CCRI(I)/03–47

NRC Activities and Publications, 2001–2003 Report to CCRI(I) Meeting, BIPM May 21 –23 2003

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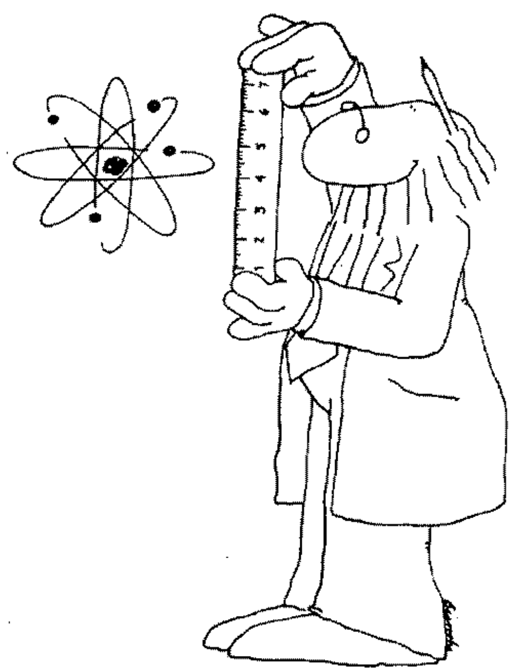

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Contents

1 Introduction

The Ionizing Radiation Standards (IRS) group at NRC is part of the Institute for National Measurement Standards (INMS). There are currently 13 full-time staff positions (with 3 more to be filled), 3 of whom are on “soft” money. There are 4 others working with the group on a part-time basis and a full-time graduate student. Most of the research work of the group results in publications and a full list of these is given in section 6. The previous report in this series was in 2001 (CCRI(I)/01–23).

1.1 Highlights Since May 2001

Aside from the significant changes in staff since the last meeting of the CCRI (see below), there have been several major events related to the group.

- In March 2002 we took delivery of an Elekta clinical accelerator for research purposes. The machine has 3 photon beams (nominal 6 MV, 10 MV and 25 MV) and 5 electron energies ranging from 4 MeV to 22 MeV. The accelerator has been commissioned and some initial experiments carried out but full characterization of the beams is on-going. Funding for the accelerator comes 50% from NRC's internal Major Initiatives Committee and the rest is an internal loan to be repaid by the group's income from Monte Carlo licensing revenue over the next few years.
- In summer 2001, Iwan Kawrakow won the Farrington Daniels Award of the AAPM for the best radiation dosimetry article published in the journal Medical Physics in 2000 for his paper describing EGSnrc.
- The group has been quite successful in licensing Monte Carlo software in the last few years. The BEAM code has been licensed to 5 institutions for commercial use with a total revenue to date of about $200K and the VMC++ code has been licensed to 2 companies with an expected revenue of about $5M (dependent on total sales). Iwan Kawrakow, David Rogers, and others at NRC and MDS-Nordion won an FPTT Award in 2001 for negotiating the first of these licensing deals (Federal Partners in Technology Transfer).

1.2 Presence on the WWW

NRC, INMS and IRS all have a presence on the WWW. NRC has a home page as does the Institute for National Measurement Standards. This latter page includes links to information such as our directory of services and a map of how to find us in Ottawa. We also maintain a series of research oriented sites which can all be reached from http://www.irs.inms.nrc.ca/inms/irs/irs.html. One main sub-site contains a link to a list of publications since 1951 and also to a number of papers which are fully on-line (in html) as well as available as postscript files and in some cases as pdf files. There are also pages devoted to the dissemination of the EGSnrc Monte Carlo systems and the BEAMnrc system for simulating radiotherapy units and calculating doses in a phantom specified by CT data.

1.3 IRS Staff 2001–2003

Research Officers
George Daskalov: discrete ordinates techniques for brachytherapy treatment planning (moved to Ottawa Regional Cancer Centre, July 2001)
Iwan Kawrakow: theoretical dosimetry and Monte Carlo techniques
Norman Klassen: absorbed dose measurements and radiation chemistry (retired Nov 2002, now part time 1day/week)
John McCaffrey: radiation dosimetry, air-kerma standards and chamber calibration services
Malcolm McEwen: radiation dosimetry, absorbed-dose and air-kerma standards (joined March 2002 from NPL)
David Rogers: dosimetry protocols, Monte Carlo simulation (group leader)
Carl Ross: radiation dosimetry, responsible for linear accelerators
Patrick Saull: radiation dosimetry, β-ray standards, neutron calibrations (joined April 2002 from DESY)
Ken Shortt: radiation dosimetry, responsible for ^{60}Co standards (moved to IAEA in August 2001)
Len van der Zwan: responsible for x-ray and β-ray standards (retired Nov 2002)
Ge Zeng: alanine dosimetry (joined Dec 2001 as a PDF working with Norman Klassen)

Technical Officers
Feridoun Farahvash: electronics
Leo Heistek: electronics (1/3 time)
Dave Hoffman: ion chamber calibration services (retired Feb 2002)
Matt Kosaki: responsible for linac operations (retired Jan 2003, now 1/3 time)
Ernesto Mainegra-Hing: support of Monte Carlo calculations
David Marchington: instrument maker, experimental assistant
Hong Shen: ion chamber calibration services (joined June 2001)
Stewart Walker: electronics
Blake Walters: OMEGA/BEAM and EGSnrc computing support

Other Support
Heather Matchett: secretary/organiser
Michel Proulx: computing system manager (part time)
David Niven: University co-op student for 12 months.

Physics Graduate Students
Lesley Buckley: Carleton University PhD student working on calculational radiation dosimetry (began Sept 2001, supervisor Rogers)
Steve Davis: MSc student working on TLD dosimetry (supervisor Ross, MSc McGill University, Aug 2002)
Nina Kalach: MSc student working on beam quality specification (supervisor Rogers, MSc Carleton University, July, 2001)

2 Air-kerma standards

2.1 Low-energy X-ray standards

The group provides low-energy x-ray standards from 10kV to 300 kV. These are based on free-air chambers. Calibrations based on these standards form a significant fraction of the calibration service provided by the group, including a quality assurance service for providers of TLD personnel monitoring services.

Table 1 summarises the final results of a comparison with the BIPM done in 1998.[1] This comparison was done by calibrating 3 NE2571 chambers at both NRC and the BIPM.

As reported at the last meeting, we have also taken part in a comparison held at NIST. NRC took part by calibrating a set of 2 ion chambers at NRC and at NIST using the NIST and NPL standards. The preliminary results indicate that in the M100, M150, M200 and M250 beams, NRC and NIST agree within 0.22% and by using the results of the NPL/NIST comparison in the same beams we can establish that the NRC standards are within 0.15% of the NPL standards except for the M250 beam where the NRC standard is 0.36% higher than the NPL standard. This is in contrast to the comparison with BIPM where the NRC beam at 250 kV is 1% lower than the BIPM standard.

Table 1: Comparison of the NRC and BIPM air-kerma standards for x-rays in the medium energy range using 3 cylindrical ionization chambers, type NE2571. The uncertainty in the comparison is 0.27%. Taken from ref.[1]

kV	HVL		$N_{K,NRC}/N_{K,BIPM}$
100	4.0	mm Al	0.9946
135	0.49	mm Cu	0.9932
180	0.99	mm Cu	0.9910
250	2.53	mm Cu	0.9905

Continuing some work reported at the previous meeting, it has been shown that errors of up to 0.8% are possible in x-ray and ^{60}Co beams if ion chambers are not sufficiently pre-irradiated. This is dealt with more fully in a separate submission to the CCRI.[2]

2.2 Energy response of LiF TLDs

As part of a study related to environmental dosimetry, we have measured the energy response of thermoluminescent dosimeters (TLDs) based on LiF. Both standard (LiF:Mg,Ti) and high sensitivity (LiF:Mg,Cu,P) forms of LiF were studied. Materials were obtained from Thermo Electron RM&P (formerly Harshaw TLD) and are denoted by TLD-100 and TLD-100H for LiF:Mg,Ti and LiF:Mg,Cu,P, respectively.

