Progress Report on Radiation Dosimetry at NPL

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April 2011

1 Introduction

This report gives a brief overview of radiation dosimetry activities at NPL during the period May 2009 to April 2011. More detailed scientific information can be found in the publications listed in Section 7.

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 2009.

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 in 2012.

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 ceased to support this type of irradiator, but a new supplier has been found and the irradiator is scheduled for reloading in April 2011.

A holder is being constructed for the Gammacell 220 irradiator to enable routine irradiations of dosimeters at temperature between -80ºC and +60ºC. This is required to meet the needs of industry for dosimetry at cryogenic temperatures, when irradiating medical devices containing active pharmaceutical and biological components.

2.3 Accelerator Facilities

Monte Carlo source models have been developed, initially for reference conditions, for the seven x-ray and nine electron energies from the new NPL Elekta clinical linac. The source model for each x-ray energy was fine-tuned in a 30 cm x 30 cm field by matching calculated depth-dose and beam profile data at different depths in water against measured plotting tank data. The tuned model was then validated by comparing with similar measurements in a 10 cm x10 cm field at the standard reference depth in water. Further fine tuning of these x-ray models are planned to support measurements in more clinically relevant fields.

The source model for each electron beam quality was adjusted by matching depth-dose distributions in water from a 20 cm x 20 cm square field measured using a Scanditronix NACP-02 parallel plate ionisation chamber, taking into account the non-unity perturbation corrections for this ionisation chamber which are depth- and spectrum-dependent. These models have now been completed with just final fine adjustments being made.

Following the opening of the Elekta clinical linac in November 2008, graphite calorimetry with the existing primary standard calorimeter, and ionisation chamber measurements in both graphite and water phantoms, were made at each of the seven available x-ray energies. Monte Carlo simulations of the NPL Elekta linac, the existing primary standard calorimeter and both graphite and water phantoms under reference conditions were also completed in support of the measurements to enable the complete realisation of absorbed dose to water for photon beams. This work has now re-established the existing UK primary standard of absorbed dose to water on this new facility for use in the photon therapy level calibration services offered by NPL. The NPL reference set of 2611 type ionisation chambers were calibrated in terms of absorbed dose to water, N_w, with a total standard uncertainty of 0.49% (k=1). The values of k_Q , the ratio of the calibration factor at a beam quality Q to that in a cobalt-60 beam, showed good agreement (within 0.4%) with k_Q values currently in use. For now, 2611 ionisation chamber calibrations will continue to be reported by normalising the existing k_Q curve, however this will be reconsidered when the new NPL primary standard calorimeter is commissioned and sufficient data from this new calorimeter is available. An external NPL report (Pearce *et al*., 2010) has been published on this work and a paper has been submitted to Metrologia.

Electronic Portal Imaging Device (EPID) Dosimetry

The dose-response characteristics of the amorphous silicon (*a*-Si) EPID on the clinical linac have been investigated over a wide range (4-25 MV) of clinically relevant photon energies. The investigation covered ghosting and image lag effects as well as field size dependence. This is the start of a project to calibrate the EPID for use as an *in vivo* dosimeter.

2.4 HDR brachytherapy afterloader

The HDR ^{192}Ir brachytherapy afterloader continues to be maintained. No further upgrades have been made during the reporting period.

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

No changes to report for the NPL air kerma standard.

4.2 50kV Free Air Chamber

No changes to report for the NPL air kerma standard.

4.3 Primary Standard Cavity Chambers

No changes to report for the NPL air kerma standard.

Commissioning of the replacement primary standard cavity chambers is ongoing, but work has not progressed as far as expected because of a series of problems, including dimensional metrology, leaks and broken electrodes/stems. The design of the stems is being reviewed, with the aim of modifying them slightly to improve performance.

5 Absorbed Dose Standards

5.1 Graphite Calorimetry

Construction of calorimeters for measuring absorbed dose to graphite in electron and photon beams, proton beams, and with high dose rate brachytherapy sources, has been completed, together with their associated electronics and control/measurement software. These calorimeters are now being commissioned. They have all been designed to enable absorbed dose to graphite to be measured using substitution of electrical heating by radiation, while maintaining constant temperatures in the components.

