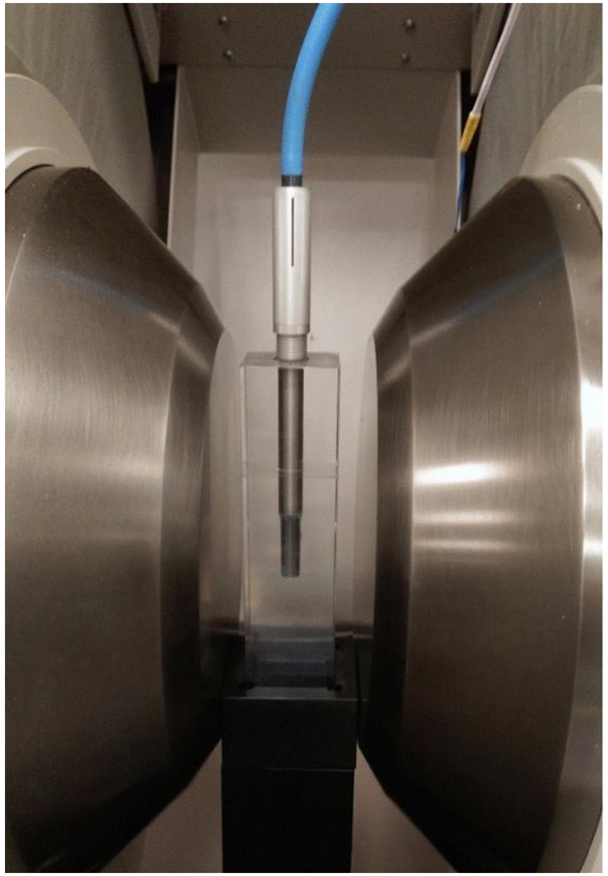


* Malkov et al. (2018). "Monte Carlo study of ionization chamber magnetic field correction factors as a function of angle and beam quality." Med. Phys. 45(2), 908–925

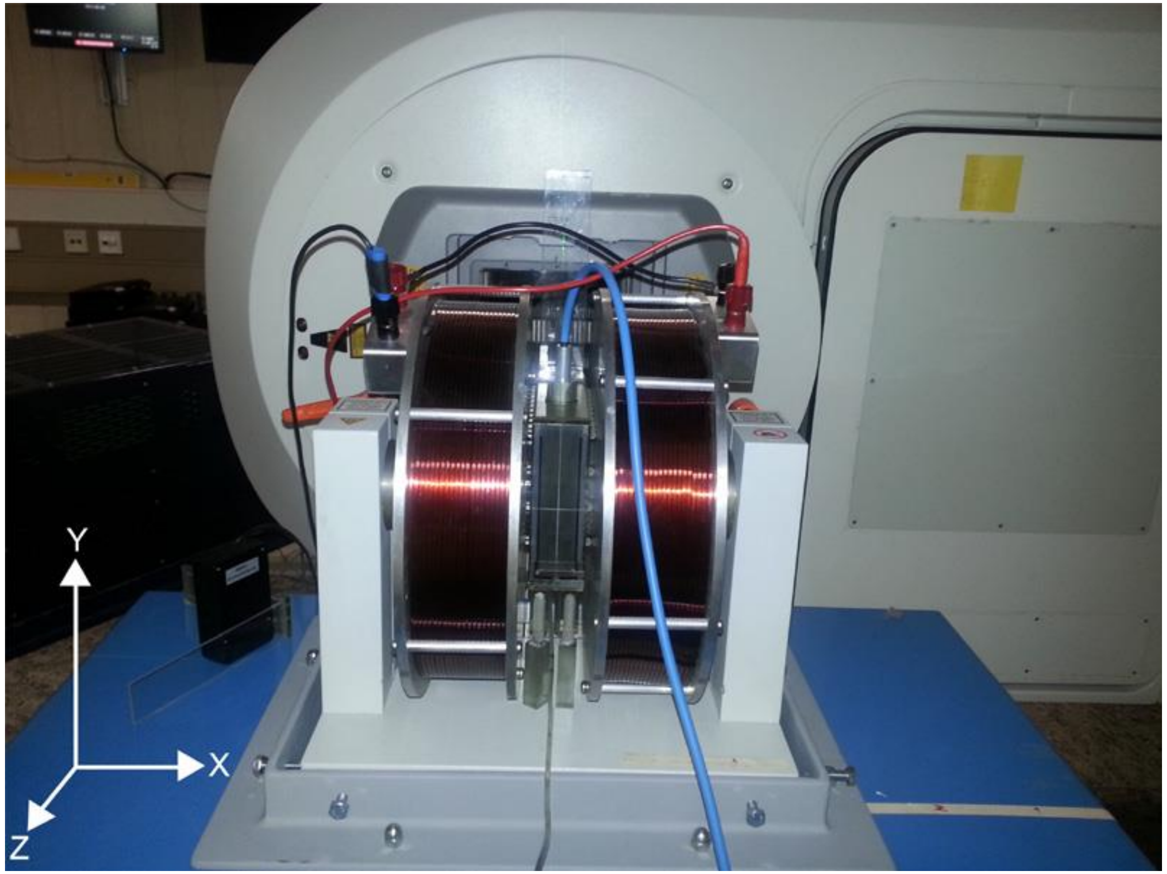
Electromagnet Setups

Adaptation Strategies

- Range of magnetic fields
- Requires small volume water phantom
  – limited phantom scatter / field size
- Chamber is restricted to an orientation perpendicular to the magnetic field and the beam



