Determination of absorbed dose calibration factors for therapy level electron beam ionization chambers

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Abstract

Over several years the National Physical Laboratory (NPL) has been developing an absorbed dose calibration service for electron beam radiotherapy. To test this service, a number of trial calibrations of therapy level electron beam ionization chambers have been carried out during the last 3 years. These trials involved 17 UK radiotherapy centres supplying a total of 46 chambers of the NACP, Markus, Roos and Farmer types. Calibration factors were derived from the primary standard calorimeter at seven energies in the range 4 to 19 MeV with an estimated uncertainty of ±1.5% at the 95% confidence level. Investigations were also carried out into chamber perturbation, polarity effects, ion recombination and repeatability of the calibration process. The instruments were returned to the radiotherapy centres for measurements to be carried out comparing the NPL direct calibration with the 1996 IPEMB air kerma based Code of Practice.

It was found that, in general, all chambers of a particular type showed the same energy response. However, it was found that polarity and recombination corrections were quite variable for Markus chambers—differences in the polarity correction of up to 1% were seen. Perturbation corrections were obtained and were found to agree well with the standard data used in the IPEMB Code. The results of the comparison between the NPL calibration and IPEMB Code show agreement between the two methods at the ±1% level for the NACP and Farmer chambers, but there is a significant difference for the Markus chambers of around 2%. This difference between chamber types is most likely to be due to the design of the Markus chamber.

1. Introduction

Over several years the National Physical Laboratory (NPL) has been developing an absorbed dose calibration service for electron beam radiotherapy. This is based on the primary standard electron-beam graphite calorimeter and yields a direct calibration of an ionization chamber in terms of absorbed dose to water (Burns et al 1994, McEwen et al 1998). This calibration is a two-step process. First, reference ionization chambers are calibrated against the calorimeter...
in a graphite phantom. User chambers are then compared with the NPL reference chambers in a water phantom. The uncertainty in such a calibration is approximately ±1.5% at the 95% confidence level, representing a significant improvement over air kerma based protocols.

To test this service, a number of trial calibrations of electron beam ionization chambers have been carried out during the last 3 years. These trials involved 17 UK radiotherapy centres supplying a total of 46 chambers. All chamber types recommended in the IPEMB Code of Practice (1996) were calibrated. These are the NACP-02 manufactured by Scanditronix (Mattsson et al 1981, NACP 1981), the Markus design (Markus 1973) manufactured by PTW (type 23343), the NE2571 Farmer-type chamber manufactured by NE Technology Ltd and the Roos design manufactured by PTW (type 34001). In addition, two other graphite-walled Farmer-type chambers were calibrated—the NE2505/3 and the PTW 30004. During this programme of work, Wellhöfer released a version of the Roos chamber (type PPC35) and a reduced set of measurements were made on a number of these chambers.

Calibration factors were derived from the primary standard calorimeter at seven energies in the range 4 to 19 MeV. After calibration, the radiotherapy centres were asked to carry out measurements comparing the NPL absorbed dose to water calibration protocol with the IPEMB Code of Practice for electron beam dosimetry (IPEMB 1996).

2. Determination of absorbed dose-to-water calibration factors

McEwen et al (1998) describe the theory in detail. The absorbed dose to water calibration factor for a user chamber, \( N_{\text{user},w} \), is given by:

\[
N_{\text{user},w} = N_{\text{ref},g} \frac{M_{\text{ref},w}}{M_{\text{user},w}} \frac{p_{\text{ref},w}}{p_{\text{ref},g}} \frac{s_{w/\text{air}}}{s_{g/\text{air}}}
\]  

(1)

This equation has four components:

- \( N_{\text{ref},g} \)—the graphite calibration factor for the NPL reference chamber (taken as the mean response of four chambers).
- \( M_{\text{ref},w} / M_{\text{user},w} \)—the ratio of reference and user chamber measurements in water.
- \( p_{\text{ref},w} / p_{\text{ref},g} \)—the ratio of perturbation corrections in water and graphite for NPL reference chambers.
- \( s_{w/\text{air}} / s_{g/\text{air}} \)—the effective stopping power ratio, water to graphite, taking into account the air volume of the chamber.

The graphite calibration factor, \( N_{\text{ref},g} \), has been determined over the last 3 years by comparing the NPL reference chambers (type NACP-02) with the primary standard electron-beam graphite calorimeter, and this work is detailed by McEwen et al (1998).

