MV Photon Dosimetry in the Clinic
This document discusses both the scientific methods and the system of work required to calibrate a field instrument expanding upon the practical details of both.

1. Introduction

The current UK Code of Practice (CoP) for high-energy photon therapy dosimetry was issued by the then Institute of Physical Sciences in Medicine (IPSM) in 1990. It describes a methodology by which the quantity absorbed dose to water can be accurately measured in the clinic based upon a calibration which is traceable to the primary standard graphite calorimeter maintained by the NPL.

Note that the CoP was written at a time when linacs only produced conventionally flattened beams. Consequently it is not intended for direct use with:

- FFF beams – $N_{Dw}$ can vary from one beam to another, even if those beams have exactly the same TPR. An effect of somewhere between 0 to 0.6% is likely: a ~0.3% effect was seen by NPL when comparing measurements made in a lightly filtered and flattened beam (the original NPL set-up) and a more heavily filtered beam (an extra 10 cm of Al filtration was added to the beam), and a 0.4% to 1.0 % effect has been calculated from Monte Carlo calculations (Xiong and Rogers, Med. Phys. 35:2104 (2008)). The true answer will have to wait until NPL has performed calorimetry in a FFF beam. The IPEM FFF Working Party should be publishing guidance for FFF this year and are likely to make a preliminary recommendation of a 0.3% correction.
- CyberKnife – a solution at the moment is to use the NPL Alanine reference dosimetry service to transfer a traceable calibration to an ion chamber in the CyberKnife beam.

The CoP details the scientific methods for:

- the calibration of field instruments against a secondary standard which has been calibrated by the NPL absorbed dose service
- measuring radiation output in terms of absorbed dose to water in from a hospital cobalt-60 unit or high-energy photon accelerator

Rather importantly, what the CoP does not tell us is:

- who should have responsibility for, or perform the measurements, and what experience they should have.
- that an independent second measurement is required.

For this we need to look at the guidance first issued in 1992 by the IPSM on “procedures for definitive calibrations in radiotherapy” in the first edition of Scope. This guidance was subsequently enshrined in HSE Guidance Note PM77, but was removed in the most recent 3rd edition (March 2006), instead referencing IPEM Report 81, Physical aspects of quality control in radiotherapy, whose appendix A is effectively a reprint of the Scope article (with updated references), and the Medical and Dental Guidance Notes, Appendix 15, IPEM 2002. (Note that both the MDGN and IPEM 81 are being updated. The revised IPEM 81 (with a new IPEM Report No) is due for publication relatively soon – but the date is as yet unconfirmed.) The fundamental principle behind this guidance is:

- any definitive measurement should be subjected to an independent check and that procedures should incorporate specific cross checks

In addition it states that:

- responsibility for definitive calibration must be vested in a physicist appropriately experienced in radiotherapy physics i.e. 6 years. (Note that this definition is likely to change over the next few years as the definition of a Medical Physics Expert (MPE) moves away from a ‘years of experience’ definition to an ‘appropriate training’ definition. See the new EUROPEAN GUIDELINES ON MEDICAL PHYSICS EXPERT 2014: http://ec.europa.eu/energy/nuclear/radiation_protection/doc/publication/174.pdf)
• written procedures must be drawn up and followed. Measurements and observations must be fully documented.
• any parameters upon which the calibration depends must be checked according to the procedures in the quality assurance programme.
• all factors and quantities in any calculations must be written down even if they are unity.

2. Calibration of a Field Instrument

2.1 IPEM Guidelines for Definitive Calibration of Field Instruments

The IPEM guidelines specifically state that a definitive calibration of dose measuring equipment which is to be used for the definitive calibration of radiotherapy treatment machines must be carried out:
• for new equipment.
• following major repair.