The TLDs were in chip form and were mounted five at a time in a cylindrical Lucite holder thick enough to provide charged particle equilibrium. The irradiations were carried out using ^{60}Co and ^{137}Cs γ-ray beams as well as ISO-quality x-ray beams with mean energies from 24 to 207 keV. Canadian primary standards for air kerma were used to establish the air kerma rate for each of the photon beams.

The air kerma response, defined as R/K_a, where R is the corrected output from the TLD reader and K_a is the air kerma, was measured for each beam quality. The EGSnrc Monte Carlo code was used to calculate D_{TLD}/K_a, the dose to the TLD chip per unit air kerma, for each of the photon beams. By taking the ratio of the measured air kerma response, R/K_a, to the calculated value of D_{TLD}/K_a, we obtain the absorbed dose response to the TLD chip, defined as R/D_{TLD} , and the results are shown in Figure 1.

Our results, which are in general agreement with published data, show that the dose response as a function of energy is very different for the two materials. We note that the change in LET from ^{60}Co to ^{137}Cs is sufficient to lead to a difference in response of the two materials of about 5%. The difference becomes much more dramatic as the energy decreases. The structure below about 100 keV is due to changes in the electron spectrum as the photoelectric cross section becomes more important.

LiF:Mg,Ti (TLD-100) is often used for brachytherapy dosimetry but there remains some confusion in the literature as to the energy dependence of the dosimeter. The mean photon energies of the most commonly used brachytherapy seeds range from 22 keV to 380 keV. Our results show that the variation of the dose response with energy will lead to corrections of up to 10% in this energy range, assuming the dosimeters have been calibrated using ^{60}Co γ-rays.

This work is described in the MSc thesis of S. D. Davis[3] and in a paper which has been submitted for publication.[4]

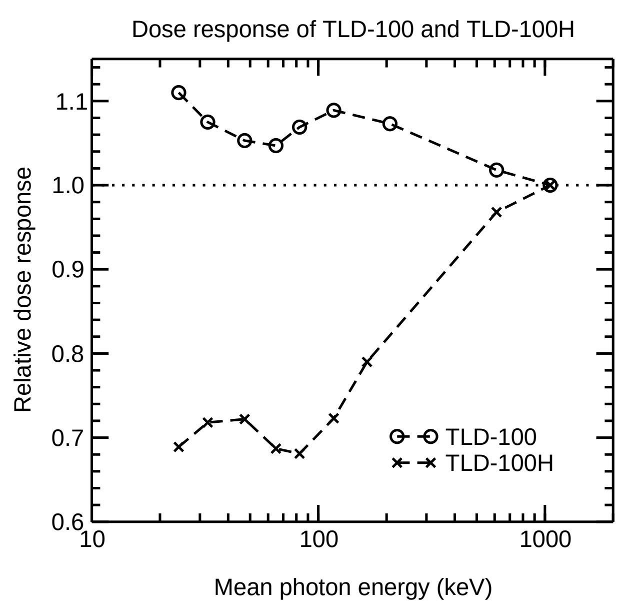

Figure 1: Results for the absorbed dose response as a function of energy for TLD-100 and TLD-100H. The absorbed dose is average dose delivered to the TLD chip. The Type A standard uncertainty on each point is typically 0.6%.

2.3 ^{60}Co air-kerma standards

The ^{60}Co air-kerma standards are based on cavity ion chambers with graphite walls.[5] The other major calibration services of the group are based on these standards.

In the last few years NRC has carried out formal comparisons of the ^{60}Co air-kerma standards with NIST, BIPM, ARL (ARPANSA), LNHB and OFMET and the results of these comparisons are summarised in table 2. A comparison with NPL is on-going. When three laboratories compare their standards in pairs, one can predict one of the results based on the other two, as done in column 5 of the table. This gives an estimate of the overall consistency of the comparisons. Table 2 shows that the degree of consistency is reasonable in all cases, with the loop closing at the 0.2% level or better.

Table 2: Results of comparisons of NRC's standard for air-kerma in a ^{60}Co beam

NMI	date	NMI/NRC	NMI/BIPM	implied NRC/BIPM
BIPM[6]	1998	0.9980(31)	1.000	1.0020(31)
ARPANSA[7,8]	1998	1.0006	1.0028(32)	1.0021
OFMET (in prep)	1998	0.9991	1.000	1.001
NIST[9]	1998	0.9939(40)	0.9980	1.004
LNHB[10]	1998	1.0014(50)	1.0025	1.001

2.3.1 Monte Carlo correction factors for air-kerma standards

Extensive calculations related to the correction factors for the NRC standard 3C chamber have been published[11] and will be incorporated into the NRC standard soon. The major effect is a 0.46% increase due to a correction for the rather large polystyrene insulator present in the chamber. The overall effect of the re-evaluation of correction factors is 0.54%. The changes are summarized in table 3.

One interesting sidelight in that paper was a Monte Carlo investigation of the accuracy of the approximation for the mean chord length in a cavity as given by $L = 4V/S$ which is rigorously true for isotropic radiation in a concave ion chamber, but also turns out to be accurate for electrons slowing down in a directed ^{60}Co beam incident on some very non-concave ion chambers (*e.g.* the BIPM pancake chamber and the Canadian 3C ion chamber with a very large electrode). Table 4 summarizes these results.

An important aspect of this study was a systematic estimate of the uncertainties on the various calculated correction factors needed for air-kerma standards. Although the uncertainties calculated were specifically for the Canadian 3C chamber, the estimated uncertainties would apply to values calculated in a similar manner for other primary standards. These values are summarized in table 5.

Table 3: Summary of the proposed changes to the Canadian primary standard for air kerma based on the current Monte Carlo calculations. The first row of the stopping-power ratio data corresponds to using the density effect corresponding to the grain density of graphite whereas the second line corresponds to no change in the stopping powers used (which is what NRC will adopt unless CCRI changes its recommendations).

Quantity	1990 Value	Present value	% Change
$\left(\frac{\overline{L}}{\rho}\right)^{\text{graphite}}_{\text{air}}$	1.0005	0.9987	$-0.18\%^{a)}$
		1.0010	$+0.05\%^{b)}$
K_{wall}	1.0218	1.0220	$+0.02\%$ $^{c)}$
1.0 - $\overline{g}$	0.9968	0.9969	+0.01%
K_{comp}	1.000	1.0046(3)	+0.46%
K_{an}	0.9999(6)	1.0004(4)	+0.05%
Overall change: with sp$^{d)}$ change: +0.31%		without sp$^{d)}$ change: +0.54%	

$^{a)}$ -0.23% from change in density effect, +0.14% from change in spectrum -0.07% going to Δ = 19 keV, +0.02% from using EGSnrc and -0.04% from using regeneration.
$^{b)}$ as in $^{a)}$ but with no change in the stopping power used.
$^{c)}$ −0.08% using a spectrum, +0.12% using a point source, −0.02% using EGSnrc.
$^{d)}$ sp = stopping power. The change referred to is from changing density effects.

