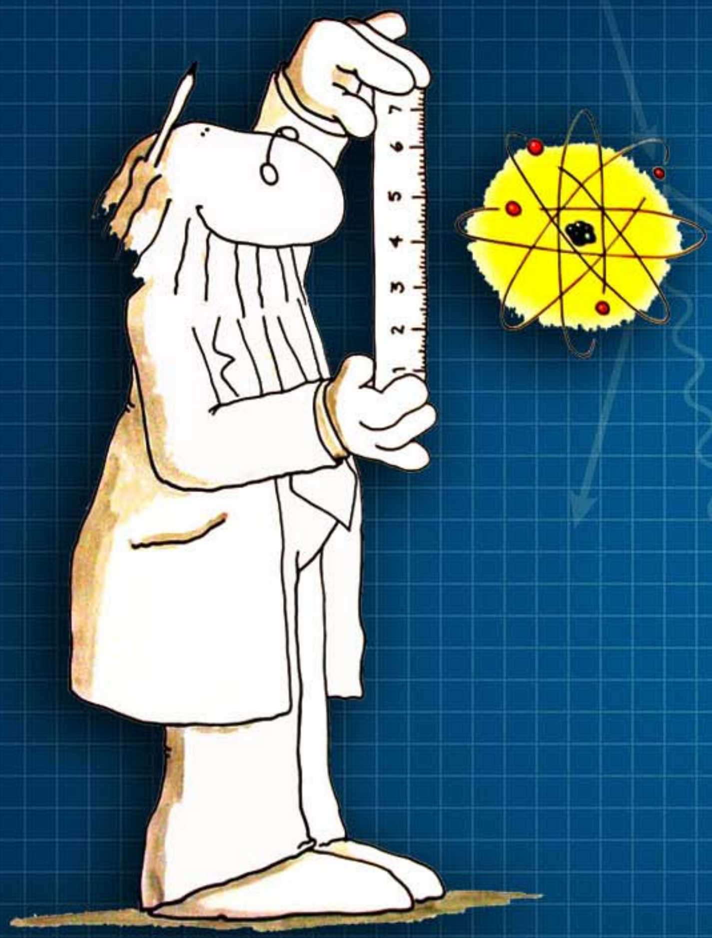

Updating reference dosimetry a decade after TG-51

Malcolm McEwen

Ionizing Radiation Standards

Institute for National Measurement Standards

National Research Council, Canada

CE Presentation at AAPM Annual Meeting, Philadelphia, 2010

Background

1. Reference dosimetry for linac beams based on a ^{60}Co calibration.
2. Simple step-by-step procedure.
3. Covers photon and electron beams.
4. Very successful, extensively tested, no significant problems reported.

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

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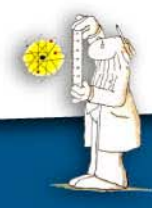
A protocol is prescribed for clinical reference dosimetry of external beam radiation therapy using photon beams with nominal energies between ^{60}Co and 50 MV and electron beams with nominal energies between 4 and 50 MeV. The protocol was written by Task Group 51 (TG-51) of the Radiation Therapy Committee 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 $\geqslant 10\times 10$ cm^2 on the surface of the phantom ($\geqslant 20\times 20$ 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 $\geqslant 10\times 10$ cm^2 ($\geqslant 20\times 20$ 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. © *1999 American Association of Physicists in Medicine.* [S0094-2405(99)00209-6]

Background

BUT

1. Almost 10 years have passed since TG-51 came out.
2. A large number of ionization chambers have come onto the market since ‘99.
3. Data from the US ADCLs indicates that users are obtaining ^{60}Co absorbed dose calibration coefficients for these chambers.
   i. To use such chambers correctly in linac beams with TG-51 requires more than just ‘following the recipe.’
   ii. Not all may be suitable for reference dose measurements.
4. A number of papers suggest that the electron dosimetry section of the protocol requires updating to take account of revised correction factors.
5. Time for something to be done?



AAPM Working Group on TG-51

- Formed November 2006

- Charge includes, “The WG will thus present a review of measured and calculated k_Q data as well as a clarification document for TG-51 that contains tables of k_Q for chambers currently not listed in the protocol.”

- Comprises: Malcolm McEwen (Chair, National Research Council Canada), David Rogers (Carleton University), Jan Seuntjens (McGill University), Larry DeWerd (UWisc ADCL), Geoff Ibbott (RPC), Steve Seltzer (NIST), Hugo Palmans (NPL, UK)

- Due to report in 2011

TG-51 reminder

- TG-51 is a procedure to give you a measurement of the absorbed dose to water at a point in a water phantom

- It's based on measurements with a calibrated ion chamber:

$$D_{w,Q} = N_{D,w}^{^{60}Co} \, k_Q \, M_{ion}$$

- $N_{D,w}$ is obtained from an ADCL or primary standards laboratory (e.g., in Canada)

- k_Q is the factor that converts from the calibration beam (^{60}Co) to the uses linac beam, defined by beam quality Q

- Q can represent a photon or electron beam

Update – the same approach for photons & electrons?

- Photons – requirements are:
  1. k_Q factors for an updated list of chambers
  2. Review of calculated k_Q factors
  3. Uncertainty analysis
  4. Implementation guidance notes (clarification)

Most pressing is the need for new k_Q factors with so many new chambers on the market

Update – the same approach for photons & electrons?

- Electrons – requirements are:
  1. Improved values for k_{ecal} (conversion from ^{60}Co to high-energy electron beam)
  2. Implications of non-zero perturbation correction factors for parallel-plate chambers (revised $k'_{R_{50}}$ values)
  3. Recommendation on calibration in ^{60}Co versus cross-calibration
  4. Cylindrical or parallel-plate chamber?

Note that two of the points require correction to the data in TG-51

Conclusion?

Split the review into 2 parts:

1. Photons – **update** of TG-51 (new document adds to original, no significant revision, straightforward)

2. Electrons – **revision** of TG-51 (new document replaces original, not straightforward)

Part 1 - photon addendum

The report will cover the following:

A. k_Q factors for new chambers

B. Comparison of measured and calculated k_Q factors

C. Uncertainty analysis for implementation of TG-51

D. Recommendations for implementation

TG-51 photons – what stays?

- TG-51 remains based on a calibration coefficient obtained in Co-60.
  - ✓ MV standards and calibration services are already available in certain countries but widespread dissemination in the US is not realistic at the present time.
- %dd(10)$_x$ remains the beam quality specifier.
  - ✓ Research has shown that TPR$_{20,10}$ and %dd(10)$_x$ are both valid in heavily filtered beams but %dd(10)$_x$ provides greater consistency in assignment of k_Q factors across varied MV beams (low-Z targets, flattening free linacs, *etc*).
- Thimble chambers remain the recommended chamber type for photon beams.
  - ✓ Still question marks over parallel-plate chambers for absolute measurements in MV photon beams.

Ionization chambers

- What are we talking about?

