3.1 Introduction

The term “absolute” is widely used in dosimetry, but it has two distinct meanings. Clinical physicists commonly use the term absolute to emphasize that a measurement is not relative; for instance, the calibration of machine output requires such an absolute measurement, while the acquisition of percentage depth dose and beam profile data involves relative measurements. In some dosimetry calibration laboratories, the term absolute is reserved for measurements made with a primary standard such as a calorimeter; the clinical physicist’s “absolute” measurement may instead be referred to as a “reference” measurement.

There is room for further confusion, since the measurement conditions specified in a reference dosimetry protocol would normally be referred to as “reference” conditions, and any measurement following the protocol would normally be referred to as a “reference” dose measurement. The confusion arises if an absolute measurement, whether or not it is made using a primary standard, is made under nonreference conditions. Such a measurement may be “absolute,” and is possible provided that an appropriate correction is made for the change in sensitivity of a dosimeter when it is used under nonreference conditions rather than reference conditions; however, it is not a “reference” measurement.
This chapter is concerned with measurements that are absolute as opposed to relative, it includes some discussion of absorbed dose primary standards, but the main concern is the accurate measurement of absorbed dose using a calibrated ion chamber under reference conditions.

3.2 Detectors Used for Reference Dose Measurements

3.2.1 Requirements for a Reference Dosimetry System

Reference dosimetry requires a detector that has a calibration coefficient traceable to a standards dosimetry laboratory, which provides the conversion of the detector signal to absorbed dose to water. These reference detectors are generally reserved for the output calibration of radiation therapy machines. Most radiotherapy departments have only one reference dosimetry system with a calibration traceable to a standards dosimetry laboratory. However, calibration factors for other detectors can be obtained through a transfer calibration procedure (e.g., IAEA, 2000; Abdel-Rahman et al., 2009).

In a reference dose measurement, the detector reading is multiplied by its calibration coefficient to give absorbed dose to water. The sensitivity of a reference detector must remain stable over the time that elapses between calibration and use, and it must be possible to correct readings for the effect on detector sensitivity of any change in ambient circumstances such as temperature, pressure, and so on. In a relative measurement, the detector is used to determine the ratio of absorbed dose, for example, at two different points in the same field, or at the same point in two different fields. There is no need for the detector to show good long-term stability, and ambient circumstances can generally be assumed not to change significantly between the two readings. The sensitivity of a silicon diode, for example, varies with temperature in a nontrivial way. Consequently, the uncertainty in correcting for temperature dependence would be unacceptable in reference dosimetry, but becomes negligible in a relative measurement because the correction would cancel in the dose ratio. Air-filled ion chambers can meet the requirements of reference dosimetry, provided they show good dimensional stability and have a large enough sensitive volume to generate an adequate signal. Further requirements are summarized below. Other detectors such as alanine, synthetic single crystal diamond, and plastic scintillator detectors, which are discussed in detail in Chapter 4, offer some promise, but are unlikely to replace the use of air-filled ion chambers for reference measurements of absorbed dose at a point. Currently most, if not all, absorbed dose protocols use ion chambers for reference dosimetry (e.g., Almond et al., 1999; IAEA, 2000; McEwen et al., 2014).

3.2.2 Reference-Class Detectors

In Chapter 4, characteristics of point detectors and their use for dosimetry in modern radiation therapy are discussed. Most of these detectors are not suitable for reference dosimetry and only ion chambers are recommended for this purpose. Even not all types of ion chambers are appropriate for reference dosimetry, and a specification of the characteristics of reference-class ion chambers to be used for the measurement of absorbed dose in megavoltage (MV) photon beams are provided in the addendum to the AAPM TG-51 protocol (McEwen et al., 2014).
The aspects of chamber performance identified in that addendum as being crucial to determining reference-class behavior are chamber stabilization, leakage current, polarity correction, recombination correction, and long-term stability. Table 3.1 gives specifications for these properties for reference-class ion chambers.

