NRC Activities and Publications, 2003-2005
Report to the CCRI(I) Meeting, BIPM
May 2005

Compiled by Carl Ross (Group Leader)
Ionizing Radiation Standards
Institute for National Measurement Standards
National Research Council
Ottawa, Canada K1A 0R6

Tel: 613-993-9352
Fax: 613-952-9865
E-mail: carl.ross@nrc.ca

Table of Contents

1 Introduction

The Ionizing Radiation Standards (IRS) Group at NRC is part of the Institute for National Measurement Standards (INMS), which is Canada's national metrology institute. The group has 13 full-time staff members, 3 former staff members who work part-time, two graduate students, two undergraduate students and one visiting worker.

The group is responsible for Canadian calibration services in the field of ionizing radiation. A listing of the calibration services offered can be found at: http://inms-ienm.nrc-cnrc.gc.ca/calserv/ionizing_radiation_e.html

A database of INMS publications is available at:
http://serpent.cisti.nrc.ca/DBTW-WPD/textbase/inms/search_e.html
This database is presently under construction and not all features are operational. In particular, it is not yet possible to request just those publications from IRS. However, searches by author or keyword are now working.

Details on research activities related primarily to Monte Carlo modeling can be found at:
http://inms-ienm.nrc-cnrc.gc.ca/research_and_development/ionizing_radiation_std_projects_e.html

2 Organizational changes since May 2003

INMS undertook a major change in its organizational structure in 2004. A new Director General, Dr. Jim McLaren, has been appointed, and two Directors, one for Metrology and one for Business and Administration, will report to him. Competitions for the Directors' positions are now closed but the successful candidates have not yet been announced.

Within IRS, Dave Rogers, who had served as group leader for almost 20 years, left in December 2003 to take a position at Carleton University. After a competitive process, Carl Ross was appointed as the new group leader in October 2004.

3 ISO 17025 Quality System

IRS underwent an internal audit in March 2005 of those calibration services for which it is seeking ISO 17025 accreditation. Most of our procedures and documentation were found to be acceptable, although some gaps were noted.

Those requiring most work relate to software control and software verification. Non-conformances will be addressed by June, at which time we will establish a schedule for external review.

4 Air kerma standards

4.1 For kV x-rays

(John McCaffrey and Patrick Saull)

IRS provides kV x-ray calibrations in the energy range from 10 to 300 kV. Two free-air chambers serve as standards, one covering the low-energy range up to about 60 kV and the second covering the range from 60 to 300 kV. A second high-energy chamber is under construction. It will be used as a spare, and for exploratory studies of some of the factors that affect the response of free-air chambers.

4.2 For ^{60}Co and ^{137}Cs

(John McCaffrey)

^{60}Co and ^{137}Cs air kerma standards are based on a graphite cavity chamber. As a result of a re-evaluation of the correction factors, the standard now provides estimates for the air kerma that are 0.59 % higher than before ([15]). The calibration service was adjusted to account for this change on October 1, 2003.

Although the air kerma standard is based on a cylindrical chamber, IRS has a parallel-plate chamber and a spherical chamber that can also be used to provide an estimate of the air kerma. The ratio of the air kerma for a given chamber to that of the standard is 1.003 and 0.997 for the parallel-plate and spherical chambers, respectively ([10]). The difference of 0.6 % between the pancake and spherical chambers is unacceptably large and requires further investigation.

5 Absorbed dose standards

5.1 For ^{60}Co

(John McCaffrey, Malcolm McEwen and Carl Ross)

A new source (220 TBq) was installed in our irradiator in March 2004, giving an absorbed dose rate of approximately 1 Gy/min at the reference point (SSD of 100 cm and SCD of 105 cm). An extensive series of water calorimeter measurements was carried out using the new source. The estimated absorbed dose rate could be compared using transfer chambers with that established by calorimetry on the old source. The values differed by 0.15 %, well within the estimated uncertainty.

5.2 For MV x-rays

(Malcolm McEwen and Carl Ross)

Our new Elekta clinical accelerator provides x-ray beams of 6, 10 and 25 MV. We have completed a series of calorimeter measurements using these beams and have calibrated several chambers that will be used as secondary standards. We have also carried out calorimetry measurements at additional beam qualities using our Vickers research accelerator. A summary of results obtained at NRC for k_Q for an NE-2571 chamber is shown in Figure 1.

