NRC·CNRC

Developments in clinical reference dosimetry: Updates to reference dosimetry protocols

Bryan Muir

August 1, 2017

NRC Measurement Science and Standards, Ottawa, Canada

Background

- Based on ion chamber calibrated in cobalt-60
- Simple ‘recipe’ for beam calibration
- Covers photon and electron beams

AAPM’s TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams

Peter R. Almond
Brown Cancer Center, Louisville, Kentucky 40202

Peter J. Biggs
Department of Radiation Oncology, Massachusetts General Hospital, Boston, Massachusetts 02114

B. M. Coursey
Ionizing Radiation Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899

W. F. Hanson
M.D. Anderson Cancer Center, University of Texas, Houston, Texas 77030

M. Saiful Huq
Kimmel Cancer Center of Jefferson Medical College, Thomas Jefferson University, Philadelphia, Pennsylvania 19107

Ravinder Nath
Yale University School of Medicine, New Haven, Connecticut 06510

D. W. O. Rogers[a)]
Ionizing Radiation Standards, National Research Council of Canada, Ottawa K1A OR6, Canada

(Received 17 September 1998; accepted for publication 4 June 1999)

A protocol is prescribed for clinical reference dosimetry of external beam radiation therapy using photon beams with nominal energies between ^{60}Co and 50 MV and electron beams with nominal energies between 4 and 50 MeV. The protocol was written by Task Group 51 (TG-51) of the Radiation Therapy Committee of the American Association of Physicists in Medicine (AAPM) and has been formally approved by the AAPM for clinical use. The protocol uses ion chambers with absorbed-dose-to-water calibration factors, $N_{D,w}^{^{60}\mathrm{Co}}$, which are traceable to national primary standards, and the equation $D_w^Q = M k_Q N_{D,w}^{^{60}\mathrm{Co}}$, where Q is the beam quality of the clinical beam, D_w^Q is the absorbed dose to water at the point of measurement of the ion chamber placed under reference conditions, M is the fully corrected ion chamber reading, and k_Q is the quality conversion factor which converts the calibration factor for a ^{60}Co beam to that for a beam of quality Q. Values of k_Q are presented as a function of Q for many ion chambers. The value of M is given by $M = P_{\mathrm{ion}} P_{\mathrm{TP}} P_{\mathrm{elec}} P_{\mathrm{pol}} M_{\mathrm{raw}}$, where M_{raw} is the raw, uncorrected ion chamber reading and P_{ion} corrects for ion recombination, P_{TP} for temperature and pressure variations, P_{elec} for inaccuracy of the electrometer if calibrated separately, and P_{pol} for chamber polarity effects. Beam quality, Q, is specified (i) for photon beams, by $\%dd(10)_x$, the photon component of the percentage depth dose at 10 cm depth for a field size of 10×10 cm^2 on the surface of a phantom at an SSD of 100 cm and (ii) for electron beams, by R_{50}, the depth at which the absorbed-dose falls to 50% of the maximum dose in a beam with field size $\geq 10\times10$ cm^2 on the surface of the phantom ($\geq 20\times20$ cm^2 for $R_{50}>8.5$ cm) at an SSD of 100 cm. R_{50} is determined directly from the measured value of I_{50}, the depth at which the ionization falls to 50% of its maximum value. All clinical reference dosimetry is performed in a water phantom. The reference depth for calibration purposes is 10 cm for photon beams and $0.6R_{50}-0.1$ cm for electron beams. For photon beams clinical reference dosimetry is performed in either an SSD or SAD setup with a 10×10 cm^2 field size defined on the phantom surface for an SSD setup or at the depth of the detector for an SAD setup. For electron beams clinical reference dosimetry is performed with a field size of $\geq 10\times10$ cm^2 ($\geq 20\times20$ cm^2 for $R_{50}>8.5$ cm) at an SSD between 90 and 110 cm. This protocol represents a major simplification compared to the AAPM’s TG-21 protocol in the sense that large tables of stopping-power ratios and mass-energy absorption coefficients are not needed and the user does not need to calculate any theoretical dosimetry factors. Worksheets for various situations are presented along with a list of equipment required.
[S0094-2405(99)00209-6]

Review – reference dosimetry with TG-51

- Starting point is $N_{D,w}^{60_{Co}}$ for your chamber (ADCL)

- D_w required in clinical beam (quality Q ≠ cobalt-60)

$$D_w^Q = MN_{D,w}^Q = Mk_Q N_{D,w}^{60\mathrm{Co}}$$

- Requires M with $N_{D,w}^{60_{Co}}$ and beam quality conversion factor, k_Q

Why update?

- Advances since 1999 publication
- Semi-analytic approach:

$$k_Q = \frac{\left[\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^{\text{water}} P_{\text{cel}} P_{\text{repl}} P_{\text{wall}}\right]_Q}{\left[\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^{\text{water}} P_{\text{cel}} P_{\text{repl}} P_{\text{wall}}\right]_{^{60}Co}}$$

- New chambers available
- Deliberately avoided uncertainties
- Extensive revision for electron beams

AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams

Peter R. Almond
Brown Cancer Center, Louisville, Kentucky 40202

Peter J. Biggs
Department of Radiation Oncology, Massachusetts General Hospital, Boston, Massachusetts 02114

B. M. Coursey
Ionizing Radiation Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899

W. F. Hanson
M.D. Anderson Cancer Center, University of Texas, Houston, Texas 77030

M. Saiful Huq
Kimmel Cancer Center of Jefferson Medical College, Thomas Jefferson University, Philadelphia, Pennsylvania 19107

Ravinder Nath
Yale University School of Medicine, New Haven, Connecticut 06510

D. W. O. Rogers[a)]
Ionizing Radiation Standards, National Research Council of Canada, Ottawa K1A OR6, Canada

(Received 17 September 1998; accepted for publication 4 June 1999)

