NRC Activities and Publications, 2009-2011
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Table of Contents

1 Introduction ... 2
2 INMS Organizational Structure ... 3
3 ISO 17025 Quality System ... 3
4 EGSnrc Monte Carlo System ... 3
5 Air kerma standards ... 3
5.1 For kV x-rays ... 3
5.2 For ^{60}Co and ^{137}Cs ... 4
5.3 For ^{192}Ir high dose rate (HDR) brachytherapy ... 4
6 Free-air chamber correction factors ... 4
7 Absorbed dose standards ... 5
7.1 For ^{60}Co ... 5
7.2 For MV x-rays ... 6
8 BIPM comparison of absorbed dose to water for MV x-rays ... 6
9 k_Q factors for parallel-plate chambers in MV photon beams ... 7
10 Using ion chamber measurements to locate the water-air interface ... 7
11 Using a plastic scintillation detector to determine perturbation factors ... 8
12 Development of a calorimeter-Fricke hybrid dosimetry system ... 9
13 Effective point of measurement ... 10
14 β-ray dosimetry ... 10
15 Investigation of the PTW Starcheck™ 2-D ion chamber array ... 11
16 Refereed publications, 2009-11 ... 13
17 Conference presentations, 2009-11 ... 14

1 Introduction

The Ionizing Radiation Standards (IRS) Group of the National Research Council of Canada (NRC) is part of the Institute for National Measurement Standards (INMS), which is Canada's national metrology institute. The group has fifteen full-time staff members and one former staff member who works part-time. 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://inms-ienm.nrc-cnrc.gc.ca/calserv/ionizing_radiation_e.html

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

2 INMS Organizational Structure

The management team of INMS comprises a Director General (Jim McLaren) and two Directors, one for Metrology (Alan Steele) and one for Business and Research Support (Katalin Deczky). The Groups Leaders, each of whom is responsible for one or more areas of metrology, report to the Director of Metrology.

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 fall of 2009. Both an internal and an external audit were carried out in the spring of 2011.

4 EGSnrc Monte Carlo System

New versions of the software were released in March 2010 and April 2011. Additional details about the IRS codes can be found at: http://irs.inms.nrc.ca/software/egsnrc/. Two important contributors to the Monte Carlo program, Iwan Kawrakow and Blake Walters, left NRC during this reporting period. Despite this loss, IRS remains committed to a strong program developing and applying Monte Carlo techniques.

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.

A key comparison with the BIPM for low-energy X-rays has recently been published in *Metrologia*. A second key comparison for low-energy X-ray mammography qualities is in preparation.

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.

A consistent set of free-air chamber correction factors is being calculated using the EGSnrc Monte Carlo code. The Monte Carlo technique allows for the investigation of effects that are otherwise difficult to investigate, such as the assumption of charged particle equilibrium within the sensitive volume of the free-air chamber.

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 graphite cavity chamber. Two additional graphite cavity chambers, one spherical and one plane parallel are under development as complimentary air kerma standards.

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, offering improved accuracy through the use of a Pb wedge to determine the scatter component k_{sc} at each measurement position. Well-chamber calibrations have been performed for Canadian cancer centres, and 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 2011.

6 Free-air chamber correction factors

(Ernesto Mainegra-Hing)

A methodology for the Monte Carlo (MC) calculation of a self-consistent set of FAC correction factors has been used to calculate these corrections for the Canadian standards for low and medium x-ray beam qualities, the LEES and the MEES FACs, respectively. This methodology was implemented in the new EGSnrc C++ user-code *egs_fac* which will be shortly available as part of the 2011 EGSnrc release at the end of April 2011.

FAC Correction factors are being computed using full simulations of the x-ray tube and a detailed model of the FACs. In the medium-energy range, excellent agreement with measured A_{att}, A_{scat} and A_{eloss} values is observed. The newly introduced correction factors for backscatter (A_b), beam geometry (A_g) and lack of charged particle equilibrium along the beam axis (A_{cpe}) are negligible (A_b and A_g) or very small (A_{cpe}, which reaches 1.00015 at 250 kV). It is shown that the evacuated-tube technique used at NRC to measure the attenuation correction overestimates A_{att} by about 0.03% in this energy range. The observation that aperture leakage must be taken into account, noted in previous works, is confirmed. Changes in the total correction A_{total} at these energies due to the inclusion of the aperture correction, A_{ap}, will still lie within the standard uncertainties assigned previously to these corrections.