- 2 main types –
  I. Cylindrical (thimble) chambers
  II. Parallel-plate chambers

- Thimble chambers recommended for photon beam dosimetry

- 3 sub-types (NOTE: WGTG51 definitions) –
  i. 0.6 cm^3 reference chambers (e.g., NE2571, PR-06C)
  ii. 0.125 cm^3 scanning chambers (e.g., PTW31010, IBA CC13)
  iii. 0.02 cm^3 micro chambers (e.g., Exradin A16, Pinpoint™)

Examples

PTW31010 — 0.125 cm^3
Scanning chamber

IBA CC01 — 0.01 cm^3
Micro chamber

Exradin A12 — 0.6 cm^3
‘Farmer’ chamber

NE2577 — 0.25 cm^3
‘Short Farmer’

A. Calculation of k_Q factors

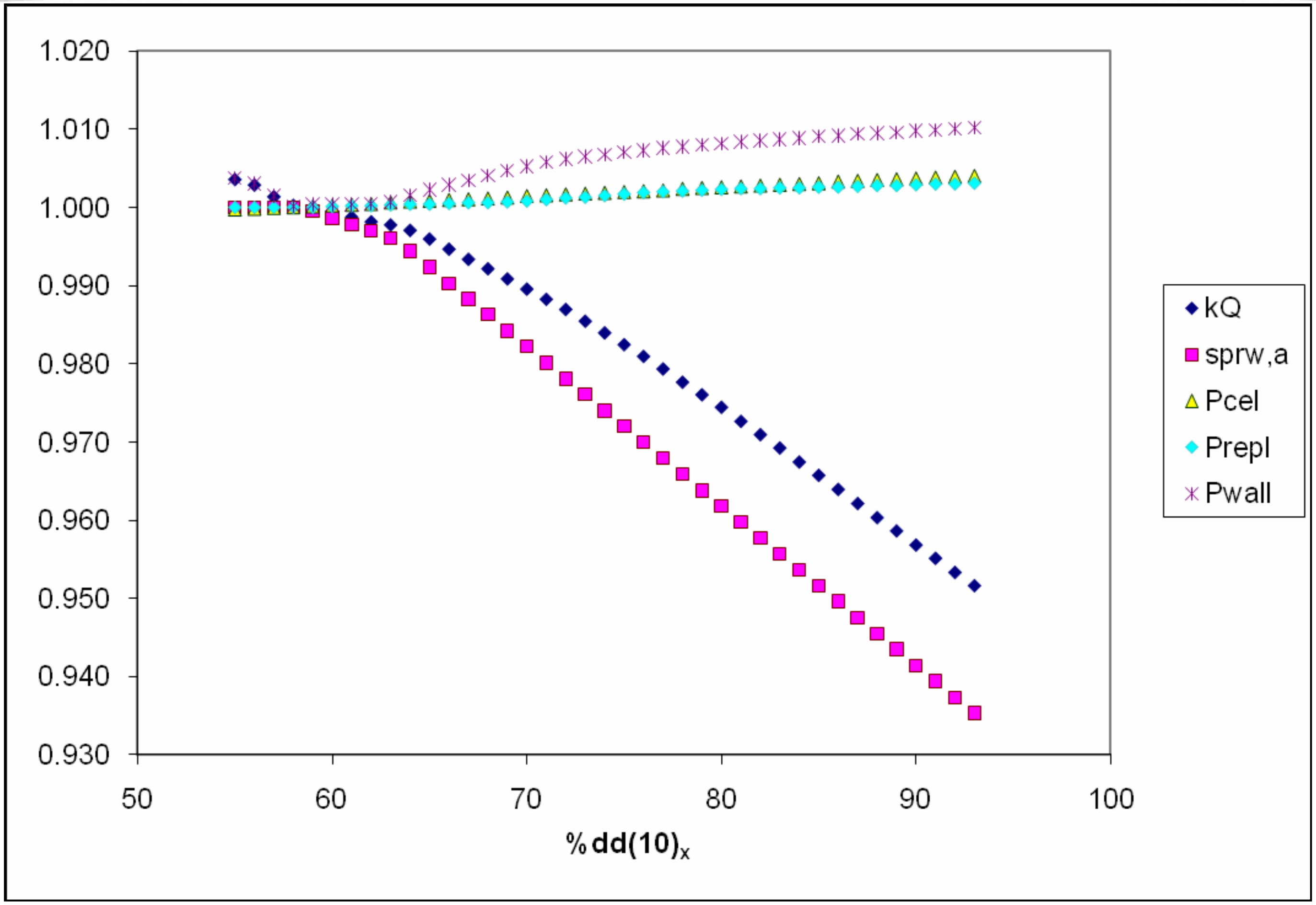
$$D_{w,Q} = N_{D,w}^{^{60}Co}\, k_Q\, M_{ion}$$

- To be consistent with TG-51 the same analytical approach has been taken:

$$k_Q = \left(\left(L / \rho \right)_{air}^{water} \; P_{cel}\, P_{repl}\, P_{wall} \right)_{Co-60}^{Q}$$

- values calculated for chambers from all three major manufacturers – PTW, Standard Imaging, IBA
- Same program used as for TG-51
- All metal electrodes treated as 1 mm diameter aluminum