A protocol is prescribed for clinical reference dosimetry of external beam radiation therapy using photon beams with nominal energies between ^{60}Co and 50 MV and electron beams with nominal energies between 4 and 50 MeV. The protocol was written by Task Group 51 (TG-51) of the Radiation Therapy Committee of the American Association of Physicists in Medicine (AAPM) and has been formally approved by the AAPM for clinical use. The protocol uses ion chambers with absorbed-dose-to-water calibration factors, $N_{D,w}^{^{60}\text{Co}}$, which are traceable to national primary standards, and the equation $D_w^Q = M k_Q N_{D,w}^{^{60}\text{Co}}$, where Q is the beam quality of the clinical beam, D_w^Q is the absorbed dose to water at the point of measurement of the ion chamber placed under reference conditions, M is the fully corrected ion chamber reading, and k_Q is the quality conversion factor which converts the calibration factor for a ^{60}Co beam to that for a beam of quality Q. Values of k_Q are presented as a function of Q for many ion chambers. The value of M is given by $M = P_{\text{ion}} P_{\text{TP}} P_{\text{elec}} P_{\text{pol}} M_{\text{raw}}$, where M_{raw} is the raw, uncorrected ion chamber reading and P_{ion} corrects for ion recombination, P_{TP} for temperature and pressure variations, P_{elec} for inaccuracy of the electrometer if calibrated separately, and P_{pol} for chamber polarity effects. Beam quality, Q, is specified (i) for photon beams, by $\%dd(10)_x$, the photon component of the percentage depth dose at 10 cm depth for a field size of 10×10 cm^2 on the surface of a phantom at an SSD of 100 cm and (ii) for electron beams, by R_{50}, the depth at which the absorbed-dose falls to 50% of the maximum dose in a beam with field size $\geqslant 10\times10$ cm^2 on the surface of the phantom ($\geqslant 20\times20$ cm^2 for $R_{50} > 8.5$ cm) at an SSD of 100 cm. R_{50} is determined directly from the measured value of I_{50}, the depth at which the ionization falls to 50% of its maximum value. All clinical reference dosimetry is performed in a water phantom. The reference depth for calibration purposes is 10 cm for photon beams and $0.6R_{50} - 0.1$ cm for electron beams. For photon beams clinical reference dosimetry is performed in either an SSD or SAD setup with a 10×10 cm^2 field size defined on the phantom surface for an SSD setup or at the depth of the detector for an SAD setup. For electron beams clinical reference dosimetry is performed with a field size of $\geqslant 10\times10$ cm^2 ($\geqslant 20\times20$ cm^2 for $R_{50} > 8.5$ cm) at an SSD between 90 and 110 cm. This protocol represents a major simplification compared to the AAPM's TG-21 protocol in the sense that large tables of stopping-power ratios and mass-energy absorption coefficients are not needed and the user does not need to calculate any theoretical dosimetry factors. Worksheets for various situations are presented along with a list of equipment required.
[S0094-2405(99)00209-6]

What stays?

- Procedure and formalism remains the same
- Still based on ion chamber calibrated in cobalt-60
- Calculated (but updated with accurate Monte Carlo) k_Q factors
- Solid phantoms still prohibited
- $\%dd(10)_x$ and R_{50} for beam quality specification
- Addendum published (2014) for photon beams, wider revision for electron beams

Photon beam addendum to the TG-51 protocol

- k_Q data sets
- Specifications for reference chambers
- Bias voltage and ion recombination, P_{ion}
- Polarity correction, P_{pol}
- Application to FFF linacs
- Uncertainties

Addendum to the AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon beams

Malcolm McEwen[a]
National Research Council, 1200 Montreal Road, Ottawa, Ontario, Canada

Larry DeWerd
University of Wisconsin, 1111 Highland Avenue, Madison, Wisconsin 53705

Geoffrey Ibbott
Department of Radiation Physics, M D Anderson Cancer Center, 1515 Holcombe Boulevard, Houston, Texas 77030

David Followill
IROC Houston QA Center, Radiological Physics Center, 8060 El Rio Street, Houston, Texas 77054

David W. O. Rogers
Carleton Laboratory for Radiotherapy Physics, Physics Department, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario, Canada

Stephen Seltzer
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

Jan Seuntjens
Medical Physics Unit, McGill University, 1650 Cedar Avenue, Montreal, Québec, Canada

(Received 3 June 2013; revised 3 February 2014; accepted for publication 6 February 2014; published 12 March 2014)

An addendum to the AAPM's TG-51 protocol for the determination of absorbed dose to water in megavoltage photon beams is presented. This addendum continues the procedure laid out in TG-51 but new k_Q data for photon beams, based on Monte Carlo simulations, are presented and recommendations are given to improve the accuracy and consistency of the protocol's implementation. The components of the uncertainty budget in determining absorbed dose to water at the reference point are introduced and the magnitude of each component discussed. Finally, the consistency of experimental determination of $N_{D,w}$ coefficients is discussed. It is expected that the implementation of this addendum will be straightforward, assuming that the user is already familiar with TG-51. The changes introduced by this report are generally minor, although new recommendations could result in procedural changes for individual users. It is expected that the effort on the medical physicist's part to implement this addendum will not be significant and could be done as part of the annual linac calibration. [http://dx.doi.org/10.1118/1.4866223]

Key words: photon beams, dosimetry protocol, ionization chamber, beam quality conversion factors, kQ, uncertainty analysis, absorbed dose calibration coefficients