Table 4: Values of mean chord length and corresponding Δ values as calculated using the formula $L = 4V/S$ or the Monte Carlo code (for a ^{60}Co beam although for 100 keV photons the results are very similar). Values of Δ are the the energies of an electron having a residual CSDA range of L using the range data in ICRU Report 37.[12] No correction for path curvature is included. Dimensions for the BIPM pancake chamber and widely used OMH cylindrical chamber are taken from ref.[13]

Chamber	4 V / S		Monte Carlo	
	L mm	Δ keV	L mm	Δ keV
3C	7.6	19.3	8.0	19.8
Mark IV flat	2.1	9.1	1.8	8.5
Mark IV side	2.1	9.1	2.4	10.1
BIPM pancake	4.0	13.4	3.5	12.4
OMH	6.5	17.6	6.6	17.8
Baldwin-Farmer	4.8	14.8	4.6	14.5

Table 5: Summary of uncertainties in calculated factors. All values are in %. The uncertainty on the product assumes the factors are independent which is an overly conservative assumption. An uncertainty of 0.07% reflecting the accuracy of the Spencer-Attix theory without a fluence correction factor is not included

Effect	$\left(\frac{\bar{L}}{\rho}\right)^{\text{graphite}}_{\text{air}}$	K_{wall}	K_{an}	K_{comp}	product
statistics	<0.01	<0.01	0.04	0.03	
algorithm	0.02	0.02	0.02	0.02	
spectrum	0.01	<0.01	0.04	0.04	
source size	–	0.01	0.02	–	
distance	–	0.01	–	–	
Δ selection	0.05	–	–	–	
Subtotals	0.05	0.03	0.06	0.05	0.10
cross-sections					
electron	0.65	0.01	–	0.08	
photon	–	0.01	–	0.14	
Totals	0.65	0.03	0.06	0.17	0.67

3 Absorbed-Dose Standards

The demand for ^{60}Co absorbed-dose calibrations in Canada has increased dramatically with the introduction of the AAPM's TG-51 protocol which has been formally recommended by the Canadian Organisation of Medical Physicists for clinical use in Canada and is being steadily implemented across the country. During the transition most clinics asked for both air-kerma and absorbed-dose calibration coefficients for each chamber whereas now we frequently only get a request for the absorbed-dose calibration coefficient (although we always measure the air-kerma calibration coefficient for QA purposes).

3.1 ^{60}Co absorbed-dose comparisons

In the last few years NRC has performed formal comparisons of absorbed dose to water standards with NIST, BIPM, ARPANSA, OFMET and LNHB and one is on-going with the NPL. In all cases the ^{60}Co standards were compared and in the cases of OFMET and LNHB two accelerator beam qualities were compared. The results are being written up and are mostly published.[9,10,14,15] The ^{60}Co results are summarised in Table 6. The degree of consistency between the bilateral comparisons taken in groups of 3 is demonstrated in column 5 of the table and is generally at the 0.08% level or better except for the comparison with NIST where the data fail to close at the 0.3% level.

Table 6: Results of comparisons of NRC's standard for absorbed dose in a ^{60}Co beam

NMI	date	NMI/NRC	NMI/BIPM	implied NRC/BIPM
BIPM[14]	1998	1.0024(52)	1.000	0.9976(52)
ARPANSA[15,16]	1998	1.0031	1.0008	0.9977
OFMET (in prep)	1998	1.0025	1.000	0.9975
NIST[9,17]	1998	1.0050(60)	0.999	0.9947
LNHB[10]	1998	1.0020(54)	0.9988	0.9968
NPL(preliminary)	2003	0.9985	0.999	1.0005

3.2 Water calorimeter

Work at several standards laboratories has demonstrated that the sealed water calorimeter is a suitable device for establishing the absorbed dose to water. The overall uncertainty is not dramatically better than that achieved using a graphite calorimeter. However, the measurement program is simpler, especially for higher energies, because no transfer procedure is required.

The proceedings of the 1999 NPL workshop on calorimetry contains three papers relating to the water calorimetry program at NRC. One[18] contains a description of the NRC calorimeter as well as some of the results obtained for photon beams. Another[19] reports on the effects of convective heat flow when the calorimeter is operated at room temperature. The third[20] describes the characteristics and behaviour of the OFMET (now METAS) water calorimeter which was built as part of a collaborative arrangement between the two laboratories.

3.2.1 Heat Defect

In a recent publication[21] we used a reaction model to calculate the heat defect for several aqueous systems. As reported at the last CCRI meeting we have since found that some of the rate constants used from the literature were incorrect and the calculations have been redone. These calculations have been reported in the literature[22] and show a 0.4% difference between the heat defect in a H_2/O_2 system at room temperature and 4^{o}C.

3.2.2 Electron beam dosimetry using water calorimetry

As reported to the last meeting, we have developed a special glass vessel for electron beam dosimetry. It is formed as a right cylinder with a diameter of about 10 cm and a depth of about 4 cm. The entrance window has been ground down to a thickness of 1 mm while the exit window thickness is about 2 mm. The thermistors are located approximately 2 cm behind the entrance window. In order to shorten the time required to bring the vessel to equilibrium, a magnetically driven stirrer is located in a cavity at the bottom of the vessel.

The positions of the thermistor probes within the vessel are determined using a travelling microscope which is first focused on the surface of the entrance window and then translated until the thermistor bead is in focus. The effects of conductive heat transfer from the probes and vessel walls were calculated and found to be about 0.3% for a typical sequence of 120 s irradiations.

Preliminary results for the absorbed dose to water have been obtained for a 20 MeV beam. A flat dose distribution was obtained by sweeping the electron beam along the surface of an imaginary cone with its apex at the beam exit window. Other than the beam exit window (0.13 mm of Ti) no additional scattering foils were used. Measurements of the ionization and the absorbed dose as a function of depth are shown in Figure 2. The dose profile near the reference depth is shown in Figure 3.

Calorimetric measurements were carried out using three aqueous systems. These were formed by saturating high purity water with N_2 gas, H_2 gas or a 43%/57% mixture of H_2 and O_2 gases. A discrepancy of about 0.5% in the measured response of the H_2/O_2 system is still under investigation. Four ionization chambers (one Farmer chamber and three parallel-plate chambers) were calibrated in the 20 MeV electron beam. They were also calibrated in terms of absorbed dose to water for ^{60}Co so that the factor could be determined. The results are shown in Figure 4 along with the predictions of the AAPM TG-51[23] and IAEA TRS-398[24] protocols.

The agreement between the measured and calculated values of is satisfactory. There is no protocol value available for the Exradin A11 chamber. Two measured values of are shown for the cylindrical chamber. This is because of an ambiguity regarding the positioning of the chamber for direct calibrations. The IAEA protocol states that the chamber should be positioned so that its central axis is downstream from the reference depth by one half the chamber radius. On the other hand, the AAPM protocol requires that the central axis of the chamber be placed at the reference depth.

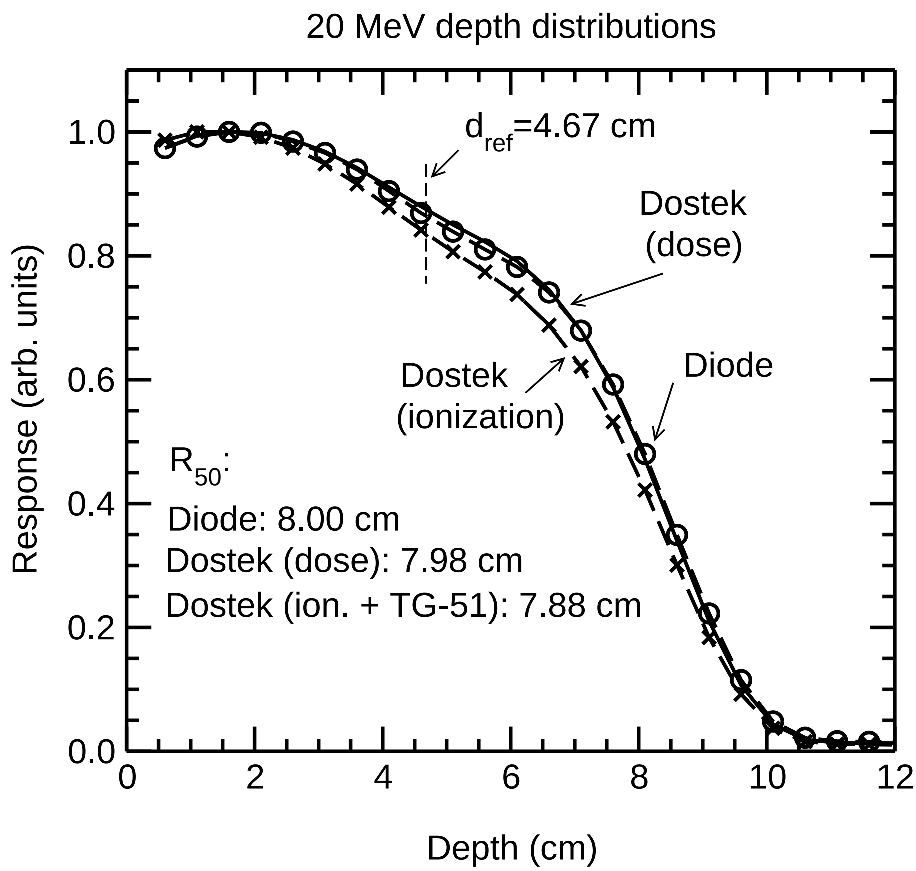

Figure 2: Measured ionization and dose as a function of depth. When the Dostek ionization measurements are converted to dose using stopping power ratios,[25] the results are virtually indistinguishable from the diode measurements. Various estimates of R_{50} are shown on the figure (note that TG–51 and TRS-398 use the same relationship for R_{50}.