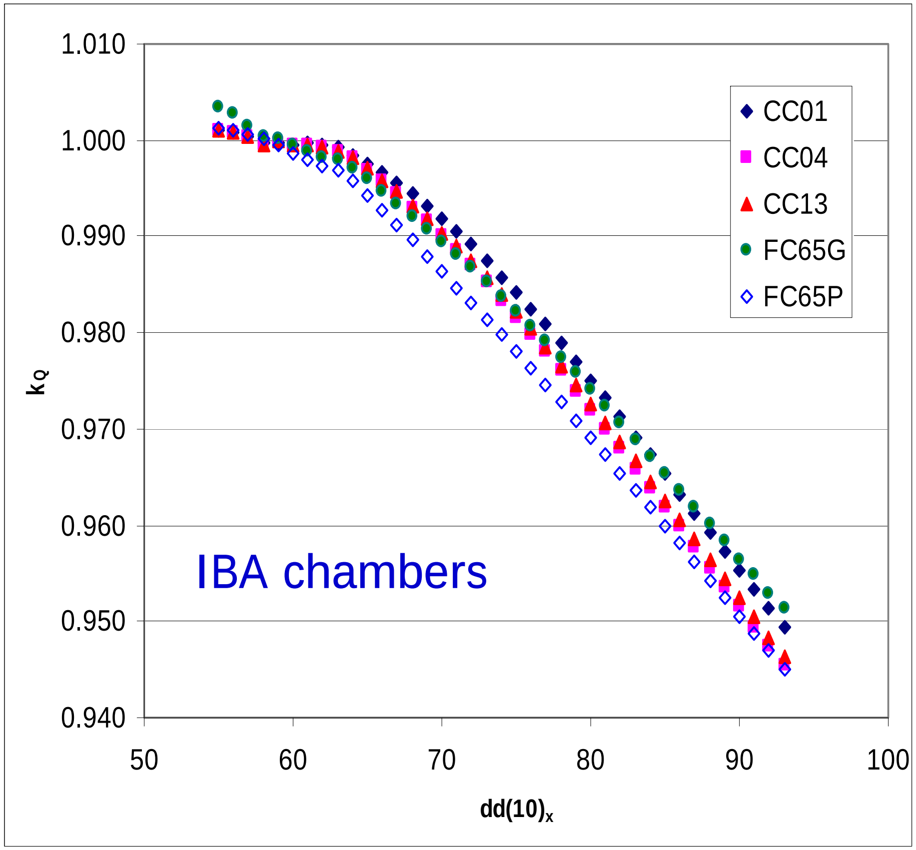
Results - calculations

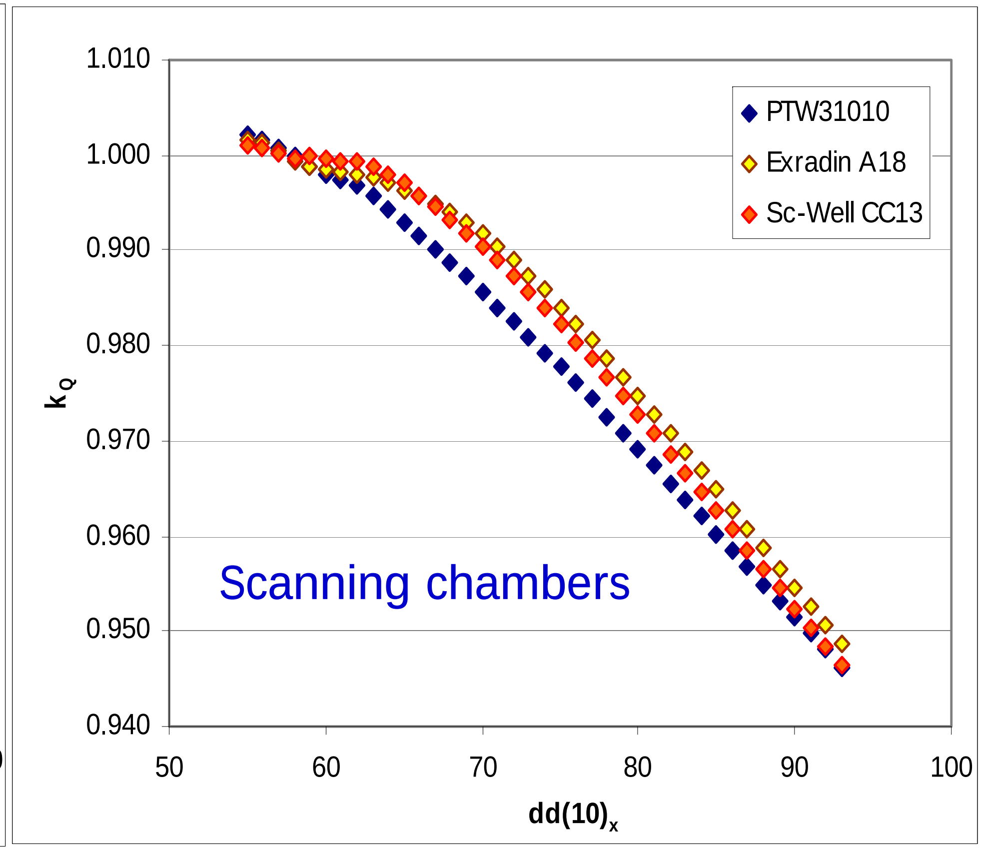


Stopping power ratio is largest contributor to the overall k_Q

P_{wall} is largest perturbation correction and can be significant

Results - calculations





There are significant differences between:

a) *Chambers from a single manufacturer*

b) *Chambers of a similar type from different manufacturers*

Limitations of calculations

$$k_Q = \left(\left(L/\rho \right)_{air}^{water} \; P_{cel} \, P_{repl} \, P_{wall} \right)_{Co-60}^{Q}$$

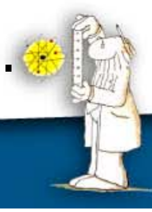
- Perturbation correction factors do not take entire geometry of chamber into account. There is no dependence in the calculation on the length of the cavity.
- Two chambers with the same central electrode, diameter and wall thickness will have identical k_Q factors irrespective of cavity length:

  Exradin A12 and A12S

  IBA CC13 and CC25

  PTW31010 and PTW31013

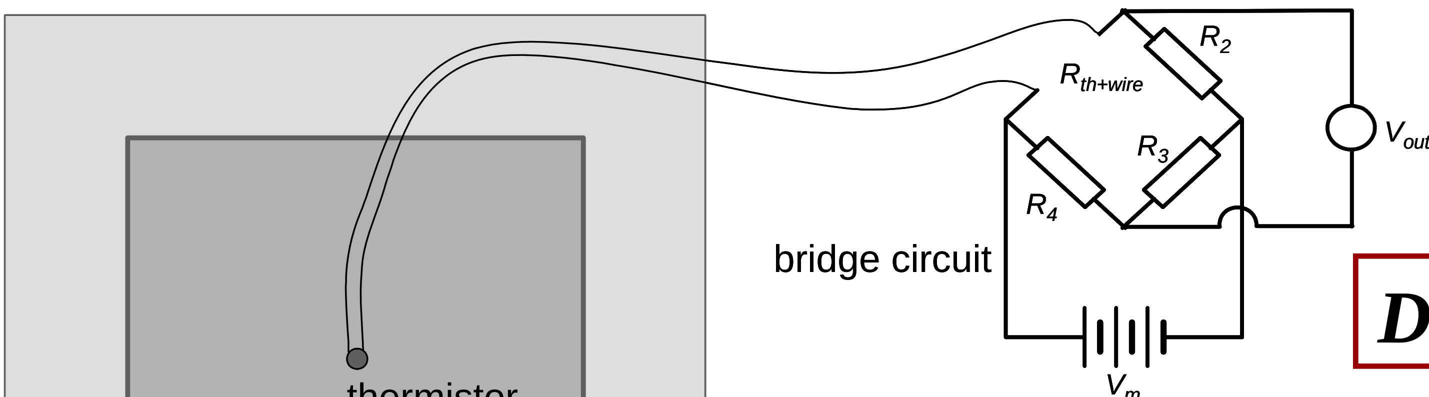
  NE2571 and NE2577
- This has not been tested in any great detail in the literature.



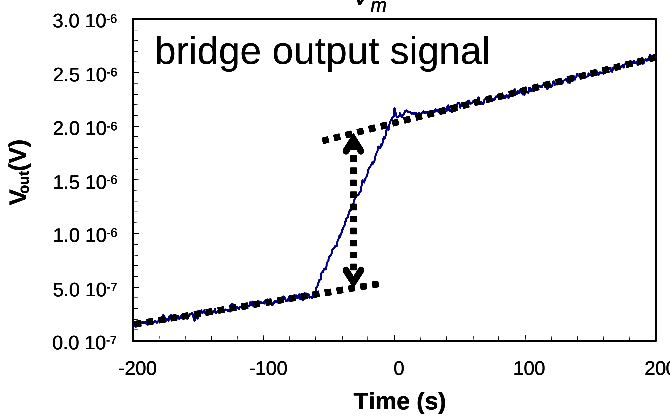
B. Experimental k_Q factors

Development of primary standards and calibration services

The primary standard for absorbed dose in linac photon beams worldwide is the **Calorimeter**



$$D_m = c_m \Delta T$$



Very simple relation between the radiation-induced temperature rise and the absorbed dose – just need the specific heat capacity

Calorimeters can look very different but all have these basic components

B. Experimental k_Q factors

Development of primary standards and calibration services

A few laboratories worldwide are working on MV standards

Primary standards for MV photons:

- NIST (US)
- NRCC (Canada)
- NPL (UK)
- PTB (Germany)
- LNHB (France)
- ENEA (Italy)
- NMi (Netherlands)
- METAS (Switzerland)
- ARPANSA (Australia)
- VNIIFTRI (Russian Fed.)

