A dosimetric intercomparison of kilovoltage X-rays, megavoltage photons and electrons in the Republic of Ireland

Andrew Nisbet a,*, David I. Thwaites a, Martin E. Sheridan b

a Department of Medical Physics and Medical Engineering, University of Edinburgh, Western General Hospital, Crewe Road, Edinburgh, EH4 2XU, UK
b Department of Radiotherapy Physics, Saint Vincent’s Private Hospital, Merrion, Dublin 4, Ireland

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Abstract

Background and purpose: A comprehensive dosimetry intercomparison has been carried out involving all the radiotherapy centres, all external beam modalities and every radiotherapy treatment unit in the Republic of Ireland.

Materials and methods: Reference point measurements were made for all megavoltage photon beams. Doses were also investigated in planned three-field distributions. One of these was in a homogeneous epoxy resin solid water phantom, whilst the second included a lung equivalent insert. The intercomparison was also carried out for three electron beam energies in each centre. The position of the depth of maximum dose for a standard field size was independently determined, as was the beam energy and a subsequent beam calibration was made. In addition, a kilovoltage X-ray intercomparison was carried out on every kilovoltage quality.

Results: For 13 megavoltage photon beams a mean ratio of intercomparison measured dose to locally measured dose of 1.002 was obtained (standard deviation 1.2%). For 12 electron beam measurements a mean ratio of intercomparison measured dose to locally measured dose of 1.018 was obtained (standard deviation 0.8%). For four kilovoltage beams a mean ratio of intercomparison measured dose to locally measured dose of 0.997 was obtained (standard deviation 1.9%).

Conclusions: The intercomparison has given confidence in the basis of clinical delivery of radiation dose in radiotherapy treatment and in the consistency (precision) of dosimetry between different centres within the Republic of Ireland. In addition, it has established a methodology for subsequent ongoing routine radiotherapy dosimetry audit and a baseline set of results to act as an initial reference point.

Keywords: Dosimetry intercomparison; Kilovoltage X-rays; Megavoltage photons; Megavoltage electrons

1. Introduction

The demands on precision in dosimetry and treatment delivery are determined by the steepness of the relevant clinical dose–effect curves, both for tumour control and for normal tissue complications. Consideration of the clinical data led to generally agreed recommendations on the required accuracy in clinical dosimetry for radical curative radiotherapy being given in International Commission on Radiation Units and Measurements (ICRU) Report 24 [11], which pointed to a need for at least ±5% accuracy in the delivery of absorbed dose to the target volume in the patient. More recent reviews [5,20] have led to recommended tolerance levels on accuracy in dose delivery of ±3.5 and ±3%, respectively, being stated as one relative standard deviation. Therefore, comprehensive quality assurance systems are necessary [2,4,27]. As part of this, the fundamental basis of consistent dosimetry is the use of carefully designed and applied international or national dosimetry protocols and codes of practice (e.g. Refs. [1,3,8–10,12,13,15,17]) ensuring traceability of dosimetry to national and international standards. However, even with protocols in place, errors may occur, for example, due to inexact implementation or misinterpretation of recommendations, equipment problems or mistakes.

Dosimetry intercomparisons are essentially designed to
establish the accuracy and precision of dosimetry at a given level in the dosimetry chain and to assess consistency between centres. By using a standard methodology, phantom(s), measurement technique and measuring system, differences between the way that different centres apply dosimetry protocols and carry out their dosimetry can be assessed. Using dosimetry intercomparisons as an audit is widely recognized as being effective in revealing the presence of errors [27,29]. Dosimetry intercomparison techniques form the basis of the practical methodology employed in the developing radiotherapy dosimetry audit networks [6,7,23,25]. Whilst audit systems can employ mailed thermoluminescent detectors (TLD) or site visits using ionization chambers, the latter approach provides the most accurate and flexible means to carry out a dosimetry intercomparison.

Dosimetry intercomparison methods and results have been reviewed recently [26,24], as have some of the rapidly developing network of routine dosimetry audit programmes [25].