The guidelines then recommend that:
• The definitive calibration of field instruments must be derived by an intercomparison against a reference dosimeter which should have a calibration traceable to the NPL.
• Two or more independent measurements must be carried out.
• Where the chamber is to be calibrated at more than one beam quality and the relative calibration factors are known for chambers of that construction, the previous requirement can be met by demonstrating that the calibrations at the different qualities are consistent within 1.5% of the expected value.
• If only one beam is available, a repeat calibration should be carried out in that beam. However, constancy of the readings made with a strontium-90 source at the previous definitive calibration may also be regarded as an independent measurement in some circumstances.
• Two experienced radiotherapy physicists should be involved in the measurements. Ideally, the calibrations should be carried out by different physicists, but it is sufficient that the second physicist should check the results.
• After a repair of a field instrument it is sufficient to show that there is no change in the calibration factor at the highest and lowest beam quality to be used.
• For a new field instrument calibrations should be carried out at all the radiation qualities at which the instrument will subsequently be used to measure absorbed dose to water. If the chamber variation in response with beam quality is not known, the calibration must be repeated by an independent physicist.
• Strontium-90 reference source measurements should be made on both the secondary standard and field instruments immediately before and after carrying out an intercomparison calibration. Corrected readings should agree to within 1%. (If regular, say 3 monthly, reference source readings made on both systems as part of a Quality Assurance programme, it may only be necessary to carry out dedicated reference source readings after the intercomparison calibration).
• Where possible, the calibration factors obtained should be compared with the supplier’s certificate of calibration.
• If practicable, the calibrated chamber should be used for the routine calibration of a teleisotope source, and the consistency of the results with previous calibrations confirmed before it is used for other calibrations.
• Repeat calibrations should be carried out annually at a representative sub-set of the radiation quantities in use. Changes in a calibration factor of greater than 1% should be investigated and if necessary a new Definitive Calibration carried out at all qualities.

2.2 Equipment

The equipment that we need in order to perform a comparison calibration of a field instrument is:
• The secondary standard (unsealed ionisation chamber connected to an electrometer by a cable)
- A close-fitting polymethyl methacrylate (trade name Perspex, Lucite or Plexiglass) waterproof sheath in which to put the secondary standard chamber (this should be the same sheath as was used when this chamber was cross calibrated against the primary standard at NPL).
- The field instrument (unsealed ionisation chamber connected to an electrometer by a cable) to be calibrated.
- For field instruments that are not waterproof, a close-fitting Perspex waterproof sheath in which to put the field chamber (this should be the same sheath as will be used subsequently when this chamber is used to measure absorbed dose to water in the hospital beam).
- An intercomparison phantom:
  - made of water, or Perspex (only for Farmer type chambers with wall materials of A150 plastic, graphite, Tufnol, aluminium or Perspex).
  - with a depth to the centre of chamber of 5.0 cm for Co-60 and 4 to 10 MV x-radiation, 7.0 cm deep for 11 to 25 MV x-radiation.
  - with either: for side by side comparisons, the chamber centre positions 3 cm apart, one either side of the beam axis or; for sequential comparisons, the chamber centred on the central axis.
  - with physical dimensions large enough to extend at least 5 cm outside the beam edges and 5 cm beyond the chamber centre along the beam axis i.e. 20 to 25 cm in cross section and at least 10 cm deep for $^{60}\text{Co}$ to 10 MV x-radiation or 12 cm deep for 11 to 25 MV x-radiation.
- Strontium-90 reference sources to enable constancy checks to be performed on both the secondary standard and field instruments.

### 2.3 Documentation
- External documentation:
  - NPL Calibration certificate for the secondary standard dosimetry system (valid for 3 years from the date of issue).
- Internal documentation:
  - Work Instructions within own Quality System detailing how to carry out the cross-calibration.
  - paper form / log book / spreadsheet /database for recording and processing the results reliably and repeatably.

### 2.4 Practical tips
When carrying out the cross calibration, or any subsequent reference dosimetry with the calibrated field instrument always:
- Check and record the type and serial numbers of all the equipment used.
- Before starting the calibration check the condition of both the chambers. The graphite thimbles should be intact and all the joints should be hand tight. Consider using a permanent ink marker on the metal parts of the chamber to record how the joints lined-up at calibration. Any subsequent loosening will then be easy to detect.
- Before and after the calibration carry out quality control checks on the linac, in particular check that the routine output, energy check value and flatness & symmetry are as expected. Again this need only be done after the calibration if these parameters are believed to be correct before by looking at the results of the routine quality control programme.
- Analyse the readings as you go, checking that the standard deviation of each set of readings is small (less than 0.1%), the difference in the intercomparison ratio between the two positions explicable from the known flatness of the beam etc.
• Check the leakage current and switching transients of both systems as part of the calibration process.
• Look back at the history of the instrument sensitivities. Any sudden change from an expected value of greater than 1% is suspicious and should be investigated.