Calibration services for MV photons:

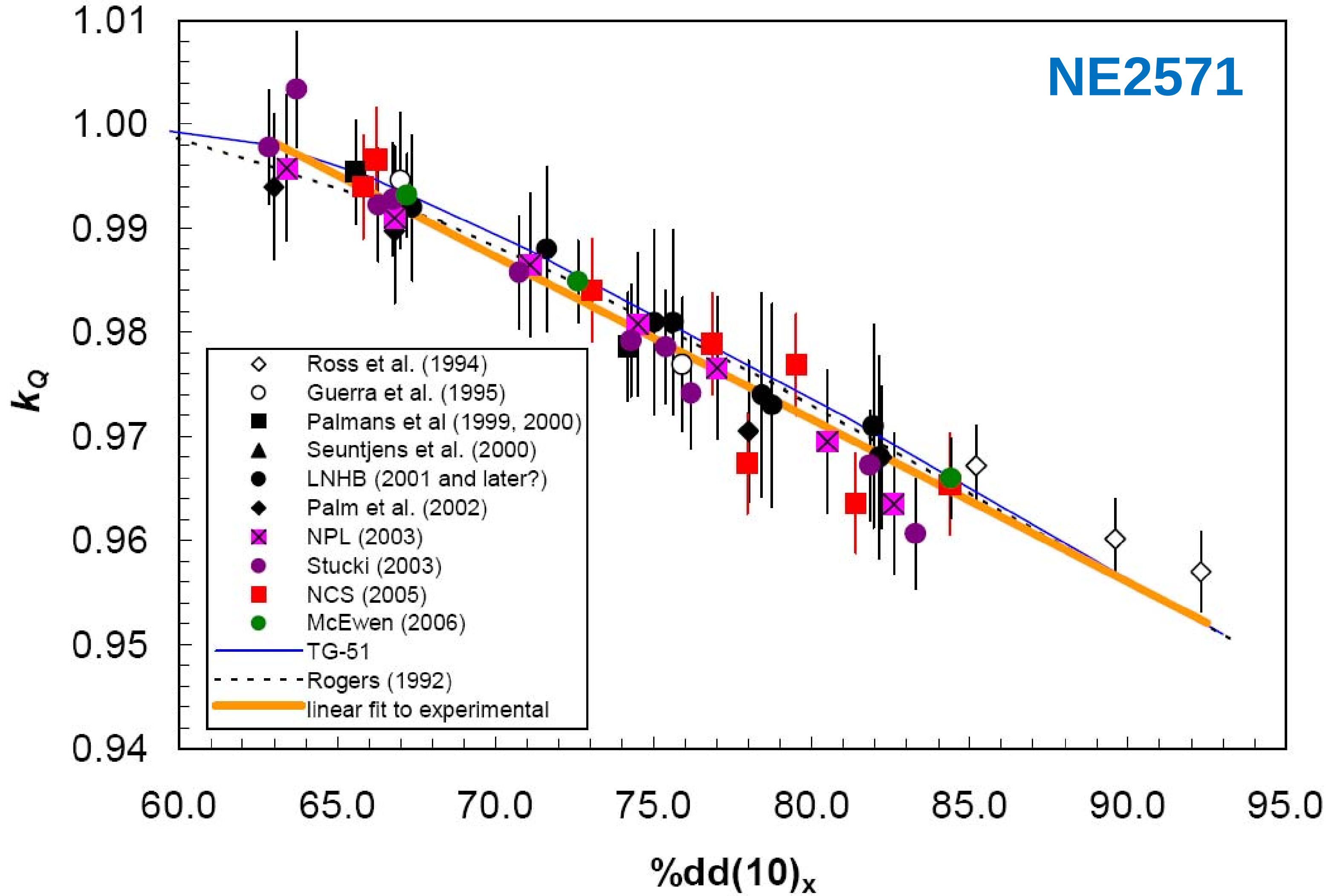
- NRCC
- NPL
- LNHB
- METAS
- VNIIFTRI

Chambers usually calibrated:

- NE2611, NE2571
- PTW30001, PTW30013
- Exradin A12
- Capintec PR-06C

Almost exclusively Farmer-type

B. k_Q factors – comparison of measurement with calculation



Reference: Report 18 of the Netherlands Commission on Radiation Dosimetry

k_Q factors – multiple chambers

Compare experimental values obtained at NRC Canada with calculated k_Q factors – 6, 10 & 25 MV photon beams (McEwen, Med. Phys., 2010)

Mean and Max evaluated for single chambers for 3 photon beams

PTW	Mean diff	Max diff	**Exradin**	Mean diff	Max diff	**IBA**	Mean diff	Max diff
PTW30010	0.0%	0.0%	A19	0.1%	0.3%	FC-65G	0.2%	0.4%
PTW30012	0.2%	0.3%	A12	0.0%	0.3%	FC-65P	0.0%	0.1%
PTW30013	0.3%	0.4%	A12S	0.1%	0.3%	FC-23C	0.2%	0.3%
PTW31010	0.5%	0.8%	A18	0.0%	0.2%	CC25	0.1%	0.2%
PTW31013	0.1%	0.4%	A1SL	0.1%	0.3%	CC13	0.2%	0.3%
PTW31014	0.0%	0.1%	A14	0.2%	0.4%	CC08	0.3%	0.4%
PTW31016	0.0%	0.3%	A16	0.7%	1.3%	CC04	0.1%	0.2%
						CC01	0.7%	1.1%

- ***Experimental data all from a single laboratory***
- ***A difference greater than 0.5% is statistically significant***

k_Q factors – multiple chambers

For TG-51 what we really want to know is whether the calculated factors are applicable to actual chambers

PTW	Mean diff	Max diff
PTW30010	0.0%	0.0%
PTW30012	0.2%	0.3%
PTW30013	0.3%	0.4%
PTW31010	**0.5%**	**0.8%**
PTW31013	0.1%	0.4%
PTW31014	0.0%	0.1%
PTW31016	0.0%	0.3%

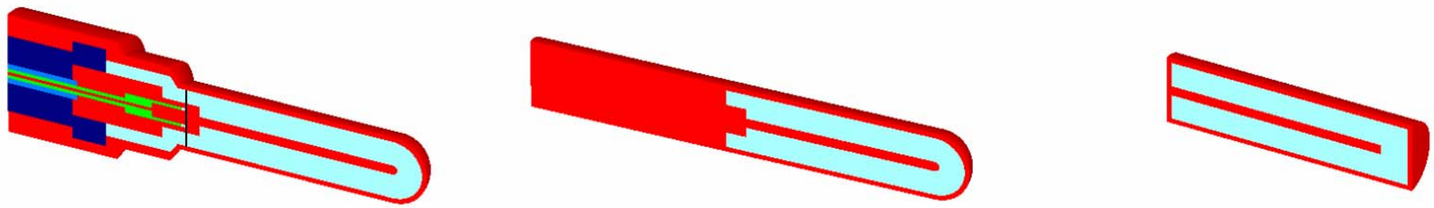
Exradin	Mean diff	Max diff
A19	0.1%	0.3%
A12	**0.0%**	**0.3%**
A12S	**0.1%**	**0.3%**
A18	0.0%	0.2%
A1SL	0.1%	0.3%
A14	0.2%	0.4%
A16	**0.7%**	**1.3%**

IBA	Mean diff	Max diff
FC-65G	0.2%	0.4%
FC-65P	0.0%	0.1%
FC-23C	0.2%	0.3%
CC25	**0.1%**	**0.2%**
CC13	**0.2%**	**0.3%**
CC08	0.3%	0.4%
CC04	0.1%	0.2%
CC01	**0.7%**	**1.1%**

Note - no apparent dependence on cavity length

k_Q factors – what about Monte Carlo?