There is an increasing number of national audit systems being established, with networking to other national or international efforts. No such nation-wide dosimetry intercomparisons or audits have been previously carried out in the Republic of Ireland and there was a need for an initial comprehensive national study to determine the currently achieved dosimetric precision in radiotherapy across the country. In addition, it was expected that such an exercise would provide a methodology and a baseline set of data which could be used as a standard for subsequent ongoing routine audit to work from and refer to. Thus, this work reports a systematic comprehensive dosimetry intercomparison covering all the radiotherapy centres, all external beam modalities and every radiotherapy treatment unit in the Republic of Ireland. The experimental work was carried out over 8 consecutive days in August 1996.

2. Materials and methods

2.1. General methods

The methods employed in this dosimetry intercomparison are largely based on those developed for the UK megavoltage photon [28] and electron beam intercomparisons [21] and the Scottish(+)-audit group [25]. The radiotherapy centres in the Republic of Ireland have traditionally followed the UK dosimetry codes of practice and hence the 1990 Institute of Physical Sciences in Medicine (IPSM) code of practice [15] has been employed for megavoltage photons in this dosimetry intercomparison. For kilovoltage X-rays, the 1991 IPSM recommendations [16] have been followed, whilst for electron beams the 1985 Hospital Physicist’s Association (HPA) code of practice [8] with its 1992 addendum [17] have been used to determine the absorbed dose to water for electron beams.

For each beam considered, the host department was asked to measure the beam calibration immediately prior to the intercomparison. Thus, the intercomparison measurement was compared directly to the local department’s statement of dose, without any significant effect of drift in the treatment machine’s monitor or control system.

2.2. Measurement systems

Megavoltage photon beam doses were measured with a Nuclear Enterprises (NE) Technology NE2570 dosimeter and an NE2571 cylindrical graphite-walled ionization chamber. The chamber was calibrated against a secondary standard dosimeter (Nuclear Enterprises model 2560/2561) in a cobalt-60 γ-ray beam and also in X-ray beams of nominal energies of 4, 6, 9 and 16 MV and with quality indices of 0.63, 0.68, 0.72 and 0.765, respectively, according to the IPSM 1990 code of practice, traceable to the UK National Physical Laboratory (NPL) primary dosimetry standards.

The same electrometer and ionization chamber assembly have also been employed for the kilovoltage X-ray dosimetry intercomparison. The chamber assembly was calibrated over a range of superficial qualities against a secondary standard system traceable to NPL primary standards and a plot of air kerma calibration factor against beam quality constructed to cover the range of kilovoltage qualities encountered in the intercomparison.

For the electron beam measurements, the NE Technology 2570 dosimeter was employed with a Scanditronix Nordic Association of Clinical Physics (NACP) type-02 plane parallel ionization chamber. An operating voltage of -250 V was employed and ion recombination was evaluated both during calibration in a cobalt-60 γ-ray beam and also in the subsequent determination of absorbed dose in an electron beam. This ensured that any changes in sensitivity at different voltages were automatically taken into account and is an acceptable alternative approach to using an operating voltage of less than 100 V [12]. The chamber was calibrated against the secondary standard system in a cobalt-60 beam according to the HPA 1985 code of practice [8], again traceable to NPL primary standards.

Ion recombination and polarity effects for each ionization chamber were determined across the range of measurement conditions encountered. Appropriate ion recombination factors were applied according to the operating dose per pulse of the pertinent accelerators considered. This was estimated from the gun pulse repetition frequency and the indicated dose rate. Time considerations prevented the actual measurement of recombination in each centre. It should be noted that an error of ±20% in the pulse repetition frequency results in an error of no more than ±0.1% in the ion recombination correction factor. Polarity effects were determined for electron beam measurements by selecting from a prepared curve of correction factors for the mean electron beam energy at the depth of measurement [22].

The stability of the measurement systems was tested
before and after the intercomparison by repeating the chamber calibration and also by using Strontium-90 check sources. The repeat calibration of the NE2571 chamber was within 0.1% and that for the NACP chamber was within 0.2%. Agreement of the Strontium-90 check measurements was within 0.1% for the NE2571 chamber and within 0.3% for the NACP chamber.