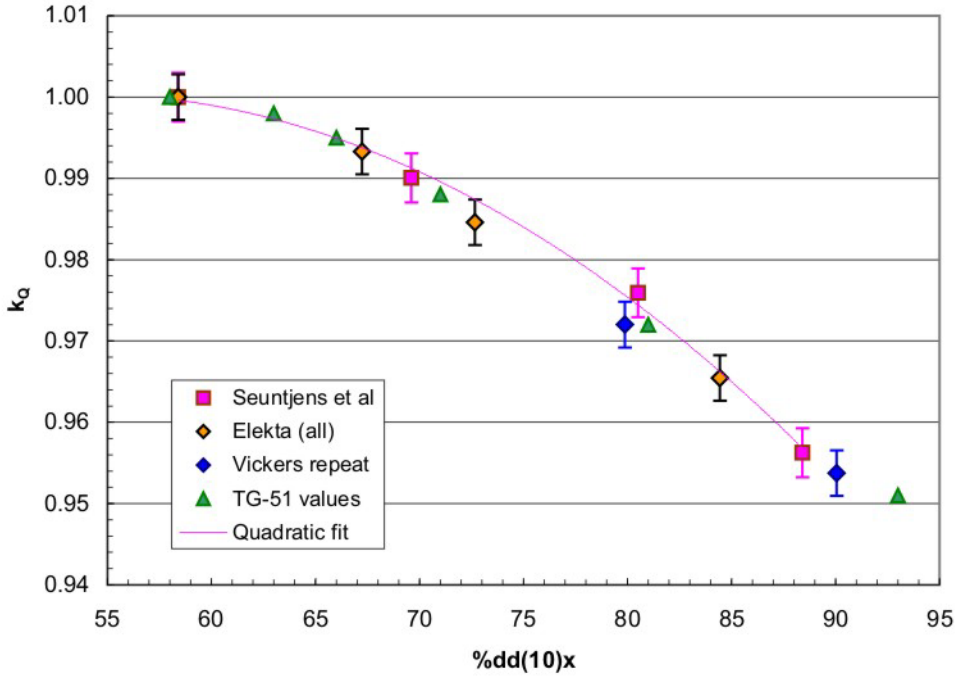

Figure 1. Beam quality conversion factors obtained at NRC for an NE-2571 chamber. The data by Seuntjens *et al* were reported in *Med. Phys.* **27** (2000) 2763.

6 Water calorimetry

(Carl Ross, Norman Klassen and Malcolm McEwen)

The advantage of water as a calorimetric material is that it gives directly the absorbed dose to water, which is the quantity of interest for radiation therapy. The main disadvantage is that radiation-induced chemical reactions can lead to a heat defect. The heat defect of pure water saturated with either an inert gas or H_2 gas is expected to be zero after an accumulated dose of a few Gy. However, both systems are sensitive to the presence of impurities so care must be taken to prepare and maintain them free from contaminants.

We have developed a vessel in which the only material in contact with the water is glass. Once properly cleaned, filled and sealed the properties of the enclosed

aqueous system can be expected to remain stable indefinitely. A similar situation is obtained with triple-point cells that are used as a key reference on the SI temperature scale (Hill (2001) *Metrologia* **38** 79-82). The properties of cells that have been sealed for almost 50 years remain largely unchanged.

An all-glass vessel is shown in Figure 2. The thermistor bead assemblies were left out of their glass envelopes until after the glass blowing was complete. The bead assemblies were then slid into their envelopes and held in place using nonadecane, a form of wax that melts at about 32 °C. After filling, the last open port on the vessel was flame-sealed. The vessel reported on here was filled with H_2-saturated water and sealed in July 2000.

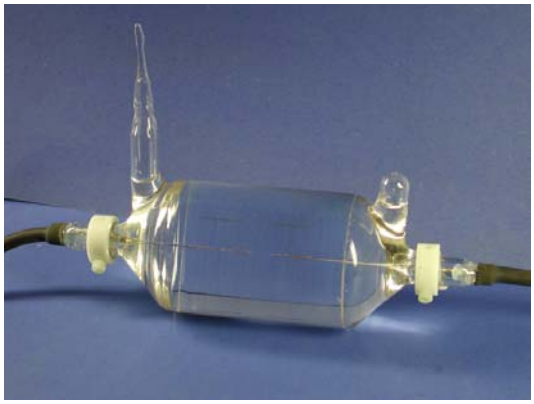

Figure 2. All-glass vessel. The nylon rings at each end are used to support the vessel in the water phantom.

Beam quality (%dd(10)$_x$)	$\frac{D_w \text{ (all-glass)}}{D_w \text{ (standard)}}$
58.4 (^{60}Co)	1.0013
67.2 (6 MV)	1.0024
72.7 (10 MV)	1.0016
84.4 (25 MV)	0.9995

Table 1. A comparison of D_w obtained with the all-glass vessel and a standard vessel.

The thermistors were calibrated by immersing the complete vessel assembly in a variable-temperature bath. Several calibration points between 1 and 7 °C were established using platinum RTD probes calibrated against the SI unit of temperature.
A summary of the results of measurements carried out during the fall and winter of 2004/05 for several beam qualities is shown in Table 1. The estimated standard uncertainty on each ratio is approximately 0.3 %. Furthermore, the response of the all-glass vessel now is the same within the estimated uncertainty with the response measured during 2000/01.

7 Alanine dosimetry

(Norman Klassen, Ge Zeng, Malcolm McEwen, Dave Rogers and John McCaffrey)

Although EPR/alanine dosimetry was developed originally for high-dose applications it has been found to be useful for doses of interest to radiation

therapy. One of the advantages of alanine for therapy applications is that its response, expressed as reading per unit absorbed dose to water, is expected to be only weakly dependent on energy. The objective of this work was to measure the alanine response for a range of beam qualities from 150 kV x-rays to 22 MeV electrons.