* Agnew et al. (2017). "Quantification of static magnetic field effects on radiotherapy ionization chambers" Phys. Med. Biol. 62(5), 1731-1743



* Spindeldreier et al. (2017). "Radiation dosimetry in magnetic fields with Farmer-type ionization chambers: determination of magnetic field correction factors for different magnetic field strengths and field orientations." Phys. Med. Biol. 62(16), 6708–6728

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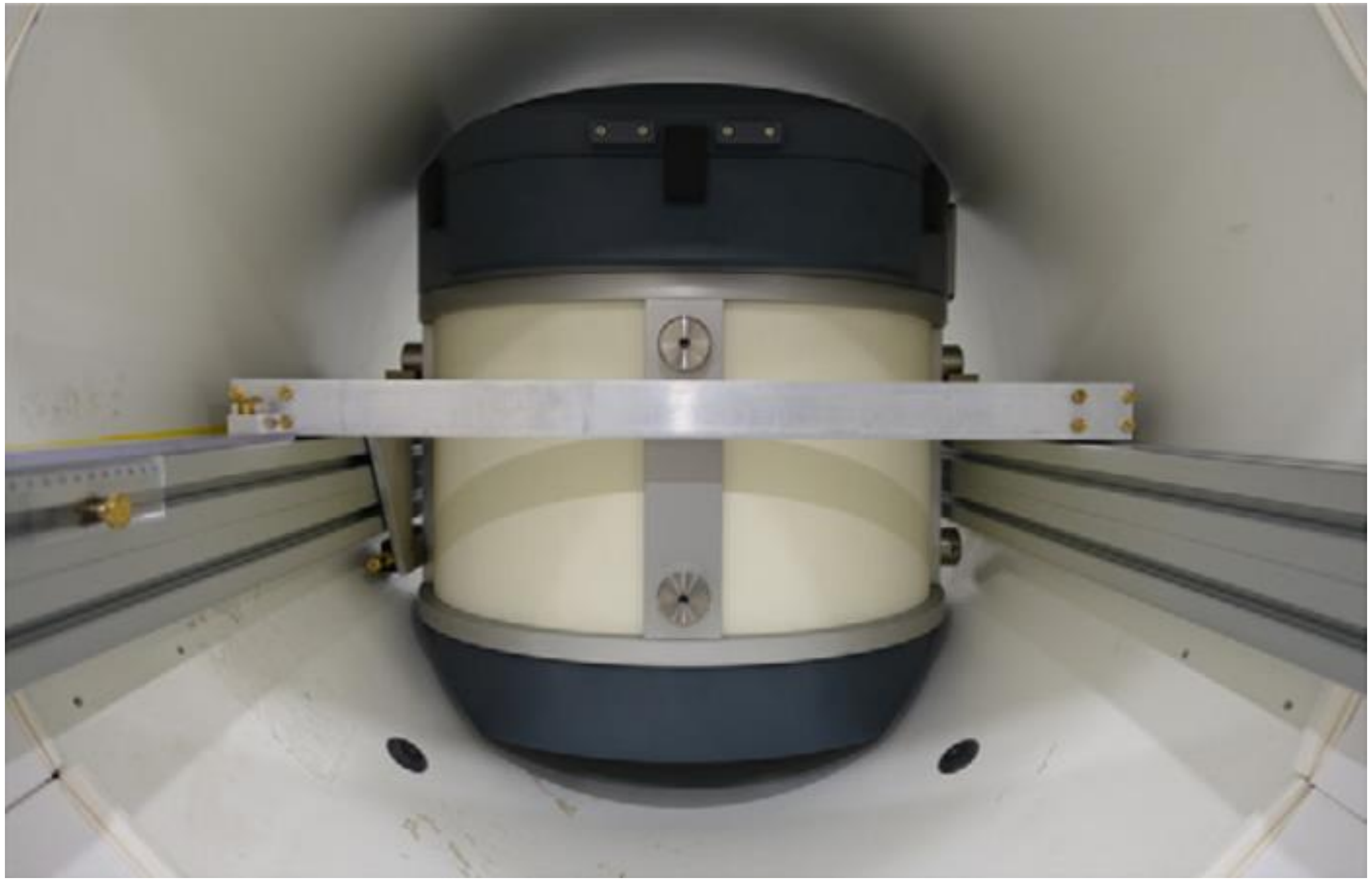
Dose to Water

Adaptation Strategies

- NPL using Alanine

- Calorimetry
  - Water calorimetry (VSL)
  - Graphite calorimetry (see next presentation)