Isn't MC the way to go?



- Chambers today can be modelled in exquisite detail
- Codes yield high-precision data, accuracy tested in multiple benchmarking investigations
- Standard approximations can be easily tested

Very useful but remember - for photon beams the starting principle was that we are not replacing TG-51

C. Uncertainties

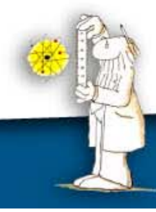
1. TG-51 made the deliberate decision not to include uncertainties.
2. Other protocols have included uncertainty budgets and/or detailed reviews of uncertainty components.
3. It’s time to give some guidance on:
    i. How to develop an uncertainty budget
    ii. Typical values for individual components.
4. The ISO GUM is the starting point
5. Improved, uniform uncertainty reporting in radiotherapy dosimetry will lead to improved QA of treatment delivery and allow better comparisons between cancer centres.

Uncertainties – what’s the GUM?

1. ISO Guide to the Expression of Uncertainty in Measurement
2. Short answer – procedure to estimate the total uncertainty in your measurement
3. Long answer – more than you ever wanted to know about probability distributions, uncertainty budgets, degrees of freedom, coverage factors and how to turn a guess into an estimate.
4. BUT, the best way to ensure that you take all uncertainty components into account properly.

✓ NIST has produced an explanatory document (a guide to the Guide) - NIST Technical Note 1297

✓ BUT, a document specific to external beam radiation dosimetry is also necessary (TG-138 deals with brachytherapy)



C. Uncertainty budget

- Discussion of Type A and B uncertainties (distinct from 'random' and 'systematic')
- Uncertainty budget broken down into:
  - Measurement
  - Calibration data
  - Influence quantities
- Typical values discussed but emphasis on individual users constructing site-specific uncertainty budgets for their calibration situations

Note - table is deliberately blank. The important point is to identify the components of uncertainty in the realization of dose.

Component of Uncertainty	Type A	Type B
Measurement		
SSD setting		
Depth setting		
Charge measurement		
P_{TP} correction		
Calibration data		
Co-60 $N_{D,w}$		
k_Q factor		
Assignment of k_Q factor		
Influence quantities		
P_{pol}		
P_{ion}		
Pre-irradiation history		
P_{leak}		
Calibration coefficient (chamber stability)		
Linac stability		
OVERALL		

D. Recommendations

A number of recommendations will be given in the photon update:

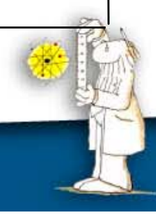
1. **Specification of a reference chamber**
2. **Choice of polarizing voltage**
3. **Solid phantoms**
4. **Effective point of measurement**

D.1 Chamber spec

Based on objective assessment of chamber performance

Measurand	Specification
Chamber settling	Must be less than a 0.5% change in reading from beam-on to stabilization
P_{leak}	< 0.1 % of chamber reading
P_{pol}	< 0.4 % correction < 0.5 % maximum variation with energy (total range)
P_{ion}	Correction must be linear with dose per pulse Initial recombination must be < 1.002 at 300 V Correction follows Boag theory for chamber dimensions. Difference in initial recombination correction between opposite polarities <0.1%
k_Q	< 0.5% difference between measured and calculated (TG-51) factors

Note - the last point is clearly less objective as it assumes the calculation is correct. Useful, however, in the absence of any other data.



D.1 Chamber spec

Based on results in the literature we can state that at least the following meet this specification:

- **NE2571 and NE2611**
- **PTW30010, PTW30012, PTW30013, PTW31013**
- **Exradin A12, A12S, A19, A18, A1SL**
- **IBA FC65-G, FC65-P, FC23-C, CC25, CC13**
- **Capintec PR-06C**

NOTE – majority are 0.6 cm^3 ‘Farmer-type’ chambers

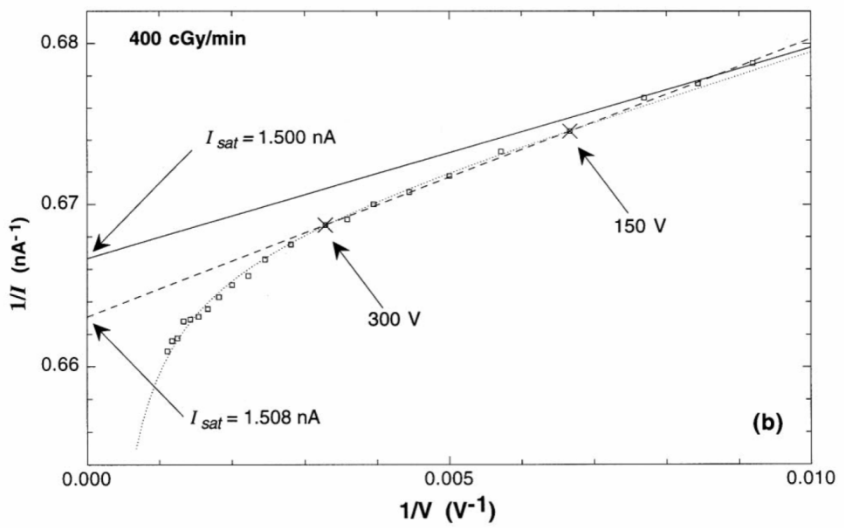
5 scanning chambers, NO microchambers

D.2 Polarizing voltage

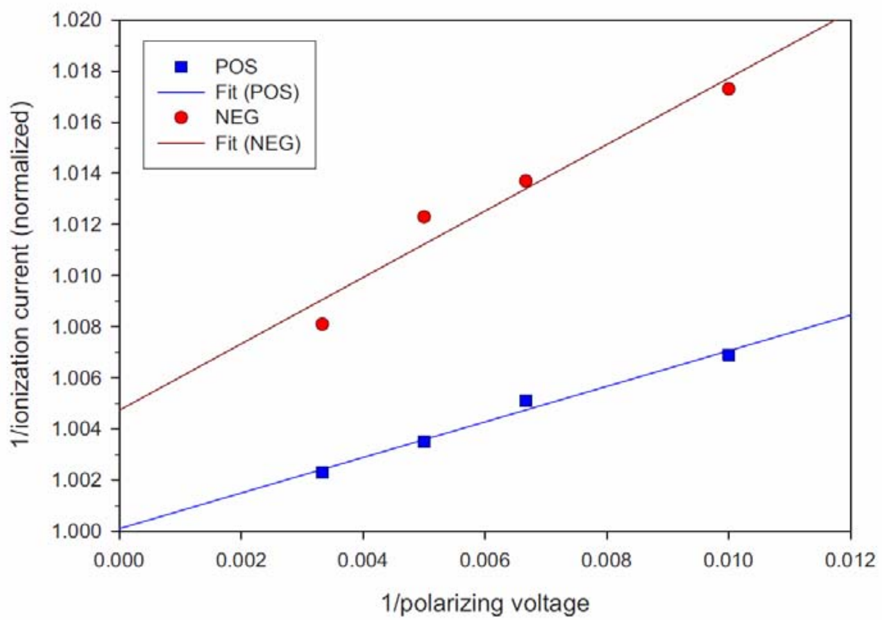
$$M_{corr,w} = M_{raw}\, P_{TP}\, P_{ion}\, P_{pol}\, P_{elec}$$

- Recombination correction directly affects measurement of absorbed dose
- Recombination correction well established <u>but</u> not always straightforward
- 2-voltage technique as set out in TG-51 applicable only to chambers exhibiting ideal behaviour
- Many examples in literature of anomalous behaviour

D.2 Polarizing voltage



Non-linearities in a plot of 1/reading vs 1/polarizing voltage indicates non-ideal behaviour.