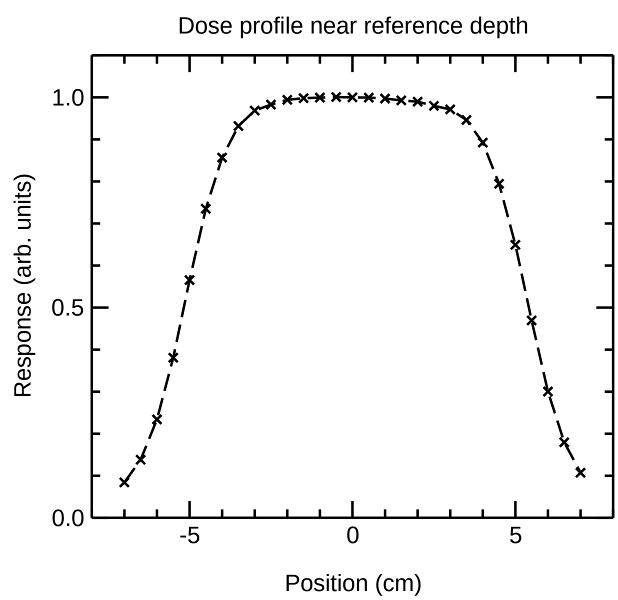

Figure 3: Measured radial dose profile near the reference depth.

3 ABSORBED-DOSE STANDARDS

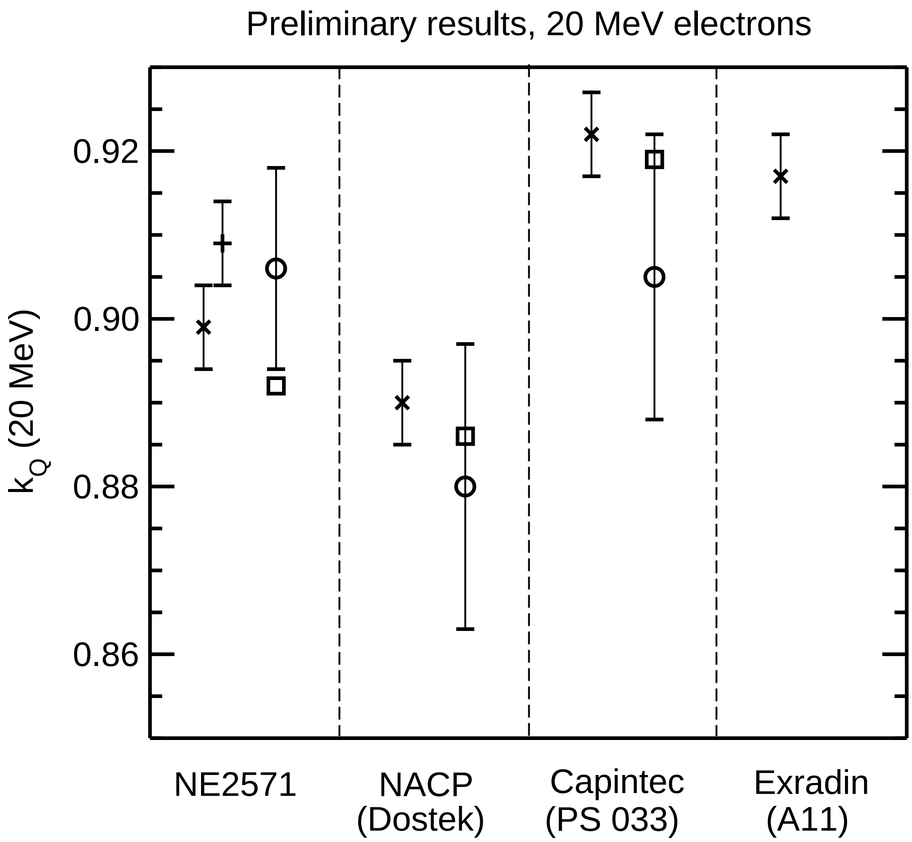

Figure 4: Measured values of k_Q for 20 MeV electrons compared to the predictions of the AAPM TG-51 and IAEA TRS-398 protocols. No protocol data are available for the Exradin A11 chamber. The symbols have the following meanings: crosses and pluses – measured values; circles –IAEA predictions; squares –AAPM predictions. Two measured values are shown for the NE 2571 chamber because the protocols use different points of measurement for direct calibrations of cylindrical ion chambers. The lower measured value for the NE2571 corresponds to the AAPM method and the cross corresponds to the IAEA method.

3.3 Fricke Dosimetry

Using the NRC Fricke dosimetry system the dose rate for ^{60}Co γ-rays can be measured with a standard uncertainty of 0.1-0.2% when based on the slope of 8 measurements made between 5-25 Gy. The system has been upgraded with the acquisition of a Varian model Cary 400 UV-Vis spectrophotometer. The optics and light measuring components of the Cary 400 performed admirably for our purposes. However, detailed testing revealed the need for significant changes to the hardware. These changes were made. As well, additions to the software package were made to conform to our user protocol. The new system achieves the same standard uncertainty as experienced with the Cary 210 previously used. A description of the current NRC Fricke dosimetry and many of the changes made to the spectrophotometer are described in a report.[26]

In Fricke dosimetry, the net increase in OD, ΔOD, is a measure of the increase in the ferric ion concentration. Using the Cary 400, a study was made of ΔOD versus absorbed dose for our Fricke solution. It is commonly asserted that Fricke dosimetry is linear with absorbed dose up to 200 Gy, above which (ΔOD per Gy) decreases due to the reduction in the concentration of oxygen caused by the radiolysis of the solution. The experimental evidence for the decrease in (ΔOD per Gy) with increased dose rests largely on the work of Cottens.[27] On the other hand, simulations with our computer model of the Fricke dosimeter (CCRI(1) 2001) indicate that the production of ferric ions, and hence ΔOD, should be linear with dose until almost 625 Gy, the dose at which both oxygen and ferrous ions are exhausted, almost simultaneously, in the standard Fricke dosimeter containing 1 mM ferrous ion in air-saturated 0.4 M sulfuric acid.

In view of the paucity of experimental results regarding the decrease in (ΔOD per Gy) with increased dose and the apparent conflict with the results of our simulations, we measured ΔOD versus dose from 8.8 Gy to 718 Gy. An abrupt fall off in (ΔOD per Gy) was observed just above 600 Gy as predicted by the computer simulation. However, below 600 Gy, a decrease in (ΔOD per Gy) with increased dose was also observed. Figure 5 shows the results of two sets of Fricke measurements made on our Eldorado ^{60}Co irradiator within a week of each other. The filled circles in Figure 6 show the ratio of the measured ΔOD to the ΔOD expected from the extrapolation of the best straight line fit to the two data points at about 8.8 Gy and the two at about 44.8 Gy in figure 6. Witin uncertainties, the line went through the origin. The straight line in Figure 6 is the best straight line through the circles. The data in Cottens' thesis are included as squares in Figure 6 and are in satisfactory agreement with the present measured results but both sets of measurements disagree with the calculated results.