2.5 Determination of the Quality Index \( TPR_{10}^{20} \)

The Quality Index (QI) or tissue phantom ratio \( TPR_{10}^{20} \) for the beam in which the field instrument is to be calibrated is required in order to interpolate an absorbed dose to water calibration factor \( N_{D,ss} \) for the secondary standard from the table of calibration factors versus Quality Index given in the NPL certificate.

\( TPR_{10}^{20} \) can be determined in one of two ways:

• it can be measured directly in a water phantom using a constant source to detector distance (SDD) for all measurements (typically 80 cm for \(^{60}\)Co and 100 cm for linear accelerators) i.e. the chamber centre is placed at the isocentre and readings taken at depths of 20 and 10 cm. The Quality Index is then simply the ratio of the readings at the two depths (after correction for any differences in chamber air temperature and pressure and for ion recombination losses).
• it can be derived from percentage depth dose data (PDDs) measured in water at constant source to surface distance (SSD) using the formulae relating TPR (or tissue maximum ratio TMR) to PDD published in BJR Supplement 25 (see Appendix 1).
• alternatively, provided that the routine “Energy Check” value for the beam is as expected the Quality Index can be assumed to be the same as measured in water during the original Definitive Calibration or machine commissioning.

2.6 Thermal equilibrium of equipment

The chambers and phantom should be placed in the treatment room in advance before starting the measurements to allow them to attain thermal equilibrium with their surroundings. The time allowed for a solid Perspex phantom to reach thermal equilibrium with its surroundings depends on the temperature change to which it may have been subjected, but to be safe several hours should be allowed. Similarly, the time allowed for a water phantom to reach thermal equilibrium with its surroundings will depend upon the difference in temperature between the air in the room and the water used to fill the phantom. Again, several hours should be allowed. Note, however, that if using a water phantom, the actual water temperature should be measured, as the temperature in the air of a chamber immersed in water is typically around 1°C less than the air temperature of the room due to evaporation from the surface of the water.

2.7 Intercomparison measurements

• Carry out the comparison using the same machines and radiation qualities as will be subsequently used by the field instrument.

The CoP allows for the intercomparison measurements to be performed side by side or sequentially. During the MV practical session we will use both these methods.

2.7.1 Measurements made sequentially.

As we are using a \(^{60}\)Co source for this practical session, we do not need to worry about the stability of the beam and we have already established the accuracy of the timer. However, when using a linac, you will either need to have confidence in the repeatability of your MV beam, or use a additional “monitor” chamber placed in the beam at the calibration depth to correct for beam fluctuations by recording the ratio of the secondary standard or field instrument to the monitor chamber.

The CoP procedure is:

• Position the secondary standard ionisation chamber (with its Perspex sheath fitted) in the intercomparison water phantom with its centre (NOT its effective point of measurement) at:
  o a reference depth of 5 cm for QIs of 0.57 and 0.58 to 0.75, nominally \(^{60}\)Co or 4 to 10 MV
• Position the field instrument in the phantom but out of the beam to allow it to come to thermal equilibrium with the water while the secondary standard measurements are being performed.
• Set the source-to-chamber distance to 100 cm.
• Set the field size at the position of the chambers to 10 cm × 10 cm.
• Measure the water temperature and air pressure.
• Irradiate the chamber sufficient dose to give a reading on the secondary standard which is at least 500 times the resolution of the range set i.e. so that the measurements have a resolution of 0.2% or better.
• Make at least five readings or until there is no observed trend (set A).
• Substitute the field instrument in place of the secondary standard and move the secondary standard to the side of the phantom.
• Measure the water temperature and air pressure.
• Make at least five readings or until there is no observed trend, (set B).
• Substitute the secondary standard back in place of the field instrument.
• Measure the water temperature and air pressure.
• Make at least five readings or until there is no observed trend (set C).
• Measure the water temperature and air pressure.
• The inter-comparison ratio should be calculated:
  o Calculate the mean readings for the three sets of measurements, each corrected for temperature, pressure and ion recombination.
  o Calculate the mean secondary standard reading for the two sets of measurements, A and C.
  o Calculate the intercomparison ratio of the secondary standard to field instrument.