References: DeBlois et al (Med. Phys., 2000), McEwen (Med. Phys., 2010)

D.2 Polarizing voltage

Based on results in the literature we can state the following:

- **Not all chambers follow standard 'Boag' theory**
- **Manufacturers' statements on voltage limits need verifying (<u>at least</u> for chamber types, if not individual chambers)**
- **Going to a higher polarizing voltage can lead to a larger uncertainty in the measurement**
- **Recombination can be a function of the sign of the charge collected**
- **WG recommends a maximum value of 300 V (lower values may be required for small-volume chambers)**

D.3 Solid phantoms

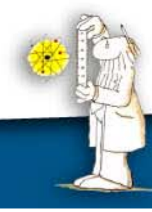
Advantages:

1. No water to spill!
2. Easy to move from one linac to another.
3. Robust setup of SSD and chamber position.
4. Improved formulations with ‘reference’ grade material now available

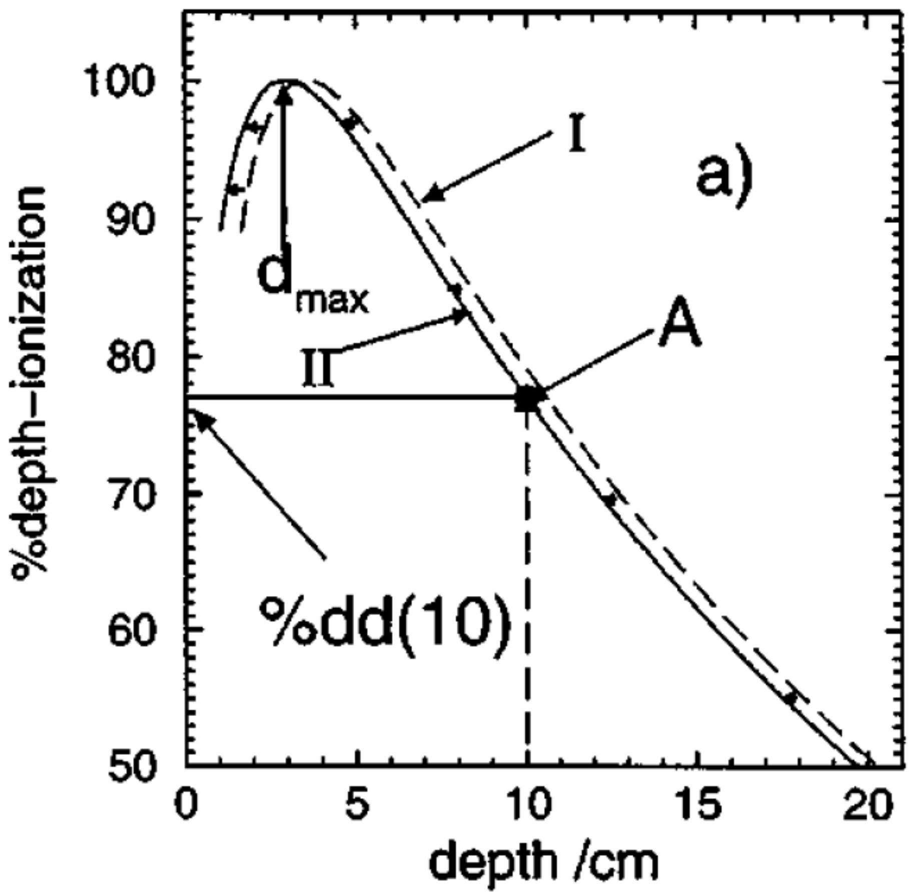
Disadvantages:

1. Not truly water equivalent for all beams.
2. Not easy to distinguish different formulations.
3. Homogeniety not guaranteed.
4. Characterization in the clinic is time consuming.

Conclusion - reference dose-to-water measurements should be based on the dose measured in a water phantom – solid phantoms <u>not</u> recommended for reference dosimetry.

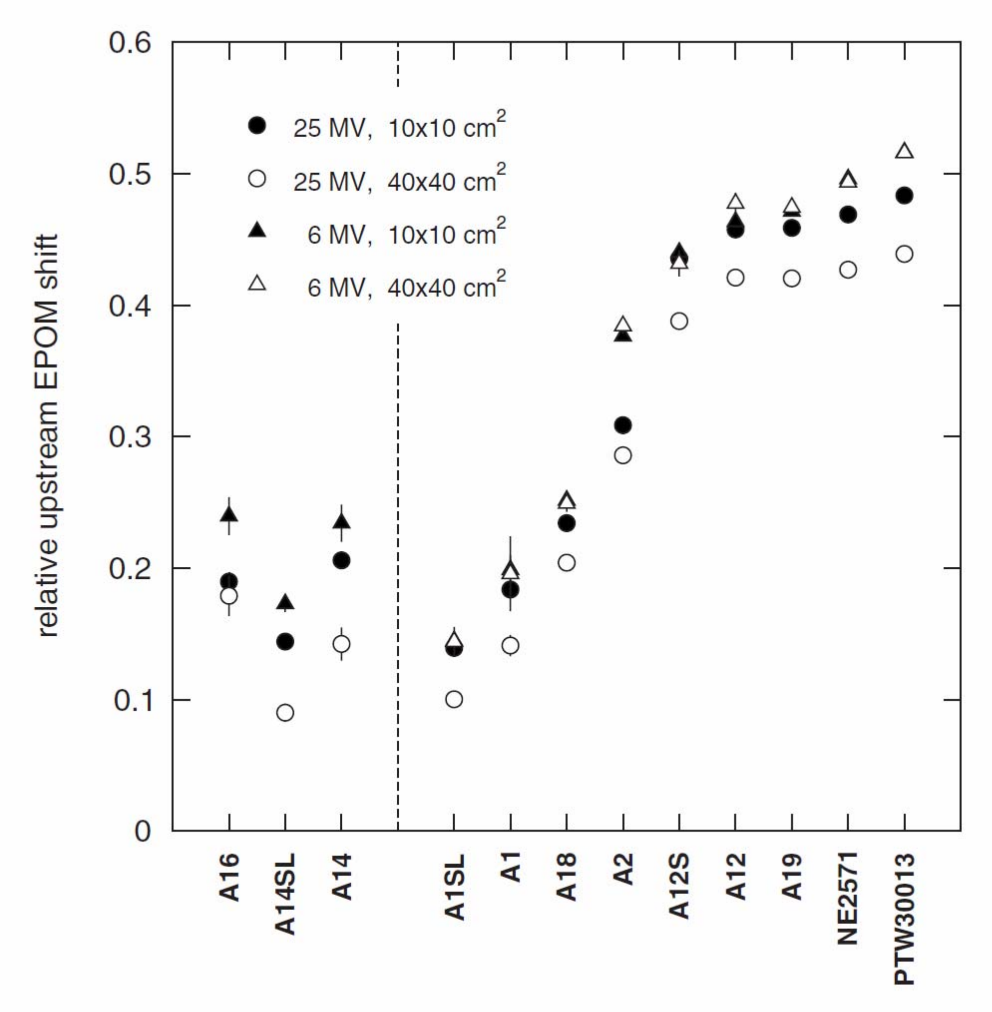


D.4 Effective point of measurement



- Measurement of depth-dose curves requires taking account of the effective point of measurement.
- For thimble chambers TG-51 recommends $0.6r_{cav}$ upstream from centre.
- Recent theoretical and experimental investigations have shown that this is not correct.

