Progress Report on Radiation Dosimetry at NPL

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1 Introduction

This report gives a brief overview of radiation dosimetry activities at NPL during the period May 2007 to April 2009. More detailed scientific information can be found in the publications listed in Section 8.

2 Facilities

2.1 X-ray Facilities

The 50kV, 300kV and 420kV X-ray facilities continue to be maintained. No further upgrades to report since April 2007.

2.2 ^{60}Co Facilities

The "Theratron" ^{60}Co therapy level irradiator was last resourced in April 2005, to give a dose rate at that time of ~1.4 Gy/min at 1m. The next resource is planned to take place towards the end of 2010.

The Nordion Gammacell 220 self-shielded ^{60}Co irradiator was resourced in May 2006, to give a dose rate at that time of ~200 Gy/min. The irradiator is due for reloading during 2011 and discussions are underway with potential suppliers about the best way of carrying this out in the light of the decision by MDS Nordion to no longer support this type of irradiator.

2.3 Accelerator Facilities

The new clinical linac building was handed over to NPL during August 2008. Elekta successfully delivered and carried out preliminary installation of the clinical linac on the 26th July 2008 and beam-on took place on the 14th August. Elekta completed their commissioning process within the twelve weeks allocated which included a weeks training for a number of NPL staff. Installation of the bespoke rails and carriage system was completed by January 2009. The opening event for the new clinical linac was held on the 13th November with talks given by Professor Mike Richards, National Clinical Director for Cancer at the Department of Health, Dr Penny Allisy-Roberts, Head of the Ionising Radiations Section at the BIPM and Dr Martyn Sené, interim Managing Director of NPL.

The installed system is a Synergy Digital Linac with iViewGT portal imaging, MOSAIQ management system, PINNACLE 3D treatment planning system and Synergy XVI 3D x-ray volumetric imaging. Three interchangeable filter sets have been provided, each giving 3 x-ray energies of 6/10/15, 4/8/18 and 6/10/25 MV respectively. The available electron energies are 4, 6, 8, 9, 10, 12, 15, 18, 20 and 22 MeV.

Work to date on commissioning the linac is given in a separate report to the CCRI(I).

3 Calibration Services

The current range of radiation dosimetry calibration services provided by NPL is summarised in Table 1, at the end of this report.

4 Air Kerma Standards

4.1 300kV Free Air Chamber

The 300kV free air chamber correction factors have been recalculated and/or re-measured, using new or improved methods. The largest overall change in the chamber sensitivity is of the order 0.1%. The decision has been taken not to disseminate these new values in order to maintain consistency. The uncertainty budget has been updated for the free air chamber in light of this work. The uncertainties quoted on air kerma calibration certificates for secondary standard therapy level chambers remain unchanged.

4.2 50kV Free Air Chamber

The fluorescence correction factors for the 50kV free air chamber have been determined analytically based on an interpolation of calculated values. The largest overall change in the chamber sensitivity is of the order 0.5%. These new values will be disseminated from 1st May 2009. The uncertainties quoted on air kerma calibration certificates for secondary standard therapy level chambers will remain unchanged.

4.3 Primary Standard Cavity Chambers

Adoption of the new chamber correction factors for ^{137}Cs and ^{60}Co γ-rays from 1st May 2009 will result in an increase of the NPL air kerma standard by ~1% for both therapy and protection levels. A letter is being sent to all holders of existing certificates notifying them of the change.

Commissioning of the replacement primary standard cavity chambers is ongoing.

5 Beta-ray Standards

Traceability for absorbed dose calibrations of ophthalmic applicators is to the graphite microcalorimeter via alanine dosimetry. Currently, a stack of thin (0.5 mm) alanine pellets are used to establish a depth dose curve for each applicator. An investigation is under way to establish if this relatively time consuming procedure can be replaced by the use of a commercial scintillation detector. The intention is to periodically calibrate the scintillator against alanine via NPL-owned applicators and use the scintillator routinely for dose and depth-dose measurements on customer applicators.