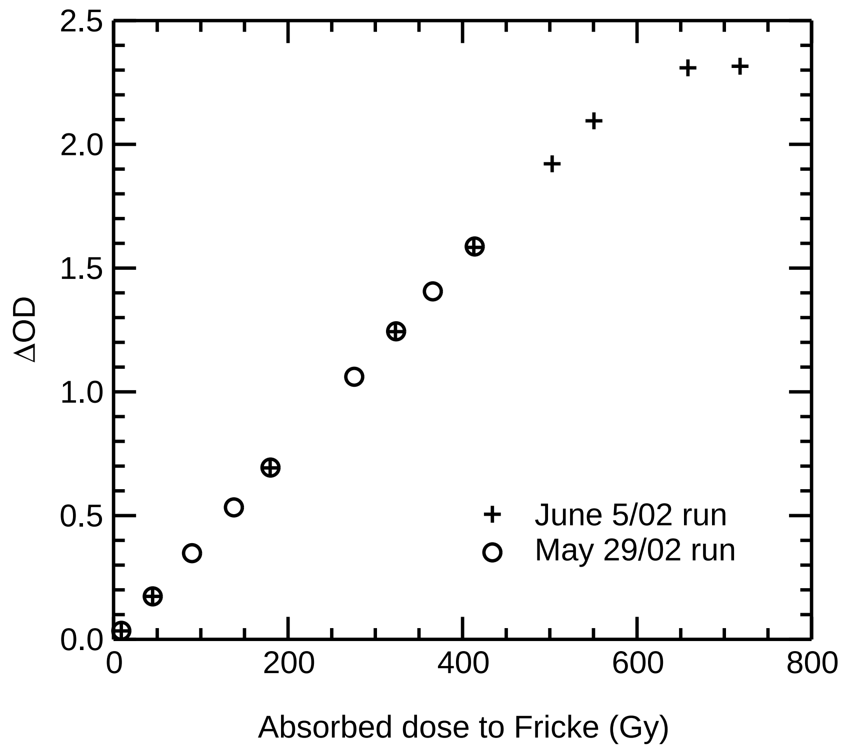

Figure 5: Measured increase in the optical density as a function of the absorbed dose delivered to the Fricke solution.

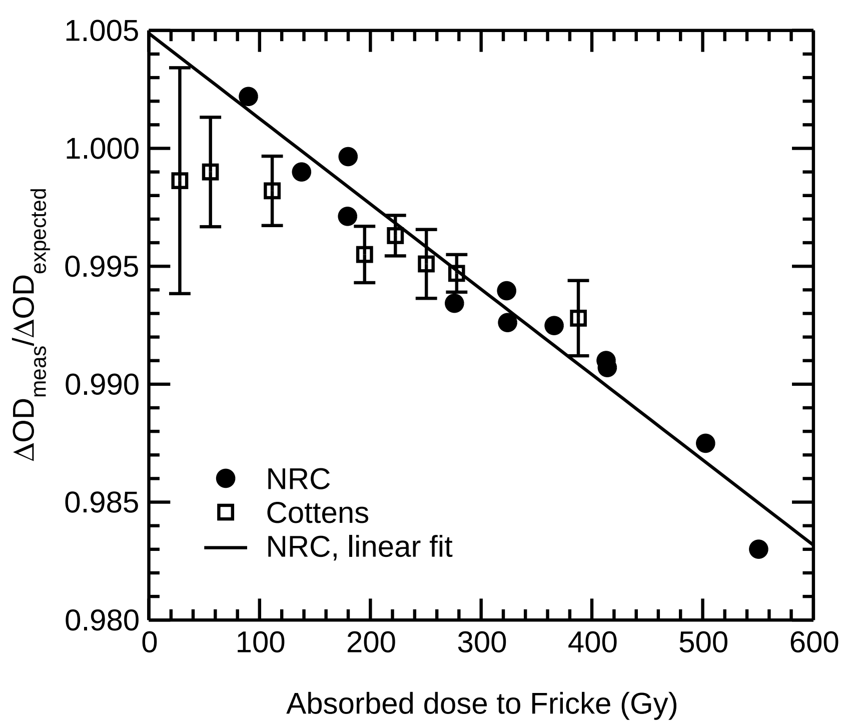

Figure 6: Measured change in the Fricke yield as a function of absorbed dose. Results obtained at NRC are compared to those of Cottens

3.4 Alanine Dosimetry

An alanine/EPR dosimetry program was initiated about 2 years ago. EPR measurements are made using a Bruker EMX 081 EPR spectrometer. By following a careful measurement protocol, using sets of 6 alanine pellets per dose and measuring the response as a function of dose from 10 to 1000 grays, we have been able to achieve a statistical precision on alanine dose readings of the order of 0.5% for doses between 10 and 1000 gray. By comparing the alanine response to the dose measured using the TG-51 protocol for a variety of clinical electron beams and photon beams, we have been able to establish that the response per unit absorbed-dose to water is constant within 0.5% for photon beams and 1% for electron beams. We have done Monte Carlo calculations of the same quality beams and find good agreement between the calculations and the measurements.

3.5 β-ray standards

NRC is re-invigorating its beta standards capability which is based on an extrapolation ion chamber. We are doing detailed Monte Carlo simulations of the source and the extrapolation chamber using the EGSnrc system and making Monte Carlo estimates of many of the required correction factors. This subject is covered in more detail in a separate contribution to the meeting.[28] Current work is based on our remaining ^{90}Sr+^{90}Y sources but we will be receiving other new sources shortly.

4 Dosimetry Protocols

4.1 Beam Quality Specification

In our last report to the CCRI we mentioned some work about beam quality specification.[29] This work addressed the questions: Is TPR^{20}_{10} a good beam quality specifier for all clinical beams? and How do we tell when a particular non-clinical beam is clinic-like for calibration purposes using TPR^{20}_{10}? It was shown that for a much wider variety of clinical beams than investigated previously, TPR^{20}_{10} is a good beam quality specifier (with the exception of the MM50 racetrack microtron). By explicit calculation it was shown that TPR^{20}_{10} is a good beam quality specifier for many of the non-clinical beams used in calibration labs (in particular, for the heavily filtered beams at NPL and NRC as well as those at Gent).

For calculations, it was shown that all clinic-like beams fall on a single universal curve relating $\%dd(10)_{\mathsf{x}}$ and TPR^{20}_{10} and that lightly filtered beams fall below this curve. This is shown in fig 7. In principal this gives us a criterion for determining when a beam is 'clinic-like' based on measured values of $\%dd(10)_{\mathsf{x}}$ and TPR^{20}_{10}. In a comparison to the values measured in standards labs, it was found that there is good agreement between the curves for the calculated and measured values. Unfortunately, a comparison to measured clinical data (see figure 8) was much less satisfactory, showing the measured data systematically above the curve (*i.e.,* the calculated TPR^{20}_{10} values are less than the measured value, or the calculated $\%dd(10)_x$ values are larger than the measured values, or a combination of both). There is no clearcut explanation available. One part of the problem may be that the calculated values of $\%dd(10)_x$ and TPR^{20}_{10} are based on spectra which are uniform across the beam. However, values of $\%dd(10)_x$ for 26 beams were calculated with full phase space files and the difference between the two methods was 0.04±0.29, so this simplification of the model doesn't help explain the discrepancy. We have also calculated TPR^{20}_{10} values for 2 beams using full phase space files and the phantom at 2 different SSDs and this increased the calculated TPR^{20}_{10} values by 0.7% on average. This partially explains the discrepancies with the experimental data, but not all of it. This issue deserves further attention.

