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 2005 to April 2007. More detailed scientific information can be found in the publications listed in Section 8.

2 Facilities

2.1 X-ray Facilities

The new 420kV x-ray facility that was installed during the move to new laboratories has been set up and commissioned. A new x-ray set, generator, monitor chamber, measurement rack and protection level carriage have been installed and commissioned in the 300kV x-ray facility. Measurement racks for both facilities have been upgraded to improve resolution.

2.2 ^{60}Co Facilities

The "Theratron" ^{60}Co therapy level irradiator was resourced in April 2005, to give a dose rate at that time of ~1.4 Gy/min at 1m.

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. Nordion have subsequently announced that they will no longer support or resource Gammacell 220 irradiators, a decision that is likely to affect a number of high dose calibration laboratories.

2.3 Accelerator Facilities

The UK Department of Trade and Industry have agreed that NPL will have a new clinical LinAc and a new building to house it. Design of the building was agreed in 2006. The building will be situated adjacent to the existing accelerator building and work to prepare the site has been completed. Construction began in April 2007 with completion expected in mid 2008.

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 are currently being recalculated and/or re-measured, using new or improved methods. The largest overall change in the chamber sensitivity is expected to be at the lowest beam quality, 1 mm Al HVL, and is likely to be at most 0.3%. The change in sensitivity is principally due to the inclusion of a correction to account of the effect of fluorescence generated by the argon content of air, which was not accounted for in previous work. This effect is less significant at higher beam qualities. The intention is to update the uncertainty budget for the free air chamber in light of this work. It is anticipated that uncertainties quoted on air kerma calibration certificates for secondary standard therapy level chambers will be significantly reduced, in part due to the improved methods used for estimating the primary standard correction factors, but also due to the improved uncertainty analysis.

4.2 Primary Standard Cavity Chambers

Manufacture of the two sets of new spherical primary standard cavity chambers (5, 10, 30 and 100 cm^3) for use with ^{60}Co, ^{137}Cs and ^{192}Ir is now complete. Dimensional metrology of the 5 and 100 cm^3 chambers is in progress at NPL using a coordinate measuring machine. Voids in the chamber stems will be eliminated by filling with ceresin wax. It is planned to complete commissioning of the two 5 cm^3 chambers for inclusion in the BIPM comparison in June 2007. These will replace the current cavity chambers, that have been in use for 50 years. The two 100 cm^3 chambers will be used as primary standards for protection level measurements, eliminating the need to use transfer standards. The same chambers will be used as the ^{192}Ir HDR brachytherapy primary standard. In addition, 10 and 30 cm^3 chambers will be commissioned and added to the primary standard set at a later date.

5 Beta-ray Standards

Traceability for the calibration of ophthalmic applicators is now to the graphite photon calorimeter via alanine and work on the extrapolation chamber has been discontinued. Calculations are planned to model the depth dose curve in a stack of alanine pellets in a PMMA holder in order to reduce the uncertainty of extrapolation to surface dose.

6 Absorbed Dose Standards

6.1 Electron beam dosimetry standards

The perturbation factors for the parallel-plate ionisation chambers designated in the UK IPEM code of practice for electron dosimetry are taken to be unity at all beam qualities and depths. However, since the Code of Practice was published, research (e.g. Verhaegen et al 2006 and McEwen et al 2006) has been undertaken which suggests that the perturbation factors are not unity and are quality dependent. Further work is required to determine best estimates of the actual values for perturbation factors in graphite and water. The combined standard uncertainty of 1.0% in $N_{D,w}$ quoted in NPL certificates now includes a contribution for the perturbation factor that acknowledges the research since the publication of the Code of Practice.

A calorimeter for operation in high dose industrial low energy (~100 keV) electron beams has been developed in collaboration with Risø National Laboratory, Denmark. The calorimeter has been used to calibrate alanine and radiochromic film dosimeters and has confirmed no significant difference in the radiation chemical yield of these systems when irradiated in electron beams at low energy (80-120 keV) and 10 MeV. The total standard uncertainty in dose measurement is estimated to be 10% between 80 and 120 keV. Work is continuing on developing practical protocols for dosimetry at these low electron energies.

6.2 Graphite Calorimetry

Three new absorbed dose primary standard graphite calorimeters are under development. 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.

The current photon primary standard calorimeter has recently been compared with the electron beam primary standard, via transfer standard NACP ion chambers, in electron beams of nominal energy from 6 MeV to 19 MeV. The correction factors for the photon calorimeter required to complete the analysis of these measurements are currently being evaluated.

6.3 Proton Dosimetry

A new graphite calorimeter for proton dosimetry will be built largely based on the design of the new photon-electron primary standard calorimeter. The main difference will be a smaller phantom resulting in a portable device whilst still establishing lateral and backscatter equilibrium conditions for clinical protons. The calorimeter is at present in the design stage.