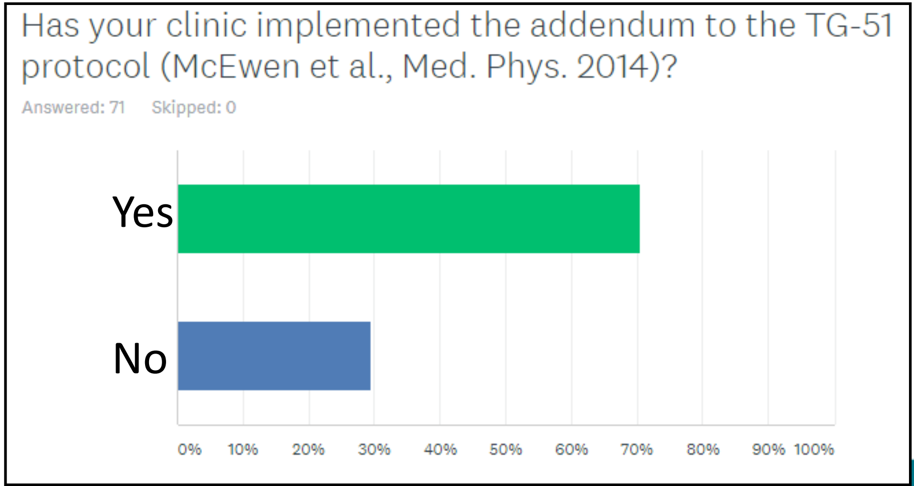
TABLE OF CONTENTS

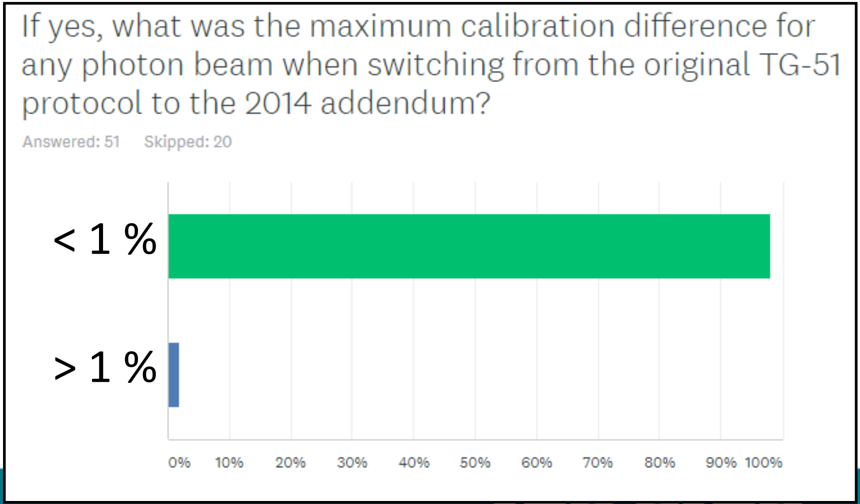
041501-1 Med. Phys. 41 (4), April 2014 0094-2405/2014/41(4)/041501/20/$30.00

What has been the impact?

- Addendum published three years ago

- WGTG51 conducted online survey





What has been the impact?

- Addendum published three years ago
- WGTG51 conducted online survey
- Impact has been minor (expected)
- Manufacturers developing new designs to address reference-class issues (small volume chambers)

NRC·CNRC

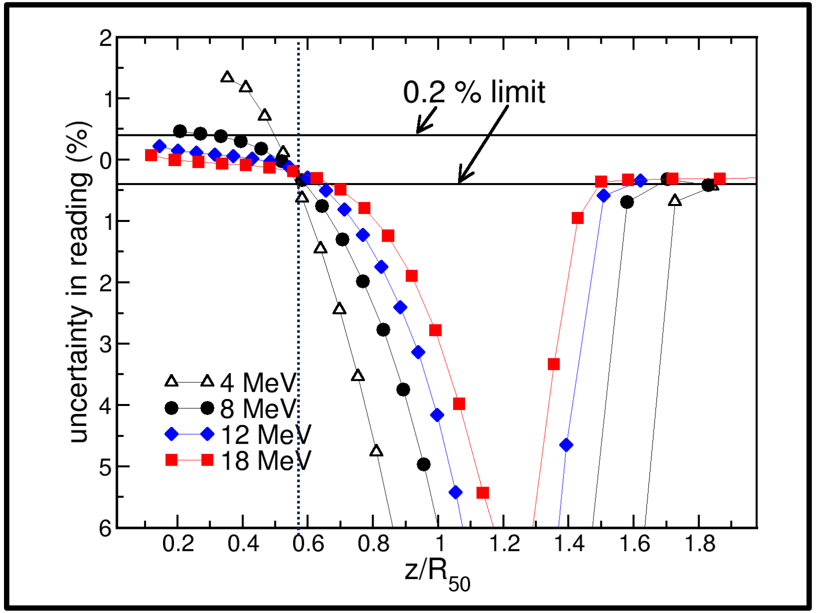
Now for electron beams – more complicated, wider revision

The problems with electron beams

- Steep dose gradients and chamber positioning

Issue independent of chamber type

Not much we can do – take care when positioning!



Assumes accurate positioning to 0.5 mm

Muir et al., PMB 5953 (2014).

The problems with electron beams

- Steep dose gradients and chamber positioning
- Plane-parallel vs cylindrical
  - Plane-parallel variability and stability
  - Cross-calibration against cylindrical
  - Cylindrical not allowed in low-energy beams
  - Measured P_{gr} required for cylindrical

Complicated procedures in TG-51

Can we simplify?

$$k_Q = P_{gr}^{Q} \, k'_{R_{50}} \, k_{ecal}$$

NRC·CNRC

The problems with electron beams

- Steep dose gradients and chamber positioning

- Plane-parallel vs cylindrical
  - Plane-parallel variability and stability
  - Cross-calibration against cylindrical
  - Cylindrical not allowed in low-energy beams
  - Measured P_{gr} required for cylindrical

- Higher uncertainty in TG-51 k_Q

$$k_Q = \frac{\left[\left(\frac{\bar{L}}{\rho}\right)_{\mathrm{air}}^{\mathrm{water}} P_{\mathrm{cel}} P_{\mathrm{repl}} P_{\mathrm{wall}}\right]_Q}{\left[\left(\frac{\bar{L}}{\rho}\right)_{\mathrm{air}}^{\mathrm{water}} P_{\mathrm{cel}} P_{\mathrm{repl}} P_{\mathrm{wall}}\right]_{^{60}Co}}$$

Need more accurate data

Plane-parallel vs cylindrical chambers

Plane-parallel: PTW Roos

Cylindrical: NE2571

- Recommended for low-energy e- beams
- Cross-calibration procedure
- k_Q required several assumptions ($P_{repl}=P_{wall}=1$)
- Measurement performance: may not be stable[1,2]

- Not recommended for low-energy e- beams
    - but based on assumptions for plane-parallel[3] – variation in k_Q with large (~5 %) corrections
- ***Very well behaved*** - stability in photon beams at 0.1 %