The EPR spectrometer was a Bruker EMX 081 and the alanine pellets and the quartz tube in which they were placed was purchased from Gamma-Service (Germany). The alanine pellets were right cylinders 5 mm in diameter and 3 mm in height, and were made of 96 % alanine and 4 % polyvinyl pyrrolidone. EPR signal amplitudes were normalized to that of a ruby crystal mounted near the bottom of the cavity.

The 150 kV x-ray beam had a mean energy of 72 keV and an air kerma rate of 0.2 Gy/min. Six alanine pellets were stacked in a cylindrical PMMA holder with a wall thickness of 1 mm. For the ^{60}Co air kerma irradiations an additional 4 mm thick sleeve of PMMA was added to the holder. The EGSnrc Monte Carlo code was used to establish the absorbed dose to alanine from the measured air kerma. The high-energy irradiations were all carried out in a water phantom. The same cylindrical PMMA holder was used for the photon irradiations, but it was placed inside a waterproof PMMA sleeve. The ^{60}Co dose rate was approximately 0.5 Gy/min while that for the high-energy x-rays was about 3 Gy/min. For the electron irradiations, the pellets were placed in a Virtual Water holder with geometry similar to that of an NACP chamber and the dose rate was approximately 5 Gy/min. The absorbed dose to water in the photon beams was established using water calorimetry. The TG-51 dosimetry protocol was used for the electron beams. Typically, four dose points between 20 and 50 Gy were used, averaging the results from all six pellets for each dose.

The results for the high-energy photon and electron beams, expressed as EPR signal per unit absorbed dose to water, are shown in Figure 3 and Figure 4. The response, relative to ^{60}Co, is lower by about 0.6 % and 1.6 % for x-rays and electrons, respectively. These differences are consistent with Monte Carlo predictions, indicating that they are due to differences in the radiation absorption characteristics of alanine and water. On the other hand, differences between the measured and calculated results for 150 kV x-rays indicate that the free radical yield in alanine is about 6 % lower for 150 kV x-rays than for ^{60}Co γ-rays. (More details on these results can be obtained from [1], [18], [19] and [20]).

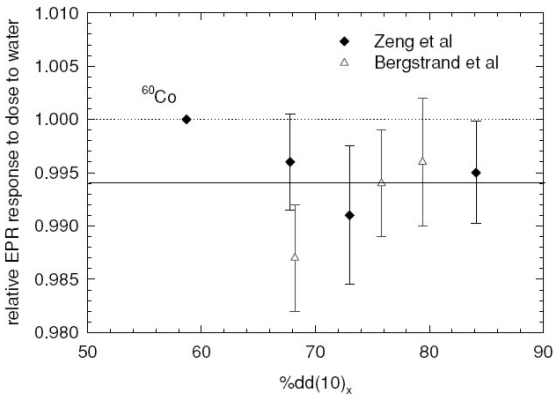

Figure 3. Measured alanine dose-to-water response for several photon beams. The results are normalized to unity for ^{60}Co γ-rays.

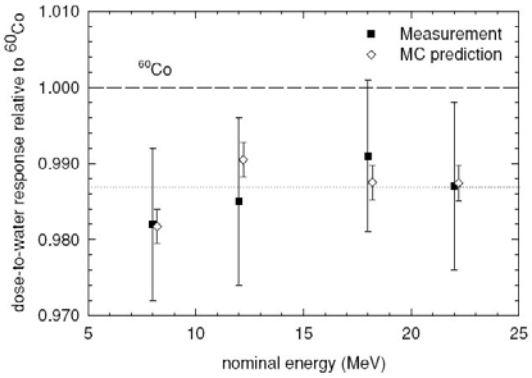

Figure 4. Measured alanine dose-to-water response for several electron beams. The results are normalized to unity for ^{60}Co γ rays.

8 Radiochromic film dosimetry

(Norman Klassen and Carl Ross, in collaboration with Slobodan Devic and Jan Seuntjens, McGill University)

A new dosimetry film, GafChromic EBT, is now available from International Specialty Products (Wayne, New Jersey, USA). EBT has been designed for radiation therapy dosimetry. EBT resembles previous GafChromic films in that absorbed dose causes the formation of a blue polymer, the optical density (OD) of which increases with absorbed dose. We are investigating EBT type A film. Overall, EBT type A is 0.23 mm thick. The active material is contained in two 17 μm thick layers cemented together by a 6 μm layer and sandwiched between two 97 μm thick clear polyester films. The increase in OD (ΔOD) versus dose is not linear and the dependence depends on the wavelength chosen for analysis. However, calibration curves are easily used to measure dose. The film sensitivity is said to be uniform to better than 1.5 % over a 200 x 250 cm sheet. Features that make this film attractive for therapy dosimetry are its sensitivity (it can be as high as a net optical density of 1.1 for a dose of 1 Gy at the peak wavelength), its low sensitivity to room light, its excellent spatial resolution and the small dependence of its response on x-ray energy. Potentially unattractive features are the dependence of the response on the orientation of the film if the analyzing light is polarized and the significant dependence of the background OD on the humidity at which the film is stored. Characteristics of EBT film are being studied in a collaboration between NRC and the Department of Medical Physics at McGill University.