A dedicated barometer ((Negretti and Zambra, aneroid type M2236) and thermometer (mercury in glass, supplied by NE Technology) were used throughout the study to determine pressure and temperature corrections to the ionization chamber readings. Both were calibrated traceable to UK national standards. The pressure and phantom temperature were measured regularly throughout each set of measurements. In each centre, a local value of pressure and temperature was compared to identify and quantify any systematic differences due to this cause.

2.3. Phantoms

The phantom employed for the megavoltage photon beam measurements was made of WT1, an epoxy resin water substitute material manufactured by Radiation Physics, St. Bartholomew’s Hospital, London. The water equivalency of this material has been confirmed and is the subject of another paper. A schematic diagram of the phantom and its dimensions is shown in Fig. 1. It has six 20 mm diameter removable water equivalent rods, one of which is machined to hold a Farmer-type ionization chamber. One hole is centred at 50 mm depth from the largest flat surface of the phantom and was employed for reference beam measurements. The other five positions made a target volume for a planned three-field distribution. The phantom also has an 8 cm diameter hole which may hold either a WT1 insert or a lung equivalent insert. Further details of the basic approach to the design and use of the phantom can be found in the paper by Thwaites et al. [28].

The phantom employed for the megavoltage electron beam measurements was made of WTe, an epoxy resin water equivalent material specifically formulated for electrons and again produced commercially by Radiation Physics, St. Bartholomew’s Hospital, London. The water equivalency of this material has been confirmed and is the subject of another paper. The WTe solid water phantom consisted of 250 × 250 mm sheets with thicknesses varying between 1 and 50 mm. For all the measurements, 100 mm of phantom material was positioned behind the ionization chamber to provide backscatter. A maximum sheet thickness of 20 mm was used to set the depth of the chamber in the phantom material and no problems with charge storage were observed with this arrangement. One 10 mm sheet of WTe was machined to hold the NACP chamber. Further details of the basic approach to the design and use of the phantom can be found in the paper by Nisbet and Thwaites [21].

For kilovoltage X-rays, all measurements were carried out in air.

2.4. Measurements

2.4.1. Megavoltage photon beam calibration

The megavoltage photon beam intercomparison was carried out on each treatment unit in each radiotherapy centre visited and for each beam quality available. The dose at 50 mm depth in WT1 was measured for three field sizes of 50 × 50, 100 × 100 and 200 × 200 mm. The beam quality, as represented by TPR\textsuperscript{200}\textsubscript{50} was also measured for each photon quality using the independent set of WTe slabs. The measured beam quality was employed to determine the appropriate absorbed dose calibration factor for the NE2571 ionization chamber. In addition, the light field size was measured for each of the three field sizes and the agreement between the mechanical front pointer, the optical distance indicator and the set-up lasers was noted.

2.4.2. Megavoltage photon three-field planned distribution

To investigate the agreement between locally planned dose distributions and independent measurements, the host department was asked to plan a three-field treatment and deliver a uniform dose of 2 Gy to an 80 × 80 × 80 mm volume centred on the central cavity in the WT1 phantom. Two plans were requested, one in a homogeneous phantom and the other with the 80 mm lung insert in place. Isocentric plans were produced by all four centres and each centre employed a nominal 6 MV photon beam. In each case the phantom was set up and the beams were treated following the plan. Doses were measured at each of the five points in the high dose volume for each field.

2.4.3. Electron beam measurements

The electron beam intercomparison was carried out on one unit in each radiotherapy centre visited and for three energies across the range. For each nominal energy, the depth of maximum dose for a standard field size, the elec-
tron beam energy and the beam calibration were independently determined. The methodology as described by Nisbet and Thwaites [21] was employed. The energy relationships given in HPA 1985 [8] were used to determine the mean incident electron beam energy and the subsequent mean electron beam energy at the depths of measurement.