In the low-energy range, the agreement of the scatter correction, A_{scat}, and the electron loss correction, A_{eloss} for both sets of beam qualities between the MC calculations and values derived from previous measurements for a finite number of beam qualities can be considered good within the previously assigned one sigma uncertainty of 0.2 % and 0.1 % respectively. The correction to account for the inconsistency of the evacuated tube technique, A_x, and the newly introduced correction for backscatter, A_b, are non-negligible at low energies and their combined effect will decrease the value of the total correction, A_{total}, by about 0.6 % for the lightly-filtered beams and 0.4 % for the mammography beams.

7 Absorbed dose standards

7.1 For ^{60}Co

(Malcolm McEwen, Carl Ross, Claudiu Cojocaru and David Marchington)

The NRC Gammabeam Co-60 irradiator was resourced in 2009. At that time the calibrated dose rate was transferred using reference ionization chambers. In August 2010 the primary standard water calorimeter was used to determine the absorbed dose to water at the reference point. The calorimeter is as described by Ross *et al* (NPL workshop, 1999) and the geometry of the glass vessel is cylindrical, with the beam entering through the curved face. Three different vessels were used: one unsealed (two sets of runs were obtained with N_2 and H_2 saturated water) and two of the sealed type (Ross, *et al*, LNHB workshop, 2007). The results are shown in Figure 1.

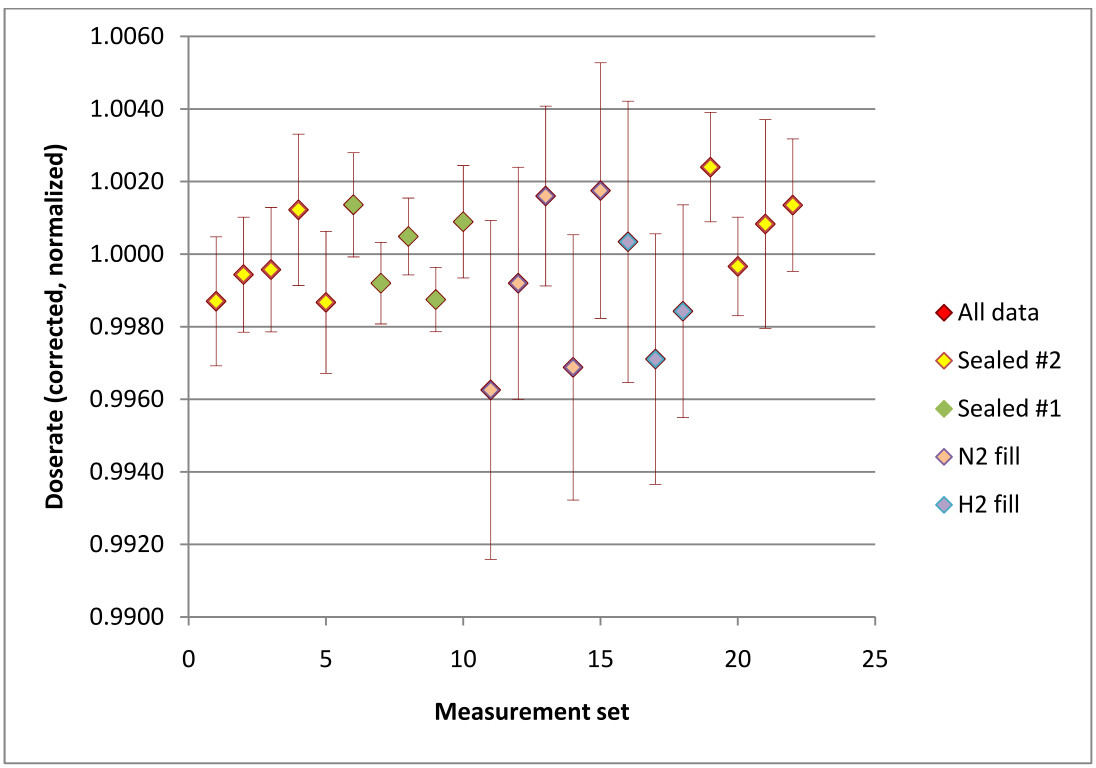

Figure 1. Water calorimetry measurements on the NRC ^{60}Co beam. Each set represents typically 15 individual runs. The absorbed dose rate to water was determined to be 2.542 cGy sec^{-1}.