D.4 Effective point of measurement



Reference: Tessier and Kawrakow (Med. Phys., 2010)

- **EPOM varies with chamber design and beam specification – shift is <u>not</u> universal.**
- **<u>No chamber</u> has the TG-51 recommended shift of 0.6r_{cav}**
- **Effect is generally small but easily measurable with modern water phantoms in the build-up region.**

NOTE - <u>no</u> significant effect on measurement of dose at d_{ref}

Dose gradient at 10 cm ~ 5% per cm.
Max shift in EPOM is ≤ 1 mm

Δ_{dose} ~ 0.5% (worst case)

Part 2 – electron dosimetry

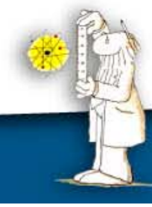
- Same basic equation is used for electrons as for photons:

$$D_{w,Q} = N_{D,w}^{^{60}Co} k_Q M_{ion}$$

- k_Q is split into 3 components:

$$k_Q = P_{gr} k_{ecal} k'_{R_{50}}$$

- P_{gr} corrects for gradient effects (thimble chambers only)
- k_{ecal} converts from Co-60 to a high-energy electron beam
- $k'_{R_{50}}$ gives relative energy dependence in electron beams



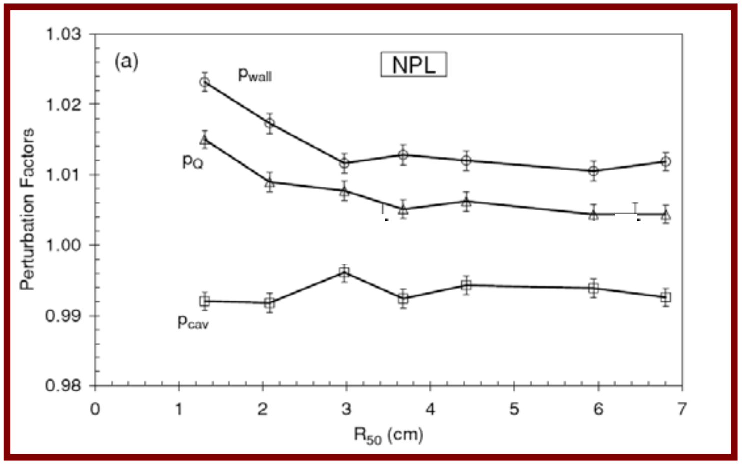
Part 2 – electron revision

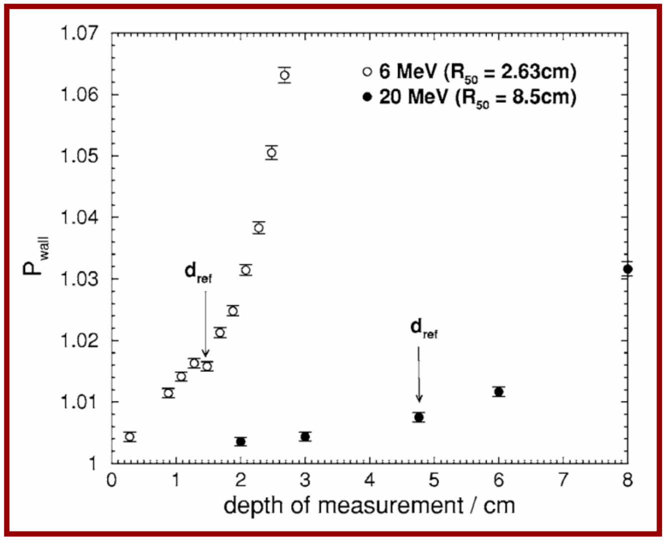
1. **DATA** - keep formalism from TG-51, dose still based on ^{60}Co but update/replace data that was incorrect in TG-51 or not provided for new types of ion chamber:

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

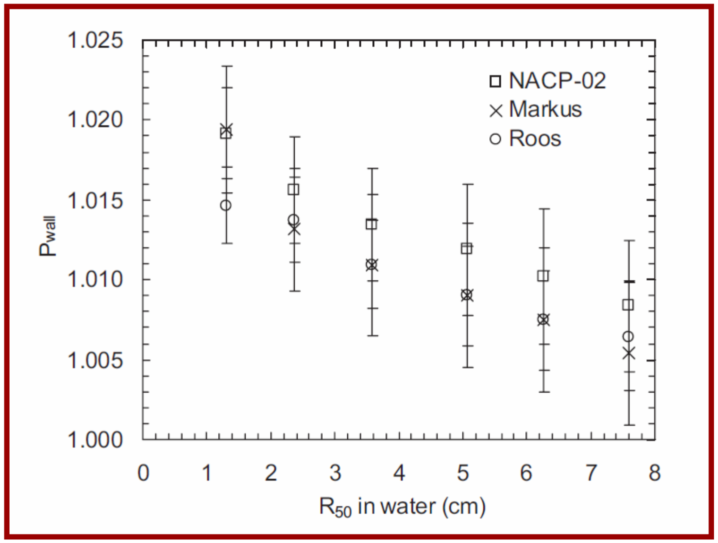
- P_{gr} - need to re-evaluate in light of new effective point of measurement data for photon beams.
- k_{ecal} – improved value available in literature for NACP-02 chamber, new values required for new chamber types (Exradin A10, IBA PPC-05, PTW34045).
- $k'_{R_{50}}$ – TG-51 assumes that well-guarded parallel-plate chambers have a unity perturbation correction. Multiple publications now show this is not the case – new data required.