Only cylindrical chambers are recommended for reference dosimetry in high-energy photon beams, as elucidated in the addendum to the AAPM TG-51 protocol (McEwen et al., 2014), and in the International Atomic Energy Agency (IAEA) Code of Practice (IAEA, 2000). For a large number of chamber types, data required for reference dosimetry are provided in these documents. Plane-parallel chambers cannot be used for reference dose measurements in MV photon beams because their long-term stability is worse and the chamber-to-chamber variation is larger than for cylindrical chambers. However, parallel-plate chambers are useful for relative dosimetry in high-energy photon beams, for instance, for measurements in the buildup region.

Plane-parallel chambers are recommended for reference dose measurements for all electron beam qualities. In the IAEA Code of Practice, it is furthermore stated that they must be used for electron beams with incident energies lower than 10 MeV, while according to the AAPM TG-51 protocol, this threshold is 6 MeV. For electron beams with energies higher than these thresholds, cylindrical chambers may be used if appropriate gradient (effective point of measurement) corrections are taken into account.

Ion chambers for dose measurements in low-energy x-ray beams are also of the plane-parallel type. These chambers must have an entrance window consisting of a thin membrane as clarified in the low-energy x-ray dosimetry protocols (IAEA, 2000; Ma et al., 2001). Cylindrical chambers are recommended for reference dose measurements in medium-energy x-ray beams.

<table>
<thead>
<tr>
<th>Measuranda</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber settling</td>
<td>Should be less than a 0.5% change in chamber reading per monitor unit from beam-on for a warmed up machine to stabilization of the ionization chamber.</td>
</tr>
<tr>
<td>$P_{\text{leak}}$</td>
<td>$&lt;0.1%$ of chamber reading ($0.999 &lt; P_{\text{leak}} &lt; 1.001$).</td>
</tr>
<tr>
<td>$P_{\text{pol}}$</td>
<td>$&lt;0.4%$ correction ($0.996 &lt; P_{\text{pol}} &lt; 1.004$).</td>
</tr>
<tr>
<td>$P_{\text{ion}} = 1 + C_{\text{init}} + C_{\text{gen}} D_{\text{pp}}^b$</td>
<td>$&lt;0.5%$ maximum variation in $P_{\text{pol}}$ with energy (total range)</td>
</tr>
<tr>
<td>General</td>
<td>$P_{\text{ion}}$ should be linear with dose per pulse.</td>
</tr>
<tr>
<td>Initial</td>
<td>Initial recombination should be $&lt;0.2%$, that is, $C_{\text{init}} &lt; 0.002$, for the TG-51 reference conditions.</td>
</tr>
<tr>
<td>Polarity dependence</td>
<td>Difference in initial recombination correction between opposite polarities should be $&lt;0.1%$.</td>
</tr>
<tr>
<td>Chamber stability</td>
<td>Should exhibit less than a 0.3% change in calibration coefficient over the typical recalibration period of 2 years.</td>
</tr>
</tbody>
</table>


* Refer to McEwen (2010) for details on how each parameter was evaluated.

* Both initial and general recombination need to be considered.

* Value derived from data presented by McEwen (2010).

* This value is derived from calibration data from dosimetry calibration laboratories.
3.3 Traceability to Primary Standards of Absorbed Dose to Water

3.3.1 The International Measurement System

Reference dose measurements, where a protocol is used to convert the measured signal to $D_w$, the absorbed dose to water, should be accurate, reproducible, and traceable to assure tumor control and mitigate normal tissue complications. High accuracy is important because it directly influences all patient treatments with that calibrated beam. General issues related to the accuracy of dose measurements in radiotherapy are discussed in Chapter 2, while the accuracy of reference dose measurements is described in this chapter, with the emphasis on traceability to primary standards of absorbed dose.