2.4.4. Kilovoltage photon beam calibration

In the kilovoltage intercomparison, a dose was measured in air for a standard applicator size. A clamp stand was employed to position the ionization chamber against the face of the applicator and an inverse square law correction was applied to correct for the offset of the chamber central axis from the end of the applicator. The half-value layer (HVL) as quoted by the host department was employed to determine the air kerma calibration factor for the ionization chamber. In order to estimate the effect of uncertainty in the quoted HVL on the dose measurements, it can be assumed that by employing a good-quality set-up [18], i.e. narrow beam and scatter-free conditions, and using high purity attenuating material, one would expect to be able to measure the HVL to within ±0.1 mm aluminium (Al) HVL. A conservative estimate on the uncertainty in the HVL as quoted by the local centre is therefore ±0.1 mm Al. This leads to an uncertainty in the air kerma calibration factor of the order of ±0.1%. The locally quoted HVL has also been employed to choose the backscatter and other applicable factors. For a 5 cm diameter applicator, the change in backscatter factor between 1.5 and 2.0 mm Al HVL is 1.8% and likewise there is 2.7% change from 2.0 to 3.0 mm Al. Other factors change by approximately 1% over this range. The total uncertainty in dosimetry due to employing the locally quoted HVL is therefore of the order of ±0.5%.

2.4.5. Procedural audit

A degree of procedural audit was incorporated at each visit. A questionnaire was designed which dealt with the quality control procedures in operation and the techniques used to determine dosimetric and related parameters. This questionnaire was sent out before the visit and was then used as a basis for discussion with local staff. The results from this part of the audit are not analyzed here but expected quality control procedures, frequency of checks and tolerances were taken to be those in IPSM Report 54 [14]. The questionnaire helped in identifying reasons for any differences observed in dosimetry between the intercomparison and that measured locally. A full analysis of any identifiable reasons for any differences in dosimetry were given with the subsequent report.

3. Results

3.1. Megavoltage photon reference point measurements

The intercomparison results, expressed as the ratio of the intercomparison measured dose to the locally stated dose, are shown in Fig. 2. The lighter areas show the results for the reference field of 100 × 100 mm and the full histogram shows the results for all three fields. The mean value of this ratio for the 100 × 100 mm field size is 1.002 (standard deviation 1.2%) with minimum and maximum values of 0.984 and 1.027, i.e. a spread in dose of 4.3% across the four centres. The mean ratio for all three field sizes is 1.001 (standard deviation 1.2%) with minimum and maximum values of 0.978 and 1.027. It should be noted that a mean value close to unity suggests that there are no significant systematic errors in the intercomparison dosimetry.

3.2. Planned dose distributions

Fig. 3 shows the average measured to calculated dose ratio for the five points in the dose distribution with the water equivalent insert. The results for the distribution with the lung equivalent insert are shown in Fig. 4. The lighter areas for both distributions are the results for the central points. It should be noted that the locally measured beam calibrations on the day have been taken into account in the calculated dose distributions. The mean ratio of intercomparison measured dose to calculated dose for all five points was 0.998 for the homogeneous phantom (standard deviation 1.1%) and 0.997 with the lung insert (standard deviation 1.3%). The mean ratio of intercomparison measured dose to calculated dose for the four central points was 1.005 for the homogeneous phantom and 1.009 for the phantom with the lung insert. This may indicate a small systematic difference between the central dose and the dose at the peripheral points.

A test of the self-consistency between the two planned dose distributions is to compare the central doses in the two plans. The average of the ratios is 0.997 and indicates no systematic difference. The normalized ratio (relative to the intercomparison dose) of central point to reference point dose is an indication of the self-consistency of the dose distribution and reference point measurements for the same beam. The mean value of this ratio is 1.003 (standard deviation 1.2%) and indicates no systematic difference.
3.3. Kilovoltage X-ray beam calibrations

Four superficial units were included in the intercomparison with quoted half-value layers of 1.35, 2.0 and 2.2 mm Al and 0.4 mm Cu (equivalent to 8.0 mm Al). The mean ratio of intercomparison measured beam calibration to locally stated beam calibration was 0.997 (standard deviation 1.9%), with minimum and maximum ratios of 0.974 and 1.018. Again it should be noted that a value close to unity suggests that there are no significant systematic errors in the intercomparison dosimetry.