Absorbed dose to water calibration coefficients were obtained for a number of NRC reference chambers. The total spread on values obtained in three determinations – in 1998, 2004 and 2010 – was 0.27 %. The standard uncertainty on the determination of $N_{D,w}$ is estimated to be 0.25 %. This leve of repeatability is very reassuring, especially as it indicates that the sealed-type glass vessel is stable at the ± 0.15 % over a decade.

7.2 For MV x-rays

(Malcolm McEwen, Brad Downton and Carl Ross)

The NRC offers a calibration service for ionization chambers in MV photon beams. 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). The standard for absorbed dose to water is a sealed water calorimeter, which measures the radiation-induced temperature rise at a depth of 10 cm in a water phantom (10 x 10 cm^2 beam, with the surface of the phantom at 1 m from the source). The nominal dose rate at the point of measurement is 300 cGy/min. For reference-class 0.6 cc cylindrical ionization chambers the standard uncertainty in the absorbed dose calibration coefficient is typically 0.5 %. Recombination, polarity and chamber equilibration behaviours are investigated. There has been continued take-up from Canadian cancer centres for what is an optional service with indications that it is being used as a QA tool for ensuring accuracy of dose determination in clinical linac beams.

8 BIPM comparison of absorbed dose to water for MV x-rays

(Malcolm McEwen, Claudiu Cojocaru, Carl Ross, David Burns, Susanne Picard and Philippe Roger)

The BIPM has developed a graphite calorimeter and associated equipment that is suitable for measuring the absorbed dose to water in MV x-ray beams. The objective is to use the device to compare the absorbed dose standards of national laboratories. In the summer of 2009 BIPM brought their graphite calorimeter to NRC to begin the first of a series of visits to several national laboratories. The measurements were carried out over a period of three weeks using the NRC Elekta linac.

A complete set of measurements was completed more quickly than expected, but technical problems with the accelerator limited the time that could be spent on repeat measurements and consistency checks.

Initial calculations were carried out at NRC using the EGSnrc Monte Carlo to convert the measured calorimeter response to absorbed dose to water. These preliminary results showed satisfactory agreement with the NRC values for all three beam qualities. Since then, more extensive Monte Carlo calculations were carried out at the BIPM using the PENELOPE code and at NRC using EGSnrc.

The results of the comparison have been published [3] and show satisfactory agreement between the BIPM and NRC standards. Since then, comparisons with several other laboratories have been completed and a possible spurious effect related to the response of the BIPM parallel plate ionization chamber used to relate the dose-to-graphite to dose-to-water has been noted. Further work will be needed to determine how the NRC comparison results may be affected.

9 k_Q factors for parallel-plate chambers in MV photon beams

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

An investigation is underway to evaluate MV photon beam k_Q factors for parallel-plate ionization chambers and is a follow-on to the work reported by McEwen (2010) for cylindrical chambers. There is little experimental data in the literature although Kapsch and Gomola (IAEA symposium, 2010) showed that two types of IBA chamber (PPC-05 and PPC-40) could potentially be used for reference dosimetry in clinical linac photon beams.

The NRC project mimicked the previous investigation of cylindrical chambers. Eleven different types of plane-parallel ionization chamber were obtained from three major ion chamber manufacturers. In most cases, at least two chambers of each type were examined. Measurements were performed using the ^{60}Co treatment unit and Elekta *Precise* linac at the National Research Council of Canada. Chamber stabilization in the ^{60}Co reference field, leakage currents and ion recombination and polarity behavior were investigated for all ion chambers. Absorbed dose-to-water calibration coefficients were measured in ^{60}Co and in 6, 10 and 25 MV photon beams to determine k_Q factors.

Chambers were not preirradiated when measurements were being made in the Cobalt-60 reference field to investigate chamber stabilization. For all chambers, the reading stabilized to within 0.05 % of the equilibrium reading within 15 minutes. For most chambers, the stabilization time was less than 6 minutes. For some chambers, polarity corrections were as high as 0.4 %, but most chambers required a polarity correction of less than 0.1 %. Ion recombination was investigated as a function of dose-per-pulse, D_{pp}, for at least three D_{pp} values.