In radiation dosimetry, primary standards dosimetry laboratories (PSDLs) developed primary standards for radiation measurement. Primary standards are instruments of the highest metrological quality, which permit determination of the unit of a quantity according to its definition, the accuracy of which has been verified by comparison with standards of other institutions of the same level, that is, with those of the BIPM, the International Bureau of Weights and Measures (Bureau International des Poids et Mesures) in Paris, France, and other PSDLs. It should always be possible to link the calibration of a detector used for reference dosimetry in a hospital back to the national primary standard of absorbed dose. This traceability consists of a chain of cross calibrations, linking one instrument to another, back to the primary standard, and helps to ensure that reference dose measurements made with different instruments across a country are compatible. International compatibility relies on a measurement infrastructure in which the various national primary standards are regularly compared in a process that is coordinated by the BIPM. In a recent comprehensive report on accuracy and uncertainties in radiation therapy, the international measurement system and the relationship between the BIPM, PSDLs, secondary standards dosimetry laboratories (SSDLs), and users have been elucidated (IAEA, 2016; van der Merwe et al., 2017).

3.3.2 Calorimeters

Because the quantity of interest in reference dosimetry is $D_w$, water calorimeters have been developed as primary standards to measure $D_w$ in x-ray and electron beams (e.g., Ross and Klassen, 1996; Seuntjens and Duane, 2009). Water calorimeters determine $D_w$ by measuring the temperature rise in water as a result of energy deposition during irradiation of a specific water volume. Graphite calorimeters have also been developed as primary absorbed dose standard because they do not need a heat defect correction, necessary because of chemical reactions in irradiated water (e.g., DuSautoy, 1996). Also the sensitive volume of a water calorimeter may increase with the duration of the measurement, which can be avoided with a graphite calorimeter (see Chapter 12). However, a conversion procedure is required for graphite calorimeters to determine absorbed dose to water, resulting in a somewhat larger total uncertainty in $D_w$ determinations. Water calorimeters are the primary standards for absorbed dose in photon beams in PSDLs in the United States, Canada, Germany, the Netherlands, and Switzerland, while graphite calorimeters are used for that purpose for photon and electron beams in the United Kingdom, France, Australia, and Italy. Ion chamber calibrations are carried
out in these PSDLs with a standard uncertainty of about 0.43% and 0.56% for water and graphite calorimeters, respectively.

With the installation of new treatment modalities, there is an increasing need that $D_w$ measurements with primary standards can be performed on-site to calibrate detectors. Portable calorimeters have been developed for this purpose for photon and electron beams (e.g., McEwen and Duane, 2000), as well as for light-ion beams (e.g., Palmans et al., 2004); issues related to the latter type of calorimeter are discussed in detail in Chapter 12. Recently VSL, the PSDL in the Netherlands, has developed a new transportable water calorimeter serving as a primary $D_w$ standard for $^{60}$Co and MV photons including magnetic resonance imaging (MRI) incorporated treatment equipment (de Prez et al., 2016). Special attention was paid to its operation in different beam geometries and beam modalities including the application in magnetic fields (Figure 3.1).

Another interesting development is the construction of probe-type calorimeters (Duane et al., 2012) such as the one shown in Figure 3.2 (Renaud et al., 2017). In the latter publication, it was demonstrated that photon-beam output measurements using the Aarrow, the ionization chamber-sized graphite calorimeter, were in agreement with chamber-based clinical reference dosimetry data within combined standard uncertainties. These devices may be used by clinical physicists as a local absorbed dose standard for high-energy photon beams, even in dosimetrically challenging situations such as in intensity-modulated radiation therapy (IMRT) and magnetic fields.

Table 3.2 shows the estimated combined standard uncertainty in $D_w$ at the reference depth in water in MV photon beams (IAEA, 2016). For most hospitals, this value will vary between 1.2% and 1.5%, while a somewhat better accuracy can be obtained if the ion chamber is calibrated in a PSDL using an accelerator having the same beam quality as the one used in the hospital.

![Figure 3.1](image_url)

The calorimeter in the vertical VSL $^{60}$Co beam (left), inside the bore of an Elekta Atlantic MRI-linac combination at UMC Utrecht, the Netherlands (top right) and in a horizontal beam orientation in front of an Elekta Versa HD accelerator at the Netherlands Cancer Institute in Amsterdam, the Netherlands (bottom-right).