6 Absorbed Dose Standards

6.1 Electron beam dosimetry standards

The maximum dose rate of the electron beams produced by the Elekta linac, 4 Gy/min, is significantly lower than the 10 Gy/min dose rate of the beams in which the therapy-level primary standard has been used to date. The relatively low dose rate reduces the signal to noise ratio to a point where the accuracy requirements of radiotherapy cannot be met. It turns out that by an appropriate choice of build-up thickness, the NPL photon beam primary standard can realise absorbed dose under reference conditions for all the Elekta beams, from 4 MeV to 22 MeV. Good agreement has previously been obtained in internal comparisons of the photon and electron primary standards in a 16 MeV electron beam. Accordingly it was decided to extend the scope of the present photon beam primary standard to include electron beams. Further details are given in a separate report to the CCRI(I) on commissioning of the new NPL linac.

6.2 Graphite Calorimetry

The components for three new absorbed dose primary standard graphite calorimeters have been manufactured, the relevant metrology has been carried out and the calorimeters are currently being assembled. One will replace the existing independent primary standards for high-energy photon and electron beams. Another will serve as a primary standard for the measurement of absorbed dose in proton beams (see below), and the third is designed for the measurement of absorbed dose from an HDR brachytherapy source. Monte Carlo simulation and thermal modelling has been used to optimise and validate the calorimeter designs. In operation each calorimeter measures absorbed dose by the substitution of radiation heating by electrical heating under conditions of constant temperature inside a vacuum enclosure.

6.3 Proton Dosimetry

Progress has been made with the construction of a dedicated primary standard level graphite calorimeter for dosimetry in therapeutic proton beams. The design and operational characteristics are identical as for the new photon/electron primary standard apart from the size of the phantom and supporting structures which are smaller for the proton calorimeter. For more details, see above. In collaboration with the Slovak Primary Standard Lab (SMU) a design study has been published for a total absorption calorimeter that can serve as an instrument for beam energy characterisation (Palmans et al. 2007a)

The conversion between absorbed dose to graphite and absorbed dose to water has been further investigated for low-energy clinical proton beams since this is an essential step in applying a graphite calorimeter as a primary standard for absorbed dose to water. Experimental comparisons of tissue phantom ratios in graphite and water have been performed as well as supporting simulations using analytical models based on ICRU interaction data (ICRU reports 49 and 63) and Monte Carlo simulations using MCNPX and Geant4. Preliminary results from these four methods indicate corrections on a simple scaling with stopping power ratios to be not larger than 0.5% with an acceptably low uncertainty. This work forms part of an IAEA Coordinated Research Project on nuclear interaction data for particle therapy (Palmans and Capote-Noy, 2008).

The absorbed dose sensitivity of NPL's alanine has been characterised for dosimetry of an anti-proton beam. Good agreement was found between predictions based on a track structure model implemented in the FLUKA Monte Carlo code and the experimental results as published by Bassler et al. (2008). Although this work is of limited practical interest on the short term given the availability of anti-proton beams in the therapeutic energy range, it supports the application of alanine in other mixed particle fields such as carbon ion beams. The absorbed dose sensitivity of NPL's alanine has also been further characterised in low-energy proton beams at Clatterbridge Centre of Oncology and at the University of Birmingham using an improved experimental set-up, resulting in a detailed energy-response curve. This forms part of contracted work for the LIBRA project on laser induced proton beams (http://www.libra-bt.co.uk). In collaboration with SMU an experimental set-up has been established which also enables the characterisation of the alanine response to very low-energy protons (Palmans et al. 2007b).

6.4 Alanine Dosimetry

Two studies have been undertaken into the effect of irradiation temperature on the response of the alanine dosimeter. The first at cryogenic temperatures used for radiation processing of pharmaceutical and biological materials and the second at high temperatures experienced during high dose industrial electron beam irradiations.

A cryostat has been constructed to enable irradiations to be carried out in the Gammacell 220 ^{60}Co irradiator at controlled temperatures between ~80 K and ~300 K. The work has demonstrated complex dose dependent behaviour, with the dosimeter response falling steadily as the temperature decreases from room temperature until a sharp discontinuity is observed at ~160 K. Below this temperature, there is no further effect of irradiation temperature on the response of the dosimeter down to the lowest temperature studied (~80 K) (Sharpe et al., 2009a).