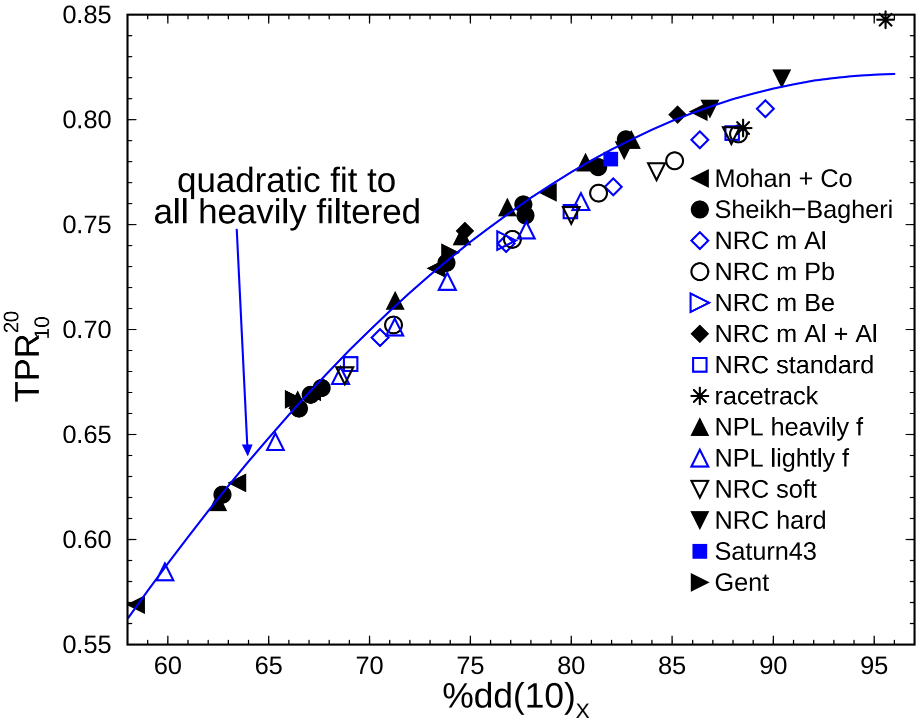

Figure 7: Calculated values of TPR^{20}_{10} versus $\%dd(10)_x$ for 14 sets of spectra. The line is a quadratic fit to all the heavily filtered beams which are all shown as closed symbols. The fit to a third-order polynomial is given by Eq. 3 in the paper with an rms deviation of 0.0034 and a maximum deviation of 0.007 in TPR^{20}_{10}.

4.2 Re-calculation of P_{wall} factors for plane-parallel chambers

These calculations, which were mentioned in the previous report have been published.[33] Several interesting features arose as the paper was finalized. Firstly, on average the EGSnrc calculated values of P_{wall} are 0.8% higher than the previous EGS4/PRESTA results and are thus in better agreement with experimental values. The internal and theoretical consistency of the calculations was found to be good at better than the 0.1% level although this required special attention to the proper and consistent definitions of each correction factor. It was explicitly shown that values of P_{wall} calculated for an ion

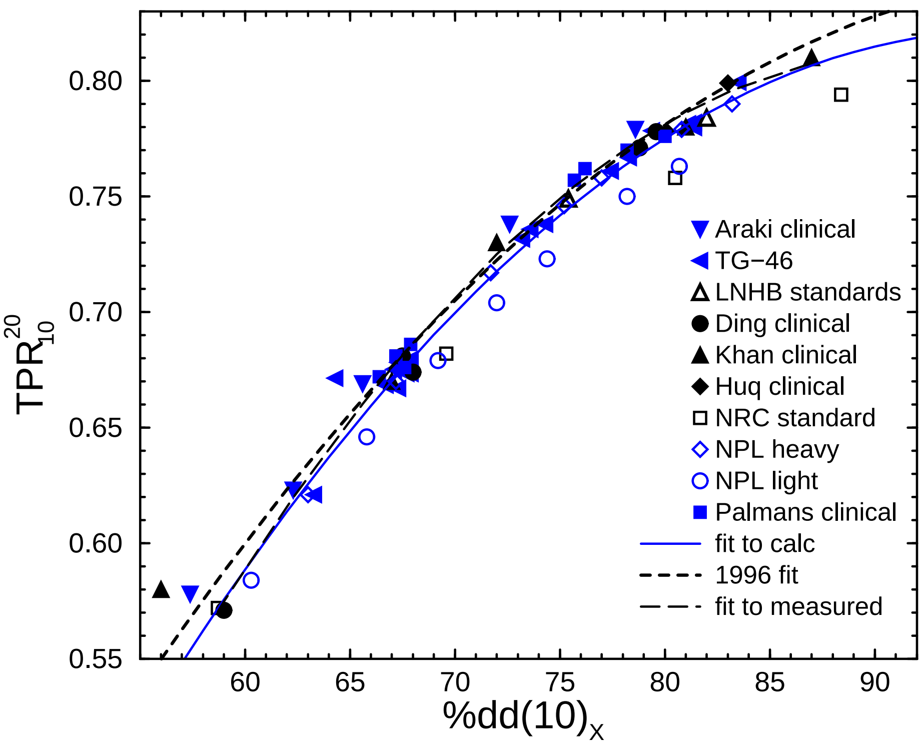

Figure 8: Measured vs fitted values of TPR_{10}^{20} versus $\%dd(10)_{\mathrm{x}}$. The solid line is the fit to the calculated heavily filtered beams. Closed symbols are published measured data for clinical beams and the data from the AAPM's TG-46 compendium. Open symbols are measured data from standards laboratories.[10,30,31] The long dashed line is a quadratic fit to the measured data for clinical beams (excluding the two ^{60}Co results with lowest values of $\%dd(10)_{\mathrm{x}}$). Also shown for comparison is an early crude fit by Kosunen and Rogers (short dashed line) to similar data for the Mohan spectra and the 50 MV racetrack beam.[32]

chamber in air with a water buildup cap were equivalent to P_{wall} values calculated in a phantom, to within the statistical precision of 0.1%. Finally, the paper makes an effort to systematically estimate the uncertainties in the calculated correction factors, including an estimate of the uncertainty due to cross-section uncertainties. For P_{wall} the uncertainties in the photon and electron cross-sections used imply an uncertainty of 0.14% and 0.24% (one standard deviation) respectively.

5 Monte Carlo simulation of radiation transport

The EGSnrc system has been maintained and various enhancements have been made to the user-codes. Two significant improvements in the last two years are worth reporting on. The statistics packages in all the major user-codes were upgraded to utilize event-by-event scoring which has greatly reduced the fluctuations in uncertainty estimates.[34] The BEAM code system has been ported to use the EGSnrc system, although the default transport parameters in BEAMnrc use several features of EGS4/PRESTA to avoid slowing down the calculation.

In one pair of papers,[35,36] the sensitivity of BEAM calculations to the parameters used in the model (e.g. the beam energy and the radius of the beam spot) was investigated and an algorithm for determining the best parameters was presented.

In on-going work, a new variance reduction technique (direction bremsstrahlung splitting) has been introduced into BEAMnrc. This technique has the ability to speed up photon accelerator simulations by at least a factor of 5 compared to using the standard selective bremsstrahlung splitting.

Another on-going project is a port of the EGSnrc and BEAM systems to a new approach which is more platform independent, in particular allowing the system to be used on Microsoft equipment.

5.1 Fast Monte Carlo calculations for treatment planning

The development of the VMC++ system into commercial products continues with 2 licensing agreements signed and another under negotiation. Before being sold, MDS Nordion (now Nucletron) released a commercial version of the VMC++ for electron beam treatment planning. It is now in routine use in at least one clinic (Ottawa Regional Cancer Centre).

In an associated piece of research, methods for the statistical smoothing of Monte Carlo calculated dose distributions were investigated. A new technique was developed, along with metric's for assessing the validity of any smoothing algorithm. The work was published last year.[37]

6 IRS Publications, 2001 – 2003

Publications of Staff of IRS: 2001 – 2003
Institute for National Measurement Standards
National Research Council of Canada
Ottawa, K1A-OR6

Refereed Publications

[1] G. M. Daskalov and J. F. Williamson, **Monte Carlo-aided dosimetry of the new Bebig IsoSeed ^{103}Pd interstitial brachytherapy seed**, Med. Phys. **28**, 2154 – 2161 (2001).

[2] C.-M. Ma, C. W. Coffey, L. A. DeWerd, R. Nath, C. Liu, S. M. Seltzer, and J. Seuntjens, **AAPM protocol for 40 – 300 kV x-ray beam dosimetry in radiotherapy and radiobiology**, Med. Phys. **28**, 868 – 893 (2001).