Values of k_Q for chambers of the same type no difference was larger than 0.4 %, with a typical difference of only 0.2 %, averaged over all chambers and energy. This indicates that chamber-to-chamber variation is not a significant issue, although perhaps larger than for cylindrical chambers. Differences in k_Q factors for chambers of different types are as large as 1.7 % in the 25 MV beam. This sort of variation is expected, based on the material used, from that for different types of cylindrical ionization chamber.

Measurements are ongoing to expand the number of type of chamber calibrated and to look at the long-term stability of these plastic-walled chambers. Results from other laboratories, primarily in electron beams, indicate that the long-term stability and expected lifetime of parallel-plate chambers are not as good as for reference-class cylindrical chambers.

10 Using ion chamber measurements to locate the water-air interface

((Malcolm McEwen, in collaboration with Jeffrey Siebers and Jim Ververs of Virginia Commonwealth University, Richmond, VA))

In the commissioning of clinical linear accelerators, depth-dose curves are usually obtained in a vertical beam geometry and the ionization chamber is scanned *through* the water surface. Analysis of such build-up curves obtained for cylindrical chambers indicates that there is an inflection point as the chamber approaches the water surface and Monte-Carlo calculations by Ververs et al (2009) demonstrated that the inflection point should be exactly at the point the outer radius of the chamber reaches the surface. The obvious advantage of this method for determining the water surface (and thus the origin for the depth-dose scan) is that it requires no external reference (usually some form of mechanical positioner). All one needs to know is the type of ion chamber used to acquire the scan. The comparison of depth-dose curves obtained over long periods becomes more robust and independent of the personnel operating the scanning system.

Depth-ionization curves for 11 cylindrical ionization chambers of differing designs were obtained and the dependence of the inflection point on beam energy, electron contamination, and chamber design was investigated. To experimentally test the conclusion of the Monte-Carlo investigation one requires to know the position of the water surface and this was achieved using an optical system with an accuracy better than 0.1 mm. At this level of accuracy evaporation is not insignificant and therefore this was monitored over the course of the measurements. Depth-ionization measurements were obtained in 6, 10 and 25 MV photon beams for a field size of 10×10 cm^2. The effect of the 1 mm Pb foil required in the AAPM's TG-51 protocol was also investigated.

The inflection point in the measured depth-ionization data is determined by finding the maximum in its second derivative. It was found that the location of each chamber-specific inflection point is invariant to changes in beam energy, electron contamination, and chamber orientation within the measurement resolution. The location of each chamber's inflection point is most strongly impacted by its outer radius and corresponds with the shallowest depth at which the chamber is fully submersed in the water.

11 Using a plastic scintillation detector to determine perturbation factors

(Malcolm McEwen and Claudiu Cojocaru in collaboration with F Lacroix (CHUM. Montreal), M Guillot & L Beaulieu (CHUQ, Quebec))

A plastic scintillator detector (PSD) was used to extract the overall perturbation factor P_Q (the product of P_{wall} and P_{repl} in the notation of the TG-51 protocol), for IBA NACP-02 and PTW Roos parallel-plate chambers in megavoltage electron beams [Lacroix et al, 2010]. The method was based on the comparison of depth-dose (depth-ionization) curves obtained with the reference PSD and ionization chambers. Such a comparison requires a high-accuracy scanning tank and the system developed by McEwen et al (2008), with an absolute positioning accuracy of 0.1 mm was used. Measurements were made in 6, 12 and 18 MeV clinical electron beams from a Varian linear accelerator at the centre hospitalier universitaire de Québec (CHUQ).

The plastic scintillation detector used in this work consists of a 1 mm diameter and 3 mm long scintillating plastic fiber coupled to a clear optical fiber of the same diameter. The scintillating fiber is a polystyrene core optical fiber in which fluorescent organic molecules are dissolved in a proportion lower than 3 % of the weight. The core of the scintillating fiber is surrounded by a 30 µm thick PMMA cladding and encapsulated in a 0.6 mm thick opaque polyethylene jacket.

The water equivalence (i.e., zero perturbation correction) of this detector was confirmed by simulation using the EGSnrc radiation transport code.

A comparison of the depth-ionization curves obtained using the two types of parallel-plate chamber showed that these chambers have the same perturbation correction, a result previously reported in the literature that has been interpreted as indicating a zero perturbation correction for both chambers. However, the comparison with the PSD showed that perturbation factors for the NACP and Roos chambers increase substantially with depth, especially for low energy electron beams (P_Q=1.15 at R_{50} for a 6 MeV beam). The experimental results are in general agreement with the Monte-Carlo simulation results of various authors on the subject (Buckley and Rogers, Chin et al, Araki). A suitable choice of the effective point of measurement (EPOM) significantly reduces the variation in the perturbation correction with depth but it is not possible to determine a 'universal' EPOM.