Using a Cary 400 UV-Vis spectrophotometer, the absorption spectra (OD vs. wavelength) were measured for 3 pieces of unirradiated film cut from a single sheet at 0°, 45° and 90° from the vertical axis of the sheet (Figure 5) and ΔOD

versus wavelength for the same pieces of film after they had received a dose of 1 Gy (^{137}Cs γ-rays) (Figure 6).

The highest sensitivity results from measuring the OD at the peak of the spectrum. Unfortunately, sufficiently intense light sources that allow one to limit the analyzing light to a narrow band pass are most likely to have a significant degree of polarization. Under those circumstances, the orientation of the film must be carefully controlled.

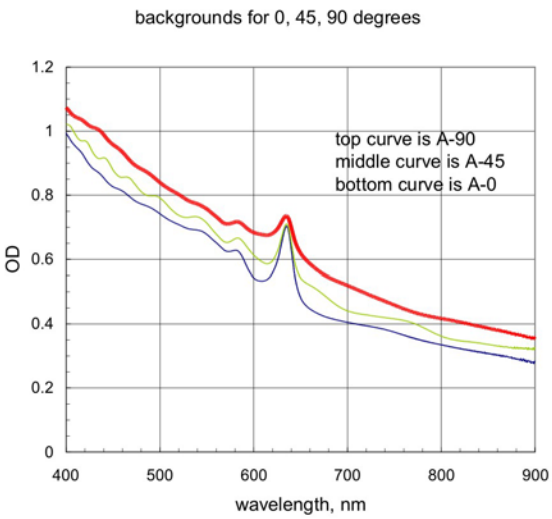

Figure 5. Background spectra for film strips cut at different orientations from a single larger sheet.

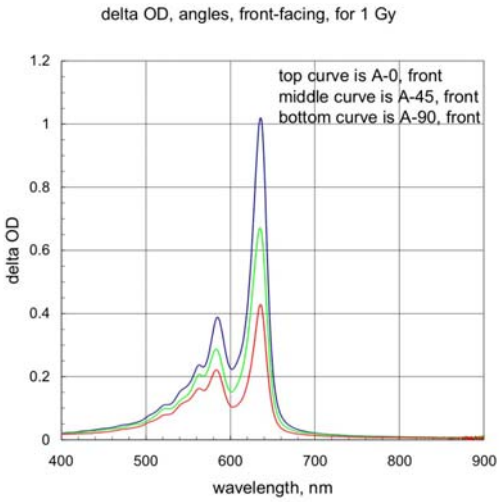

Figure 6. Spectra after 1 Gy for the same film strips used in Figure 5.

Another problem we have investigated is the dependence of OD on the humidity at which the film is stored. The dependence on humidity seems to be mainly that of the background spectrum (the fairly smooth curve in Figure 5, not the peaks seen in Figure 6). At 635 nm, the wavelength of peak response, the unirradiated film had ODs of about 1.36, 0.64, 0.55 and 0.44 after coming to equilibrium with relative humidities of 86 %, 44 %, 33 % and 5.5 %, respectively. We have shown that the effect is reversible and that moisture enters the film at different rates at the edges than it does through the polyester layers inside which the sensitive layer is situated.

A cursory examination of the response, expressed as ΔOD per unit air kerma, indicated that it is about the same for ^{60}Co γ-rays and 30 kV x-rays.

9 EUROMET comparison 605

(Malcolm McEwen and Carl Ross)

NRC participated in this comparison, organized by METAS. Four cylindrical ion chambers (NE2571, NE2561, NE2611 types) were calibrated in terms of absorbed dose to water in a ^{60}Co γ-ray beam and 6, 10 and 25 MV x-ray beams from the Elekta linear accelerator. Beam quality measurements were made in the megavoltage photon beams in order to compare the efficacy of $\%dd(10)_x$ and $TPR_{20,10}$ as beam quality specifiers.

It was found that for $TPR_{20,10}$ there appeared to be a slight dependence on the chamber used for the measurements, as shown in Table 2. The differences are small but measurable - a higher value is obtained with a smaller volume chamber. The standard uncertainty on each value is estimated to be 0.03%.

	NE2571	NE2611	NACP	PTW233642
vol (cc)	0.6	0.3	0.15	0.13
6 MV	0.6804		0.6811	0.6817
10 MV	0.7307		0.7317	0.7322
25 MV	0.7989	0.7998	0.8008	0.8004

Table 2. $TPR_{20,10}$ values obtained with different ion chambers.

An investigation of the determination of $\%dd(10)_x$ showed that this parameter was more sensitive to setup errors (e.g., defining zero depth), equipment used (e.g., water phantom) leading to a significantly higher standard uncertainty (0.25%). However, this uncertainty would not significantly influence the choice of chamber calibration factor.