\[ \frac{M_{SS}}{M_{FI}} = \frac{M_{SSA} + M_{SSC}}{M_{FIB}} \]  

2.7.2 Measurements made side by side.

The CoP procedure is:
• Position the secondary standard ionisation chamber (with its Perspex sheath fitted) and the field instrument ionisation chamber (with its Perspex sheaths fitted if is not a waterproof chamber) in the calibration phantom with their centres (NOT their effective points of measurement) at:
  o a reference depth of 5 cm for QIs of 0.57 and 0.58 to 0.75, nominally ⁶⁰Co or 4 to 10 MV
  o a reference depth of 7 cm for QIs of 0.75 to 0.81, nominally 11 to 25 MV
• The CoP does not specify a source to detector distance for this measurement however this would normally be the same SDD as for the QI measurements.
• The field size at the position of the chambers should be set to 10 cm × 10 cm.
• Irradiate the chambers simultaneously with sufficient dose to give readings on both the secondary standard and field instruments which are at least 500 times the resolution of the ranges set i.e. so that the measurement have a resolution of 0.2% or better.
• Calculate the intercomparison ratio. This is equal to the secondary standard reading divided by the field instrument reading.
• Most published guidance says to take at least three readings with the chambers in this position (set-up A). Three readings are not enough! The intercomparison ratio measurement should be repeated until the ratio is stable. It can be helpful to plot this ratio in real time using a spreadsheet so that trends in the ratio can be more easily seen.
• Calculate the arithmetic mean of these ratio measurements as:

\[ \left[ \frac{M_{SS}}{M_{FI}} \right]_{A1} \]  

• Swap the position of the chambers (set-up B) and repeat the measurements to give a second value for the intercomparison ratio (to compensate for the effect of an asymmetric beam):

\[ \left[ \frac{M_{SS}}{M_{FI}} \right]_{B} \]
• In order to randomize the effect of set up errors the chambers positions should be swapped once more, again taking at least three readings of the intercomparison ratio to yield one more average for position A:

$$\left[ \frac{M_{ss}}{M_{fr}} \right]_{A_2}$$

(4)

• Calculate the arithmetic mean of the two A position values:

$$\left[ \frac{M_{ss}}{M_{fr}} \right]_A = 0.5 \times \left( \left[ \frac{M_{ss}}{M_{fr}} \right]_{A_1} + \left[ \frac{M_{ss}}{M_{fr}} \right]_{A_2} \right)$$

(5)

• Calculate the geometric mean of the values of the intercomparison ratio for the two set-ups:

$$M_{ss} / M_{fr} = \frac{1}{2} \left( \left[ \frac{M_{ss}}{M_{fr}} \right]_A \times \left[ \frac{M_{ss}}{M_{fr}} \right]_B \right)$$

(6)

### 2.8 Ion recombination correction

The CoP states that correction to the readings of each chamber for ion recombination should be made. For continuous radiation from a Cobalt unit, these corrections are generally very small. According to the CoP, the ion recombination factor for the NE2561 with -200 V polarising voltage is independent of dose-rate and equal to 1.0014. For the pulsed radiation from a linear accelerator, however, it is generally a significant loss. Ion recombination can be either measured or calculated.

#### 2.8.1 Measuring Ion Recombination

It can be measured for any ionization chamber quite easily by using the two-voltage technique. In this approach two ionization chamber readings are taken in the same irradiation conditions, one at the normal collecting voltage ($V_1$, reading $M_1$) and one at a lower voltage ($V_2$, reading $M_2$). For small corrections ($k_{\text{ion}} < 1.05$), the ion recombination is given by

$$k_{\text{ion}} = \frac{(M_1 / M_2 - 1)}{(V_1 / V_2 - 1)} + 1$$

(7)

Although the CoP suggests using a ratio $V_1/V_2$ of two, more recent guidance is to use a ratio of three (see IAEA TRS-398 or a current NPL secondary calibration certificate). For ultimate accuracy, a full $1/I$ against $1/V$ plot should be measured. The process is exactly the same as that for measuring ion recombination in an electron beam (and performed as part of the electron practical session) so won’t be repeated here.