Irradiations at controlled high temperatures up to 80 ºC in ^{60}Co radiation have shown that the effect of temperature on the response of the alanine dosimeter is linear up to ~50 ºC, but significant, dose dependent, deviations from linearity occur at temperatures above that. The results are consistent with data obtained under variable (almost adiabatic) temperature conditions in high dose industrial electron beams and have led to a recommendation that the alanine dosimeter should not be subjected to peak temperatures greater than 70 ºC during high dose irradiation (Sharpe et al., 2009b).

Current NPL alanine pellets (cylinders 5 mm diameter and 2.5 mm thick) are too large for calibrations in the narrow beams used in a number of emerging radiotherapy techniques. A batch of smaller pellets 2.5 mm diameter and 2.5 mm thick has been prepared and a new EPR holder designed for their measurement. Work is at present underway to optimise the measurement technique and reduce the minimum dose to a level acceptable for radiotherapy applications.

7 Comparisons

The NPL standards of air kerma in low and medium energy x-rays and in ^{137}Cs and ^{60}Co radiation were compared with those of the BIPM in 2007. The absorbed dose to water standard in ^{60}Co radiation was also compared. Reports for these comparisons are in preparation.

An “unofficial” comparison of HDR brachytherapy standards has been carried out with ARPANSA, Australia and the results published (Butler 2008).

8 Reports and Publications (May 2007 – April 2009)

H. Palmans, J. Dobrovodský, N. Durný, C. Gouldstone, P. Kováč, J. Martinkovič, M. Mozolík, M. Pavlovič, K. Rosser, P. Sharpe and O. Szöllős, “Experimental set-up for alanine dosimetry in protons below 18 MeV”, NPL report IR3 (Teddington: National Physical Laboratory) 2007b (ISSN 1754-2952)

H. Palmans, D. Shipley, J. Martinkovič and J. Dobrovodský, N. Durný, “Literature review and simulations for total absorption calorimetry in a proton beam,” NPL report IR4 (Teddington: National Physical Laboratory) 2007a (ISSN 1754-2952)

D. C. Crossley and P. H. G. Sharpe, “Extension of the NPL Alanine Reference Dosimetry Service to 100 kGy”, NPL Report IR13, (Teddington: National Phyisical Laboratory) 2008, (ISSN 1754-2952)

H. Palmans and R. Capote Noy, “Summary Report First Research Coordination Meeting on Heavy Charged-Particle Interaction Data for Radiotherapy,” INDC(NDS)-0523 Distr. G (Vienna, Austria: IAEA) 2008

R. Alfonso, P. Andreo, R. Capote, M. Saiful Huq, W. Kilby, P. Kjäll, T. R. Mackie, H. Palmans (corresponding author), K. Rosser, J. Seuntjens, W. Ullrich and S. Vatnitsky, “A new formalism for reference dosimetry of small and non-standard fields,” Med. Phys. 35 5179-5186, 2008

R. Alfonso, P. Andreo, R. Capote, M. Saiful Huq, W. Kilby, P. Kjäll, T.R. Mackie, H. Palmans (corresponding author), K. Rosser, J. Seuntjens, W. Ullrich and S. Vatnitsky, “A new formalism for reference dosimetry of small and non-standard fields,” Med. Phys. 35 5179-5186, 2008

N. Bassler, J.W. Hansen, H. Palmans, M.H. Holzscheiter, S. Kovacevic and the AD-4/ACE Collaboration, “The antiproton depth dose curve measured with alanine detectors,” Nucl. Instr. Meth. B 266 929-936, 2008

D. Butler, A. Haworth, T. Sander and S. Todd , “Comparison of Ir-192 air kerma calibration coefficients derived at ARPANSA using the interpolation method and at the National Physical Laboratory using a direct measurement,” Australas. Phys. Eng. Sci. Med. Vol. 31 No. 4 332-338, 2008

E. Chin, D. Shipley, M. Bailey, J. Seuntjens, H. Palmans, A DuSautoy and F. Verhaegen, “Validation of a Monte Carlo model of a NACP-02 plane-parallel ionization chamber model using electron backscatter experiments,” Phys. Med. Biol. 53 N119-126, 2008

