

The role of the National Physical Laboratory in monitoring and improving dosimetry in UK radiotherapy

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Synopsis

Introduction

National or international protocols for therapy level dosimetry define the procedures by which the medical physicist measures absorbed dose in radiotherapy centres. These procedures can be quite complex and, since under- or over-dosing can have a significant effect on the outcome of radiotherapy treatment, some kind of check is required to avoid the possibility of serious error. Inter-departmental checks are an obvious way of addressing this problem at the local level, but a centrally organised system is required to ensure national consistency. In the UK, the National Physical Laboratory, in conjunction collaboration with the Institute for Physics and Engineering in Medicine operates an audit programme to fulfill this need. This paper summarises the results of these audits.

Method

The present programme covers dosimetry of megavoltage photons and electrons (3-19 MeV) and low and medium energy (10-300 kV) photons. The aim of each audit is to verify the local measurement of absorbed dose at by the particular radiotherapy centre. The audit measurements – principally beam quality and linac output - are made following the same protocol as the clinic but using different equipment. The audit is not an absolute measurement of the absorbed dose but is amounts limited to a checking that the equipment used by the centre is operating as expected and that the Code of Practice is being followed correctly. The protocols used in the UK are IPSM 1990 for high-energy photons, IPEMB 1996 for electrons and IPEMB 1996 for low energy photons. For the purpose of these audits, NPL maintains a set of calibrated ionisation chambers (types NE2561, NE2571, NACP-02 and PTW Roos).

Results and Discussion

Over the last six years around twenty-five audits of megavoltage photon beams have been carried out. The ratio of local and audit measurement is unity within the measurement uncertainties ($\pm 0.4\%$). Experimental procedure within the centres appears to have improved in recent years with a reduced scatter in the results. Solid-state alanine dosimeters have been used to investigate the performance of $\text{TPR}_{20,10}$ as an adequate photon beam quality specifier. The dose measured using alanine agreed with the dose measuring using an ion chamber for a range of $\text{TPR}_{20,10}$ values indicating that any uncertainty in calibration factors due to TPR was less than 1%. Audits of electron beams have recently started and initial results show agreement between NPL and the clinic at the $\pm 0.5\%$ level. This level of agreement is particularly encouraging in view of the complexity of the air-kerma based protocol currently in use. The UK intends to move over to an absorbed-dose based Code of Practice during 2002 and audits will be one means of ensuring that this transfer goes smoothly. Trial audits for kV photon beams show reproducibility is achievable at the $\pm 2\%$ level but have highlighted problems with dosimetry at very low photon energies and the need for more accurate chamber data.

1 INTRODUCTION

There are approximately 60 radiotherapy centres in the UK. In 1999 these centres carried out over 102,000 treatments in 1.2 million fractions (UK DoH, 2000). These centres are organised by IPEM into eight geographical regions for the purpose of inter-departmental audits, which have been carried out on a regular basis to check the uniformity of dosimetry, treatment planning, record keeping *etc.* Thwaites *et al* (1992) carried out a dosimetric intercomparison of megavoltage photon beams in all UK radiotherapy centres obtaining a mean value for the ratio audit/local dose of 1.003 with a standard deviation of 1.5%. In 1997 Nisbet *et al* carried out a similar intercomparison for electron beams and repeated the photon intercomparison. They found agreement within $\pm 1\%$ for photons and within $\pm 2\%$ for electrons. Since it was unrealistic to carry out such exhaustive comparisons on a regular basis but desirable to maintain national uniformity of dosimetry the Institute for Physical Sciences in Medicine (IPSM) asked the National Physical Laboratory (NPL) to carry out regular audits across the whole of the UK to ensure that there were no significant inter-region differences.