An experiment has been performed with the Clatterbridge Centre of Oncology (CCO) to characterise the ion recombination correction for ionization chambers in proton beams (Palmans et al 2006).

Perturbations have been calculated for a comparison between water calorimetry and ionization chambers in collaboration with Lund University and the Uppsala University Hospital in Sweden (Medin et al 2006). This work resulted in a new determination of the mean energy required by protons to produce an ion pair in dry air, $(w_{air})_p$. This value will be included in a new evaluation of $(w_{air})_p$ in a new ICRU report. An earlier value measured in collaboration with the CCO will also be included in this new evaluation.

An analytical model has been developed for calculating gradient corrections for cylindrical ionization chambers in proton and light-ion beams on which an NPL report has been published. This model was compared with Monte Carlo simulations on NPL's distributed computing grid (Palmans 2006).

A comparison exercise has been performed in collaboration with the CCO and the University of Liverpool on the modelling of an ocular proton beam line with three different Monte Carlo codes (Baker et al 2006).

A collaboration has been set-up with the Slovak Institute of Metrology (SMU), Biont and the Slovak Technical University (STU). As part of this collaboration an experimental beam line was set up at the 18 MeV cyclotron of Biont for the characterisation of alanine at low clinical proton energies. A literature and theoretical study was performed aiding the design of a total absorption calorimeter which is intended to be combined with a time of flight experiment at a new 72 MeV cyclotron which is currently being built on the SMU/Biont site. Two NPL reports are in preparation describing this work.

6.4 Alanine Dosimetry

A cylindrical Rexolite™ (polystyrene) phantom has been designed for the irradiation of alanine dosimeters and ionisation chambers in helical tomotherapy beams. The phantom, which is 10 cm diameter and 22 cm long, has a 15 mm hole down the central axis into which can be inserted PMMA adaptors for a range of dosimeters. Currently, adaptors are available for a stack of alanine pellets in a PMMA holder and for NE2611, NE2571 or Exradin A1SL ion chambers. A protocol has been established to determine the response of the chambers relative to alanine in helical beam treatments. This provides a calibration under the conditions of use that is traceable to absorbed dose primary standards. Typically, three measurements would be carried out using 5, 2.5 and 1 cm beams with the phantom centred on the axis of rotation, and one measurement in a 2.5 cm beam with the phantom placed off-axis. In each case, a treatment plan is prepared to deliver a uniform dose to a cylindrical volume, 8 cm diameter and 10 cm long, centred on the phantom. In addition, a measurement is also made in a static beam in a rectangular phantom. A total dose of 9 Gy is given to the alanine in three 3 Gy treatment fractions. The alanine adaptor contains 14 pellets, each ~2.4 mm thick, along the axis of the phantom and this allows measurement of the beam uniformity. Results to date on five machines have indicated agreement to within ±2% between alanine dose and chamber and treatment planning system dose for on-axis irradiations. However, a larger than expected (up to 5%) "thread-effect" has been observed under certain conditions, when the phantom is irradiated away from the axis of rotation.

7 Comparisons

A comparison of the new NPL HDR brachytherapy standard with LNHB (France) has demonstrated agreement within ~0.5%. A final report is currently in preparation. (EUROMET 814).

Irradiations have been carried out for EUROMET supplementary comparison of NMI air kerma standards for ISO 4037 narrow spectrum series radiation qualities (EUROMET 545).

Irradiations have been carried out for EUROMET supplementary comparison of the personal dose equivalent for photon radiation (EUROMET 738).

A comparison involving the NPL transportable medium energy x-ray primary standard chamber was carried out with NMi (The Netherlands) in spring 2006. Good agreement (within 0.4%) was obtained for the high dose rate qualities, but a poor signal-to-noise ratio limited the data that could be obtained at low dose rate qualities.

A comparison of absorbed dose to water in high-energy electron beams has been undertaken with METAS (Switzerland). Preliminary results indicate agreement within ~1%, but further detailed analysis is required. It is hoped that this work can form the basis of a EUROMET key comparison.

Comparisons of the NPL air kerma and absorbed dose standards should be made with BIPM in 2007 under the CCRI “ten year rule”. It is planned to carry out the air kerma comparisons in 2007. A comparison of absorbed dose in ^{60}Co radiation will be carried out when the new primary standard graphite calorimeter is operational.