#### 2.8.2 Calculating Ion Recombination

For the NE 2561 or 2611 secondary standard chambers, the ion recombination correction, $\kappa$, can be calculated if the dose per pulse, $P$ in cGy, is known, using the following relationship given in the CoP:

$$\kappa = 1.0014 + 0.23P$$

(8)

For other ionization chambers, the general ion recombination can also be calculated by using the following equations (Boag 1950, ICRU 1982):

$$k_{\text{ion}} = \frac{u}{\ln(1+u)}$$

(9)

Where $u$ is calculated using equation (10)

$$u = \frac{\mu P s^2}{V}$$

(10)

and where $\mu = 10.2 \text{ V·mm}^{-2}\cdot\text{cGy}^{-1}$

$P$ = Dose per pulse in cGy

$s$ = Effective Plate Separation in mm

$V$ = Collecting voltage in volts
For example, for the NE 2571 \( s = 3.1 \) mm, and for the NE 2581 \( s = 1.7 \) mm. When operated at -250 V with a dose per pulse of 0.028 cGy (typical dose per pulse for a Varian 2100 EX as shown below) we get:

\[
k_{\text{ion}}(2571) = 1.005 \quad \text{and} \quad k_{\text{ion}}(2581) = 1.002
\]

(11)

For the PTW 30013 \( s = 2.9 \) mm, so when operated at -400 V with a dose per pulse of 0.028 cGy we get:

\[
k_{\text{ion}}(30013) = 1.00298
\]

(12)

One way of measuring \( p \) is to deliver an irradiation whilst simultaneously measuring the dose in cGy with a calibrated chamber and the number of pulses delivered with a universal counter attached to a convenient test point e.g. the Target pulse test socket on a Varian 2100C. The dose per pulse is then simply the quotient of these two values.

Alternatively the dose per pulse can be calculated using the measured dose-rate at the ionization chamber and accelerator pulse repetition frequency (PRF) if known:

\[
p[\text{cGy/pulse}] = \frac{1}{\text{PRF}[\text{Hz}]} \times \frac{\dot{D}[\text{cGy/min}]}{60[\text{s}]}
\]

(12)

So for a Varian 2100 EX, with a PRF of 360 Hz and a dose-rate of 600 cGy.min\(^{-1}\) we get:

\[
p[\text{cGy/pulse}] = \frac{1}{360} \times \frac{600}{60} = 0.028 \text{ cGy}
\]

But be careful! When measuring the PRF with an oscilloscope, remember that some Varian linacs regulate the dose rate by dropping pulses!

2.9 Derivation of field instrument calibration factor

The field instrument absorbed dose to water calibration factor is given by:

\[
N_{D,FI} = \left[ \frac{M_{SS}}{M_{FI}} \right] N_{D,SS} \kappa \times N_{\text{elec,SS}} \times f_{\text{non-lin,SS}}
\]

\[
k_{\text{ion}} \times N_{\text{elec,FI}} \times f_{\text{non-lin,FI}}
\]

(14)

where:

- \( \left[ M_{SS}/M_{FI} \right] \) is the mean intercomparison ratio measured in the clinical beam (equation 6)
- \( N_{D,SS} \) is the absorbed dose to water calibration factor for the secondary standard for this beam (in Gy/C or Gy/Instrument Reading) taken or interpolated from the NPL calibration certificate
- \( \kappa \) is the correction for ion recombination for the secondary standard in this beam
- \( k_{\text{ion}} \) is the correction for ion recombination for the field instrument in this beam
- \( N_{\text{elec}} \) is the calibration coefficient from the electrometer certificate
- \( f_{\text{non-lin}} \) is the non-linearity correction factor from the electrometer certificate

And for the secondary standard (SS) and field instrument (FI) respectively:

The CoP states that correction for changes in temperature and pressure (standard temperature of 20°C and ambient air pressure of 1013.25 mbar) should be applied to the readings taken during cross calibration. However if the chambers are at the same ambient conditions, these corrections cancel out.

