NRC Activities and Publications, 2011-2013
Report to the CCRI(I) Meeting, BIPM
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1 Introduction

The Ionizing Radiation Standards (IRS) Group of the National Research Council of Canada (NRC) is part of the Measurement Science and Standards (MSS) Portfolio, which is responsible for Canada's national metrology institute activities. The IRS group has fifteen full-time staff members. An overview of activities and staff can be found at: http://irs.inms.nrc.ca/.

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://www.nrc-cnrc.gc.ca/eng/solutions/advisory/calibration/ionizing_radiation.html

A searchable database of NRC publications is available at:
http://nparc.cisti-icist.nrc-cnrc.gc.ca/npsi/ctrl?lang=en.

2 Organizational Structure

The Measurement Science and Standards (MSS) Portfolio is headed up by a General Manager (Alan Steele) who also has the role of Canada's Chief Metrologist. Activities are assigned to one of three areas: i) Measurement Science for Emerging Technologies; ii) Metrology for Industry and Society; and iii) Support for the National Measurement System. Relevant to CCRI, the third area covers international comparisons and maintenance of the MSS Quality System.

3 ISO 17025 Quality System

The IRS quality system is based on ISO 17025 and approved by SIM (Sistema Interamericano de Metrologia). An internal audit was carried out in the Autumn of 2012.

4 EGSnrc Monte Carlo System

IRS continues to ensure the maintenance and development of the EGSnrc code system, about which additional information can be found at: http://irs.inms.nrc.ca/software/egsnrc/. A significant addition to the code, instigated by external collaborators, is the ability to simulate dynamic radiotherapy treatment modalities, wherein the treatment head and the patient motion are synchronized. The next release of the software is planned for April 2013. On the short term we are also forward to releasing the code under an official GPL open source licence to facilitate dissemination of the software and encourage external contributions to the code.

Training courses continued to be offered. Jointly with Carleton University, a course on the user code BEAMnrc, attracting thirteen international attendees, was held at NRC from 15 to 18 October 2012.

5 Air kerma standards

5.1 For kV x-rays

(John McCaffrey, Ernesto Mainegra-Hing and Hong Shen)

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.

Key comparisons with the BIPM for low-energy X-and low-energy X-ray mammography qualities have been published in *Metrologia* in 2011.

IRS participated in a SIM comparison (SIM.RI(I)-K3) of medium-energy x-ray standards piloted by NIST. The final report is expected soon.

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

(John McCaffrey and Brad Downton)

^{60}Co and ^{137}Cs air kerma standards are based on a cylindrical graphite cavity chamber. To provide redundancy and investigate possible systematic effects two additional graphite cavity chambers with different geometries - one spherical and one plane parallel - are under development. Stability testing of the plane parallel chamber has demonstrated primary-standards level performance while work on the speherical has focused on an accurate mechanical determination of the chamber volume.

Work is also ongoing to develop an improved calibration chain between the therapy –level air kerma primary standard and protection level doserate calibrations of survey instruments. A series of spherical ion chambers, with a range of volumes, is currently being characterized.

5.3 For ^{192}Ir high dose rate (HDR) brachytherapy

(John McCaffrey and Brad Downton)

A new Canadian ^{192}Ir HDR brachytherapy calibration capability has been developed. Work in the last two years has included refinement of the source-ion chamber positioning system and improved measurement/calculation of the source scatter correction, resulting in improved uncertainties available from the system. Well-chamber calibrations are now available during the first quarter of every year. This standard will participate in a formal international comparison for HDR brachytherapy, tentatively scheduled for 2013/2014.

5.4 For ^{125}I and ^{103}Pd low dose rate (LDR) brachytherapy

(Ernesto Mainegra-Hing, Hong Shen and John McCaffrey)

A wide angle free air chamber (WAFAC) was purchased and installed in 2012. After initial testing the mechanical and software components were refined, and the sytem is now being commissioned to provide LDR brachytherapy calibrations. Following on from the work on the standard NRC free-air chambers, a complete, self-consistent set of Monte Carlo based correction factors are being calculated. It is expected that the capability will be ready for comparisons and calibrations in 2014.

6 Absorbed dose standards

6.1 For ^{60}Co

(Brad Downton, Malcolm McEwen and Carl Ross)

The absorbed dose rate to water in a ^{60}Co beam is established using a water calorimeter. A Gammabeam X-200 irradiator (Best Theratronics) is used to disseminate this standard.