The results have been published in *Medical Physics* (Lacroix et al, 2010).

12 Development of a calorimeter-Fricke hybrid dosimetry system

(Claudiu Cojocaru, Malcolm McEwen and Carl Ross)

The aim of this project is to develop a dosimetry system based on the Fricke (ferrous sulphate) dosimeter that can be used to determine absolute dose in regions of large dose gradients in megavoltage photon and electron beams. Building on the techniques first used at the Swiss national standards laboratory, METAS, we have developed a system where Fricke solution can be irradiated in polyethylene bags rather than the usual glass vials. This approach means that there is almost no wall correction and the dosimeter size and shape can be tailored to each application. As a first test the Fricke system was used to determine the absorbed dose absolutely in low energy electron beams. The Fricke response was compared with the NRC primary standard water calorimeter and calibrated ionization chambers using the TG-51 protocol. Measurements were made in 4, 8, 12, 18 and 22 MeV beams and the delivered dose was in the range of 7 Gy to 50 Gy. The accuracy and precision of the Fricke dosimetry is very dependent on solution preparation and contaminants, which affect the readout. It was found that the contaminating effect of the polyethylene bag on the readout signal was small and could be accurately corrected by using unirradiated controls. The standard uncertainty in the sensitivity coefficient of the Fricke system was found to be typically 0.2-0.3 % and the standard uncertainty in the determination of absorbed dose to water was estimated to be 0.6 %. As an application, the experimental energy dependence was determined for a PTW Roos parallel-plate ionization chamber. The results were similar to the TG-51 and TRS-398 predictions for higher energies of 22 MeV, 18 MeV and 12 MeV, but differ by up to 1 % for 4 MeV electron beams. These findings are in good agreement with recent Monte Carlo and experimental investigations of chamber perturbation corrections. The Fricke dosimeter system remains relevant to megavoltage dosimetry, offering accuracy comparable with, or better than, other integrating systems. The dosimeter is insensitive to dose homogeneities and can be used to determine mean dose to arbitrary volumes. It therefore has applications in reference dosimetry for (TG-51) non-compliant beams as well as dose verification in IMRT.

13 **Effective point of measurement**

(Frédéric Tessier)

We have continued our investigation regarding the effective point of measurement (EPOM) for thimble ionization chambers in megavoltage photon beams. The EPOM is the point at which the measured dose would arise in the measurement medium in the absence of the probe: for cylindrical chambers, it is shifted upstream relative to the central axis of the chamber. Current dosimetry protocols prescribe a unique upstream EPOM shift of 0.6*r*, with *r* the chamber cavity radius. However, we showed in previous work that this is simplistic, and that the EPOM varies dramatically with beam characteristics and chamber design parameters. Our approach relies on EGSnrc Monte Carlo calculations, upheld by a detailed Elekta *Precise* linac treatment head simulation and realistic chamber models.

We extended our study to 27 thimble ionization chamber, thus essentially covering what is available commercially today: **Exradin** A1, A1SL, A2, A12, A12S, A14, A14SL, A16, A18, A19; **IBA** CC01, CC04, CC13, CC25, FC23C, FC65G, FC65P; **PTW** 31010, 31013, 31014, 31016, 31015, 30010, 30011, 30012; **NE** 2571, 2581.

Our findings for the additional chambers are consistent with our initial calculations (involving only the Exradin models): in all cases we find that the upstream EPOM shift is smaller than the prescribed 0.6*r* value, and that it varies significantly depending on the chamber design. So much so, in fact, that we were able to design a thick-walled thimble ionization chamber with no EPOM shift at all! In this case the center of the chamber is the reference point of measurement for both reference and relative dosimetry, a desirable feature. This finding was reported in a *Medical Physics* Letter in early 2010.