[3] K. R. Shortt, C. K. Ross, J. P. Seuntjens, F. Delaunay, A. Ostrowsky, P. Gross, and E. Leroy, **Comparison of dosimetric standards of Canada and France for Photons at ^{60}Co and higher energies**, Phys. Med. Biol. **46**, 2119 – 2142 (2001).

[4] G. M. Daskalov, R. S. Baker, D. W. O. Rogers, and J. F. Williamson, **Multigroup discrete ordinates modelling of ^{125}I 6702 seed dose distributions using a broad energy-group cross section representation**, Med. Phys. **29**, 113 – 124 (2002).

[5] I. Kawrakow, **On the de-noising of Monte Carlo calculated dose distributions**, Phys. Med. Biol. **47**, 3087 – 3104 (2002).

[6] N. V. Klassen and C. K. Ross, **Water Calorimetry: A Correction to the Heat Defect Calculations**, J. Res. Natl. Inst. Stand. Technol. **107**, 171 – 178 (2002).

[7] D. W. O. Rogers, **Review of 'ICRU Report 64: Dosimetry of high-energy photon beams based on standards of absorbed dose to water'**, Phys. Med. Biol. **47**, 3663 – 3665 (2002).

[8] D. Sheikh-Bagheri and D. W. O. Rogers, **Sensitivity of megavoltage photon beam Monte Carlo simulations to electron beam parameters**, Med. Phys. **29**, 379 – 390 (2002).

[9] D. Sheikh-Bagheri and D. W. O. Rogers, **Calculation of nine megavoltage photon beam spectra using the BEAM Monte Carlo code**, Med. Phys. **29**, 391 – 402 (2002).

[10] K. R. Shortt, A. F. Bielajew, C. K. Ross, K. J. Stewart, J. T. Burke, and M. J. Corsten, **The effect of wall thickness on the response of a spherical ionization chamber**, Phys. Med. Biol. **47**, 1721 – 1731 (2002).

[11] B. R. B. Walters, I. Kawrakow, and D. W. O. Rogers, **History by history statistical estimators in the BEAM code system**, Med. Phys. **29**, 2745 – 2752 (2002).

[12] 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 60Co γ-rays**, Radiat. Prot. Dosim. (submitted Feb 2003).

[13] N. I. Kalach and D. W. O. Rogers, **When is an accelerator photon beam "clinic-like" for reference dosimetry purposes**, Med. Phys. **30** (accepted, 2003).

[14] 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).

[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] L. A. Buckley, I. Kawrakow, and D. W. O. Rogers, **An EGSnrc investigation of cavity theory for ion chambers measuring air kerma**, Med. Phys. (accepted, March 2003).

Published in Proceedings

[1] M. Fippel, M. Alber, M. Birkner, W. Laub, F. Nüsslin, and I. Kawrakow, **Inverse treatment planning for radiation therapy based on fast Monte Carlo dose calculation**, in *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications: Proceedings of the Monte Carlo 2000 Meeting Lisbon*, edited by A. Kling, F. Barao, M. Nakagawa, L. Távora, and P. Vaz, pages 217 – 222, Springer, Berlin, 2001.

[2] I. Kawrakow, **VMC^{++}, electron and photon Monte Carlo calculations optimized for Radiation Treatment Planning**, in *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications: Proceedings of the Monte Carlo 2000 Meeting Lisbon*, edited by A. Kling, F. Barao, M. Nakagawa, L. Távora, and P. Vaz, pages 229 – 236, Springer, Berlin, 2001.

[3] I. Kawrakow and D. W. O. Rogers, **The EGSnrc System, a status report**, in *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications: Proceedings of the Monte Carlo 2000 Meeting Lisbon*, edited by A. Kling, F. Barao, M. Nakagawa, L. Távora, and P. Vaz, pages 135 – 140, Springer, Berlin, 2001.

[4] D. W. O. Rogers, **Monte Carlo techniques for primary standards of ionizing radiation and for dosimetry protocols**, in *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications: Proceedings of the Monte Carlo 2000 Meeting Lisbon*, edited by A. Kling, F. Barao, M. Nakagawa, L. Távora, and P. Vaz, pages 291 – 298, Springer, Berlin, 2001.

[5] J. P. Seuntjens, I. Kawrakow, J. Borg, F. Hobeila, and D. W. O. Rogers, **Calculated and measured air-kerma response of ionization chambers in low and medium energy photon beams**, in *Recent developments in accurate radiation dosimetry, Proceedings of an International Workshop*, edited by J. P. Seuntjens and P. Mobit, pages 69 – 84, Medical Physics Publishing, Madison WI, 2002.

Internal Reports

[1] D.W.O. Rogers, I. Kawrakow, N.V. Klassen, J. P. McCaffrey, C.K. Ross, K.R. Shortt, L. van der Zwan, and G. Daskalov, **NRC Activities and Publications, 1999–2001: Report to CCRI(I) Meeting, BIPM**, CCRI(1)00–23 (2001).

[2] N. Kalach and D. W. O. Rogers, **What consitutes a clinic-like radiotherapy beam**, BIPM document CCRI(1)/01–26 (BIPM, Sèvres, France) (2001).

[3] N. V. Klassen, **A model for computer simulations of the Fricke dosimeter**, BIPM document CCRI(1)/01–27 (BIPM, Sèvres, France) (2001).

[4] N. V. Klassen, L. van der Zwan, J. Cygler, and J. P. Seuntjens, **Experimental determination and Monte carlo simulations of backscatter factors in clinical kilovoltage x-ray beams using GafChromic MD-55-2 radiochromic film**, BIPM document CCRI(1)/01–24 (BIPM, Sèvres, France) (2001).

[5] C.-M. Ma, D. W. O. Rogers, and B. Walters, **DOSXYZnrc Users Manual**, NRC Report PIRS 509b(revF) (2001).

[6] E. Mainegra-Hing, D. W. O. Rogers, and I. Kawrakow, **Revision of correction factors for calibration of plane-parallel ionization chambers in ^{60}Co photon beams using EGSnrc Monte Carlo simulation system**, BIPM document CCRI(1)/01–28 (BIPM, Sèvres, France) (2001).

[7] D. W. O. Rogers, C.-M. Ma, G. X. Ding, B. Walters, D. Sheikh-Bagheri, and G. G. Zhang, **BEAMnrc Users Manual**, NRC Report PIRS 509(a)revF (2001).

[8] D. W. O. Rogers, J. McCaffrey, I. Kawrakow, and K. R. Shortt, **Wall correction factors for graphite walled ion chambers**, BIPM document CCRI(1)/01–25 (BIPM, Sèvres, France) (2001).

[9] J. A. Treurniet, B. R. B. Walters, and D. W. O. Rogers, **BEAMnrc, DOSXYZnrc and BEAMDP GUI User's Manual**, NRC Report PIRS 0623(rev B) (2001).

[10] D. T. Burns, K. R. Shortt, and L. V. der Zwan, **Comparison of the air-kerma standards of the NRC and the BIPM in the medium-energy x-ray range**, BIPM Report BIPM–02/15 (2002).

[11] A. Olszanski, N. V. Klassen, C. K. Ross, and K. R. Shortt, **The IRS Fricke dosimetry system**, Technical Report PIRS–815, NRC, Ottawa, Canada, 2003.

Other

[1] N. Kalach, **What constitutes a clinic-like radiotherapy photon beam**, MSc. thesis, Carleton University, Ottawa (2001).

[2] S. D. Davis, **High sensitivity lithium fluoride as a detector for environmental dosimetry**, MSc. thesis, McGill University, Montreal (2002).

7 References cited in report

[1] D. T. Burns, K. R. Shortt, and L. V. der Zwan, Comparison of the air-kerma standards of the NRC and the BIPM in the medium-energy x-ray range, BIPM Report BIPM–02/15 (2002).