6.2 For MV x-rays

(Malcolm McEwen, Claudiu Cojocaru and Carl Ross)

The NRC calibration service for ionization chambers in MV photon beams has been operational since 2007. Absorbed dose to water calibrations are carried out at the three x-ray energies produced by the linear accelerator maintained at the laboratory. The nominal beam energies are 6, 10 and 25 MV and the corresponding values of %dd(10)$_x$ (TPR$_{20,10}$) are 67.4(0.681), 72.4(0.731) and 84.0(0.800). Canadian cancer centres continue to make use of this service and repeat calibration requests indicate that clients view this as an ongoing chamber QA tool, rather than simply an experimental evaluation of chamber k_Q factors. Sufficient data has been obtained to allow a statistical analysis of chamber calibration coefficients for the most popular chamber types:

	Standard deviation			
	^{60}Co	6 MV	10 MV	25 MV
Chamber type	($N_{D,w}$)	(k_Q)	(k_Q)	(k_Q)
NE2571	1.03%	0.05%	0.11%	0.09%
PTW30013	0.54%	0.10%	0.08%	0.06%
IBA FC-65G	0.42%	0.14%	0.14%	0.14%

Although there are relatively large variations in the ^{60}Co $N_{D,w}$ coefficients the chamber-to-chamber variation in k_Q is very small. This indicates that, as one might expect, the variation in calibration coefficients is primarily due to variations in the cavity air volume, rather than differences in the chamber wall, electrode or stem.

7 Beta-ray dosimetry

(Patrick Saull, Brad Downton, David Marchington and Stewart Walker)

IRS maintains a standard for absorbed dose to tissue in a β-ray field using an extrapolation chamber. This instrument has been fully integrated into an automated data-acquisition system with two PTW β-source irradiators. Using these irradiators and our well-established standard, we maintain an independent testing and calibration facility and continue in the role of "reference calibration centre" as part of the Canadian Nuclear Safety Commission's regulatory standard on quality assurance. All dosimetry service providers operating in Canada are required to undergo annual independent testing of their extremity dosimeters at NRC.

8 Linear accelerators for ionizing radiation standards at NRC

(Carl Ross, Malcolm McEwen, David Marchington, Stewart Walker, Claudiu Cojocaru)

The Ionizing Radiation Standards Group operates two electron linear accelerators - a 3-40 MeV Vickers research accelerator, installed in 1968, and an Elekta *Precise* clinical accelerator installed in 2002. The complementary nature of the two linacs has proved very useful over the last decade. The clinical linac is straightforward to operate and provides clinic-like electron and photon beams for the dissemination of the NRC primary standard of absorbed dose to water. The research linac provides very well defined beams that have been used for a number of benchmarking investigations in recent years. Reliability of both machines has been impressive and a major upgrade of the Vickers linac is planned for 2013/14 to provide automated beam control and simplified maintenance. Although the Elekta linac is reaching the end of what would be a typical clinical 'life' the accelerator is operating fully within specifications and replacement is not anticipated before 2020.

9 Determination of relative perturbation factors for parallel-plate ion chambers in high energy electron beams

(Brian Muir (Carleton University, Ottawa) and Malcolm McEwen)

A collaboration between NRC and Carleton University has been looking at using high-precision depth-ionization curves to extract relative perturbation corrections for parallel-plate chamber in electron beams. A number of groups have been investigating ion chamber perturbation factors in electron beams as part of the development of electron primary standards and improvement of dosimetry protocols. However, measurements at the reference depth only provide limited data, especially at low energies where the perturbation correction is likely to be varying rapidly. A comparison of depth-ionization curves yields not only significantly more data but gives the energy dependence directly, since the mean electron energy varies continuously from the surface to the practical range. Beam quality correction factors can then be obtained from such relative perturbation corrections by comparing one chamber against the primary standard.

The investigation has focused on: a) validating the method with a wide range of chambers in a number of electron beams, and b) investigating how one can accurately relate measurement depth to mean electron energy. Regarding (a), the primary issues are chamber positioning, energy stability and chamber equilibration. The last point was investigated by obtaining the polarity correction obtained from the depth-ionization curve and comparing with data obtained only at the reference depth. The result is shown in Figure 1.