2 THE NPL AUDIT SCHEME

One option for an audit scheme would be to use a mailed dosimeter such as TLD or alanine, which is the route taken by ESTRO with the EQUAL dosimetry quality assurance network (Marre *et al*, 2000) or the IAEA mailed dosimetry service (Izewska *et al*, 2000). However, since there are advantages to carrying out the audit in person (e.g. procedures as well as doses are verified, problems can be addressed immediately) this was the approach taken. The present programme covers dosimetry of megavoltage photons and electrons and low and medium energy (10-300 kV) photons. Megavoltage photon audits have the longest history, while electron audits began in 2000 and kV audits are only at the pilot stage.

2.1 Megavoltage photon audits

In 1990 the IPSM published a UK Code of Practice (IPSM, 1990) for megavoltage photon dosimetry based upon the NPL's absorbed dose calibration service (Burns *et al*, 1987). The calibration service is based upon the primary standard graphite calorimeter and via a dose-conversion process yields the calibration of a secondary standard ionisation chamber in terms of absorbed dose to water. The energy range covered is from Co-60 to 19 MV and beam quality is defined by $\text{TPR}_{20,10}$. The overwhelming majority of chambers calibrated have been of type NE2561, with a small number of NE2571 and similar graphite walled Farmer-type chambers. In the clinic, the calibrated secondary standard chamber is not used for routine measurements of linac output but is used instead to calibrate field instruments (usually a Farmer-type chamber).

The aim of the audit is to verify the local measurement of absorbed dose in the clinic. The audit measurements are made following the same protocol but using different equipment. The scope of the audit therefore amounts to a check that the equipment used by the centre is operating as expected and that the Code of Practice is being followed correctly - it is not an absolute measurement of the dose. For the purpose of these audits, NPL maintains a set of NE2561 and NE2611 chambers, calibrated against the primary standard calorimeter.

In the UK few centres now use Co-60 sources and all the megavoltage photon audits have involved linac beams. The procedure followed is as follows:

1. The host department selects the beam quality to be audited, generally 6 MV or 8 MV, which are the most commonly used qualities in UK radiotherapy.
2. The host provides values for the beam quality index $\text{TPR}_{20,10}$ and for machine output (in terms of grays per monitor unit). These may be based on measurements made on the day or, more commonly, have been determined previously.
3. NPL staff measure $\text{TPR}_{20,10}$, and use this value to infer the appropriate calibration factor for the

NPL chamber in the clinical beam. Recombination corrections and output factors are obtained for the chosen photon beam using NPL equipment. Measurements are made in water, on the axis of a horizontal beam, in an NPL phantom, at depths of 5 (or 7), 10 and 20 g/cm² from the front face. The source-to-chamber distance is set at around 100 cm, and the field size at the chamber is 10 x 10 cm. As far as possible, NPL provides its own instruments, all traceably calibrated to national standards (secondary standard ionisation chamber and measuring assembly; thermometer, barometer *etc*).

4. The calibration of the host field instrument is obtained by substituting their chamber for the NPL chamber in the NPL phantom. Recombination is also measured for the field instrument.

UK radiotherapy departments operate under considerable time pressures, and scheduling time for audit visits only adds to this pressure. In practice, audit measurements are generally carried out during evenings, and their scope is limited by the amount of time available.

Since 1994 twenty-five audits have been carried out and the overall results are summarised in Table 1 and shown in Figures 1-3.

Table 1 Summary of results for megavoltage photon audits

Quantity	Ratio (NPL/Host)	Standard deviation (%)
TPR	0.9981	0.64
Machine output	1.0032	0.80
Field instrument calibration	0.9998	0.72