3. Detectors for Reference Dosimetry

Figure 3.2
(a) A cross-sectional schematic diagram of the Aerrow design and (b) a digitally reconstructed radiograph of a microcomputed tomography scan of the prototype calorimeter showing multiple embedded thermistors and leads. (c) The comparable size of the Aerrow to that of a Farmer-type ionization chamber is illustrated by the Exradin A12 positioned alongside the probe calorimeter (internal Aerrow structure is shown as a blended rendering) and a 5 cent coin (21 mm wide) for scale. PMMA, poly-methyl-methacrylate. (Reproduced from Renaud J. et al., Med. Phys., 2017.)
3.4 Absorbed Dose Calibration and Measurement

3.4.1 Calibration of MV Photon Beams

The sensitivity of a given detector, in terms of absorbed dose to water, depends on the properties of the radiation field at the position of the detector in the phantom. For an air-filled ion chamber used in MV photon beams, the variation in sensitivity can approach 5%. Inevitably the radiation field is perturbed by the presence of the detector and, for definiteness, the calibration coefficient is defined so that the measurement is of absorbed dose at a point in the undisturbed phantom, that is, when the detector is removed. It is not practical to specify the radiation field completely in terms of the distributions in energy and in angle of electron and photon fluences. Instead, dosimetry protocols (e.g., Almond et al., 1999; IAEA, 2000; McEwen et al., 2014) specify reference conditions under which measurements must be made. The conventional conditions for MV photon beams are the following:

1. A unidirectional beam is normally incident on a full scatter rectangular water phantom.
2. The beam is collimated to produce a 10 cm × 10 cm field in the plane of measurement.

Table 3.2 Estimated Combined Standard Uncertainty in $D_w$ at the Reference Depth in Water in Megavoltage Photon Beams

<table>
<thead>
<tr>
<th>Physical Quantity or Procedure</th>
<th>Relative Standard Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SSDL Co-60</td>
</tr>
<tr>
<td>Step 1: Standards laboratory</td>
<td></td>
</tr>
<tr>
<td>$N_{D,w}$ calibration of the secondary standard</td>
<td>0.5</td>
</tr>
<tr>
<td>Long-term stability of the secondary standard</td>
<td>0.1</td>
</tr>
<tr>
<td>$N_{D,w}$ calibration of the used dosimeter at the standards laboratory</td>
<td>0.4</td>
</tr>
<tr>
<td>Combined uncertainty of Step 1</td>
<td>0.6</td>
</tr>
<tr>
<td>Step 2: Hospital</td>
<td></td>
</tr>
<tr>
<td>Long-term stability of user dosimeter</td>
<td>0.3</td>
</tr>
<tr>
<td>Establishment of reference conditions</td>
<td>0.4</td>
</tr>
<tr>
<td>Dosimeter reading relative to timer or beam monitor</td>
<td>0.6</td>
</tr>
<tr>
<td>Correction for influence quantities</td>
<td>0.4</td>
</tr>
<tr>
<td>Beam quality correction</td>
<td>1.0a</td>
</tr>
<tr>
<td>Combined uncertainty of Step 2</td>
<td>1.3</td>
</tr>
<tr>
<td>Combined standard uncertainty in $D_w$ (Steps 1 and 2)</td>
<td>1.5</td>
</tr>
</tbody>
</table>


Note: $N_{D,w} =$ absorbed dose to water calibration coefficient, $D_w =$ absorbed dose to water.

PSDLs, primary standards dosimetry laboratories; SSDLs, secondary standards dosimetry laboratories.

a Calculated values.
b Measured values normalized to $^{60}$Co.
3. The measurement point is on the central axis at a specified depth, usually 5 or 10 g/cm².
4. The beam has a nominally flat profile.
5. Beam quality is parameterized in terms of its penetrating power using a quality index such as \(\%d_{10,0,X}\) or \(\text{TPR}_{20,10}\) as defined in dosimetry protocols.
6. Ion chamber readings are corrected to standard air density, for example, 20°C and 1013.25 mbar, to 50% relative humidity, and for saturation.