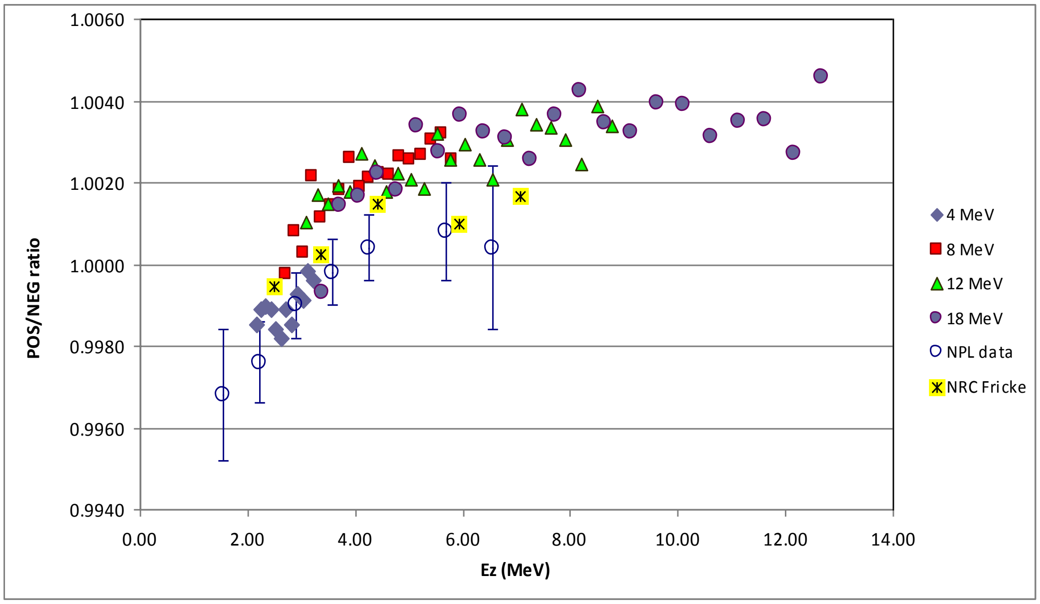

Figure 1. Polarity ratio for NACP chamber obtained from depth-ionization curves in a range of clinical electron beams. “NPL data” refer to those published by Bass et al; “NRC Fricke” refers to measurements made at the reference depth in a separate investigation on Fricke dosimetry.

The data is encouraging as there is very good overlap between the different energy beams and the scanned data reproduces the ‘standard’ method quite well. Results for the relative perturbation of the PTW Roos chamber relative to the NACP chamber are given in Figure 2.

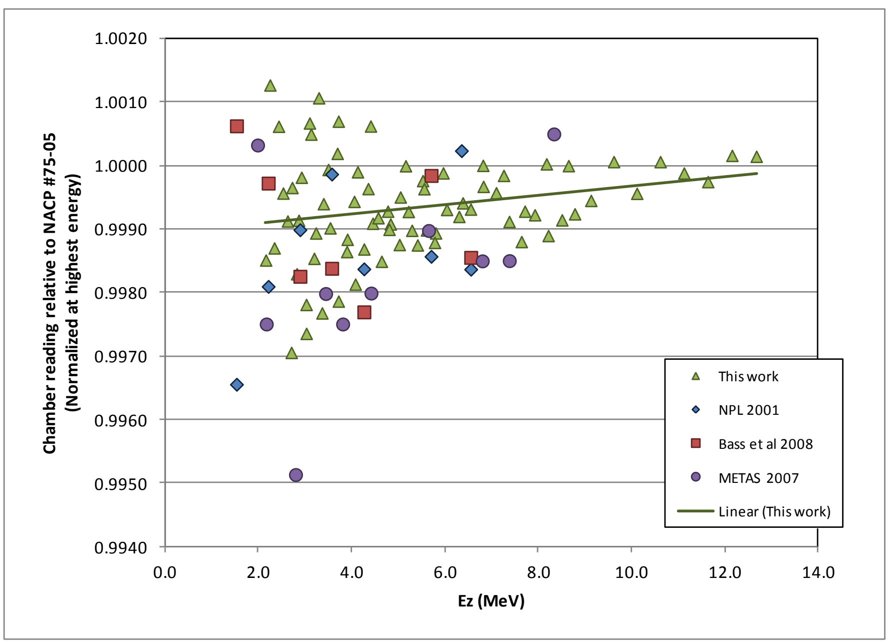

Figure 2. Comparison of Roos/NACP ratio obtained using this method with data from the literature.

Overall there is very good agreement between this new method and published data. One might even conclude that the data is superior, providing a similar level of statistical noise but with a significant increase in the number of data points.

10 Quantitative air communication testing of ion chambers for megavoltage dosimetry

(Malcolm McEwen, Islam El Gamal (Carleton University))

Ionization chambers for external beam reference dosimetry are vented (i.e., the air cavity directly communicates with the external environment) and it is generally assumed that any vent is not blocked. The application of the standard correction for air density (P_{TP} in the TG-51 protocol) requires this to be the case but this assumption is not tested by users, and not universally verified by calibration laboratories. An air communication protocol for calibration and testing of cylindrical and parallel-plate ionization chambers has been implemented at NRC. The system adopted comprises a Sr-90 check source in a vacuum/pressure vessel. Vacuum feed-throughs allow the measurement of air pressure, air temperature and ionization current. The vacuum vessel is rated down to -100 kPa but investigations were limited to realistic air pressure values, from 0 kPa ('standard see level') to -20 kPa (an altitude higher than Denver, CO).

In commissioning the system both cylindrical and parallel-plate chambers were investigated (using commercial cylindrical and planar Sr-90 sources respectively). Investigations focused on repeatability, potential systematics (e.g., equilibration time and order of pressure values), polarity effect and dependence on chamber type. Any effect of the air attenuation of the Sr-90 beta-rays with varying air pressure was ignored due to the small source-chamber distance (< 5 mm). Initial measurements showed that the air temperature within the chamber did not change significantly during the measurement procedure and so temperature was not routinely monitored.

For each ion chamber, a set of ionization current values were obtained as a function of vessel air pressure. The results of the investigation can be summarized as follows:

Measurement procedure. No significant difference was seen between measurements made quickly (wait time between pressure changes ~ 30 seconds) and slowly (wait time ~ 300 seconds). It was also found that the order used for the pressure values had no significant effect on the obtained data.