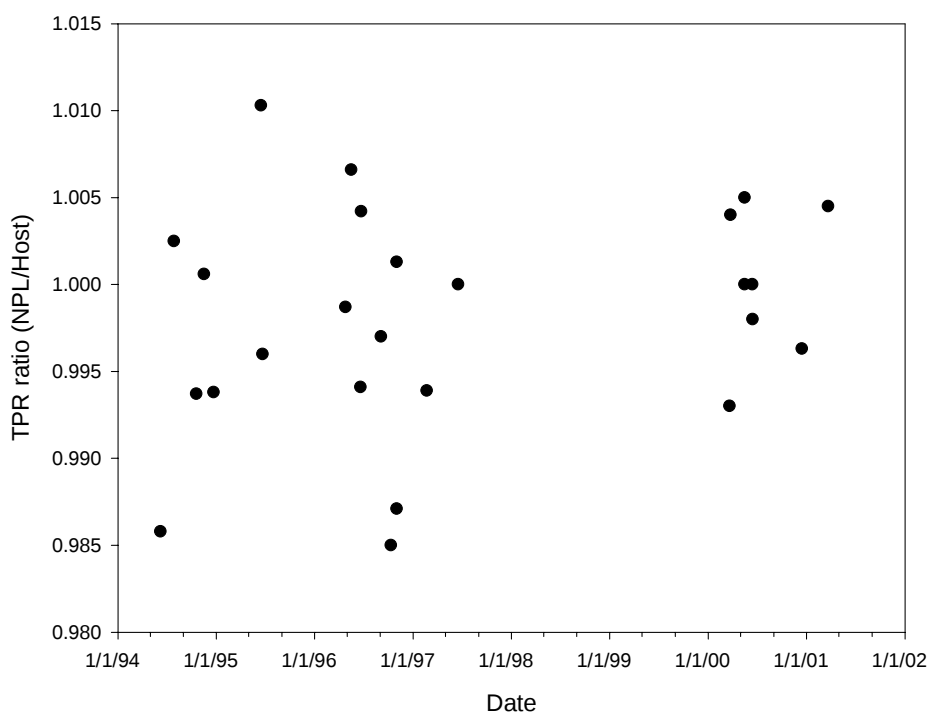


Figure 1 Photon audit results - $TRP_{20,10}$

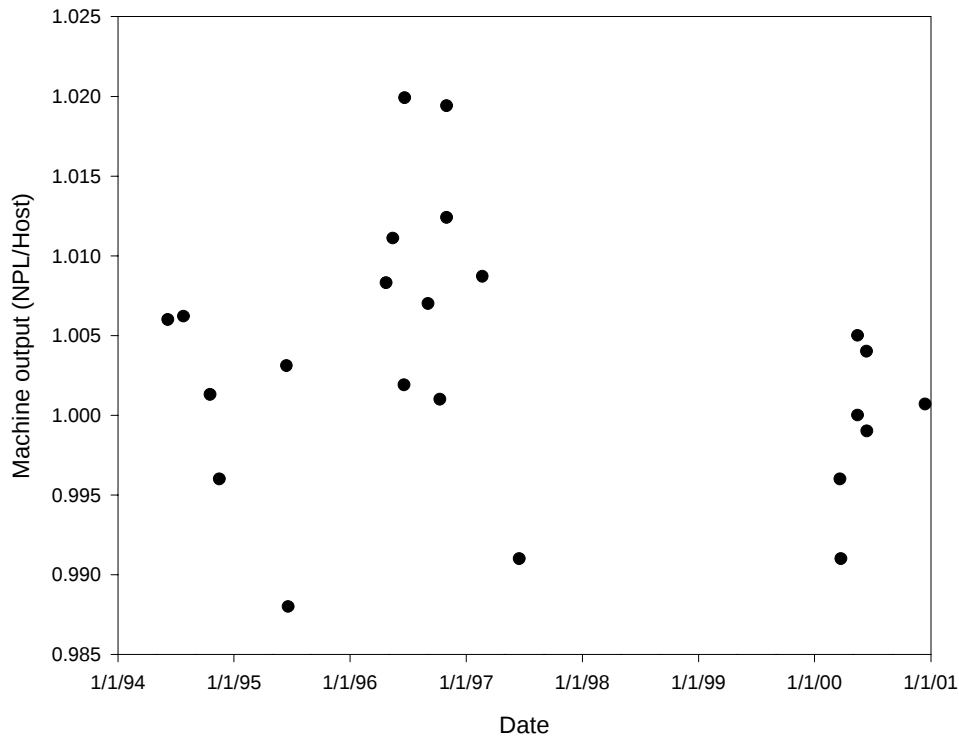


Figure 2 Photon audit results - measurement of linac output

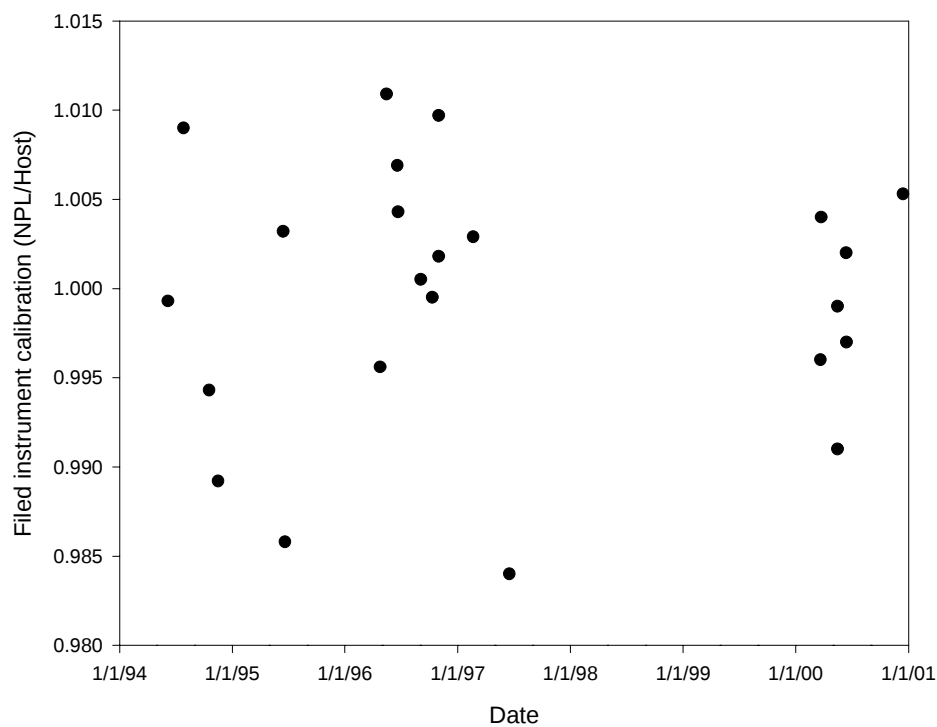


Figure 3 Photon audit results - calibration of field instrument

The spread on these results appears to reduce over the period of the audits and is significantly smaller than that reported by Thwaites *et al* (1992), indicating that there has been a steady improvement in dosimetry technique within the clinics. The overall standard uncertainty (as defined by ISO, 1995) of the NPL calibration is $\pm 0.7\%$ but one should find greater consistency among measurements made with

different dosimeters whose calibration is traceable to the same NPL standard. This would certainly appear to be the case for the most recent series of audits (standard deviation $\sim 0.4\%$), indicating that the Code of Practice is being implemented fully. The audits reported above cover linacs from a wide range of manufacturers and there is no difference in the results for different manufacturers or for machines of different ages.