14 **β-ray dosimetry**

(Patrick Saull, 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: our original Beta Secondary Standard (BSS1) acquired in the early 1980s, and the newer BSS2 system from Isotrak acquired in 2003. Our primary standard was put to the test in 2005 using the Pm-147, Kr-85, and Sr-Y-90 sources of the BSS2 irradiator, as part of our participation in the EUROMET comparison titled "Supplementary comparison of absorbed dose rate in tissue for beta radiation" (EUROMET project No. 739, BIPM KCDB: EUROMET.R(I)-S2). We have recently upgraded the system with the capability to set the chamber depth remotely, thus enabling fully automated, operator-free extrapolation chamber measurements.

Using the BSS1/BSS2 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.

15 Investigation of the PTW Starcheck™ 2-D ion chamber array

(Mark Xu (McGill University, Montreal), Malcolm McEwen)

The Starcheck 2-D chamber array is a high spatial resolution ion chamber array produced by PTW. Its 4 main chamber arrays are X, Y, and two diagonal lines, with chamber spacing of 3 mm. The manufacturer specifies 2 % calibration accuracy for the central (on-axis) chamber and 1 % relative accuracy for the arrays. This project investigated the claims made by the vendor and other aspects of Starcheck when used as a relative and absolute dosimeter.

The PTW Starcheck was mounted in a Virtual Water™ phantom and irradiated with 6, 10, and 25 MV photon beams from an Elekta Precise linear accelerator. The supplied BeamAdjust software was used to record the absolute dose profiles and the exported .mcc file was analyzed in Matlab to extract the desired detector array data. Relative chamber stability and detector linearity was investigated by irradiating the Starcheck with different MU's. Relative dose profiles of a 10 x 10 cm field at 5 cm depth in 6, 10, and 25 MV photons beams were measured with Starcheck and compared to profiles measured by water tank scanning with a diode and ion chamber, as well as a Thebes 1-D ion chamber array (also mounted in a Virtual Water phantom). The relative calibration and repeatability of the Starcheck was investigated by moving it step-wise through a wedged field. For absolute dose calibration, the Starcheck was calibrated against an Exradin A19 Farmer type chamber in a Virtual Water phantom and the calibration coefficient was compared to the ^{60}Co calibration supplied by the vendor.

The linearity of Starcheck was investigated by irradiating it to eight different doses from 0.25 Gy to 8 Gy in three photon energies in both 10 x 10 cm and 20 x 20 cm fields. The Starcheck linearity was found to be at the 0.1 % level for all energies. The relative dose profiles obtained at two dose levels were compared, and short term stability is shown to be at the 0.1 % level as well. Having confirmed the quality of Starcheck calibration in an open field, we investigated the relative response of its chambers in a wedge field. The Starcheck was mounted on a Velmex linear translational stage and 300 MU was delivered after every 9 mm of movement. The response of all detectors irradiated at the beam axis was compared to response of central chamber. Deviations of up to 1.5 % were observed. Mounting the Starcheck on a rotating stage indicates that the two perpendicular arrays agree within ± 0.5 %.

We compared the Starcheck against a calibrated Exradin A19 Farmer type chamber at 5 cm and 10 cm in a Virtual Water phantom and the results are shown in the table below. For the A19 results the correct k_Q is applied, for the Starcheck doses k_Q is assumed to be unity so effective k_Q can be determined. There is good agreement for the 6 MV and 10 MV results at the two depths but energy dependence is not consistent with the expected behavior for an air-filled ionization chamber and indicates some significant perturbation correction.

	5 cm Virtual Water			10 cm Virtual Water		
Energy	A19 (Gy)	Starcheck (Gy)	$k_{Q,\ Starcheck}$ (Starcheck/A19)	A19 (Gy)	Starcheck (Gy)	$k_{Q,\ Starcheck}$ (Starcheck/A19)
6MV	0.853	0.822	**1.037**	0.6610	0.640	**1.033**
10MV	0.902	0.857	**1.053**	0.7210	0.688	**1.048**
25MV	0.957	0.907	**1.054**	0.7960	0.746	**1.066**

In comparison with other detectors, the Starcheck array produced a dose profile that gave a better match with the chamber scan than the THEBES™ 1-D ion chamber array or electron diode scanned in water. Note that Starcheck does not suffer field edge effects shown by the THEBES 1-D array. Since Starcheck matches ion chamber scan results to better than 0.5 %, it can serve as a substitute for ion chamber scans in routine clinical applications.

16 Refereed publications, 2009-11

[1] Burns, D.T., Kessler, C. and McCaffrey, J.P., "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** Tech. Suppl. 06002 (2011).

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