Intra and inter-measurement repeatability. Repeat measurements obtained at the same pressure during a single 'run' showed an average difference of less than 0.1%. Measurements on the same chamber at different times showed similar variations, indicating an uncertainty in the chamber reading at -20 kPa (relative to that at room air pressure) of less than 0.2%.

Polarity effect. In investigating the polarity effect it was expected that the low energy electrons from the Sr-90 source would induce a significant polarity effect . However, it was not clear if there would be a differential effect with a change in air pressure. In fact, air-density-dependent polarity effects were observed for many chamber types, both cylindrical and parallel-plate, with corrections generally larger for pp chambers.

The estimated standard uncertainty in a single charge measurement is 0.15%, which means that the system can be used for more than simply checking that an ion chamber communicates with the environment. A summary of results obtained to date are shown in Figure 3.

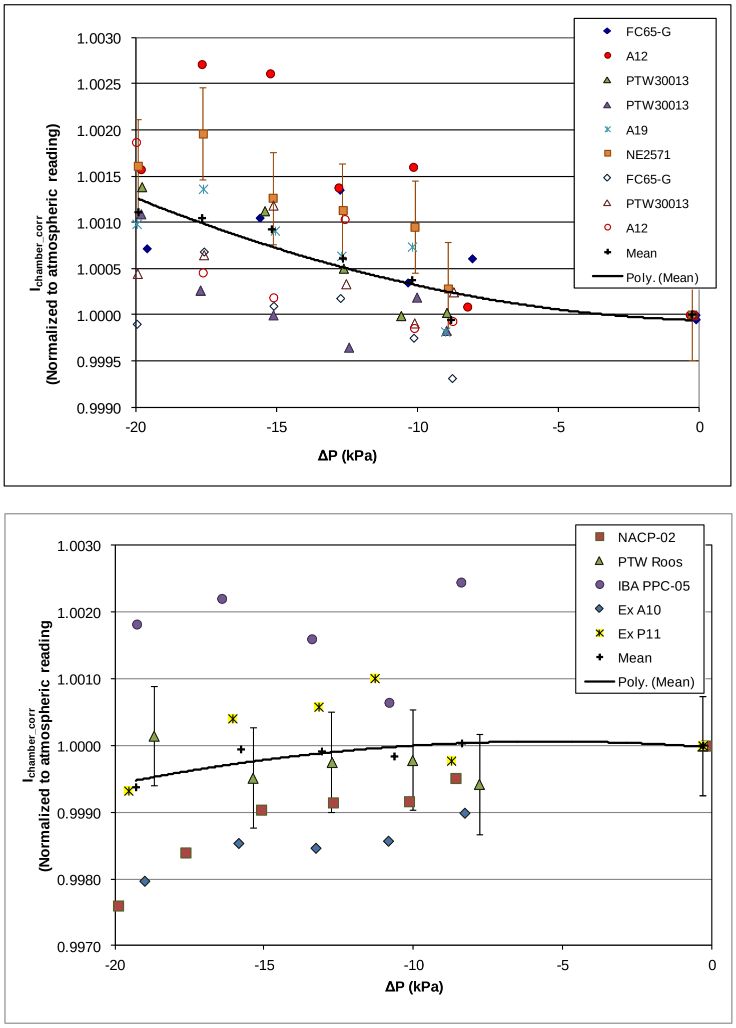

Figure 3. Summary of results (polarity corrected) for cylindrical Farmer-type chambers (left) and parallel-plate chambers (right). Variations between chamber versions appear to be similar for the two types, although the residual deviation from the ideal response is slightly larger for the cylindrical chambers. This may be an artifact of the irradiation geometry or the effect of direct collection of electrons in the electrode.

11 Development of a Fricke-based dosimetry standard for HDR brachytherapy

(Islam El Gamal (Carleton University), Malcolm McEwen and Claudiu Cojocaru)

The replacement of air kerma-based standards with dose-based standards for ^{192}Ir HDR brachytherapy is being pursued at a number of institutions worldwide, including NRC. The approach taken has been to investigate the potential of the Fricke dosimeter to provide an absorbed dose to water standard. The obvious advantage of Fricke over calorimetry techniques is the insensitivity to the self-heating of the source. The main disadvantages are related to chemical contamination and determination of the G-value.

As a first step it was decided to reproduce the experiment of Austerlitz et al. (Med. Phys. **35**, 5360 (2008)), where the Fricke solution is placed in a ring-shaped holder around the ^{192}Ir source. A number of modifications/improvements were applied to address issues of contamination, signal-to-noise and position reproducibility.

The Fricke holder is machined from PMMA and shown in Figure 4. The ^{192}Ir source is delivered using a Nucletron Microselectron HDR unit and the vertical position of the source is located using a diode scanned along the length of the catheter. An optical telescope is then used to position the Fricke holder relative to the source position with an uncertainty of <0.25 mm.