Ion-chamber perturbation corrections





Monte Carlo investigations



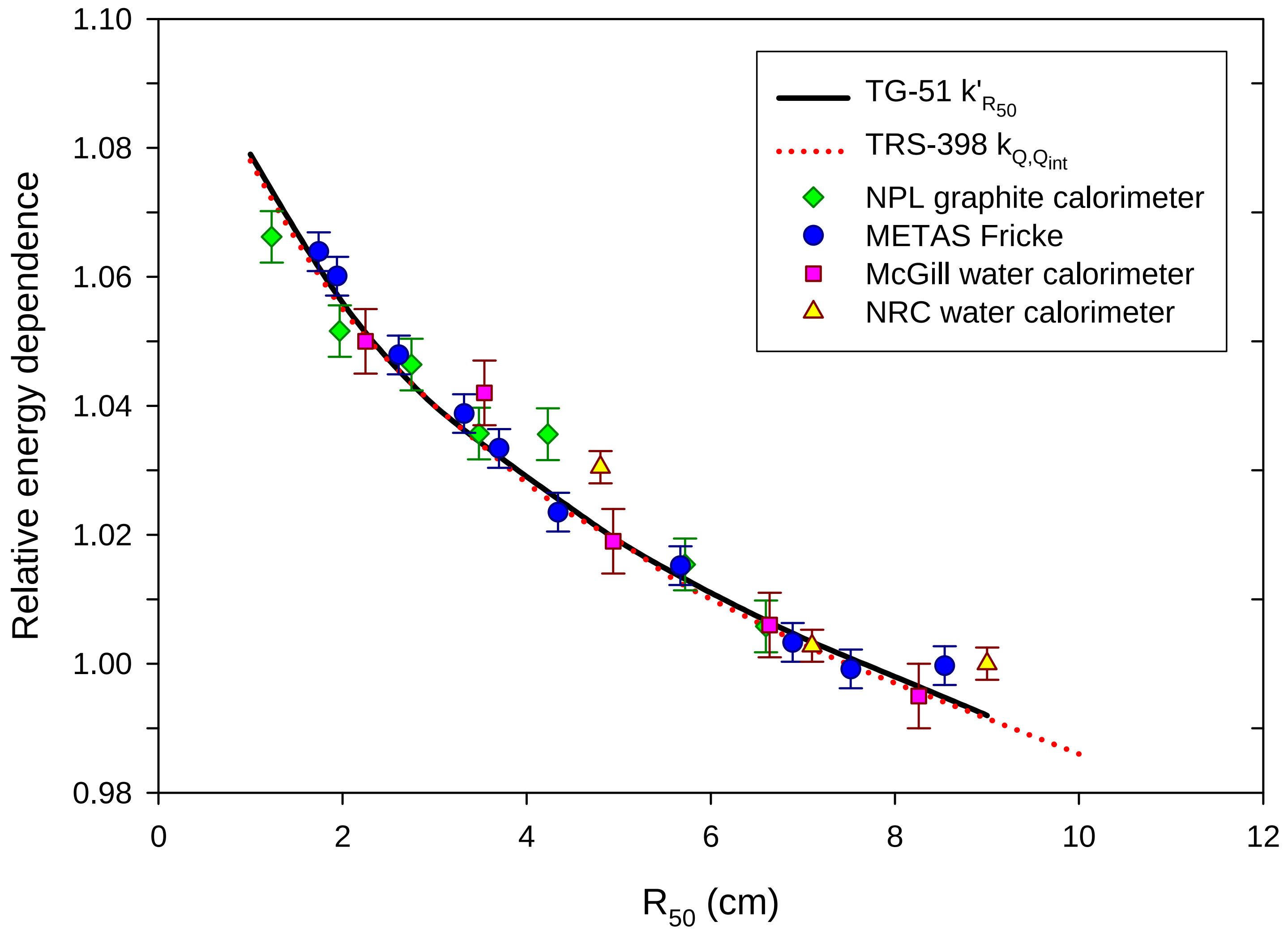
All show significant chamber perturbation corrections at d_{ref} for low energy beams and a significant variation with depth

References: Verhaegen et al (PMB, 2006), Buckley and Rogers (Med. Phys., 2006), Araki (Med. Phys., 2008)

Choice of chamber type needs addressing

2. **Chamber type** – what should be the recommendation regarding ion-chamber types and low energy beams?
   - i) Most commonly used beams are 6 & 9 MeV
   - ii) Some protocols <u>insist</u> on using parallel-plate chambers, TG-51 allows cylindrical down to R_{50} = 2 cm
   - iii) Objectively, which is better?
   - iv) Requires accurate experimental data comparing different detectors together with experimental values of k_{ecal} and k'_{R50}

Measurement of k'$_{R_{50}}$

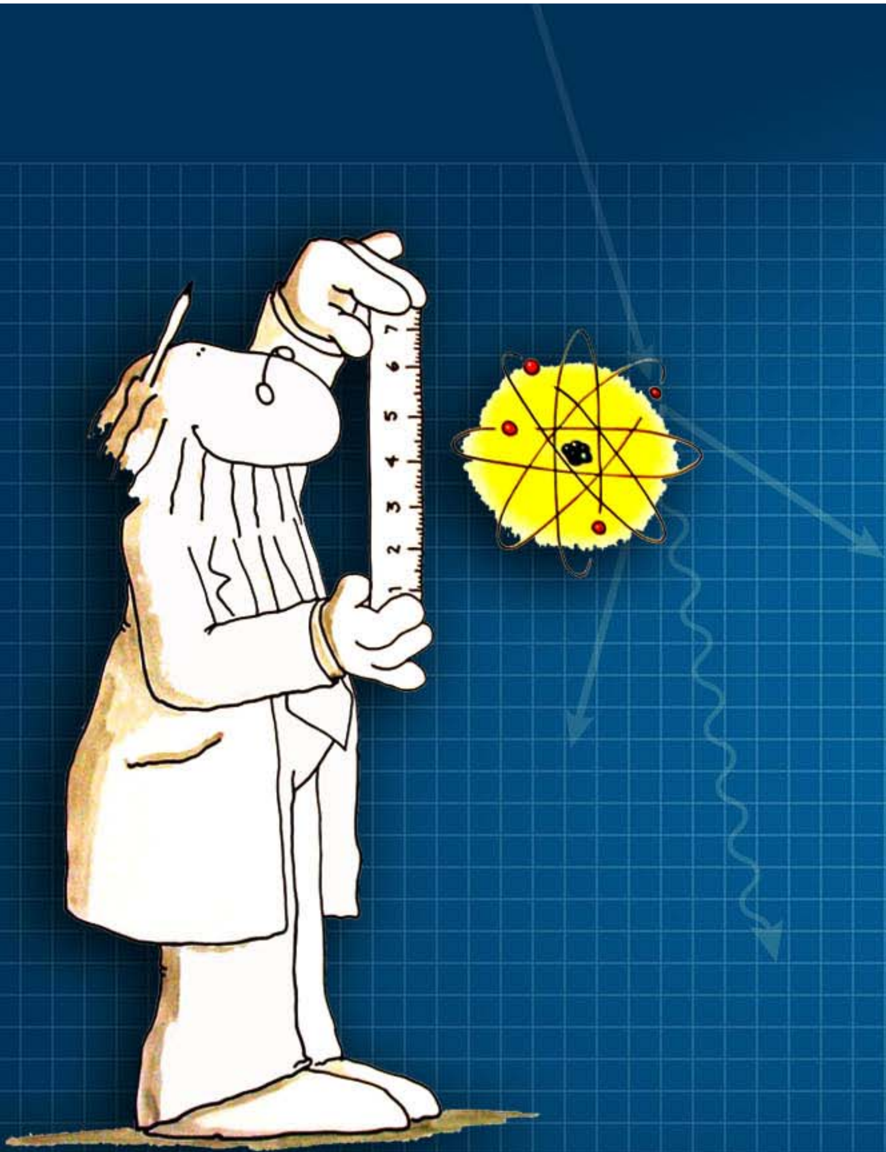


Limited high-accuracy data at present – more required.

Reference: McEwen and DuSautoy (Metrologia, 2009)

Conclusion

- Changes to TG-51 are coming
- Photons – the changes will not be dramatic
- Electrons – a (somewhat) revised protocol is required
- The basic calibration/reference field for clinical dosimetry will remain 10 cm x 10 cm @ 1 m for some time



Thank you