There has been much debate (Rosser *et al*, 1994, Andreo, 2000, Rogers 2000) in recent years over the sufficiency of $\text{TPR}_{20,10}$ as a beam quality specifier for the purpose of ion chamber calibration in terms of absorbed dose to water. This leads to a contribution to the overall uncertainty in absorbed dose measurements from the transfer of chamber calibration between primary laboratory and user X-ray beams. The validity of this transfer cannot be established merely by making more measurements with an ion chamber: for that, one needs to use a dosimetry system based on different physical principles, such as alanine/ESR. Work at NPL has shown that, when calibrated in terms of absorbed dose to water, any variation in the sensitivity of alanine is not more than $\pm 0.5\%$ over the energy range covered by the NPL linac (Sharpe *et al*, 1999). Figure 4 shows the consistency between the NPL values of absorbed dose at the radiotherapy centers audited, determined using the secondary standard ion chamber and alanine. The two systems are irradiated side by side in a Perspex/polystyrene phantom. Exchanging chamber and alanine mid-way through each irradiation eliminates most of the uncertainties associated with set-up and beam non-uniformity. The results are plotted in Figure 4 - the error bars indicate only the internal consistency (1 sigma) of the ratios obtained. As can be seen, there is no variation with beam quality, which indicates that the uncertainty introduced during the transfer from primary laboratory to clinic is unlikely to be as large as 1%.

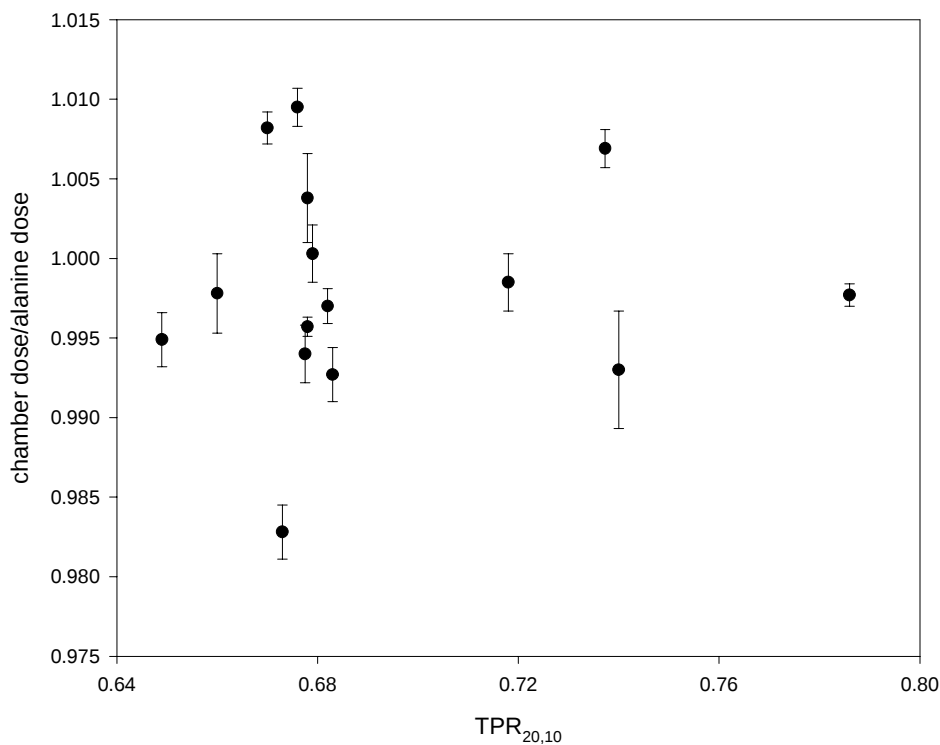


Figure 4 Comparison of doses measured using ion chamber and alanine

2.2 Electron audits

Dosimetry for electron beam radiotherapy in the UK, as for the rest of the world, remains traceable to Co-60 air kerma standards (IPEMB, 1996), instead of to a primary standard of absorbed dose for electron beams. NPL has launched a calibration service for electron beam radiotherapy, traceable to a new primary standard (McEwen *et al*, 1998), and a working party of IPEM (Institute of Physics and Engineering in Medicine) is currently working on a Code of Practice to match. Trial calibrations involving a limited number of UK centres have allowed the comparison of the existing and proposed Codes of Practice (McEwen *et al*, 2001). The new calibration service is also compatible with the recently published IAEA Absorbed Dose Code of Practice (IAEA, 2001), as is the photon calibration service. In the meantime, audits have been carried out to establish uniformity of application across the UK of the present Code.