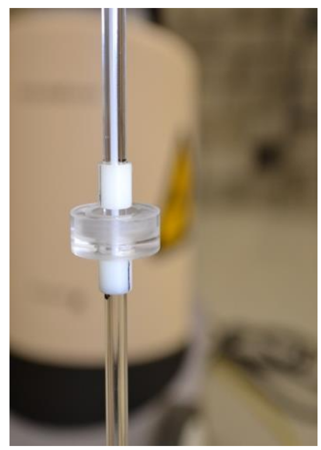

Fig 4. Experimental setup showing the Fricke holder and source positioning apparatus, Microselectron HDR unit and the stoppers used in marking the position of the device.

Chemical contamination can have a significant effect on the accuracy and precision of the Fricke dosimeter so much care was taken in cleaning the PMMA holder and transferring the irradiated solution to the read out system. Control (unirradiated) runs were used to evaluate any effect of ‘leaching’ from the PMMA walls and this was found to be small and reproducible (standard uncertainty of 0.2 %). Prior to detailed ^{192}Ir irradiations, a complete test of the system was performed by irradiating Fricke dosimeters in Co-60 and successfully comparing with historical NRC data.

Due to the geometry of the holder and the rapidly-changing dose distribution around the source, the standard uncertainty in the decay-corrected net absorbance readings for the ^{192}Ir irradiations was larger than for the Co-60 irradiations (0.5 % and 0.2 % respectively). However, this compares very favourably with that of Austerlitz et al, who obtained an equivalent value of 1.8 %. The level of precision is very encouraging and allows us to progress with other aspects of the project to develop an absorbed dose to water standard.

Current research is focused on experimentally determining the G-value of Fricke for ^{192}Ir energies and using Monte Carlo simulations to correct dose-to-Fricke in an inhomogeneous holder arrangement to dose-to-water in an undisturbed phantom. In addition, this project has indicate that the Fricke dosimeter can be applied to a range of dose measurements where an arbitrary or specific dose-measuring volume is required (for example, in newer radiation therapy modalities such as Tomotherapy, VMAT or Rapid Arc.

12 **MC benchmarking**

(Claudiu Cojocaru, Malcolm McEwen, Elsayed Ali (Carleton University), Carl Ross)

Two independent, but complementary investigations have been carried out using the NRC Vickers research linac to test, or benchmark, Monte Carlo radiation transport codes (specifically the EGSnrc system). In the first, x-ray transmission data were acquired with the aim of unfolding photons spectra, and in the second, lateral x-ray distributions were measured for a range of bremsstrahlung target materials.

Transmission measurements – on-axis transmission measurements were made for 8 beams from 10-30 MV, with fully-stopping bremsstrahlung targets of Be, Al and Pb. The attenuators chosen were pure C and Pb. The attenuator dimensions were fully mapped in 3D for accurate mass thickness estimates to avoid errors, which were found to be up to 4%. Density uniformity of the graphite bars was established from CT scans and from sensitivity studies during data acquisition. The radiation beam was collimated to good beam geometry before and after the attenuator and the signal was acquired at ~3 m from the linac exit window using an Exradin A19 ion chamber, once with a low-Z cap (PMMA) and once with a high-Z cap (W-alloy). This is equivalent to two detectors of differing energy response. A protocol was established to monitor and correct for many influence quantities including profile flatness and symmetry (within 0.3 mm), beam output normalization (5%), beam drifts (2%), polarity (6%), ion recombination (0.2%), leakage (0.3%), short-term repeatability (0.2%), spectrum stability (0.15%), room scatter (0.8%), apparatus scatter (negligible), and alignment/positioning uncertainties (negligible). Based on a detailed uncertainty budget, the typical uncertainty on the smallest measured signals is 0.4%. The EGSnrc system was used to calculate the transmission signals from a full model of the setup (including blueprint models of the detectors), and the results were compared with the experimental signals. EGSnrc was also used to generate bremsstrahlung spectra from the known linac electron parameters, and the results were compared with the spectra unfolded from the measured transmission data and from previously published data.