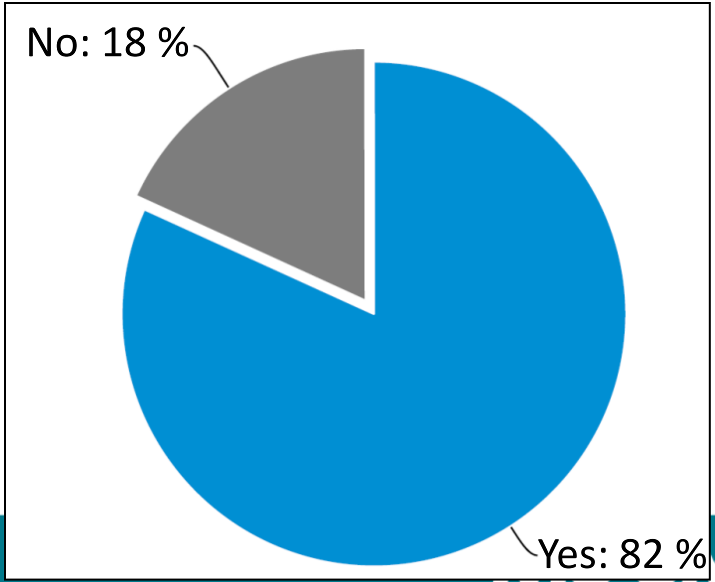
[1]Bass et al., PMB N115 (2009). [2]Muir et al., Med. Phys. 1618 (2012). [3]Wittkamper et al., PMB 1639 (1991).

NRC·CNRC

Can we simplify by using cylindrical chambers for all e^- beams?

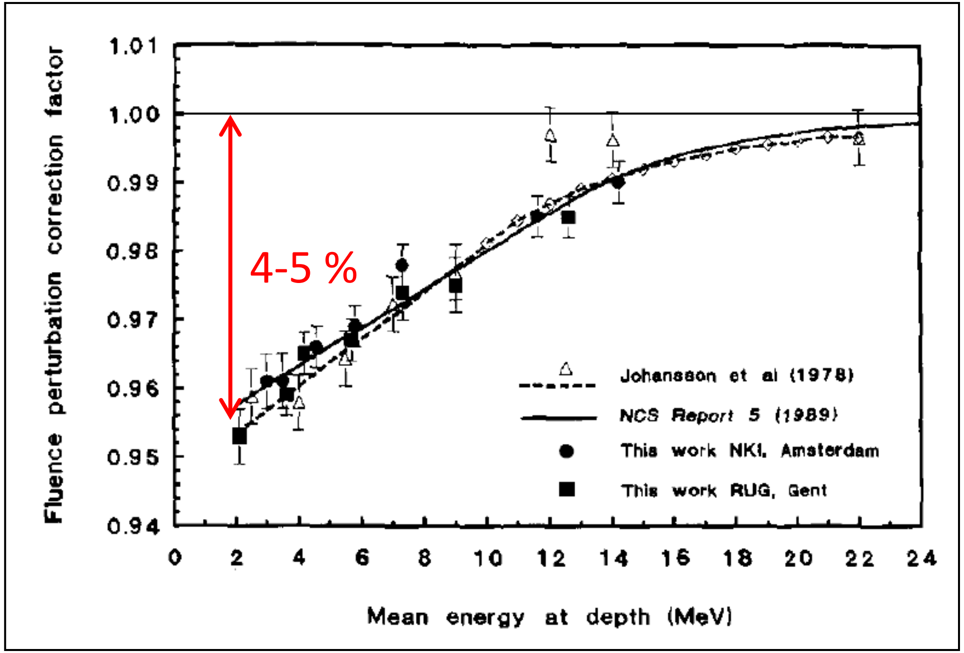
- Would eliminate problems using plane-parallel, cross-calibration
- In fact, recent survey indicates clinical physicists already doing this

"Do you use the same chamber for photon beam calibration as for e^- beams?"



Muir et al., JACMP 182 (2017).

Revisit older experiments with focus on variability



So, are corrections really more variable for cylindrical chambers?

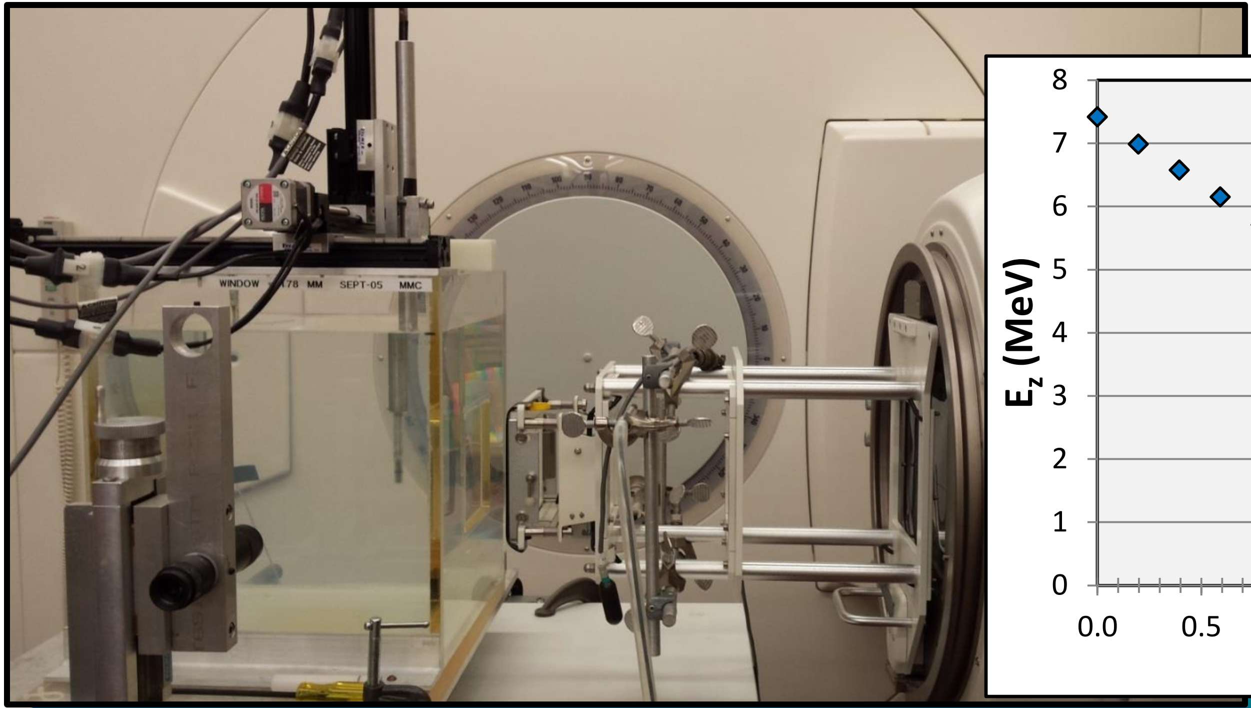
Revisit older experiments with focus on variability