8 Reports and Publications (May 2005 – April 2007)

H Palmans, *Effective water depth of an ionization chamber in a proton beam: analytical model,* NPL, Teddington (2006), NPL Report DQL-RD 002

L Hao, J Gallop, J MacFarlane, H Palmans, T Sander and S Duane, *Low-Temperature Calorimetry for Ionising Radiation Dosimetry*, NPL, Teddington (2006), NPL Report DEM-TQD 008

H Palmans, R Thomas, D Shipley, A Kacperek, *Light ion beam dosimetry*, NPL, Teddington (2006), NPL Report DQL-RD 003

T Sander, R Nutbrown, *The NPL air kerma primary standard TH100C for high dose rate* ^{192}*Ir brachytherapy sources*, NPL, Teddington (2006), NPL Report DQL-RD 004

M McEwen, J Sephton, P Sharpe, *Alanine as a precision validation tool for reference dosimetry*, Proceedings of the 216th PTB Seminar “Alanine Dosimetry for Clinical Application”, PTB, Braunschweig (2006), PTB-Dos-51

P Sharpe and J Sephton, *Therapy level alanine dosimetry at the NPL*, Proceedings of the 216th PTB Seminar “Alanine Dosimetry for Clinical Application”, PTB, Braunschweig (2006), PTB-Dos-51

H Palmans and F Verhaegen, *Assigning nonelastic nuclear interaction cross sections to Hounsfield units for Monte Carlo treatment planning of proton beams***,** Phys. Med. Biol. 50 (2005) 991-1000

D Shipley, H Palmans, A Kacperek and C Baker, *GEANT4 simulation of an ocular proton beam and benchmark against other Monte Carlo codes*, In: “The Monte Carlo Method: Versatility Unbounded in a Dynamic Computing World”, Illinois, USA: American Nuclear Society (2005) 14 pages

H Palmans, *McPTRAN.CAVITY and McPTRAN.RZ, Monte Carlo codes for the simulation of proton beams and calculation of proton detector perturbation factors*, In: “The Monte Carlo Method: Versatility Unbounded in a Dynamic Computing World”, Illinois, USA: American Nuclear Society (2005) 11 pages

J Helt-Hansen, A Miller, S Duane, P Sharpe, M McEwen, S Clausen, *Calorimetry for dose measurement at electron accelerators in the 80–120 keV energy range,* Radiat. Phys. Chem. 74 (2005) 354-371

J Helt-Hansen, A Miller, P Sharpe, *Dose response of thin-film dosimeters irradiated with 80–120 keV electrons,* Radiat. Phys. Chem. 74 (2005) 341-353

J Pearce, R Thomas and A DuSautoy, *The characterization of the Advanced Markus ionization chamber for use in reference electron dosimetry in the UK*, Phys. Med. Biol. 51 (2006) 473–483

D T Burns, P J Allisy-Roberts, M F Desrosiers, V Yu Nagy, P H G Sharpe, R F Laitano, K Mehta, M K H Schneider , Y L Zhang, *CCRI supplementary comparison of standards for absorbed dose to water in* ^{60}*Co gamma radiation at radiation processing dose levels*, Radiat. Phys. Chem. 75 (2006) 1087-1092

C Baker, D Shipley, H Palmans, A Kacperek, *Monte Carlo modelling of a clinical proton beam-line for the treatment of ocular tumours*, Nuclear Instruments and Methods in Physics Research A 562 (2006) 1005–1008

H Palmans, D J Butler and D V Webb, *Shift in absorbed dose for megavoltage photons when changing to TRS-398 in Australia*, Australas. Phys. Eng. Sci. Med., 28 (2005) 155-164

J Medin, C K Ross, N V Klassen, H Palmans, E Grusell and Jan-Erik Grindborg, *Experimental determination of beam quality factors,* k_Q*, for two types of Farmer chamber in a 10 MV photon and a 175 MeV proton beam*, Phys. Med. Biol. 51 (2006) 1503–1521

F Verhaegen, R Zakikhani, A DuSautoy, H Palmans, G Bostock, D Shipley and J Seuntjens *Perturbation correction factors for the NACP-02 plane-parallel ionization chamber in water in high-energy electron beams*, Phys. Med. Biol. 51 (2006) 1221–1235

M McEwen, H Palmans and A Williams, *An empirical method for the determination of wall perturbation factors for parallel-plate chambers in high-energy electron beams*, Phys. Med. Biol. 51 (2006) 5167–5181

H Palmans, *Perturbation factors for cylindrical ionization chambers in proton beams. Part I: corrections for gradients*, Phys. Med. Biol. 51 (2006) 3483–3501

H Palmans, R Thomas and A Kacperek, *Ion recombination correction in the Clatterbridge Centre of Oncology clinical proton beam*, Phys. Med. Biol. 51 (2006) 903–917

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: 3 - 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 Gy/min	< 20 kGy/min	2 - 55 kGy	5 Gy - 70 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	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