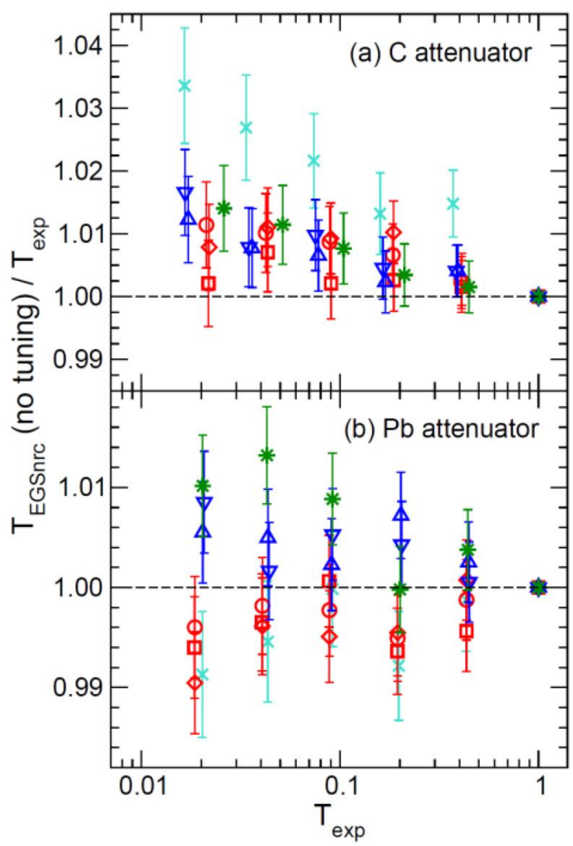

Fig 5. Transmission signals: calculated (T_{EGSnrc}) versus measured (T_{exp}). Data are shown for the following MV/target combinations: 10MV/Al (×), 15MV/Be (○), 15MV/Al (□), 15MV/Pb (◊), 20MV/Al (△), 20MV/Pb (▽), and 30MV/Al (✳).

Figure 5 shows direct comparisons between the measured and calculated transmission signals. Overall, the agreement is excellent given that there is no tuning in the Monte Carlo model. For C, the agreement is 2% for all beams except for the less-stable 10 MV beam (3.3%). For Pb, the agreement is 1%. Scaling the photon cross sections used in EGSnrc by up to ±0.5% makes the majority of the data agree with unity within the uncertainty bars. Therefore the discrepancies beyond the uncertainty bars can be attributed to cross section uncertainties of ±0.5%, which are within the typically quoted uncertainty of 1-2%.

A full description of this project has been published (Ali et al, Med. Phys. 39, 5990 (2012); Ali et al, Med. Phys. 39, 6585 (2012)).

Lateral beam profiles - the aim of this work is to provide accurate benchmark data for bremsstrahlung beams generated in thick targets fully stopping high energy electron beams. A number of recent publications have reported the need for more accurate data sets for testing Monte Carlo radiation transport codes to benefit applications in medical physics such as: radiotherapy dose calculation in regions with inhomogeneities, step dose gradients, low transmission, detector response, activation analysis and leakage calculations.

In this work, electron beams with energies of 15 MeV and 20 MeV were used to create the x-ray fields. A selection of five targets (beryllium, aluminum, copper, tantalum and lead) was used in order to fully stop the electrons and create the bremsstrahlung with the same end point energy but different spectra. The x-ray fields were scanned in a transverse plane to the electron beam direction using Farmer-type ionization chambers in one of six build-up caps (PMMA, aluminum, copper, brass, tin and W-alloy). Similar to the transmission measurements described above, changing the build-up cap is equivalent to using a detector with a different energy response. Influence factors including polarity and recombination effects, dependence on chamber geometry and long stability were investigated to give confidence in the experimental results as a benchmark. With an uncollimated field, the polarity effect was very large, particularly at large distances off-axis where the signal is significantly reduced.

The EGSnrc system and its associated user codes BEAMnrc, cavity and FLURZnrc were used to compare the results of the simulations with the newly acquired data. An example is shown in Figure 6. The quantities being compared are: Exp – the corrected ion chamber reading (T, P, polarity, recombination); MC – dose to the air cavity of the ion chamber. Agreement for small angles is generally better than ± 2.5 %, similar to results reported previously. The 'structure' close to on-axis is very sensitive to the beam divergence at the linac exit window.

The larger discrepancies for Be and Pb targets at large off-axis distances are still being investigated – the Be data in particular has implications for graphite cross-sections implemented in EGSnrc. The intent is to make this experimental data freely available for benchmarking other MC codes.

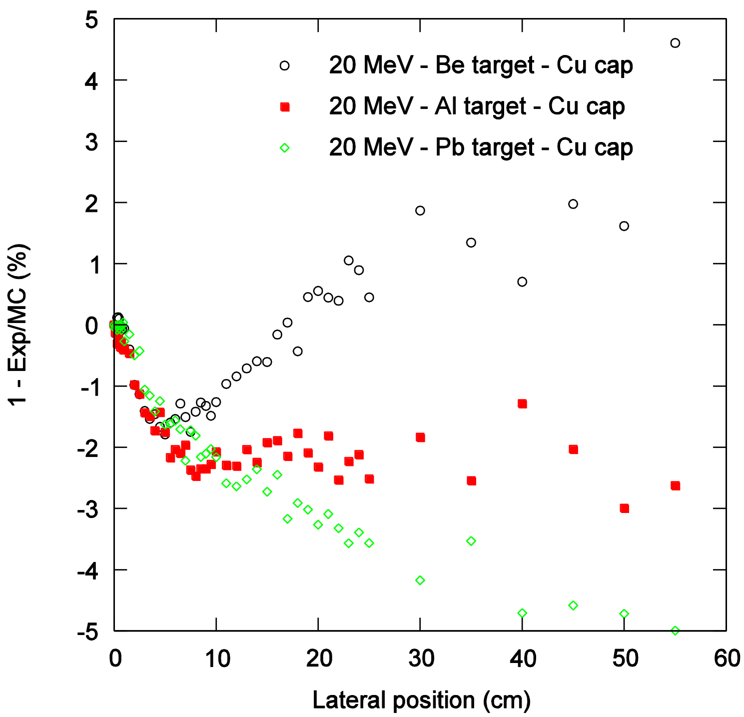

Fig 6. Comparison of measured later beam profiles with those calculated using the EGSnrc MC system.