3.4. Electron beam calibrations

The intercomparison results, expressed as the ratio of the intercomparison measured dose to the locally measured dose, are illustrated in Fig. 5. The mean value of this ratio is 1.018 (standard deviation 0.8%), with minimum and maximum values of 1.002 and 1.027. This systematic difference may be partly attributed to the different calibration chains employed for the intercomparison and the local centres. It should be noted that the mean ratio of the air kerma calibration factor \( N_f \) for the local electron beam chambers (two NACP chambers and two Markus chambers) determined during the intercomparison and the air kerma calibration factor quoted locally was 1.016 (standard deviation 0.6%). The cross-calibration against the intercomparison Farmer chamber was carried out in the WTe phantom material.

3.5. Electron beam energy

With six beams the agreement in energy between that determined during the intercomparison and that quoted locally was within ±0.1 MeV. With 10 beams the agreement was within ±0.2 MeV and all but one were within ±0.3 MeV. The maximum positive difference in nominal electron beam energy was 0.27 MeV and the maximum negative difference was 0.60 MeV. The difference of 0.60 MeV occurred for a nominal 12 MeV electron beam and the subsequent difference in dose is estimated to be 0.5%. For the former case, the difference in energy determination of 0.27 MeV occurred for a nominal electron beam energy of 12 MeV and the subsequent difference in dose is estimated to be 0.1%.

3.6. Depth of maximum dose

With seven electron beams the determined depth of maximum dose was within ±1 mm and in 11 of the 12 beams the
The maximum positive difference was 1.5 mm and the maximum negative difference was 2.5 mm. The latter case occurred for a nominal 12 MeV electron beam and the subsequent difference in dose is estimated to be 0.2%. The former case occurred for a nominal 12 MeV electron energy and the subsequent difference in dose is estimated to be 0.4%. The mean difference was 0.6 mm. This highlights the fact that a large percentage of centres take the effective measuring position of a parallel plate chamber to be on the front face of the chamber rather than at the inside of the front face.

3.7. Uncertainties

All uncertainties are quoted as one standard deviation (1 SD). The type A uncertainties (random uncertainties) have been estimated and are listed in Table 1.

The type B uncertainties (systematic uncertainties) which are common to the intercomparison system and the local departments assessed cannot obviously be identified in such an intercomparison. They may be assessed by comparison to other systems [24,25]. However, specific types of uncertainty on the intercomparison dosimetry which may affect the results of an intercomparison may arise, for example, from the calibration of the ionization chambers and the accuracy of the thermometer and barometer. In addition, the use of the solid water phantom materials may increase the uncertainties. By considering the mean ratio of intercomparison measured dose to locally measured dose in the larger UK intercomparison, an uncertainty of ±0.6% for electron beams and ±0.3% for megavoltage photon beams may be estimated. For kilovoltage X-rays, where the measurement is in air, an uncertainty of ±0.2% is estimated.

The total uncertainties are therefore estimated at ±0.8% for electron beams, ±0.7% for megavoltage X-rays, ±0.6% for cobalt-60 γ-ray beams and ±1.4% for kilovoltage X-rays.

4. Discussion

Table 2 summarizes the results. In conclusion, the study has demonstrated generally consistent basic radiotherapy dosimetry for megavoltage photon and electron beam dosimetry and kilovoltage X-ray dosimetry at the level of beam calibration with no beams being outside the intercomparison tolerance level of 3%. It has provided quantitative information on the currently achieved precision of dosimetry for all external beam modalities across the whole country. The methodology described has been shown to identify causes of differences in dosimetry to a fraction of a percent. Therefore, it would be possible to identify problems at the selected tolerance limits and allow them to be investigated and rectified. The intercomparison has given confidence in
the basis of clinical delivery of radiation dose in radiotherapy and treatment and in the consistency (precision) of dosimetry between different centres within the Republic of Ireland. In addition, it has established a methodology for subsequent ongoing routine radiotherapy dosimetry audit and it has established a baseline set of results to act as an initial reference point. It is intended that the Republic of Ireland will establish and continue with an independent audit system which will occasionally cross-link to the UK audit network via the Scottish(+v) audit group.

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References