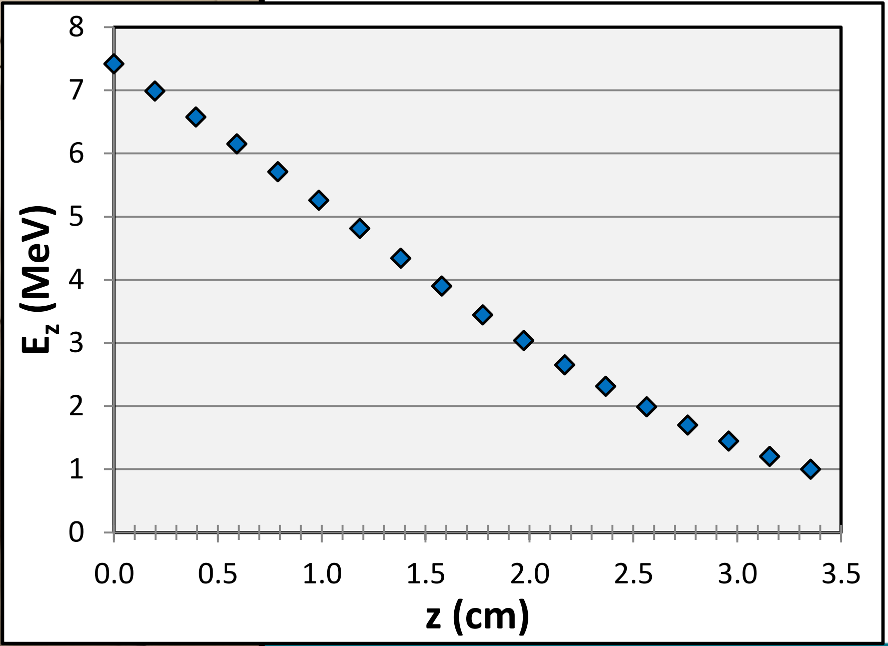
$$\left[\frac{M_2}{M_1}\right]_{Q_{ecal}}^{Q} = \left[\frac{P_{Q,1}}{P_{Q,2}}\right]_{Q_{ecal}}^{Q}$$

- Measure **corrected M** for several chambers in electron beams
- Normalize in 18 MeV beam (Q_{ecal})
- Variation/uncertainty in **overall perturbation correction P_Q (k_Q)** for similar chambers

Revisit older experiments with focus on variability

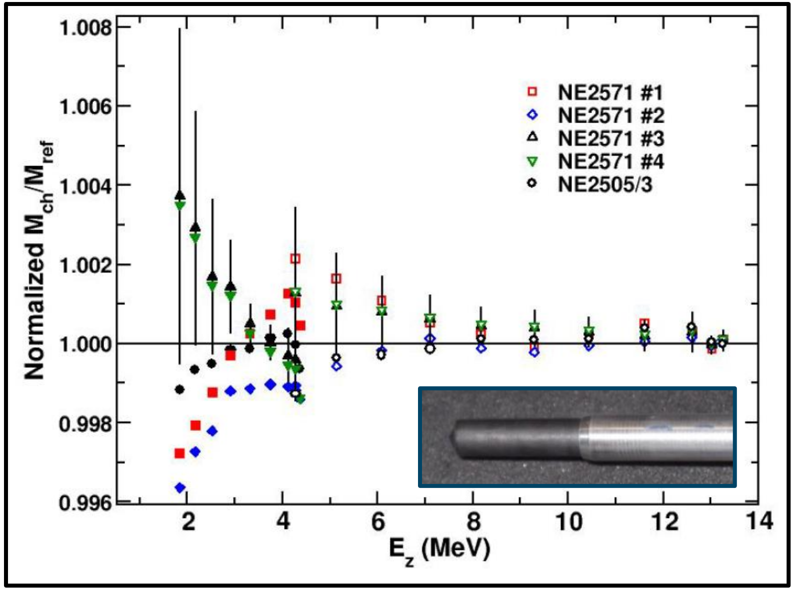
- M measured vs. depth in 8 and 18 MeV

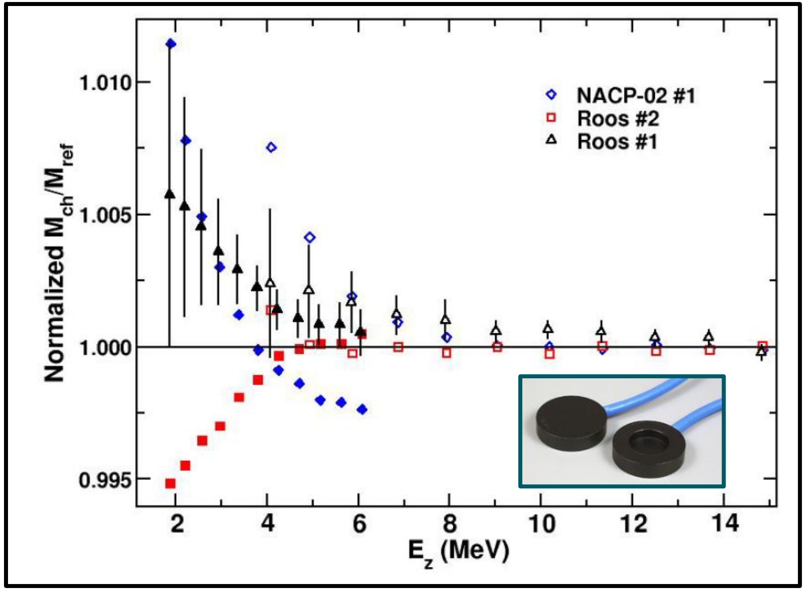




No, corrections aren't more variable using cylindrical chambers!

- Variability at +/- 0.4 %, no worse than plane-parallel chambers[1]





- Appropriate to use cylindrical chambers in all beams using generic k_Q

[1]Muir and McEwen, Med. Phys. (conditionally accepted, 2017).