The audit procedure for electrons is significantly more complicated than for photons because of the many steps required to obtain absorbed dose to water. Starting with a NE2561/NE2611 chamber calibrated in terms of air kerma for a Co-60 beam, the steps in the IPEMB 1996 Code are:

1. Comparison of Secondary Standard chamber with a NE2571 Farmer chamber in a PMMA phantom in a Co-60 (or 6 MV) beam. This yields an absorbed dose to air calibration factor, $N_{D,air}$, for the Farmer chamber.
2. Derivation of $N_{D,air}$ for a parallel plate chamber by comparison with the Farmer chamber in a water phantom in a high energy electron beam. This two-step approach is used because of the potential problems of operating parallel plate chambers in a Co-60 beam (IAEA, 1997).
3. Application of the $N_{D,air}$ factor together with chamber perturbation factors and water/air stopping power ratios to derive absorbed dose to water.

Four chamber types are recommended in the Code – one cylindrical chamber (the NE2571 Farmer-type) and three parallel-plate chambers (NACP, Roos and Markus).

As for the photon audits, the aim is to measure the absorbed dose to water in a water phantom at the reference depth for a standard field size. Each of the individual steps as describe above is checked - this is to make sure that no fortuitous combination of wrong $N_{D,air}$ and stopping power values can give an apparently correct dose measurement. The audit procedure is as follows:

1. Prior to audit, the host supplies depth-ionisation data for the electron beams selected. There is insufficient time to include measurement of depth-ionisation curves so only an independent analysis of the clinic's data to derive reference depths, perturbation factors and stopping power ratios is carried out.
2. NPL staff derive the $N_{D,air}$ factor for an NPL Farmer chamber using an NPL NE2611 chamber in the user's 6 MV photon beam.
3. NPL staff derive $N_{D,air}$ factors for a number of parallel plate chambers using NPL equipment in a high energy electron beam (> 15 MeV).
4. NPL staff measure recombination and polarity corrections and output factors for the chosen electron beam(s) using NPL equipment.
5. The host measures recombination and output factors using local equipment.

The IPEMB 1996 Code recommends that all measurements in electron beams are carried out in a water phantom but allows the use of solid phantoms. For these audits a WTe phantom was used (manufactured by St Bartholomew's Hospital, UK). WTe is an epoxy-based material designed to be water equivalent and significant work was carried out prior to these measurements to establish that this was the case. The results were in agreement with other authors (e.g. Nisbet *et al*, 1998) showing that 1 cm WTe is equivalent to 1 cm water with no fluence-ratio correction required. Although the use of a solid phantom simplified the experimental setup, the complexity of the electron protocol means that a full day is required to complete the audit.

At the time of writing, three audits have been carried out measuring output factors for six electron beams. Interestingly, these three audits have covered linacs from three major manufacturers - Philips, Varian and Siemens. Output factors were measured using both NACP and PTW Roos chambers and the results are summarised in Table 2.

Table 2 Comparison of output factors

Centre	E_{nom} (MeV)	Machine output (NPL/host)	
		NACP	PTW Roos
1	9	1.0103	0.9924
1	12	1.0035	0.9961
2	6	1.0042	1.0026
2	10	1.0007	0.9950
3	6	1.0043	1.0026
3	9	1.0061	1.0053

From a brief analysis of the IPEMB 1996 Code one can see that the any error in the determination of $N_{D,\text{air}}$ for a NE2571 chamber will affect all dose measurements in an electron beam. Ideally, this should be carried out in a Co-60 beam, but as the number of such facilities in the UK has rapidly decreased in recent years, the IPEMB 96 Code allows for the measurements to be carried out in a low energy linac photon beam (usually 6 MV). The results of these initial audits indicate that there may be a difference of up to 0.7% in the value of $N_{D,\text{air}}$ derived by these two routes. Further measurements are required to confirm this finding.