13 'Fundamental' dosimetry data

(Claudiu Cojocaru, Malcolm McEwen, Carl Ross)

As shown by Svensson and Brahme in 1986, the detailed measurements of calorimeter/ion chamber ratios by Domen and Lamperti (Med. Phys. 3, 294, 1976) can be analyzed to provide a value of W_{air} for high energy electron beams. An exhaustive Monte Carlo investigation of that data has now been carried out at NRC, in consultation with Steve Domen at NIST. The complete geometry of the calorimeter-chamber comparison has been simulated and the various correction factors applied in the 1976 paper have been investigated. The result is shown in Figure 7.

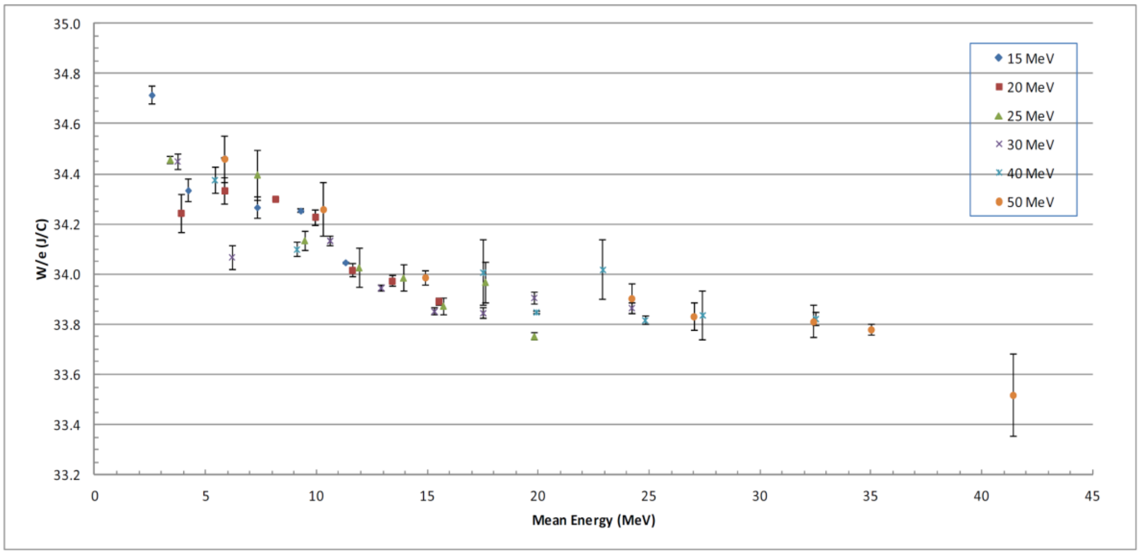

Figure 7. Results of MC re-analysis of Domen and Lamperti experiment

The trend is basically the same as reported by Svensson and Brahme, a variation in W_{air} with energy that is not consistent with measurements for low photon energies. Further investigations have indicated that the apparent increase at low energies can be explained by realistic changes in the density of the graphite plates used and/or the exit energy of the NIST linac, neither of which can be confirmed so long after the original experiment.

As a result, it was decided to perform a similar (but reduced) set of measurements at NRC. A suitable parallel-plate ion chamber was identified and a graphite calorimeter constructed. Irradiations were carried out using the NRC Vickers research linac at a number of incident energies and measurement depths. Initial results are encouraging with no indication of an increase in W_{air} for low electron energies. However, further work is required to determine all the correction factors and investigate influence quantities, particularly the graphite density. Combining this work with that of Ali et al above, there is the indication that the granular nature of bulk-density graphite may be a fundamental limit to the accuracy achievable in dosimetry using this material and that alternatives may need to be considered.

Characterization of the ion chamber used for these measurements lead to an investigation of the 'vacuum' signal (ionization collected when there is no air in the cavity). The system described earlier in section 10 was extended down to pressures of 5-10 kPa and the results indicate that this unwanted signal is around 0.3 % of the ionization current measured at atmospheric pressure. This is consistent with theoretical estimates and has implications for any parallel-plate geometry ion chamber used in a similar way (i.e., as a cavity standard).