Of these conditions, 1–4 are intended to control the proportion of scattered to primary photons, and to ensure that there is at least transient charged particle equilibrium (CPE) at the point of measurement. The use of a beam quality index (5) is intended to deal with most of the variation in sensitivity of a given ion chamber from one MV beam to another. The correction for saturation in (6) is required in case the dose rate differs between calibration and use. After applying the corrections listed in (6), readings taken with a reference-class ion chamber can show long-term consistency of the order 0.1%. This level of consistency is significantly better than the combined standard uncertainty when the readings are expressed in terms of absorbed dose to water, which is usually not better than 0.5%, and dominated by the uncertainty of calibrations in the traceability chain and the uncertainty of the primary standard itself, as discussed above.

Conditions (2) and/or (4) cannot be met in beams produced by certain machines, and in this case it is necessary to specify a machine-specific reference field (Alfonso et al., 2008) as discussed in Section 3.4.3. Even when the absorbed dose calibration coefficient is expressed in terms of a beam quality index as specified in (5), there remains a small residual variation in ion chamber sensitivity from one MV beam to another. This variation may, for instance, be up to 0.5% between flattening filter free (FFF) and flattened beams. Although small, this variation illustrates that beam quality index and beam quality are distinct concepts. It turns out that the field size specification in (2) is crucial in the measurement of the beam quality index, because both \(\%d_{10,0,X}\) and \(\text{TPR}_{20,10}\) are strongly dependent on field size. However the beam quality, that is, the energy spectrum of the electron fluence, is much less sensitive to field size, and so the chamber calibration coefficient is also relatively insensitive to field size, provided that the field does not qualify as a small field.

### 3.4.2 Calibration of FFF Beams

Fano’s theorem (Bouchard et al., 2012) is a great help in understanding the response of ion chambers under conditions of CPE. An analysis based on cavity theory shows why the chamber cavity does not significantly perturb the equilibrium electron fluence, so that the water-to-air mass-stopping power ratio accounts for almost all of the observed quality dependence of ion chamber sensitivity. Full CPE is never achieved in practice because of the attenuation of primary photons, but lateral CPE exists in the interior of a large flat field and is enough to prevent disequilibrium effects provided the chamber is entirely contained within the flat part of the field.

In the case of FFF beams, there is a lateral dose gradient that increases with distance from the central axis, and this creates a small amount of lateral disequilibrium in the electron fluence. As a result, the chamber cavity slightly
perturbs the electron fluence, even on the central axis of the reference field. The effect is qualitatively identical to what happens when a small field is reduced to the point where the penumbrae begin to overlap an air-filled ion chamber used on the central axis. This fluence perturbation combines with volume averaging to further reduce the response of the ion chamber, compared to its response in a flat field of the same beam quality. This should be considered whenever a reference ion chamber is calibrated in a flat beam and then used in an FFF beam, particularly if the cavity length is comparable to that of a Farmer-type chamber.

The associated higher dose rates and doses per pulse of FFF beams improve treatment delivery efficiency but may need larger corrections for recombination and polarity behavior of ion chambers. In a recent study, several models of small-volume ion chambers have been shown to meet reference-class requirements with respect to ion recombination and polarity, even in a high dose rate environment (Hyun et al., 2017). However, the results of his study also emphasize the need for careful reference detector selection, and indicate that ion chambers ought to be extensively tested in each beam of interest prior to their use for reference dose measurements.