10 β-ray dosimetry

10.1 Experimental work

(Patrick Saull)

Our new beta irradiator (Isotrak, BSS2), comprising three sources of differing mean energy, arrived in early 2004. The control electronics has been successfully integrated with our extrapolation chamber hardware, resulting in a complete data acquisition system (DAQ) for establishing and maintaining the standard for absorbed dose to tissue in a beta-ray field. Developed at IRS, the DAQ software for controlling data collection and analysis is based on a client-server model written in C++, and includes a graphical user interface for facilitating the setup, control, and monitoring of all aspects of data-taking. Except for the occasional operator intervention to change an aspect of the physical setup, e.g., chamber depth, the DAQ process is completely automated. This

speeds up the collection and analysis of data, and reduces the possibility for human error.

One advantage of the new irradiator is the inclusion of two lower-energy sources, Pm-147 and Kr-85. These complement IRS's two older, higher-energy Sr-Y-90 sources, extending the range of study to energies lower than previously available. Correction factors, e.g., for chamber entrance window and side-wall effects, have been determined experimentally in order to improve the accuracy of the standard.

The new system will be put to the test in mid-2005 in a EUROMET intercomparison (EUROMET.RI(I)-S2) of absorbed dose rate to tissue in a β-ray field. The results will be sent to the BIPM for inclusion in the Key Comparison Database.

10.2 Theoretical work

(Palani Selvam and Dave Rogers, Carleton University, and Patrick Saull)

In order to establish the validity of existing methods for determining correction factors for the absorbed dose to tissue standard, parallel work has been carried out using the higher-intensity Sr-Y-90 source of our older irradiator system. Precise measurements have been made of beta dose rates as a function of three different variables: source-chamber distance (11 to 60 cm), chamber depth (0.025 to 0.25 cm), and added front-window absorber-material thickness (up to 150 mg/cm^2 of Mylar). These measurements, 43 in total, have been compared to Monte Carlo predictions based on the EGSnrc code system.

An accurate model of the experimental setup was developed using the BEAMnrc code, containing a detailed implementation of the geometry of NRC's extrapolation chamber and the Sr-Y-90 source. Other than the geometry and materials specification, the only input to the simulations was the Sr-Y-90 spectrum. Electrons generated according to this spectrum were transported (down to an effective energy of 1 keV) from within the source through to the air cavity of the modelled chamber, taking into account interactions in all intervening materials. Dose-per-particle predictions for each experimental setup were obtained.

A comparison of measured dose rate and corresponding predicted dose per particle yields an estimate of the source activity for each point. These were found to be consistent with each other, as well as with the known activity of the source, providing confidence in the validity of the model. A global fit of the theoretical predictions to the experimental data, using only the source activity as a free parameter, displays impressive agreement in the three variables: within 0.37 % for measurements versus source-chamber distance (most points within 0.1 %); 0.4 % for measurements versus chamber depth; and 0.46 % for those versus added absorber thicknesses up to 38 mg/cm^2 (most points within 0.2 %). Based

on these results, we conclude that the model can be used as a reliable tool to extract correction factors for beta dose-rate standards.

11 Linac in-air profiles

(Elena Tonkopi, Iwan Kawrakow and Malcolm McEwen)

In-air profiles, also known as off-axis ratios (OAR), are very useful in the commissioning of beams from a linear accelerator as they are very sensitive to the energy and spot size of the electrons incident on the bremsstrahlung target. In-air measurements are typically performed using an ion chamber inserted in a build-up cap with a wall thickness equivalent to the depth of dose maximum (d_{max}). Our goal was to investigate the influence of ion chamber response, including build-up cap, on the in-air OAR measurements in megavoltage photon beams.

In-air profiles were measured using a Farmer chamber for 6, 10 and 25 MV photon beams from an Elekta Precise linear accelerator. Build-up caps of hevimet (a tungsten alloy) and brass were used together with two PMMA mini-phantoms of different sizes. The x-ray beams were directed vertically downward and measurements were carried out with the chamber oriented horizontally (chamber axis perpendicular to the beam axis) and vertically (chamber axis parallel to the beam axis).

BEAMnrc was used to simulate the output of the linear accelerator and the user code CAVRZnrc was then used to calculate the dose deposited in the air cavity of an ionization chamber inserted in the different build-up caps. The traditional approach to store the particles emerging from the treatment head in a phase-space file and use it as a source for the dose calculation was not applicable here because the geometry of interest (ion chamber) is typically very small compared to the area (40 cm by 40 cm) of the simulated field. Two new techniques for the ion chamber positioned horizontally or vertically were developed.

For a horizontally oriented chamber pre-calculated tables of the ion chamber response for different photon energies can be used to compute the dose deposited in the chamber on the fly within the BEAMnrc simulation. For a vertically oriented chamber a modified BEAMnrc version was compiled into a shared library that can serve as a particle source for CAVRZnrc and other EGSnrc user codes. With these changes the OAR calculations can be performed ‘on-the-fly’ without intermediate phase-space file generation.

Results of MC simulations were compared with experimental in-air OAR profiles and it was found that calculated and measured in-air profiles agree within the statistical and experimental uncertainties for a horizontally oriented chamber for all investigated beams and build-up caps. Figure 7 shows in-air profiles for a 10 MV beam.