The IAEA Code of Practice for parallel plate chambers (IAEA 1997) provides a review of chamber perturbation factors, detailing the problems, as does Nahum (1996). It is generally believed that a well-guarded parallel-plate chamber such as the NACP design has a negligible perturbation. However, equation (1) allows for a perturbation in both graphite and water for the reference chamber and Monte Carlo simulations were carried out to determine the perturbation corrections in both media (Williams et al 1998).

Stopping powers are determined following the procedure proposed by Burns et al (1995), which combines measurements of electron depth-dose curves in water and graphite with Monte Carlo calculations of the full experimental geometry. This work is described in detail by DuSautoy (2000).
3. The calibration process

3.1. Ratio of chamber measurements

The method used to derive the final component of equation (1) was a direct comparison of the user chamber and NPL reference NACP-02 chambers in a water phantom in the NPL Linac beam. The water phantom was specially designed to position each chamber at the correct depth for each of the standard NPL beam qualities. The reference depth, \( d_{\text{ref}} \), is defined by Burns et al (1996) as \( d_{\text{ref}} = 0.6 R_{50} - 0.1 \) cm, where \( R_{50} \) is the depth at 50% of the peak dose. These measurements were carried out at a source-to-surface distance (SSD) of 2 m with a field size of 15 cm \( \times \) 15 cm. Other relevant Linac parameters were a pulse repetition frequency of 240 Hz and a dose per pulse of around 0.08 mGy (for all energies).

The NPL linear accelerator is a 3 to 20 MeV research accelerator and the collimation and geometry are quite different from those of a medical accelerator. However, comparisons of depth–ionization measurements together with Monte Carlo simulations have shown that measurements made in the NPL electron beam should be equivalent to those made in clinics (Burns et al 1996).

An NPL designed computer-controlled acquisition system was used for all the measurements. The PC system meant that it was possible to monitor each chamber to make sure that equilibrium had been reached. A transmission monitor was used as the transfer instrument between chambers and corrections were made for temperature and pressure as well as polarity and recombination.

3.2. Additional measurements

3.2.1. Check source measurements. All chambers were tested before and after calibration using a simple check source system. The source used for the parallel-plate chambers is the PTW type supplied with Markus chambers—a small modification to the Perspex source/chamber holder makes it suitable for both Markus and NACP chambers; a second holder was modified for the Roos chamber. The source is only 5 mm in diameter to match the Markus chamber and therefore the irradiation of the NACP and Roos chamber is not uniform. This system has been used for over 5 years to monitor the stability of the NPL reference chambers and has shown good reproducibility at the \( \pm 0.25\% \) level. An NE2503 check source was used for the Farmer chambers. After correction for source decay and temperature and pressure, the chambers showed random differences (maximum 0.3%) between the before and after measurements, most probably due to relative positioning of the source and chamber.

3.2.2. Recombination measurements. During the trials a full characterization of each chamber’s recombination response was carried out. The polarizing voltage was varied for each chamber between the calibration voltage and around 30 V in four steps (e.g. 250, 125, 75, 30) and the first voltage repeated to correct for any measurement drift. The recombination correction was obtained from a plot of the reciprocal of the ionization current against the reciprocal of the polarizing voltage. For a chamber following the Boag theory such a plot should be a straight line and a linear extrapolation of this line to infinite voltage gives the true ionization current (i.e. no ion recombination). One advantage of the NPL Linac is that it is straightforward to change the dose per pulse by changing the beam current while keeping the energy and pulse repetition frequency the same. By making measurements at a number of values of dose per pulse one can derive an equation that gives the recombination correction at any dose per pulse. This simplifies measurements in the clinic since one does not need to carry out recombination measurements as long as one knows the dose per pulse.
3.2.3. Electrometer calibration. User electrometers were calibrated by using a calibrated voltage standard and calibrated capacitor to inject a known amount of charge. As this method does not directly mimic the operation in a radiation beam an investigation was carried out to compare this method with a calibration using a current source. There was no evidence of any difference between the two methods and therefore the calibration will be valid for use in the clinic.