3. Use of Field Instrument to measure Output in a clinical MV photon beam

3.1 IPEM Guidelines for Definitive Calibration of machine Output

The IPEM guidelines specifically state that definitive calibrations of external-beam radiotherapy equipment must be carried out at each radiation quality to be used clinically:

- on all new megavoltage treatment machines as part of the commissioning procedure,
following major repairs, modifications or, in the case of Co\textsuperscript{60}, source changes. The guidelines then recommend that:

- The definitive calibration \textbf{must} be derived from two independent sets of measurements made by two experienced radiotherapy physicists using \textbf{different} calibrated field instruments (calibrated according to the procedure described in section 2). All equipment \textbf{must} be removed and all linac parameter reset between independent measurements.
- For teletherapy equipment employing a radioactive source, the definitive calibration measurement \textbf{must} be compared with the supplier’s certificate of calibration. Data derived from the certificate of calibration should not be regarded as a substitute for other recommended measurements, but any difference between these data and the definitive calibration \textbf{must} be reconciled.
- The definitive calibration \textbf{must} be checked by comparing measured and predicted doses for a different number of monitor units (or treatment time) from that used in the definitive calibration.
- Subsequent routine confirmatory calibrations may use simplified measurement procedures, but the ratios of the measurements under the two sets of conditions must be established at the time of the definitive calibration.

3.2 Equipment

- A field instrument (unsealed ionisation chamber and electrometer) which has been calibrated against a secondary standard at the radiation quality to be measured. For field instruments that are not waterproof, the close-fitting Perspex waterproof sheath in which the field chamber was fitted when calibrated.
- Suitable phantom for the measurement:
  - large full scatter water phantom for Definitive Calibration of machine output.
  - small “solid water” phantom for routine checks of machine output. This should be used at the same time as the definitive output so that the relationship between measurements made in this and the water phantom is established.
- A thermometer with a valid calibration.
- A barometer with a valid calibration.

3.3 Documentation

- External documentation:
- Internal documentation:
  - local documentation for the calibration factor of the field instrument (valid for 1 year from the date of issue).
  - work Instructions (within Quality System) detailing how to carry out the output calibration.
  - paper form / spreadsheet / database for recording and processing the results reliably and repeatably.

3.4 Determination of the Quality Index \( TPR_{10}^{20} \)

The Quality Index for the beam in which is to have its output calibrated should be accurately known (see advice in §2.5).

3.5 Thermal equilibrium of equipment

The advice given in §2.6 on allowing for thermal equilibrium to be attained should be followed.
3.6 Measurement of Absorbed dose to Water

Absorbed dose at a point at depth \( d \) in water, measured with a calibrated field instrument can be calculated from

\[
D_{\text{water}} = M_{\text{FI}} \times k_{PT} \times N_{D,FI} \times k_{\text{ion}} \times N_{\text{elec}} \times f_{\text{non-lin}}
\]  

(15)

where:
- \( M_{\text{FI}} \) is the field instrument reading at that point
- \( k_{PT} \) is the pressure and temperature correction factor as in equation (17) defined below
- \( N_{D,FI} \) is the absorbed dose to water calibration factor in the particular photon beam determined from the intercomparison with the secondary standard system and
- \( k_{\text{ion}} \) is the correction for ion recombination for the field instrument in this beam.
- \( N_{\text{elec}} \) is the calibration coefficient from the electrometer certificate
- \( f_{\text{non-lin}} \) is the non-linearity correction factor from the electrometer certificate

The value of \( k_{\text{ion}} \) for the reference depth at the isocentre will have been derived during the intercomparison calibration. For other conditions it will need to be either
- measured with the two voltage technique.
- calculated using equations (10) through to (14)

Correction for changes to relative humidity (from 50% level) are small and usually neglected (at least for measurements carried out in the UK!).