3.4.3 Calibration of Beams of Other Types of Treatment Modalities

There is an increasing number of treatment modalities for which it is impossible to meet the conditions under which reference dose measurements must be made in the way described in dosimetry protocols. For reference dosimetry of photon fields delivered by a Gamma Knife, CyberKnife, or Tomotherapy unit, machine-specific reference fields are used (Alfonso et al., 2008). The absorbed dose to water can then be derived from a detector reading by the introduction of a correction factor accounting for the detector’s difference in dose response between the conditions of field size, geometry, phantom material, and beam quality of the conventional reference field and the machine-specific reference field. Details of this approach and values for that correction factor for a number of detectors are provided in Chapter 9.

As shown in Chapter 26, the emerging field of MR-guided radiotherapy requires the presence of strong magnetic fields that can affect the performance of most conventional dosimetry systems. In that chapter, the magnitude of the effect of a magnetic field on the response of a number of detectors can be found, while in an earlier section of this chapter, the use of a water calorimeter for reference dosimetry in an MR-Linac is described (Figure 3.1). Reference dosimetry using ion chambers can be performed in the presence of strong magnetic fields with the use of magnetic field correction factors. Recently, data have been reported by O’Brien et al., (2016) for a number of cylindrical ion chamber models in a 1.5 T magnetic field. These authors showed that chamber magnetic field correction factors are smaller than 1% for reference-class Farmer-type chambers when the chambers are aligned parallel with the magnetic field lines, but can reach 4%–5% depending on the orientation. It was also observed that the TPR_{20/10} beam quality specifier is robust in the presence of magnetic fields. However, the %d_{0,X} beam quality index cannot be measured directly because of SSD restrictions and changes in the dose distribution in the build-up region, but can be derived from the TPR_{20/10} value using a conversion factor. O’Brien and colleagues also observed...
that even small air gaps around an ionization chamber altered the reading of the instrument, and therefore recommended that nonwater phantoms should not be used for reference dose measurements.

Absolute calibration of beams of low-energy x-rays used in small animal irradiation platforms is discussed in Chapter 24. As shown in that chapter, the reference dose measurements described in low-energy x-ray dosimetry protocols (IAEA, 2000; Ma et al., 2001) are not directly applicable to the potentially very small fields from these novel irradiation platforms. These dosimetry protocols recommend a calibration field size of 10 cm × 10 cm, which is impractical for precision animal irradiators. Instead, often a field of 4 cm × 4 cm is used, requiring various correction and conversion factors, some of which need to be inter-/extrapolated from the tables provided in these dosimetry protocols. A number of issues related to dose measurements in small-field animal irradiators are also valid for measurements in synchrotron microbeams, as explained in Chapter 25.

As discussed in Chapter 12, calorimeters are in principle also in light-ion beams the primary instruments for reference dose measurements. Although for photon and electron beams there is sufficient knowledge of the chemical heat defect to ensure a high accuracy, limited information is available of the chemical heat defect in light-ion beams due to its complicated linear energy transfer (LET) dependence. The more common instruments to perform reference dosimetry in light-ion beams are therefore air-filled ion chambers, having only small variations of their response as a function of energy in the clinical energy range. However, the energy dependence of the mean energy required to produce an ion pair in air, the correction for fluence perturbation, and the variation of the stopping power ratio water-to-air with LET cannot be ignored if a high accuracy is required, as will be elucidated in Chapter 12.

Several groups have developed calorimeters for absorbed dose rate measurements close to high dose rate 192Ir brachytherapy sources (Sarfehnia and Seuntjens, 2010; Guerra et al., 2012; Sander et al., 2012). Although such an approach gives an improvement in the combined standard uncertainty in the absorbed dose rate to water at a distance of 1 cm, the brachytherapy community is reluctant to change their practice of using an air kerma-based calibration method. The reason for this is that for specifying source strength using calorimetry, several changes would be needed to clinical treatment planning systems. Also, the decreased uncertainties are not substantial when the big picture of clinical procedures is considered. Finally, it is not that easy to deliver such an absorbed dose standard for sources other than 192Ir.