3.3. Radiography of chambers

Radiographs are a simple but powerful way to check the construction of an ion chamber and new chambers are now routinely radiographed at NPL. Figure 1 shows side-on radiographs of a Scanditronix and a Dosetek NACP chamber. As can be seen, the Dosetek chamber has the collector wire passing through the air volume and almost touching the HT electrode, which would significantly affect the chamber’s performance. Whether all Dosetek-manufactured NACP chambers follow this design remains to be seen, and Dosetek have now ceased production. As stated above, all the NPL reference chambers are manufactured by Scanditronix. Although radiographs are simple to carry out, parallel-plate chambers are generally constructed from low-Z plastic materials and it can be a matter of trial and error to obtain sufficient contrast to identify the various components. Klevenhagen (1993) gives a description of a large number of electron chambers, together with constructional diagrams.

3.4. Analysis

Since three of the four components in equation (1) have been previously determined, the analysis required to determine chamber calibration factors is fairly straightforward. Rather than rely on one chamber to obtain the user chamber calibration factor, the mean response of all four NPL reference chambers was taken for the value for \( M_{\text{ref},u} \) in equation (1). Since only initial results were available from the calculations to obtain the ratio of perturbation factors, it was decided to use the best value from the literature—a value of unity—although this may need to be revised if future work indicates a non-zero perturbation.
3.5. Uncertainty

The various components of equation (1) contribute to the uncertainty in the calibration of a user chamber in terms of absorbed dose to water. The uncertainties for all energies (quoted as standard uncertainties according to UKAS 3003 (UKAS 1995)) are given in table 1.

This gives an overall uncertainty in $N_{\text{user},w}$ of ±1.5% at the 95% confidence level. Further work is in progress to improve the calorimeter’s performance and determination of the stopping power ratios and perturbation factors. It is hoped that once this work is finished the overall uncertainty will be around ±1% at the 95% confidence level.

4. Results and discussion of measurements made at NPL

4.1. Calibration factors

Examples of calibration factors for all four types of chamber are shown in table 2. For convenience, a number of abbreviations are used in the following discussion. Individual chambers are designated by their serial number and the following prefixes: N, Scanditronix NACP; M, Markus; R, Roos; F, Farmer.

4.2. Chamber construction

4.2.1. NACP chambers. Figure 2 shows the relative response of each NACP chamber compared with one NPL chamber, N30-09, in a 6 MeV electron beam. This relative response corresponds to the relative volumes of the chambers. Assuming that serial numbers are chronological, there is a significant change (of some 15%) between chambers N29-05 and N31-04. Radiographs show a difference in the design of the polystyrene backing to the collector between these two chambers and therefore the volume change may be due to this design change. Comparisons made to date indicate that it is not necessary to consider these two designs as...
separate chamber types. Also shown in figure 2 are the equivalent data obtained from $^{90}$Sr check-source measurements. As can be seen, there is a good correlation between the Linac and $^{90}$Sr results, except for one chamber (N41-03), for which there is no obvious explanation. In a broad electron beam (as from the Linac) the chamber volume is defined by the chamber diameter and plate separation. However, in the $^{90}$Sr measurements, the source diameter is smaller than the cavity diameter and therefore the effective measurement volume is less dependent on the chamber diameter. One possibility therefore is that for N41-03 the cavity volume is the same as other NACP chambers, but the plate separation is larger. However, measurement of the recombination correction, which is directly dependent on the plate separation, did not confirm this.

4.2.2. Markus chambers. Figure 3 shows results for Markus chambers analysed in the same way as for the NACP chambers. There is an apparent trend with serial number (again assuming chronological numbering) for the 6 MeV data but it is small (of the order of $\pm 2\%$). No equivalent trend is seen in the $^{90}$Sr results. The difference may be due to scatter effects of the chamber body in a broad electron beam. The spread in chamber volumes is significantly smaller than for NACP chambers, indicating tighter manufacturing tolerances.

4.2.3. Farmer chambers. Three types of Farmer chamber were calibrated—the NE2571, the NE2505/3 (an older version of the NE2571) and the PTW 30004. All chambers have a graphite cap and solid aluminium electrode. The stem of the NE2571 is guarded to within 26 mm of the air volume, whereas the NE2505/3 has less of the stem guarded. In the PTW design the guard extends to within 10 mm of the air volume and there appears to be a larger area of unguarded insulator close to the air cavity. Production of the NE2505/3 ceased in 1979 and it is unlikely that there are many such chambers in regular use.