NRC·CNRC

What about k_Q and P_{gr}? Use Monte Carlo

- Equation defining k_Q: $D_w^Q = M N_{D,w}^Q = M k_Q N_{D,w}^{^{60}\mathrm{Co}}$
- Absorbed dose to the air in an ion chamber: $\boldsymbol{D_{\mathrm{air}} = \frac{M}{m_{\mathrm{air}}}\left(\frac{W}{e}\right)_{\mathrm{air}}}$
- Combine and assume $(W/e)_{air}$ constant with beam energy

$$k_Q = \frac{\left[\frac{D_w}{D_{air}}\right]_Q}{\left[\frac{D_w}{D_{air}}\right]_{^{60}Co}}$$

→ All quantities can be calculated with Monte Carlo simulations

- Aside: this is the principle behind photon beam k_Q factors in addendum

Absorbed dose simulations for k_Q factors

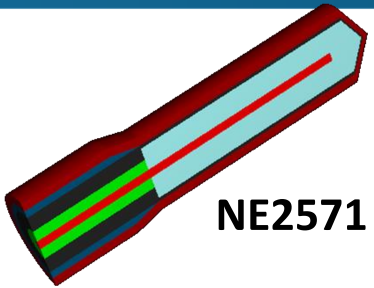
- Sources: realistic accelerator models or electron beam spectra
- Simulations with EGSnrc egs_chamber[1] user-code
- $\boxed{D_w}$ in small disc vs depth in water

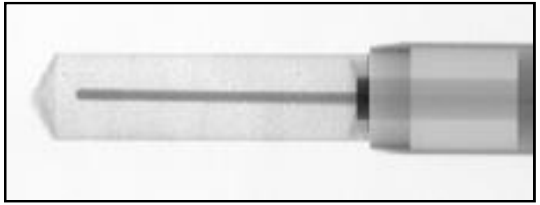
$$k_Q = \frac{\left[\frac{\boxed{D_w}}{D_{air}}\right]_Q}{\left[\frac{\boxed{D_w}}{D_{air}}\right]_{^{60}Co}}$$

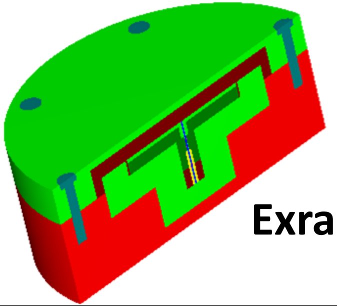
[1] J. Wulff et al., Med. Phys. 1328 (2008).

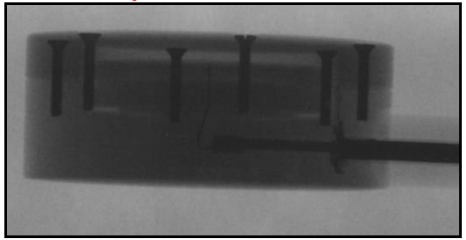
NRC·CNRC

Ion chamber simulations for k_Q factors







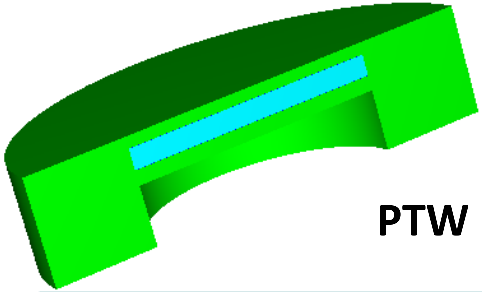


$$k_Q = \frac{\left[\frac{D_w}{\boxed{D_{air}}}\right]_Q}{\left[\frac{D_w}{\boxed{D_{air}}}\right]_{^{60}Co}}$$

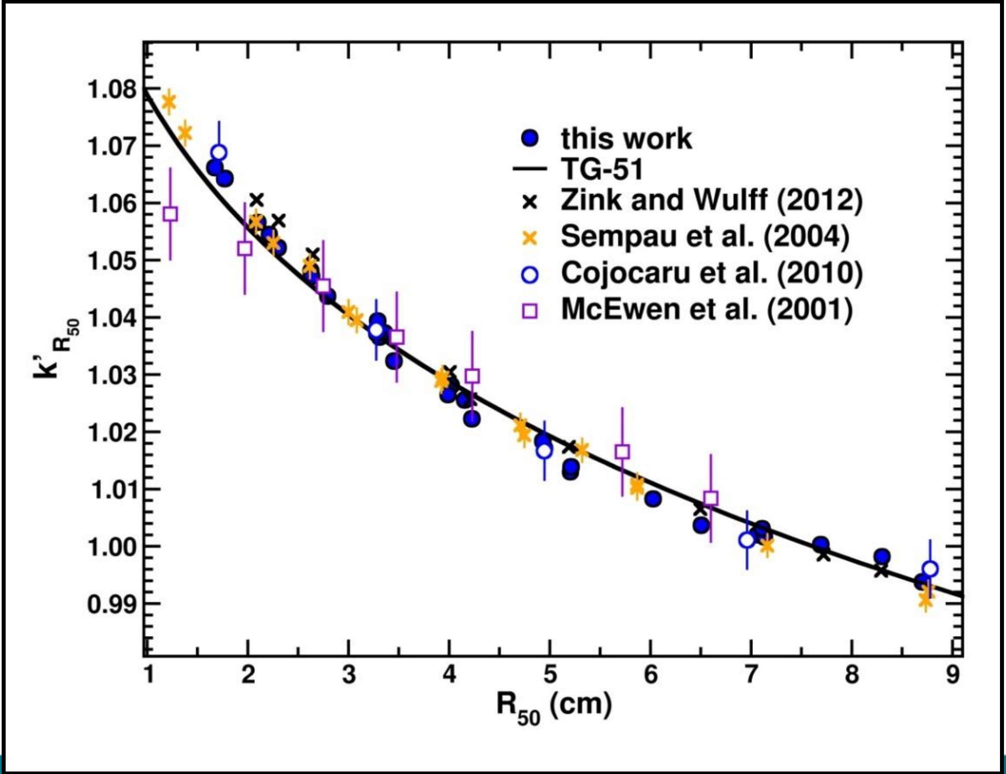
$\boxed{D_{air}}$ in fully modeled chambers vs depth in water

Comparison to high-quality literature results

- Publications report k'_{R50}: normalized k_{R50}
- Excellent agreement with published data



PTW Roos



Muir and Rogers, Med. Phys. 121722 (2013).