For linac commissioning the quantity of interest is the air kerma. Figure 8 shows the comparison of the calculated air-kerma and OAR profiles for different build-up caps. There is a 3-6% difference between air-kerma and in-air profiles for hevimet and brass and 0.5-1% for PMMA mini-phantoms. The results of our investigation demonstrate that low-density mini-phantoms are recommended over high-Z material build-up caps for in-air profile measurements of air-kerma.

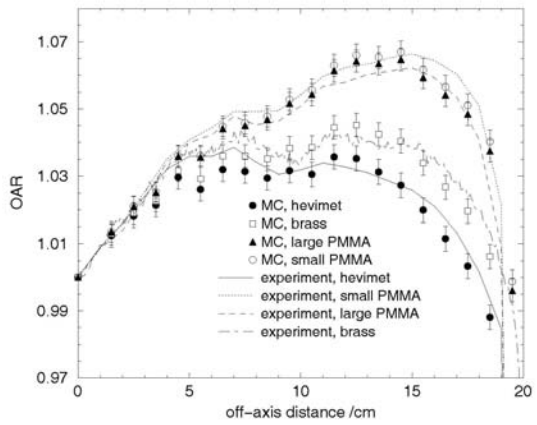

Figure 7. Off-axis ratios for a 10 MV beam and horizontally oriented ion chamber. Energy and radius of the incident beam for the MC calculations were 9.4 MeV and 0.5 mm, respectively.

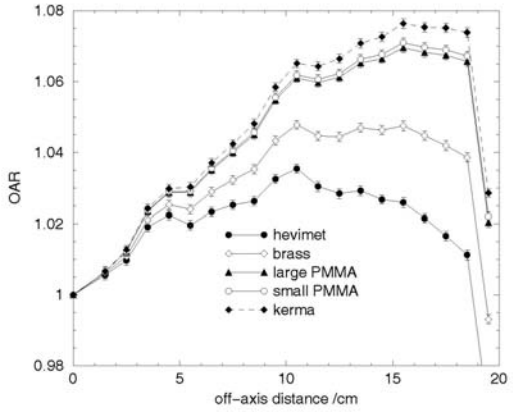

Figure 8. Comparison of calculated air kerma and OER profiles for a horizontally oriented chamber in a 6 MV beam.

12 Characterization of Virtual Water

(Malcolm McEwen)

An investigation was carried out to compare the water equivalence of two formulations of Virtual Water. The two mixes had nominally the same chemical composition but different densities. One of the aims of the project was to determine which formulation gave the closest agreement with measurements in water. In high-energy photon beams, where Compton scattering dominates, obtaining water equivalence is a matter of matching the electron density of the material to that of water. In electron beams one needs to match both the scattering and stopping powers.

The physical density of a number of plates of each mix was determined:

VW mix No. 1 = 1.059 g cm^{-3}

VW mix No. 2 = 1.047 g cm^{-3}

These values are similar to those of other epoxy-resin water equivalent materials.

Measurements were carried out in photon and electron beams using the Elekta linac and the detector used was an NACP ionisation chamber. Values of the charge per monitor unit were acquired at a range of depths in water and Virtual Water (VW) phantoms. A field size of 10 cm x 10 cm with an SSD of 1 m was used throughout (photons and electrons).

The technique of substitution was used to measure the effect of using VW in photon beams. Slabs of VW were placed in the water phantom, replacing the equivalent thickness of water. This gives a measure of the effective electron density relative to that of water. As might be expected, it was found that the effective density for photon beams is lower for Mix No. 2. However, neither formulation gives an exact match with water:

VW mix No. 1	1 cm VW is equivalent to 1,019 cm of water
VW mix No. 2	1 cm VW is equivalent to 1.008 cm of water

This leads to a difference in the dose measured, if one assumed that 1 cm VW = 1 cm water, of up to 1 % for Mix No.1 in a 6 MV photon beam.

More extensive measurements were made in electron beams – depth-dose curves were acquired in water and Virtual Water for 4, 8, 12, 18 and 22 MeV electron beams. The water and Virtual water phantoms were placed side-by-side and alternated in the electron beam. A typical result (12 MeV) is shown in Figure 9.