There were not enough chambers of the NE2505/3 or PTW30004 type to draw any conclusions on chamber construction. However, there was a significant set of NE2571 chambers. If one assumes that the serial numbers are chronological then there seems to be a slight trend of increasing chamber volume over time, although the change is only 0.8% from
the earliest to the latest and there are random chamber-to-chamber differences of a similar magnitude. This indicates good manufacturing tolerances and is probably the reason for the close agreement of the calibration factors for these chambers. The equivalent $^{90}$Sr data showed a much larger spread in the chamber ratios relative to one chamber, which is most likely to be due to the design of the check source.

4.3. Chamber performance

Taking the data for each NACP chamber relative to the mean response of the NPL reference chambers and normalizing for volume yields the relative deviation in energy response for that chamber, as in figure 4. Some chambers seem to show better agreement with the NPL chambers than others. The deviations in energy response (typically ±0.2%) appear to be random and are probably due to variations in Linac output or positioning of the chamber (which becomes more critical at low energies). The NACP chambers that were calibrated more than once during the trials showed changes of the order of ±0.2%, which is consistent with results from the NPL reference chambers. The energy dependence of the NACP calibration factor was compared with that given in the TG-51 absorbed dose protocol (AAPM 1999). Differences were generally less than 0.3%, which is encouraging since the TG-51 factors are based on calculation and not an absorbed dose electron beam standard.

The data for PTW Roos chambers shown in figure 5 indicate a slight energy dependence (i.e. perturbation correction) of approximately 0.2% over the range 4–19 MeV. However, since the measurements are relative to the NACP, it is not possible to say which chamber type has the non-zero perturbation. An analysis of the chamber designs would conclude that it is more likely that the Roos chamber has the zero perturbation correction. Results by Nilsson et al (1996) showed a similar energy response comparing the Roos and NACP chambers. Initial results indicate that Wellhofer Roos chambers have a similar energy response.

The results for the Markus chambers (figure 6) are reasonably consistent at the ±0.3% level, although one might expect smaller variations at high energies than seen here. There is also some indication that the variations from a smooth curve are systematic but this is not conclusive, and recalibration of Markus chambers showed changes in calibration factors of the
Figure 4. Energy response of NACP chambers relative to the mean response of NPL NACP reference chambers.

Figure 5. Energy response of PTW Roos chambers relative to the mean response of NPL NACP reference chambers.

order of ±0.2%. One of the problems of using a Markus chamber in water is that one needs to use the PMMA waterproof cap. Variations in the thickness of this cap will affect the results, especially at low energies. As can be seen from figure 6, the largest chamber-to-chamber variations are found at the lowest energies. However, differences in chamber construction could also produce such variations.

It was believed, from the literature and from measurements on NPL chambers, that Farmer chambers were very stable and reproducible in their response. This design of chamber has been around for some time and there is a large degree of confidence in the design. The results shown in figure 7 confirm this view on repeatability. As in the case of the other chamber types, the data are normalized to remove the chamber volume and therefore show the energy response of each chamber relative to the NACP. All 11 chambers calibrated show the same
Figure 6. Energy response of Markus chambers relative to the mean response of NPL NACP reference chambers. ‘Ideal behaviour’ is derived from published data on the Markus perturbation correction.

Figure 7. Energy response of graphite-walled Farmer chambers relative to the mean response of NPL NACP reference chambers. ‘Ideal behaviour’ is derived from published data on the Farmer perturbation correction.

energy response within ±0.15% (only five are shown in figure 7 for clarity). No particular orientation of the Farmer chambers was used and the data suggest that this is not an issue in the response of these chambers in electron beams. Radiographs of NPL Farmer chambers have shown that the central electrode was not always straight, and this would affect the electric field within the air cavity and possibly the effective point of measurement. Since no rotational dependence was observed, the effect of a non-straight central electrode must be small.
4.4. Chamber perturbation

The Roos chamber was used in a test of the NACP perturbation correction. The Roos chamber is specifically designed to have a perturbation correction in water very close to unity. The chamber is constructed entirely of PMMA (except for the graphite coatings of the electrodes) and has very little material behind the collector electrode (∼1 mm). One concern raised by Klevenhagen (1991) was that the large amount of graphite behind the collecting electrode in the NACP chamber could lead to a backscatter correction since graphite is backscatter deficient compared with water and a figure of up to 0.6% has been quoted. However, measurements by Nilsson et al. (1996) indicate that the effect is less than 0.3%. Measurements by Hunt et al. (1988) and McEwen et al. (1998) have shown that the backscatter contribution to the chamber reading is almost entirely due to the first few millimetres of material behind the cavity. A graphite disc was manufactured to fit into the recess at the rear of the Roos chamber and effectively simulate the construction of the NACP chamber. Measurements were carried out in water at a number of electron energies (with the chamber positioned at the reference depth) and the response of the chamber was compared with and without this graphite disc in place. At all energies there was a small but noticeable difference between the measurements made with and without the graphite backing:

\[
\frac{M_{\text{water behind}}}{M_{\text{graphite behind}}} = 1.0010 \pm 0.0002
\]

with \( M \) being the chamber reading (corrected for temperature and pressure). There was no energy dependence over the range 4 to 16 MeV. One would expect the reading with graphite to be less since the backscatter contribution for graphite is less than that for water. One difference that could not be modelled in this experiment is that the Roos chamber is constructed from PMMA while the NACP is graphite and polystyrene. There is polystyrene directly behind the collecting electrode and it is more backscatter deficient than PMMA. Therefore, although this is not a definitive measurement of the perturbation correction of the NACP chamber it does suggest an upper limit on the backscatter effect of 0.2%, which is closer to the result reported by Nilsson et al. (1996) than by Klevenhagen (1991). It is more difficult to measure the perturbation effect of the air cavity, although unpublished measurements by Roos (1993) in developing that chamber have indicated that a well-guarded parallel-plate chamber (such as the Roos and NACP designs) has a negligible cavity perturbation. As stated earlier, Monte Carlo calculations are in progress at NPL to determine the total perturbation correction of the NACP chamber. Williams et al. (1998) showed that the effect of the air cavity in both water and graphite was small and could not be distinguished from unity within the uncertainties.

Also shown in figure 6 of the measured Markus energy response relative to a NACP chamber is the Markus perturbation correction as given in the IPEMB Code of Practice (IPEMB 1996). This is derived from the work of Van der Plaetsen et al. (1994) and, as can be seen, there is very good agreement between that work and these measurements. This is only true as long as polarity corrections are applied. If one does not apply polarity corrections (i.e. if one assumes that the polarity correction is the same for all chambers of a particular type) then there is an apparent difference in the perturbation correction for different chambers.

Similarly, the perturbation correction for the Farmer chamber, as given in the IPEMB Code of Practice (based on the work of Johansson et al. (1978)) is plotted in figure 7 of the Farmer energy response. The difference between this published behaviour and the data acquired in this work is less than 0.2%. This is very encouraging since the perturbation correction is derived at the peak of the depth dose curve, which doesn’t correspond exactly with the reference depth used here.
### Table 3. Comparison of polarity corrections. The correction is to the reading taken with negative polarizing voltage.

<table>
<thead>
<tr>
<th>$R_{50, D}$ (cm)</th>
<th>Parallel-plate chambers</th>
<th>Farmer chambers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Markus (I)</td>
<td>Markus (II)</td>
</tr>
<tr>
<td>1.23</td>
<td>0.9974</td>
<td>0.9956</td>
</tr>
<tr>
<td>1.97</td>
<td>0.9935</td>
<td>0.9889</td>
</tr>
<tr>
<td>2.75</td>
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<td>0.9888</td>
</tr>
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</tr>
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<td>4.23</td>
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<td>1.0004</td>
</tr>
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<td>5.72</td>
<td>0.9932</td>
<td>0.9949</td>
</tr>
<tr>
<td>6.60</td>
<td>0.9970</td>
<td>0.9954</td>
</tr>
</tbody>
</table>

### 4.5. Recombination and polarity

Several authors (Burns 1991, Havercroft and Klevenhagen 1993, Burns and Burns 1993, Nisbet and Thwaites 1998) have indicated that NACP chambers can exhibit a response to changes in polarizing voltage that is not predicted by the accepted Boag (1950) theory. This will therefore affect the evaluation of the recombination correction. The problem does not appear to be unique to the NACP chamber, nor indeed to parallel-plate chambers; Derikum and Roos (1993) noted similar effects for some cylindrical chambers. In the course of characterizing the NPL reference chambers, a large number of recombination measurements were made over a range of dose per pulse values and Burns and McEwen (1998) describe this work in detail. The trials enabled their work to be extended to a much larger sample of chambers and confirmed these earlier results. A number of chambers showed nonlinear behaviour at polarizing voltages above about 100 V, although all chambers showed a linear relation between recombination correction and dose per pulse. Ideally, one would like to assign a mean recombination response to each chamber type, but the fact that a number of chambers showed ‘non-ideal’ behaviour confirms the need for characterizing individual chambers rather than relying on a mean response. All the Farmer chambers exhibited close to ‘ideal’ behaviour and gave very similar recombination corrections.