3.5 Practical Issues Related to Absolute Dose Measurements

3.5.1 Beam Quality Correction

Calibration of a machine’s output will ideally be made with an ion chamber that has been cross-calibrated in the same user beam, in order to avoid the need for a quality-dependent correction. However, that cross-calibration will require the use of a reference ion chamber, which will usually have been calibrated in another beam, and its calibration may require a quality-dependent correction. That correction factor, \( k_{Q,0} \), may be available as a function of a beam quality index such as \( %d_{10,X} \) or \( TPR_{20,10} \) as discussed in the various dosimetry protocols. The required
quality index must have been measured for the user beam and also be known for the calibration beam. However, the quality index is not sufficient to completely specify beam quality and additional care may be required in transferring the calibration of a detector from one beam to another, as discussed in a previous section of this chapter.

3.5.2 Ion Chamber Corrections and Influence Quantities

The effect of ion recombination is reduced if the polarizing voltage is increased; however, at some point charge multiplication sets in and leads to nonlinear behavior in a Jaffe plot of the inverse of the chamber reading against the inverse of the polarizing voltage (e.g., McEwen, 2010). This is not a disadvantage in relative dosimetry, because the charge multiplication is essentially independent of dose rate and so cancels when taking the ratio. However in reference dosimetry, it is essential to correct for ion recombination, and the validity of the correction should be demonstrated by using a Jaffe plot to show that the operating voltage is within the linear region. For this reason, one might choose a smaller polarizing voltage when a chamber is used for reference dosimetry compared to relative dosimetry. The polarity effect is usually small (or negligible) in photon-beam measurements, but should be checked if the chamber used has a very small volume.

The chamber must be vented in order for the air pressure in the cavity to reach equilibrium with the measured ambient pressure. A chamber will usually reach thermal equilibrium in a reasonably short time when used in water. This process may be slower in a solid phantom, if used, and a solid phantom must be left to reach a stable temperature before starting measurements.

Thimble chambers have better dimensional stability than parallel-plate (electron) chambers. Graphite-walled chambers can have particularly good long-term stability, but if a waterproof chamber is used directly in water, there may be a risk of the thimble distorting through absorption of water if the chamber is left in water for an extended period.

3.5.3 Phantoms Used for Absolute Dose Measurements

Absolute dose calibration is generally performed with a traceable calibrated ionization chamber and electrometer in a scanning water system or a small calibration water phantom. The latter types of water phantom are generally preferred due to their ease of setup and their ability to accommodate larger ion chambers such as Farmer-type chambers, as discussed in Chapter 15.

The TG-51 absorbed dose protocol (AAPM, 1999) as well as the IAEA code of Practice (IAEA, 2000) have made the use of liquid water as a phantom material for reference dosimetry mandatory for reasons of phantom material reproducibility. Also, the more recent addendum to the TG-51 protocol (McEwen et al., 2014) upholds the recommendation that a water phantom must be used for the output calibration of high-energy photon beams. As mentioned in that addendum, the main advantage of solid phantoms is in the ease of setup, but this is countered by the uncertainty in the correction factor to convert from dose in plastic to dose in water. Despite the developments in the formulation of water equivalent phantoms that have been documented in the literature, for example, Seuntjens et al. (2005), the additional uncertainty in using such materials still negates any ease-of-use issue.
3.6 Summary and Future Developments

In this chapter, detectors used for reference dosimetry are reviewed. After discussing a number of properties of reference-class ion chambers, the traceability of a calibration of these chambers, that is, the link to primary standards of absorbed dose is discussed in detail. Special attention is paid to the role of calorimeters in reference dosimetry. Details of the absorbed dose calibration and measurement process, including the calibration in FFF beams, as well as a number of practical issues related to reference dose measurements, are also given in this chapter.

New developments can be anticipated in reference dose measurements of treatment modalities for which it is difficult to meet the conditions described in dosimetry protocols. For instance, for reference dosimetry in light-ion beams, as well as in photon beams in the presence of strong magnetic fields, improvement of existing procedures might be expected when new data become available. An interesting development is also the use of probe-type calorimeters for reference dosimetry purposes.

References