R. D. H. Chu, W. L. McLaughlin, A. Miller, P. H. G. Sharpe (Report committee) "ICRU Report 80 - Dosimetry Systems for Use in Radiation Processing" Journal of the ICRU, **8**, 2008

G. Douysset, T. Sander, J. Gouriou and R. Nutbrown, "Comparison of air kerma standards of LNE-LNHB and NPL for Ir-192 HDR brachytherapy sources: EUROMET project no 814," Phys. Med. Biol. 53 N85-N97, 2008

M. Bailey, J. P. Sephton and P. H. G. Sharpe "Monte Carlo modelling and real time dosemeter measurements of dose rate distribution at a ^{60}Co industrial irradiation plant." Radiat. Phys. Chem, *In press*. 2009

E. Chin, H. Palmans, D. Shipley, M. Bailey and F. Verhaegen, "Analysis of dose perturbation factors of a NACP-02 ionization chamber in clinical electron beams," Phys. Med. Biol. 54 307-326, 2009

M. McEwen and A. R. DuSautoy, "Primary standards of absorbed dose for electron beams", Metrologia 46**,** S59–S79, 2009

J. Seuntjens and S. Duane, "Photon absorbed dose standards", Metrologia 46**,** S39–S58, 2009

P. H. G. Sharpe, A. Miller, J. P. Sephton, C. A. Gouldstone, M Bailey and J. Helt-Hansen "The effect of irradiation temperatures between ambient and 80 ºC on the response of alanine dosimeters." Radiat. Phys. Chem, *In press*. 2009a

P. H. G. Sharpe, J. P. Sephton and C. A. Gouldstone "The behaviour of alanine dosimeters at temperatures between 100 K and 300 K." Radiat. Phys. Chem, *In press*. 2009b

TABLE 1. NPL Calibration Services in Photon and Electron Dosimetry

	Photon Standards						Electron & Beta-ray Standards			Reference Dosimetry	
	Protection	Diagnostic	Therapy			Industrial	Ophthalmic Applicators	Therapy	Industrial	Dichromate	Alanine
Beam Qualities	x-rays: 8 kV – 300 kV γ-rays: ^{241}Am,^{137}Cs,^{60}Co	x-rays: 25 - 150 kV	γ-rays: ^{192}Ir	x-rays: 8 kV – 280 kV γ-rays: ^{60}Co	x-rays: 4 - 19 MV γ-rays: ^{60}Co	γ-rays: ^{60}Co	beta: ^{90}Sr, ^{106}Ru	electrons: 6 - 19 MeV	electrons: 3 - 10 MeV	^{60}Co	x-rays: > 2 MV ^{137}Cs,^{60}Co e^- > 1 MeV
Dose / Dose rate	50 mGy/h	5 – 50 mGy/h	20 - 50 mGy/h	0.1 –1 Gy/min	0.5- 1 Gy/min	0.2 kGy/min	1 - 50 Gy/min	1 - 2 Gy/min	< 20 kGy/min	2 - 55 kGy	5 Gy - 100 kGy
Primary Standards	ion chambers: 50 kV free air 300 kV free air ^{60}Co cavity	ion chambers: 50 kV free air 300 kV free air	cavity ion chamber	ion chambers: 50 kV free air 300 kV free air ^{60}Co cavity	graphite photon calorimeter	graphite photon calorimeter	graphite photon calorimeter	graphite electron calorimeter	graphite electron calorimeter	graphite photon calorimeter	graphite photon calorimeter
Primary Quantity	air kerma rate	air kerma rate	air kerma rate	air kerma rate	absorbed dose to graphite	absorbed dose to graphite	absorbed dose to graphite	absorbed dose to graphite	absorbed dose to graphite	absorbed dose to graphite	absorbed dose to graphite
Calibration Quantity	air kerma	air kerma	reference air kerma rate	air kerma	absorbed dose to water	absorbed dose to water	absorbed dose rate to water	absorbed dose to water	absorbed dose to water / silicon	absorbed dose to water	absorbed dose to water