14 Refereed publications, 2011-13

[1] J Renaud, D Marchington, J Seuntjens and A Sarfehnia, “ Development of a graphite probe calorimeter for absolute clinical dosimetry”, Med. Phys. 40, 020701 (2013)

[2] H Bouchard and M McEwen, “Comment on “Linearization of dose-response curve of the radiochromic film dosimetry system” Med. Phys. 39, 4850-4857 (2012)”, Med. Phys. 39, 7171 (2012)

[3] E. S. M. Ali, M. R. McEwen, and D. W. O. Rogers, “Unfolding linac photon spectra and incident electron energies from experimental transmission data, with direct independent validation”, Med. Phys. 39, 6585 (2012)

[4] E. S. M. Ali, M. R. McEwen, and D. W. O. Rogers, “Detailed high-accuracy megavoltage transmission measurements: A sensitive experimental benchmark of EGSnrc”, Med. Phys. 39, 5990 (2012)

[5] J. P. McCaffrey, F. Tessier, and H. Shen, “Radiation shielding materials and radiation scatter effects for interventional radiology (IR) physicians”, Med. Phys. 39, 4537 (2012)

[6] J. Dubeau, S.S. Hakmana Witharana, J. Atanackovic, A. Yonkeu, J.P. Archambault, "A Neutron Spectrometer Using Nested Moderators", Rad. Prot. Dos. 150(2) (2012)

[7] B. R. Muir, M. R. McEwen, and D. W. O. Rogers, “Beam quality conversion factors for parallel-plate ionization chambers in MV photon beams”, Med. Phys. 39, 1618 (2012)

[8] B. Downton and S. Walker, “Humidity effects on calibrations of radiation therapy electrometers”, Med. Phys. 39, 984 (2012)

[9] C Kessler, D T Burns and J P McCaffrey, “Key comparison BIPM.RI(I)-K7 of the air-kerma standards of the NRC, Canada and the BIPM in mammography x-rays”, Metrologia 48 06022 (2011)

[10] D T Burns, C Kessler and J P McCaffrey, “Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the NRC, Canada and the BIPM in low-energy x-rays”, Metrologia 48 06002 (2011)

[11] E Heath, F Tessier and I Kawrakow, “Investigation of voxel warping and energy mapping approaches for fast 4D Monte Carlo dose calculations in deformed geometries using VMC++”, Phys. Med. Biol. 56, 5187 (2011)

[12] F. Lacroix, M. Guillot, M. McEwen, L. Gingras, and L. Beaulieu, "Extraction of depth-dependent perturbation factors for silicon diodes using a plastic scintillation detector", Med. Phys. 38, 5441 (2011)

[13] B. R. Muir, M. R. McEwen, and D. W. O. Rogers, "Measured and Monte Carlo calculated kQ factors: Accuracy and comparison", Med. Phys. 38, 4600 (2011)

15 **Conference presentations, 2011-13**

[1] M McEwen, C Cojocaru, F Tessier and C Ross, "Determining the value of W_{air} in the radiotherapy energy range", CIRMS 2012 Meeting, Gaithersburg, MD (2012)

[2] J Renaud, D Marchington, J Seuntjens, A Sarfehnia, "Development of a pgrahite probe calorimeter for absolute clinical dosimetry", CIRMS 2012 Meeting, Gaithersburg, MD (2012)

[3] J Dubeau, S Witharana, J Atanackovic, A Yonkeu, W Matysiak, A Waker, A Ibrahim, J P Archambault, "A Field Portable Neutron Spectrometer Based on the Bonner Sphere Principles", IEEE Nuclear Science Symposium an Medical Imaging Conference (2012)

[4] F Tessier, "Improved ionizing radiation measurements: reaching further with Monte Carlo", Canadian Association of Physics Congress (2012)

[5] C D Cojocaru and C K Ross, "Sci-Sat AM: Brachy -02: Extracting W_{air} from the 1976 electron beam measurements of Domen and Lamperti", Med. Phys. 39, 4645 (2012)

[6] I El Gamal, C Cojocaru, C Ross, D Marchington, and M McEwen, "Sci—Sat AM: Brachy — 03: Feasibility study of the determination of absorbed dose to water using a Fricke based system", Med. Phys. 39, 4645 (2012)

[7] M McEwen and I El Gamal, "Sci—Fri PM: Delivery — 04: Quantitative air communication testing of ion chambers for megavoltage dosimetry", Med. Phys. 39, 4643 (2012)

[8] B Muir, D Rogers, and M McEwen, "Sci—Thur PM: YIS — 07: Monte Carlo simulations to obtain several parameters required for electron beam dosimetry", Med. Phys. 39, 4623 (2012)

[9] E Ali, M McEwen, and D Rogers, "Sci—Thur PM: YIS — 02: A validated approach for clinical linacs to accurately determine the photon spectra and the incident electron energy", Med. Phys. 39, 4622 (2012)

[10] P Watson, E Mainegra-Hing, E Soisson, I El Naqa, and J Seuntjens, " Sci-Fri PM: Delivery -12: Scatter-B-Gon: Implementing a fast Monte Carlo cone-beam computed tomography scatter correction on real data", Med. Phys. 39, 4644 (2012)

[11] L DeWerd, J Seuntjens, M Rivard, and M McEwen, "TU-A-213AB-01: Dosimetry for Ir-192 HDR Brachytherapy - Present Status and Future Direction", Med. Phys. 39, 3884 (2012)

[12] M McEwen, A DuSautoy, and G Bass, "SU-E-T-66: A Particle-Counting Method to Determine Electron Stopping Powers", Med. Phys. 39, 3717 (2012)

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