NRC·CNRC

Comparison to high-quality literature results

- Recent calorimetry measurements in high-energy beams for k_{ecal}
- Very good agreement for commonly used chambers

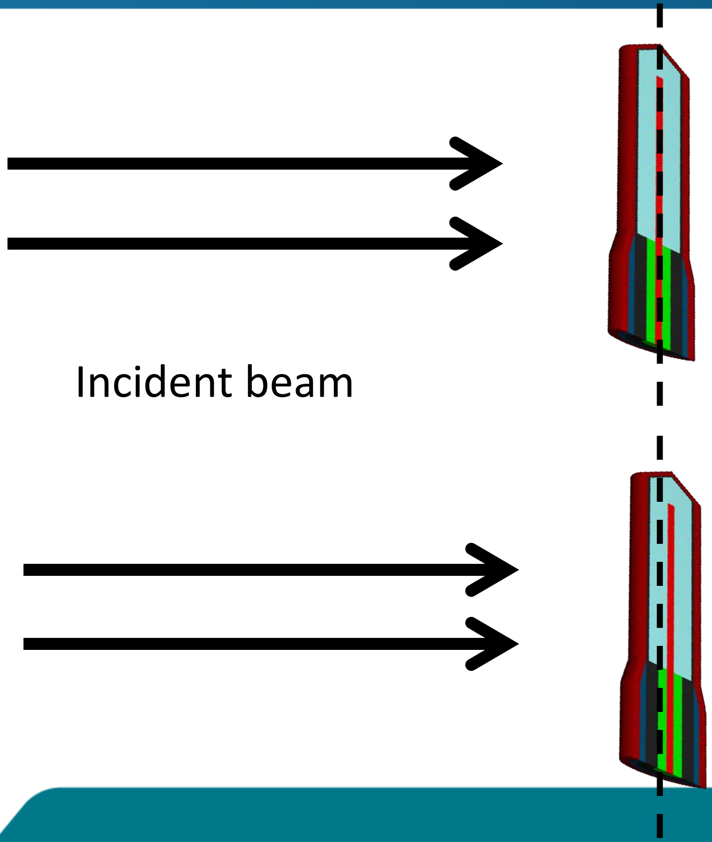
Difference between MC and calorimetry (%)

Plane-parallel	
PTW Roos	-0.28
PTW Markus	-0.46
PTW Advanced Markus	-0.68
Exradin A10	0.01
Exradin A11	1.38
Scanditronix NACP-02	-0.27
IBA PPC-05	0.07
IBA PPC-40	-1.20
Cylindrical	
NE2571	0.26
IBA FC65-G	0.17
PTW30013	-0.09
Exradin A19	0.44
Exradin A18	-0.05
Exradin A1SL	0.10

Muir et al., Med. Phys. (in press, 2017).

NRC·CNRC

What about the gradient correction?



Where is the electron fluence really sampled?

At the center of the chamber?

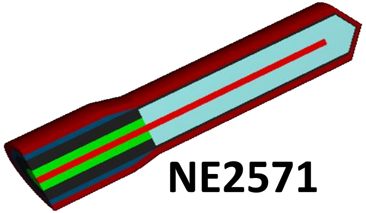
Closer to the curved front surface?

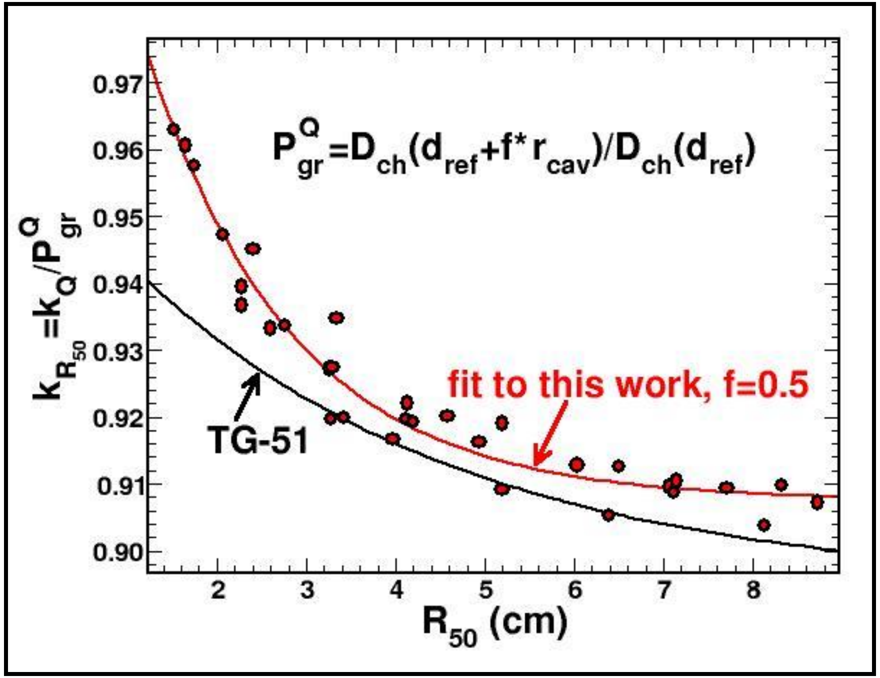
How can we account for this?

- Shift or correction

$$k_Q = P_{gr}^Q k_{R_{50}} \longrightarrow P_{gr} = M(d_{ref} + 0.5r_{cav})/M(d_{ref})$$

What about the gradient correction?