The results of the polarity measurements shown in table 3 are interesting in that there are marked differences between chamber types. For NACP chambers the polarity corrections are very similar for all chambers so that it is possible to define a generic correction. This is also true for the Roos chambers (PTW and Wellhofer types appear to be identical). However, for the Markus chambers there are significant differences between chambers of up to 0.5%. The reason for this is not clear, although it may be due to the insulating properties of the PMMA body of the chamber. These measurements show that it is important to measure the polarity correction for each individual chamber and not assume that all chambers of the same type behave in the same way. All three types of Farmer chamber calibrated also exhibit different polarity effects. The difference between the NE2505/3 and NE2571 types is presumably due to a slight difference in the guarding arrangement (more of the stem is guarded in the NE2571). It is likely that the difference in the polarity correction for the PTW Farmer is also due to constructional differences (e.g. charge build-up on the insulator).

### 4.6. Electrometer performance

Nine different types of electrometer were calibrated as part of this investigation including NE2570, NE2610, NE2670, PTW Unidos and Keithley 35040. All electrometer types
exhibited linear behaviour at the ±0.05% level and absolute accuracy of the order of ±0.1%. No single type stood out as the ‘best’. One may question the validity of calibrating the chamber and electrometer separately, since they will be used together. One good reason for separate calibrations is that, often, one electrometer is used with a number of chambers, so it would be inconvenient to calibrate it with every chamber. An IPEM Working Party is currently looking at recommendations for electrometers with the aim of producing a specification for a secondary standard instrument (IPEM 2000).

5. Procedure for comparing NPL calibration with IPEMB Code of Practice in centres

Each centre received the calibration data for their chamber together with a brief procedure to derive absorbed dose measurements. One significant difference from the IPEMB Code of Practice is in the definition of reference depth—the IPEMB code defines the reference depth as $d_{\text{max}}$ or $0.5R_{50}$, whichever is the greater. This difference in $d_{\text{ref}}$ means that centres must correct from one depth to another to compare the absorbed dose calibration with the IPEMB code. By using measured depth-dose curves, the uncertainty in this correction should not be significant.

6. Results and discussion of measurements made by centres

Comparisons of the NPL calibration and the IPEMB Code of Practice for NACP and Markus chambers are given in figure 8, and for Farmer chambers in figure 9. The results are expressed as dose(NPL)/dose(IPEMB) and the $R_{50}$ values shown correspond to the clinical beams used. The various centres are not identified, to prevent bias in interpreting the results. There are no data at present from the centres for Roos chambers.

Considering the NACP data first in figure 8, the agreement looks promising. The ratio NPL/IPEMB is within 1% of unity and there is little indication of a trend with energy. These results are in agreement with measurements made at NPL comparing the two procedures.
Figures 9. Comparison of doses derived using the NPL calibration factor and the IPEMB Code of Practice for graphite-walled Farmer chambers, expressed as NPL/IPEMB. Each line represents a different chamber.

(McEwen et al. 1998), which indicated that the new method should result in doses approximately 1% higher than the IPEMB Code. Indeed, one might expect agreement for NACP chambers since they are the same as the NPL reference chambers and are of a well-guarded design. The results for the Markus chambers are not so encouraging, showing a NPL/IPEMB ratio significantly greater than unity and a trend with energy. The results of the comparison for Farmer chambers, as shown in figure 9, indicate agreement at the ±1% level, although the results are somewhat variable. The spread on the Farmer results is larger than for the parallel-plate chambers, which is slightly surprising since they all exhibited very similar behaviour at NPL. One centre supplied a Farmer, Markus and NACP chamber. The fact that the NACP and Farmer gave agreement between the NPL calibration and the code while the Markus did not indicates a problem with the calibration or use of the Markus chambers, rather than an implicit error in the formalism of either the Code of Practice or the NPL procedure.