[2] M. McEwen, J. P. McCaffrey, and D. Niven, Pre-irradiation of ionization chambers used in x-ray and gamma-ray calibrations, Proc. of 2003 COMP Annual Meeting (Canadian Organization of Medical Physicists, Edmonton, Alberta) (2003).

[3] S. D. Davis, High sensitivity lithium fluoride as a detector for environmental dosimetry, MSc. thesis, McGill University, Montreal (2002).

[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 60Co γ-rays, Radiat. Prot. Dosim. (submitted Feb 2003).

[5] K. R. Shortt and C. K. Ross, The Canadian ^{60}Co Exposure Standard, National Research Council of Canada Report PIRS-0052 (1986).

[6] P. J. Allisy-Roberts, D. T. Burns, K. R. Shortt, and C. K. Ross, Comparison of the air kerma standards of the NRC and the BIPM for ^{60}Co γ rays, Rapport BIPM-99/12 (2000).

[7] K. R. Shortt, R. B. Huntley, L. H. Kotler, and J. F. Boas, A comparison of the Australian and Canadian standards of air kerma and absorbed dose to water for ^{60}Co γ radiation, in preparation (2003).

[8] P. J. Allisy-Roberts, J. F. B. M. Boutillon, and R. B. Huntley, Comparison of the air kerma standards of the ARL and the BIPM for ^{60}Co γ rays, BIPM Report BIPM–98/4 (1998).

[9] K. Shortt, J. Shobe, and S. Domen, Comparison of Dosimetry Calibration factors at the NRCC and the NIST, Med. Phys. **27**, 1644 – 1654 (2000).

[10] K. R. Shortt, C. K. Ross, J. P. Seuntjens, F. Delaunay, A. Ostrowsky, P. Gross, and E. Leroy, Comparison of dosimetric standards of Canada and France for Photons at ^{60}Co and higher energies, Phys. Med. Biol. **46**, 2119 – 2142 (2001).

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

[12] ICRU, Stopping powers for electrons and positrons, ICRU Report 37, ICRU, Washington D.C., 1984.

[13] D. W. O. Rogers and J. Treurniet, Monte Carlo calculated wall and axial non-uniformity corrections for primary standards of air kerma, NRC Report PIRS–663, NRC, Ottawa, 1999 (see http://www.irs.inms.nrc.ca/inms/irs/papers/PIRS663/pirs663.html).

[14] P. J. Allisy-Roberts, D. T. Burns, K. R. Shortt, C. K. Ross, and J. P. Seuntjens, Comparison of the standards of absorbed dose to water of the NRC, Canada and the BIPM for ^{60}Co γ rays, Rapport BIPM-99/13 (2000).

[15] K. R. Shortt, C. K. Ross, J. P. Seuntjens, R. B. Huntley, L. H. Kotler, and J. F. Boas, A comparison of the Australian and Canadian standards of air kerma and absorbed dose to water for ^{60}Co γ radiation, in preparation (2001).

[16] P. J. Allisy-Roberts, D. T. Burns, J. F. Boas, R. B. Huntley, and K. N. Wise, Comparison of the standards of absorbed dose to water of the ARPANSA and the BIPM for ^{60}Co γ radiation, Rapport BIPM-99/17 (2000).

[17] P. J. Allisy-Roberts and J. Shobe, Comparison of the standards of absorbed dose to water of the NIST and the BIPM for ^{60}Co γ rays, Rapport BIPM-98/5 (1999).

[18] C. K. Ross, J. P. Seuntjens, N. V. Klassen, and K. R. Shortt, The NRC Sealed Water Calorimeter: Correction Factors and Performance, in *Proceedings of NPL Workshop on Recent Advances in Calorimetric Absorbed Dose Standards*, edited by A. J. Williams and K. E. Rosser, pages 90–102, National Physical Laboratory, Teddington, UK, 2000.

[19] J. P. Seuntjens, I. Kawrakow, and C. K. Ross, Revisiting Convective Motion in Stagnant Water Calorimeters Operated at Room Temperature, in *Proceedings of NPL Workshop on Recent Advances in Calorimetric Absorbed Dose Standards*, edited by A. J. Williams and K. E. Rosser, pages 103–119, National Physical Laboratory, Teddington, UK, 2000.

[20] J. Medin, J. Seuntjens, N. Klassen, C. Ross, and G. Stucki, The OFMET Sealed Water Calorimeter, in *Proceedings of NPL Workshop on Recent Advances in Calorimetric Absorbed Dose Standards*, edited by A. J. Williams and K. E. Rosser, pages 65–73, National Physical Laboratory, Teddington, UK, 2000.

[21] N. V. Klassen and C. K. Ross, Water Calorimetry: the Heat Defect, J. Res. Natl. Inst. Stand. Technol. **102**, 63 – 74 (1997).

[22] N. V. Klassen and C. K. Ross, Water Calorimetry: A Correction to the Heat Defect Calculations, J. Res. Natl. Inst. Stand. Technol. **107**, 171 – 178 (2002).

[23] P. R. Almond, P. J. Biggs, B. M. Coursey, W. F. Hanson, M. S. Huq, R. Nath and D. W. O. Rogers, AAPM's TG–51 Protocol for Clinical Reference Dosimetry of High-Energy Photon and Electron Beams, Med. Phys. **26**, 1847 – 1870 (1999).

[24] IAEA, *Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water*, volume 398 of *Technical Report Series*, IAEA, Vienna, 2001.

[25] D. T. Burns, G. X. Ding, and D. W. O. Rogers, R_{50} as a beam quality specifier for selecting stopping-power ratios and reference depths for electron dosimetry, Med. Phys. **23**, 383 – 388 (1996).

[26] A. Olszanski, N. V. Klassen, C. K. Ross, and K. R. Shortt, The IRS Fricke dosimetry system, Technical Report PIRS–815, NRC, Ottawa, Canada, 2003.

[27] E. Cottens, Geabsorbeerde dosis kalorimetrie bij hoge energie elektronenbundels en onderzoek van de ijzersulfaat dosimeter, PhD. thesis, Rijksuniversiteit, Gent, Belgium (1980).

[28] P. R. B. Saull and D. W. O. Rogers, ^{90}Sr+^{90}Y dose rate measurements with the NRC extrapolation chamber and a comparison to EGSnrc Monte Carlo simulations , Proc. of 2003 COMP Annual Meeting (Canadian Organization of Medical Physicists, Edmonton, Alberta) (2003).

[29] N. I. Kalach and D. W. O. Rogers, When is an accelerator photon beam "clinic-like" for reference dosimetry purposes, Med. Phys. **30** (accepted, 2003).

[30] J. P. Seuntjens, C. K. Ross, K. R. Shortt, and D. W. O. Rogers, Absorbed-dose beam quality conversion factors for cylindrical chambers in high-energy photon beams, Med. Phys. **27**, 2763 – 2779 (2000).

[31] B. R. B. Walters and D. W. O. Rogers, Monte Carlo estimates of %dd(10)$_X$ for the NPL photon beams, NRC Report PIRS–659, NRC, Ottawa, 1999.

[32] D. W. O. Rogers, Fundamentals of Dosimetry Based on Absorbed-Dose Standards, in *Teletherapy Physics, Present and Future*, edited by J. R. Palta and T. R. Mackie, pages 319 – 356, AAPM, Washington DC, 1996.

[33] 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).

[34] B. R. B. Walters, I. Kawrakow, and D. W. O. Rogers, History by history statistical estimators in the BEAM code system, Med. Phys. **29**, 2745 – 2752 (2002).

[35] D. Sheikh-Bagheri and D. W. O. Rogers, Sensitivity of megavoltage photon beam Monte Carlo simulations to electron beam parameters, Med. Phys. **29**, 379 – 390 (2002).

[36] D. Sheikh-Bagheri and D. W. O. Rogers, Calculation of nine megavoltage photon beam spectra using the BEAM Monte Carlo code, Med. Phys. **29**, 391 – 402 (2002).

[37] I. Kawrakow, On the de-noising of Monte Carlo calculated dose distributions, Phys. Med. Biol. **47**, 3087 – 3104 (2002).