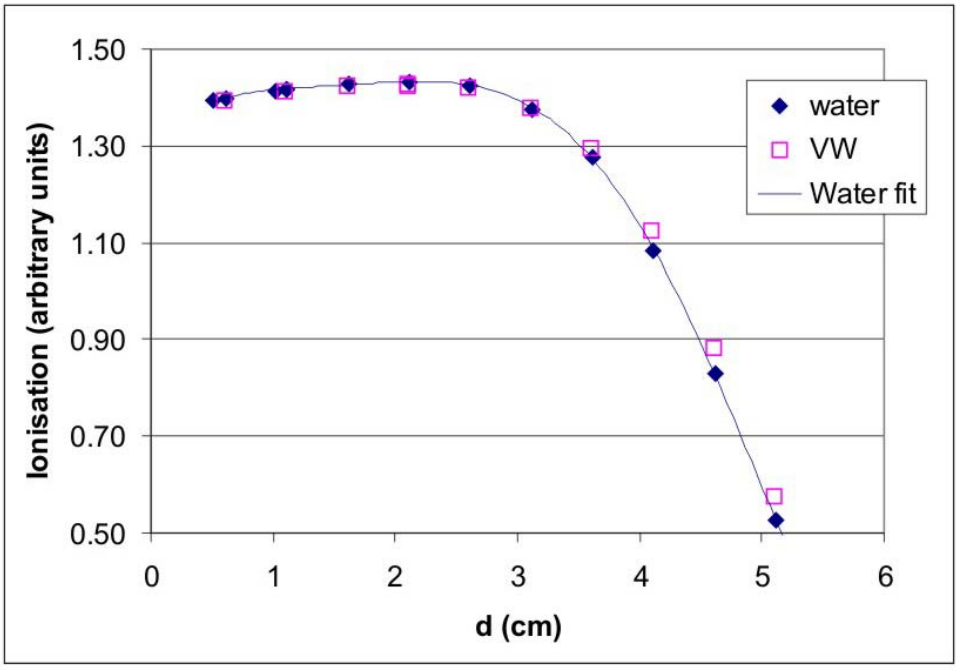

Figure 9. Comparison of water and Virtual Water (new mix) in a 12 MeV electron beam.

As can be seen, the effective stopping power for VW is lower than that of water (opposite to the photon results).

VW mix No. 1	1 cm VW is equivalent to 0.990 cm of water
VW mix No. 2	1 cm VW is equivalent to 0.978 cm of water

Although this difference in stopping power results in significant fluence differences (> 5 %) between the VW and water on the falling portion of the depth-dose curve the effect on the build-up portion and around the peak, the region of interest in the clinical situation, is small. For both materials the fluence correction is less than 0.5 % from d_{max} to d_{ref} (the standard uncertainty on this correction is estimated to be 0.2 %).

These results would indicate that there is a compromise between photon and electron performance. For both mixes the effective density in photons is greater than unity while that for electrons is less than unity. If one makes the assumption that 1 cm VW = 1 cm water then in photons this will result in dose errors of up to 1 % at the reference depth of 10 cm. In electron beams the fluence correction around d_{max} is less than 0.5 % at all energies. For measurements beyond the peak one must take account of the difference in stopping power between water and VW. It is recommended that VW not be used for the measurement of electron range parameters (R_{50}, R_p) in water.

13 Refereed publications, 2003-05

[1] E. S. Bergstrand, K. R. Shortt, C. K. Ross, and E. O. Hole. An investigation of the photon energy dependence of the EPR alanine dosimetry system. *Phys. Med. Biol.*, 48:1753 – 1771, 2003.

[2] L. A. Buckley, I. Kawrakow, and D.W. O. Rogers. An EGSnrc investigation of cavity theory for ion chambers measuring air kerma. *Med. Phys.*, 30:1211 – 1218, 2003.

[3] L. A. Buckley, I. Kawrakow, and D. W. O. Rogers. CSnrc: Correlated sampling Monte Carlo calculations using EGSnrc. *Med. Phys.*, 31:3425 – 3435, 2004.

[4] S. D. Davis, C. K. Ross, P. N. Mobit, L. Van der Zwan, W. J. Chase, and K. R. Shortt. The response of LiF TLDs to photon beams in the energy range from 30 kV to ^{60}Co γ-rays. Radiat. Prot. Dosim., 106:33 – 44, 2003.

[5] R. Doucet, M. Olivares, F. DeBlois, E. B. Podgorsak, I. Kawrakow, and J. Seuntjens. Comparison of measured and Monte Carlo calculated dose distributions in inhomogeneous phantoms in clinical electron beams. *Phys. Med. Biol.*, 48:2339–2354, 2003.

[6] N. I. Kalach and D. W. O. Rogers. When is an accelerator photon beam “clinic-like” for reference dosimetry purposes. *Med. Phys.*, 30:1546 – 1555, 2003.

[7] I. Kawrakow, D. Rogers, and B. Walters. Large efficiency improvements in BEAMnrc using directional bremsstrahlung splitting. *Med.Phys.*, 31:2883 – 2898, 2004.

[8] E. Mainegra-Hing, I. Kawrakow, and D. W. O. Rogers. Calculations for plane-parallel ion chambers in ^{60}Co beams using the EGSnrc Monte Carlo code. *Med. Phys.*, 30:179 – 189, 2003.

[9] E. Mainegra-Hing, D. W. O. Rogers, and I. Kawrakow. Calculation of photon energy deposition kernals and electron dose point kernals in water. *Med. Phys.*, 32:685 – 699, 2005.

[10] J. P. McCaffrey, E. Mainegra-Hing, I. Kawrakow, K. R. Shortt, and D. W. O. Rogers. Evidence for using Monte Carlo calculated wall attenuation and scatter correction factors for three styles of graphite-walled ion chamber. *Phys. Med. Biol.*, 49:2491 – 2501, 2004.

[11] M. R. McEwen. Comment on “Determination of the depth of the 50% of maximum ionization, I_{50}, for electron beams by the divided difference method”. *Med. Phys.*, 31:3158 – 3159, 2004.

[12] M. R. McEwen and A. R. DuSautoy. Characterization of the water equivalent material WTe for use in electron beam dosimetry. *Phys. Med. Biol.*, 48:1885 – 1893, 2003.