The new HDR brachytherapy calorimeter for the measurement of absorbed dose from an HDR brachytherapy source comprises three main parts: the graphite calorimeter inside a vacuum housing, the associated electronics and the measurement and control software. The design of the brachytherapy calorimeter was optimised for dealing with the source self-heating and steep dose gradients close to brachytherapy sources. The graphite calorimeter measures the absorbed dose to graphite at a distance of 2.5 cm from the source centre by either determining the temperature increase in the core due to radiation heating (quasi-adiabatic mode) or by substituting the radiation heating by electrical heating while keeping the temperatures of all graphite components inside the vacuum enclosure constant (isothermal mode).

5.2 Proton Dosimetry

Further 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 to those of the new photon/electron primary standard apart from the size of the phantom and supporting structures, which are smaller for the proton calorimeter.

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 (either directly measured or derived from depth dose curves) have been performed, as well as Monte Carlo simulations using MCNPX, FLUKA, SHIELD-HIT, GEANT4 and PTRAN. Both the experiments and simulations result in a fluence correction factor of unity with an estimated relative standard uncertainty of 0.3%. This work forms part of an IAEA Coordinated Research Project on nuclear interaction data for particle therapy and is supported by the EU FP7 programme ERA-NET Plus. Similar work was performed for other materials that are relevant for dosimetry: aluminium, copper, A150 tissue-equivalent plastic (Al-Sulaiti *et al*., 2010) and three different types of water-equivalent plastics (PW, PWDT, WT1).

The absorbed dose sensitivity of NPL's alanine has been characterised as a function of energy and depth for dosimetry of carbon ion beams. Good agreement was found between predictions based on a track structure model implemented in the FLUKA Monte Carlo code and the experimental results (Rochus *et al*. 2011). Furthermore, alanine has been used to measure dose in a neutron field at a reactor for BNCT of liver (Schmitz *et al*., 2010). NPL has contributed to the quantification of the absorbed dose sensitivity of radiochromic film as a function of energy and depth for dosimetry of proton beams (Kirby *et al*., 2010).

A micro-calorimeter based on SQUID technology is under development that can directly measure micro-dosimetric energy deposition distributions in a water equivalent (low-Z) absorber. The design concept has been published by Galer *et al*. (2011) and a prototype is currently under construction using a grant from the National Institute for Health Research under its Invention for Innovation programme. This work will contribute to the effort to establish a new physical quantity more closely related to the biological response of radiation than absorbed dose.

5.3 Small and composite field dosimetry

NPL was involved in IPEM's Small Field Working Party which has published a new report entitled "Small Field MV Photon Dosimetry" (Aspradakis *et al*., 2010). The report discusses the difficulties and challenges associated with treatment fields smaller than 4 cm and is, to date, the only comprehensive report published in this area.

NPL is involved in an international effort by the IAEA and AAPM to develop codes of practice for small and composite photon field dosimetry. Within this framework alanine has been used in step-and-shoot and dynamic IMRT fields, GammaKnife, CyberKnife and TomoTherapy to determine overall ionisation chamber correction factors in machine-specific reference fields and plan-class specific reference fields.

A study on ion recombination in ionisation chambers used for TomoTherapy was performed consisting of both experiment and theoretical modelling, with specific emphasis on the influence of instantaneously inhomogeneous irradiation conditions (Palmans *et al*., 2010). This work revealed that the same dose at the same unit delivered helically with a 1 cm slit field can lead to 50% lower values of the volume recombination correction as compared to a broad field. The models developed for the spatial and time dependent dose distributions can be generalized for any IMRT delivery sequence.