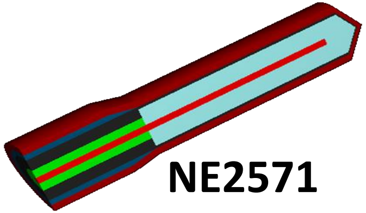


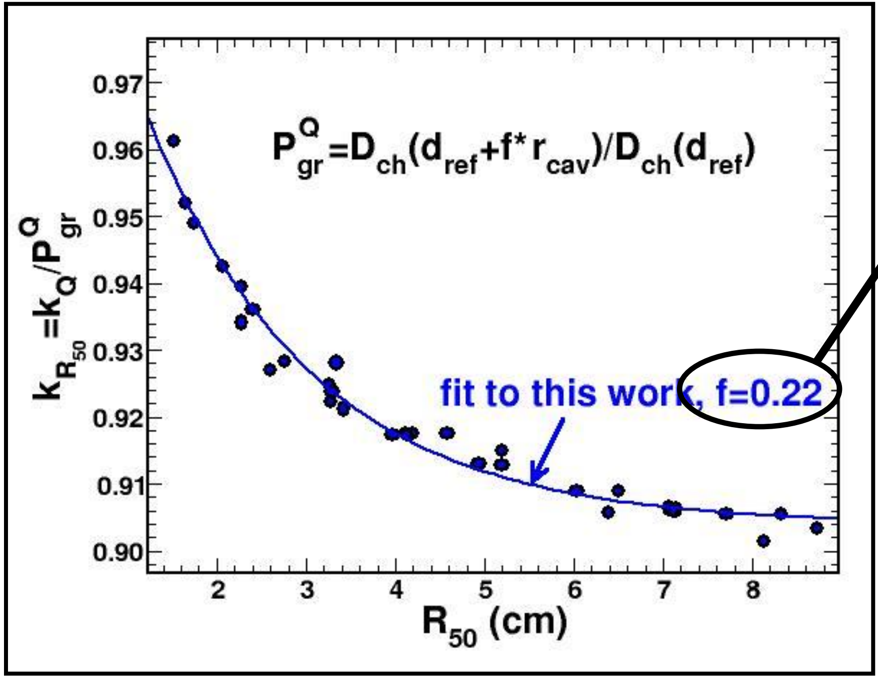


Using TG-51 recommendation – scattered results

Muir and Rogers, Med. Phys. 121722 (2013).

What about the gradient correction?





This is getting pretty small (0.6 mm)

What if we take lim f → 0?

That is, let MC k_Q take care of P_{gr}

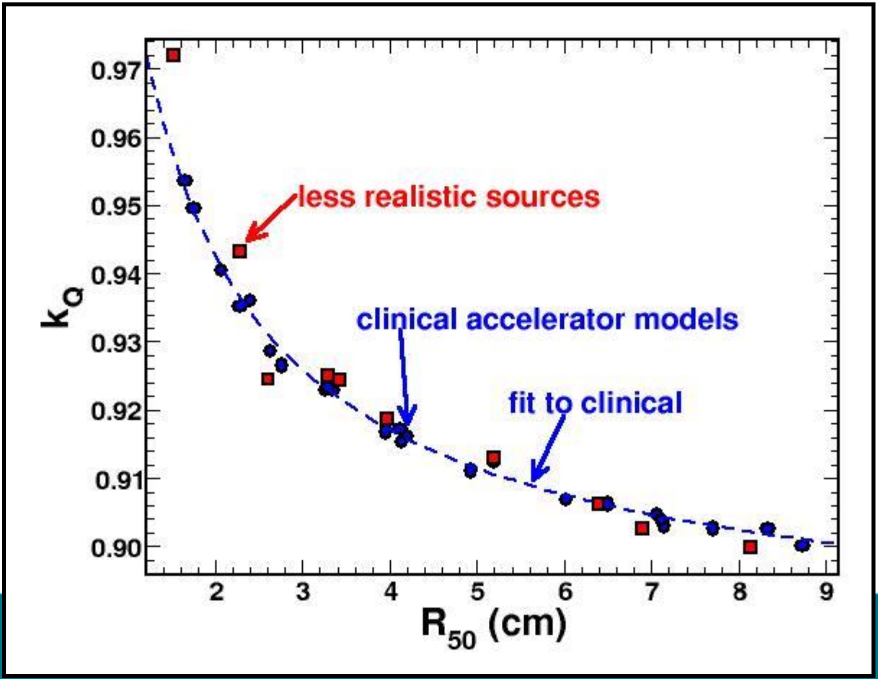
Can use different shift for P_{gr} to reduce scatter

Muir and Rogers, Med. Phys. 121722 (2013).

Can we avoid use of P_{gr}?

- Most common source of electron beam calibration errors

- Using MC calculated k_Q includes gradient effects



Muir and Rogers, Med. Phys. 121722 (2013).

Can we avoid use of P_{gr}?

- Most common source of electron beam calibration errors

- Using MC calculated k_Q includes gradient effects **and simplifies procedure**

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

$$\cancel{\boxed{P_{gr}^Q \, k'_{R_{50}} \, k_{ecal}}}$$

NRC·CNRC

The (resolved) problems with electron beams

- Steep dose gradients and chamber positioning → Take care when positioning chambers[1]
- Plane-parallel vs cylindrical
  - Plane-parallel variability and stability
  - Cross-calibration against cylindrical
  - Cylindrical not allowed in low-energy beams
  - Measured P_{gr} required for cylindrical → Monte Carlo k_Q include P_{gr}, can remove requirement

Can use cylindrical chambers for all beams

- Higher uncertainty in TG-51 k_Q

$$k_Q = \frac{\left[\left(\frac{\bar{L}}{\rho}\right)^{\mathrm{water}}_{\mathrm{air}} P_{\mathrm{cel}} P_{\mathrm{repl}} P_{\mathrm{wall}}\right]_Q}{\left[\left(\frac{\bar{L}}{\rho}\right)^{\mathrm{water}}_{\mathrm{air}} P_{\mathrm{cel}} P_{\mathrm{repl}} P_{\mathrm{wall}}\right]_{^{60}Co}}$$

→ Now have high-quality data

[1]Ververs et al., Med. Phys. 3839 (2017).

NRC·CNRC

Summary

- Reviewed TG-51 protocol – problems and reasons to update

- Review of addendum published April 2014

  - As expected, impact has been minor

- Much wider revision for electron beams

  - Just use cylindrical chambers
  - No cross-calibration or P_{gr}
  - Updated, accurate k_Q factors

→ **Simplified (more like photons) to make life easier, reduce errors!**

Thank you

Bryan R. Muir
Research Officer
Tel: (613) 993-2715 x239
Bryan.Muir@nrc-cnrc.gc.ca
www.nrc-cnrc.gc.ca