3.7 Beam output measurements

Beam output is defined as the absorbed dose in water (in Gy) per Monitor Unit (MU) for linacs or time (minute) for \(^{60}\text{Co}\) under calibration conditions. An example of an isocentric linear accelerator beam calibration is shown in Figure 2 for a photon beam of energy 10 MV or less. In the case shown the linac output is calibrated at the isocentre at a depth of 5 cm in a 10 x 10 cm plain (open) field.

![Diagram of linac beam calibration under isocentric conditions](attachment:Figure_2.png)

**Figure 1:** Example of linac beam calibration under isocentric conditions.

**WARNING!** It should be noted that the calibration conditions will vary between departments. Some will set the machine to give 1 Gy/100 MU at the isocentre at the depth of maximum dose build-up...
$d_{D_{\text{max}}}$, some at the isocentre but at depth of 5, 7 or 10 cm, and others may calibrate the output at the depth of maximum dose build-up $d_{p_{\text{max}}}$, but with the isocentre coincident with the phantom surface i.e SSD of 100 cm for linac photon beams. The tolerance value for routine checks on beam output for external beam treatment units is usually $\pm 2\%$. The absorbed dose to water should be measured at the same reference depth as used for the cross-calibration and then corrected to the calibration depth used in the Radiotherapy Department. The way in which this depth correction is done depends upon whether or not the surface is placed at the isocentre (PDD method) or the centre of the chamber is positioned at the isocentre (TMR method). Examples of each, both for the output specified at the depth of maximum dose build-up $d_{p_{\text{max}}}$, are given in §3.7.1 and §3.7.2.

### 3.7.1 Beam output measurement using PDDs

\[
D_{\text{max}} = \frac{M_{\text{f}} \times k_{\text{PT}} \times N_{\text{D,f}} \times k_{\text{ion}} \times N_{\text{elec}} \times f_{\text{non-lin}}}{PDD}
\]

### 3.7.2 Beam output measurement using TMRs

\[
D_{\text{max}} = \frac{M_{\text{f}} \times k_{\text{PT}} \times N_{\text{D,f}} \times k_{\text{ion}} \times N_{\text{elec}} \times f_{\text{non-lin}}}{TMR}
\]

### 4. Acknowledgements

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Appendix 1 – derivation of Quality Index from PDD data

BJR Supplement 25 (page 156, equations (2a) and (2b)) formulas relating TMRs and TPRs to PDDs are:

\[
TMR[d,S] = \frac{1}{100} \times PDD[d,f,S\cdot St/(f + d)] \times \frac{PSF[St/(f + d)]}{PSF[St/(f + d_m)]} \times \left( \frac{f + d}{f + d_m} \right)^2
\]

(A1)

\[
TPR[d,S] = \frac{PDD[d,f,S\cdot St/(f + d)]}{PDD[d_{ref},f,S\cdot St/(f + d_{ref})]} \times \frac{PSF[St/(f + d)]}{PSF[St/(f + d_{ref})]} \times \left( \frac{f + d}{f + d_{ref}} \right)^2
\]

(A2)

Where,

- \( f \): SSD at which the PDDs were measured
- \( S \): Field size defined at the SSD \( f \)
- \( d \): Depth of measurement
- \( d_m \): Depth of maximum dose build-up
- \( d_{ref} \): Reference depth for the purposes of the TPR
- \( PSF[S] \): Peak scatter factor for field size \( S \) defined at SSD

For example for a 6MV X-ray beam (data from BJR Supplement 25, page 90) equation (1) for

\[
TMR[10,10] = \frac{1}{100} \times PDD[10,100,9.09] \times \frac{PSF[9.09]}{PSF[9.85]} \times \left( \frac{110}{101.5} \right)^2 = \frac{1}{100} \times 67.045 \times \frac{0.997}{0.999} \times \left( \frac{110}{101.5} \right)^2 = 0.7856
\]

and

\[
TMR[20,10] = \frac{1}{100} \times PDD[10,100,8.33] \times \frac{PSF[8.33]}{PSF[9.85]} \times \left( \frac{120}{101.5} \right)^2 = \frac{1}{100} \times 38.23 \times \frac{0.975}{0.999} \times \left( \frac{120}{101.5} \right)^2 = 0.5319
\]

Thus,

\[
TMR[^{20}_{10}] = \frac{0.5319}{0.7856} = 0.677
\]