* L de Prez et al. (2016). "A water calorimeter for on-site absorbed dose to water calibrations in 60Co and MV-photon beams including MRI incorporated treatment equipment" Phys. Med. Biol. 61(13), 5051-5076

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Published values of k_B

Adaptation Strategies

	0.1 T	0.2 T	0.3 T	0.4 T	0.5 T	0.6 T	0.7 T	0.8 T	0.9 T	1.0 T	1.1 T	1.5 T	3.0 T
-X	1.003	0.996	0.988	0.978	0.967	0.958	0.952	0.946	0.945	0.943	0.945	0.959	1.019
+X	0.993	0.985	0.974	0.961	0.952	0.941	0.936	0.932	0.931	0.931	0.933	0.954	1.037
-Y	0.998	0.999	0.998	0.996	0.994	0.993	0.992	0.992	0.992	0.992	0.992	0.992	0.992
+Y	0.999	0.999	0.998	0.995	0.994	0.994	0.992	0.993	0.993	0.992	0.992	0.993	0.990
-Z	0.999	1.000	0.998	0.997	0.997	0.997	0.995	0.994	0.994	0.993	0.993	0.990	0.984
+Z	1.000	0.999	0.998	0.999	0.997	0.995	0.995	0.995	0.993	0.994	0.992	0.990	0.983

Spindeldreier et al. (2017). "Radiation dosimetry in magnetic fields with Farmer-type ionization chambers: determination of magnetic field correction factors for different magnetic field strengths and field orientations." Phys. Med. Biol. 62(16), 6708–6728

Detector	$k_{B_{\parallel}}^{Q_{msr}}$	$k_{B_{\curvearrowright}}^{Q_{msr}}$	$k_{B_{\curvearrowleft}}^{Q_{msr}}$	Uncertainty (%)
PTW 30013	0.994	0.961	0.976	0.15
PTW 30012[a]	0.992	0.958	0.970	0.25
PTW 30011[a]	1.000	0.958	0.968	0.25
PTW 30010[a]	0.996	0.961	0.975	0.25
NE2571[a]	1.003	0.962	0.973	0.20
NE2571	1.001	0.962	0.973	0.15
Exradin A19	1.005	0.962	0.956	0.25

[a]Chambers modeled with a 1 mm thick layer of PMMA representing a water-proof sleeve.

O'Brien et al. (2016). "Reference dosimetry in magnetic fields: formalism and ionization chamber correction factors." Med. Phys. 43(8), 4915–4927

Currently published values are Monte Carlo based. Most studied chamber is the waterproof PTW 30013 Farmer chamber.

	k_B (1.5 T)	
chamber [$V(cm^3)$]	$\parallel_{ch}$	$\parallel_{ph}$
A12 (0.65)	0.9983	*0.9940*
A19 (0.62)	1.0007	0.9964
A2 (0.54)	0.9989	0.9952
T2 (0.54)	1.0004	0.9999
A12S (0.25)	0.9984	0.9962
A18 (0.125)	0.9981	0.9971
A1(0.057)	0.9962	0.9983
A1SL (0.057)	0.9966	0.9983
A14* (0.016)	**0.9718**	**0.9827**
T14*(0.016)	**0.9696**	**0.9837**
A14SL* (0.016)	**0.9725**	**0.9823**
A16* (0.016)	**0.9600**	**0.9830**
30010[W] (0.6)	**0.9872**	*0.9932*
30011[W] (0.6)	*0.9920*	1.0009
30012[W] (0.6)	**0.9870**	*0.9938*
30013 (0.6)	**0.9881**	*0.9937*
31006 (0.015)	**0.9867**	0.9953
31010 (0.125)	*0.9933*	*0.9905*
31016 (0.016)	0.9963	0.9992
31014 (0.015)	0.9951	0.9992
FC65-G (0.65)	*0.9917*	*0.9914*
FC65-P (0.65)	*0.9917*	*0.9901*
FC23-C (0.23)	0.9980	0.9972
CC25 (0.25)	0.9987	0.9968
CC13 (0.13)	0.9990	0.9969
CC08 (0.08)	0.9975	0.9973
CC04 (0.04)	0.9971	0.9998
CC01 (0.01)	**0.9805**	**0.9889**
NE2581[W] (0.6)	0.9993	1.0011
NE2571[W] (0.6)	**0.9888**	*0.9922*
NE2561[W] (0.325)	0.9963	**0.9875**
PR06C/G[W] (0.65)	0.9986	0.9973

Malkov & Rogers (2018). "Monte Carlo study of ionization chamber magnetic field correction factors as a function of angle and beam quality." Med. Phys. 45(2), 908–925

Need for standards

Need for standards

- Current protocols do not explicitly account for magnetic fields
- Adapting existing protocols in a clinic means deviating from the protocols
  (Legal implications? Accreditation implications?)
- Limited published data – need for consensus and standardization

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Thank you

daniel.obrien@elekta.com

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