[13] M. R.McEwen, J. P. Sephton, P. G. H. Sharpe, and D. R. Shipley. Use of a range scaling method to determine alanine/water stopping power ratios. *Radiat. Phys. Chem.*, 68:1017 – 1022, 2003.

[14] J. Medin, C. K. Ross, G. Stucki, N. V. Klassen, and J. P. Seuntjens. Commissioning of an NRC-type sealed water calorimeter at METAS using ^{60}Co γ-rays. *Phys. Med. Biol.*, 49:4073 – 4086, 2004.

[15] D. W. O. Rogers and I. Kawrakow. Monte Carlo calculated correction factors for primary standards of air-kerma. *Med. Phys.*, 30:521 – 543, 2003.

[16] S. R. Sheng, S. P. McAlister, J. P. McCaffrey, and S. J. Kovacic. Degradation and recovery of SiGeHBTs following radiation and hot-carrier stressing. *Solid State Electronics*, 48:1901 – 1906, 2004.

[17] D. I. Thwaites, A. R. DuSautoy, T. Jordan, M. R. Mcewen, A. Nisbet, A. E. Nahum, and W. G. Pitchford. The IPEM code of practice for electron dosimetry for radiotherapy beams of initial energy from 4 to 25 MeV based on an absorbed dose to water calibration. *Phys. Med. Biol.*, 48:2929 – 2970, 2003.

[18] G. G. Zeng and J. P. McCaffrey. The response of alanine to a 150 keV X-ray beam. *Radiat. Phys. Chem.*, 72:537 – 540, 2005.

[19] G. G. Zeng, M. R. McEwen, D. W. O. Rogers, and N. V. Klassen. An experimental and Monte Carlo investigation of the energy dependence of alanine/EPR dosimetry: I. Clinical x-ray beams. *Phys. Med. Biol.*, 49:257 – 270, 2004.

[20] G. G. Zeng, M. R. McEwen, D. W. O. Rogers, and N. V. Klassen. An experimental and Monte Carlo investigation of the energy dependence of alanine/EPR dosimetry: II. Clinical electron beams. *Phys. Med. Biol.*, 72:1119 – 1129, 2005.

14 Conference publications, 2003-05

[1] S. Duane, M. R. McEwen, and I. Stoker. Comparison of graphite standard calorimeters in megavoltage photon and electron beams. *IAEA–CN– 96/4, in Proceedings of Symposium on Standards and Codes of Practice in Medical Radiation Dosimetry, (IAEA, Vienna)*, pages 67 – 73, 2003.

[2] P. Fuochi, M. Lavalle, G. Lulli, E. Gombia, M. Prudenziati, and M. R. McEwen. Radiation induced defects in bipolar transistors: influence of radiation energy. *Proceedings of the 8th International Conference on Astroparticle, Space Physics, Detectors and Medical Physics Applications (World Science Pub. Co.)*, 2003.

[3] J. Helt-Hanson, M. Millar, M. R. McEwen, P. H. G. Sharpe, and S. C. Duane. Development of a primary standard calorimeter for low energy electron beams. *Proceedings of a Workshop on Recent Advances in Absorbed Dose Standards, (ARPANSA, Melbourne)*, http://www.arpansa.gov.au/absdos/proc.htm, 2003.

[4] M. R. McEwen and S. Duane. Portable graphite calorimeter for measuring absorbed dose in the radiotherapy clinic. *IAEA–CN–96/9P, in Proceedings of Symposium on Standards and Codes of Practice in Medical Radiation Dosimetry, (IAEA, Vienna)*, pages 115 – 121, 2003.

[5] M. R. McEwen, S. Duane, and R. A. Thomas. Absorbed dose calibration factors for parallel-plate chambers in high energy photon beams. *IAEA–CN–96/28, in Proceedings of Symposium on Standards and Codes of Practice in Medical Radiation Dosimetry, (IAEA, Vienna)*, pages 335 – 341, 2003.

[6] M. R. McEwen and C. K. Ross. Performance of an “Off-the Shelf” clinical linac for radiation standards dosimetry. *Proceedings of a Workshop on Recent Advances in Absorbed Dose Standards, (ARPANSA, Melbourne)*, http://www.arpansa.gov.au/absdos/proc.htm, 2003.

[7] K. N. G. Rajan, S. Vandanaa, M. Vijayam, J. B. Shigwan, M. R. McEwen, and S. Duane. Testing of N_K and $N_{D,w}$ based IAEA Codes of Practice for clinical photon beams. *IAEA–CN–96/57P, in Proceedings of Symposium on Standards and Codes of Practice in Medical Radiation Dosimetry, (IAEA, Vienna)*, pages 467 – 474, 2003.

[8] R. Thomas, S. Duane, M. R. McEwen, and K. E. Rosser. Role of the National Physical Laboratory in monitoring and improving dosimetry in UK radiotherapy. *IAEA–CN–96/80P, in Proceedings of Symposium on Standards and Codes of Practice in Medical Radiation Dosimetry, (IAEA, Vienna)*, pages 201 – 208, 2003.