The IPEMB '96 Code gives a figure of around $\pm 2\%$ for the overall uncertainty of a measurement of dose but the standard uncertainty in the ratios given in Table 3 is estimated to be $\pm 0.5\%$ because of the cancellation of physical constants (stopping powers *etc*). Of the three audits carried out so far, good agreement (within $\pm 0.5\%$) was obtained for five of the six beams, indicating that there are no significant errors in the application of the IPEMB 96 Code of Practice. There is, in general, good agreement (i.e. better than 0.5%) when comparing NACP and Roos results in Table 2. Any differences between the chamber types are due only to chamber readings (either in the high energy comparison with the Farmer chamber or in the output measurement) which may be due to a real effect such as beam uniformity (the Roos chamber having a larger diameter collector) or chamber perturbation or a measurement error (e.g. incorrect positioning). Further audits will determine whether there is a significant difference between the Roos and NACP chambers.

2.3 Dosimetry for kilovoltage X-rays

The determination of absorbed dose in 1996 IPEMB Code of Practice for kilovoltage photon beams is based on an ionization chamber calibrated in terms of air kerma. The Code is split into three energy ranges: very low, low and medium and Table 3 summarises the measurement procedure for each energy range.

Table 3 Summary of IPEMB 1996 low energy photon Code of Practice

Range	HVL	Recommended chamber	Method
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Very low	0.035 – 1.0 mm Al	Thin-windowed parallel-plate	Chamber placed at surface of full-scatter phantom
Low	1.0 – 8 mm Al	NE2561/NE2611	Chamber free in air Backscatter factor applied
Medium	0.5 – 4 mm Cu	NE2561/NE2611	Chamber placed at depth of 2 cm in water phantom

The audit procedure for kV photons is as follows:

1. The host department selects the energy to be audited and measures the HVL (half-value layer).
2. NPL staff measure HVL for a horizontal beam and machine output.
3. The host measures the machine output using local equipment.

As well as comparing NPL and locally-measured doses, the two audits carried out so far have looked at the overlap between energy ranges as the different measurement procedures could lead to significant differences in the reported dose. One of the problems with low energy photon dosimetry is the lack of accurate data for chamber correction factors and a difference of 7% was found at the overlap of the very low and low regions (1 mm Al HVL). Recently published data (Perrin *et al*, 2001, Ipe *et al*, 2001) give improved values for the chamber correction factors at very low energies, which would appear to explain this difference. Better agreement was found between the low and medium ranges (5 mm Al HVL) with a difference of less than 2%. These investigations also indicated that, by following the Code, reproducibility at the $\pm 2\%$ level could be achieved. Further work is required, particularly at the lowest energies, to improve the data sets and resolve these discrepancies before implementing a full audit scheme.

4 FUTURE WORK

As noted above, a working party of the IPEM is currently developing a new absorbed dose Code of Practice for electron beam radiotherapy, based on the NPL calibration service. This will offer a significant reduction in the uncertainty together with a much simpler procedure to follow. It is hoped that this protocol will be published within the next six months and, once implemented, electron audits will be carried out to ensure that the procedure is being followed correctly. As well as continuing with megavoltage and kV photon beams, it is hoped to expand the audit system to cover brachytherapy, and dosimetry for mammography and diagnostic X-rays.

A portable calorimeter has also been developed at NPL (McEwen and Duane, 2000), designed to operate in radiotherapy clinics. The calorimeter will provide a direct measurement of dose where it is required and allow the investigation of beam quality issues. The standard uncertainty in measuring absorbed dose to water is estimated to be $\pm 0.9\%$, close to that of the NPL primary standards. Initial testing has proved very successful and a series of measurements in radiotherapy clinics is planned for later in 2001.

5 ACKNOWLEDGEMENTS

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