One of the problems encountered in analysing these results is that they involve a number of participants carrying out two different procedures to realize absorbed dose to water—operator error has to be taken into account. However, a review of the measurements carried out at NPL and in the various centres has not revealed any obvious error. Analysis of the formalisms of the absorbed dose procedure and IPEMB Code has not shown any reason for the Markus results. However, there are a number of aspects of the Markus design such as narrow guard ring and shape of collecting electrode, which would suggest that it is not suitable for reference dosimetry.

7. Conclusion

As a result of the trial calibrations described here, NPL has introduced an absorbed dose to water calibration service for IPEM-designated electron chambers. The service is based on the primary standard electron beam graphite calorimeter and will use a set of NACP chambers maintained at NPL to transfer the dose from the calorimeter to user chambers. The measurements described above confirm the suitability of the NACP design as a reference chamber. The calibration factor for a user electron chamber is derived from the reference chambers by direct comparison at NPL in a water phantom. Beam quality, both in the NPL calibration beam and in the user
beam, will be specified in terms of the measured half-value $R_{50,w}$ in water, thus circumventing the need to estimate the mean energy $E_d$ at the calibration depth.

Over 40 chambers of the NACP, Roos, Markus and Farmer types were successfully calibrated at NPL in a series of trial calibrations. In addition, recombination measurements were made indicating that not all chambers of the same type exhibit the same behaviour. The results of the measurements made in the centres are somewhat unexpected, giving agreement at the 1% level for NACP and Farmer chambers but not for Markus chambers. There is no obvious reason for this discrepancy and further measurements are required to identify the source of the problem.

The calibration service provides a significant improvement in accuracy over the present air kerma-based protocol together with a simpler procedure in the clinic. A direct calibration in an electron beam also means that there is no longer any dependence on $^{60}$Co at a time when the number of cobalt units in the UK is diminishing. This service directly tests each chamber so there is no dependence on some defined mean response for a chamber type. Finally, a calorimetric-based calibration service should provide a more stable long-term basis since it will not be affected by changes in air kerma parameters (such as the energy required to produce an ion pair), as seen in recent years. An IPEM Working Party is currently drafting a new UK Code of Practice based on this calibration service (IPEM 2001), which should be published within the next year.

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References


Burns D T 1991 Measurement of the $C_z$ factor for the NACP ionization chamber in water relative to the Farmer HPA values *NPL Report RSA(EXT) 27* (Teddington, UK: National Physical Laboratory)

Burns D T, Ding G X and Rogers D W O 1996 $R_{50}$ as a beam quality specifier for selecting stopping-power ratios and reference depths for electron dosimetry *Med. Phys.* 23 383


Absorbed dose calibration factors


DuSautoy A R 2000 Determination of stopping power ratios for NPL electron-beam absorbed dose calibration service (to be published)


IAEA 1997 The use of plane parallel ionization chambers in high energy electron and photon beams IAEA Technical Reports Series 281 (Vienna: IAEA)

IPEM (Institute of Physics and Engineering in Medicine) 2000 IPEM recommendations on dosemeter systems for use as transfer instruments between the UK primary dosimetry standards laboratory (NPL) and radiotherapy centres Phys. Med. Biol. 45 2445–57

—–2001 The IPEM code of practice for electron dosimetry for radiotherapy beams of initial energy from 2 to 25 MeV based on an absorbed dose to water calibration (to be published)

IPEMB (Institute of Physics and Engineering in Medicine and Biology) 1996 The IPEMB code of practice for electron dosimetry for radiotherapy beams of initial energy from 2 to 50 MeV based on an air kerma calibration Phys. Med. Biol. 41 2557


—–1993 Physics and Dosimetry of Therapy Electron Beams (Madison, WI: Medical Physics Publishing)


NACP (Nordic Association of Clinical Physicists) 1981 Electron beams with mean energies at the phantom surface below 15 MeV Acta Radiol. Oncol. 20 401


Roos M 1993 The state of the art in plane-parallel chamber hardware with emphasis on the new Roos and Attix chambers (unpublished; available from the author at PTB, Lab. 33 45, D-38023 Braunschweig, Germany)

UKAS (United Kingdom Accreditation Service) 1995 The expression of uncertainty and confidence in measurement and calibrations Report NIS 3003 edn 8 (Teddington: UKAS)


Williams A J, McEwen M R and DuSautoy A R 1998 A calculation of the water to graphite perturbation factor ratios for the NACP type 02 ionization chamber using Monte Carlo techniques NPL Report CIRM(EXT)13 (Teddington: National Physical Laboratory)