5.4 Alanine Dosimetry

NPL alanine was used as part of a large scale UK IMRT Audit, in which 57 out of a potential 62 centres took part. The audit was carried out by post and involved two main aspects: films, to provide a check on relative dose, and alanine dosimeters, to provide absolute dose measurements. Alanine was used in both 10 cm x 10 cm reference fields and in representative IMRT fields, with a number of centres submitting results for more than one plan. For the reference fields, only 1 result in 67 showed differences between alanine and reported doses outside 5%. The mean deviation from expected dose was +0.11% with a standard deviation of 1.6% (-0.05±1.0% if the anomalous +10.1% measurements is excluded). The results from the IMRT fields relative to the TPS predicted doses showed 4 out of 78 of the measurements were outside 5%. Excluding three measurements that were outside 10%, the mean difference was 0.05% with a standard deviation of 1.5%. The anomalous results have been investigated and shown to be associated with identifiable mistakes in performing the audit. A paper on the comparison has been accepted for publication in the journal "Radiotherapy and Oncology".

A new quartz holder has been manufactured for the EPR spectrometer to enable the measurement of small alanine pellets, 2.5 mm diameter and ~2.5 mm thick. The minimum measurable dose is higher than for the standard 5 mm diameter pellets, but a pellet-to-pellet reproducibility of 0.5% has been achieved at doses above 20 Gy.

As part of work carried out under the EURAMET JRP 6 programme, an extensive set of alanine measurements has been made in a cylindrical water phantom surrounding a ^{192}Ir brachytherapy source. The phantom held stacks of alanine pellets at radial distances of 1, 1.5, 2, 3, 5, 7 and 10 cm from the source. Small (2.5 mm diameter) pellets were used to improve spatial resolution close to the source and 5 mm pellets used at greater distances. Preliminary analysis in terms of the relative dose distribution shows agreement with published data to within a few percent over radial distances from 1 to 7 cm and z-axis distances 6 cm above and below the radial source axis. This implies very little energy dependence in the alanine dosimeter over this range of depths, but more detailed analysis is underway involving Monte Carlo modelling of the phantom.

6 Comparisons

The NPL air kerma standard for high dose rate ^{192}Ir brachytherapy sources was compared with the air kerma standard of the BIPM in 2010. A report for this CCRI(I)-K8 key comparison is in preparation.

NPL and NIST alanine dosimeters were used in the CCRI(I)-S2 comparison of absorbed dose to water in ^{60}Co radiation at radiation processing dose levels. The Draft B Report has now been approved by the CCRI(I) and will be published as a Technical Supplement in Metrologia. A poster on the comparison is being presented at the International Meeting on Radiation Processing in June 2011.

A comparison of alanine dosimeters at radiotherapy dose levels (EURAMET.RI(I)-S7) has been carried out with the PTB and the LNHB. Results have been exchanged and the report is being prepared.

7 External Reports and Publications (May 2009 – April 2011)

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, **78** 453–456 2009

G A Bass, R A S Thomas, J A D Pearce "The calibration of parallel-plate electron ionisation chambers at NPL for use with the IPEM 2003 code of practice: summary data", Phys. Med. Biol. **54** N115-N124, 2009

S. Duane, R. Nutbrown and D. Shipley Changes to the NPL air kerma standard for 137Cs and 60Co. NPL Report IR 17, May 2009

H. Palmans, A. Kacperek and O. Jäkel, "Hadron dosimetry" In: Clinical Dosimetry Measurements in Radiotherapy (AAPM 2009 Summer School), Ed. D. W. O. Rogers and J. Cygler, (Madison WI, USA: Medical Physics Publishing), pp. 669-722 (ISBN: 9781888340846), 2009

J Pearce, G Bass, S Duane, R Nutbrown and D Shipley "Revised correction factor for the UK national primary standard for air kerma for ^{137}Cs and ^{60}Co gamma-rays", Metrologia **46** L26, 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, **78** 473–475, 2009

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, **78** 477–479, 2009

P. Sharpe, A. Miller "Guidelines for the Calibration of Routine Dosimetry Systems for use in Radiation Processing", NPL Report CIRM 29, 2009

L Al-Sualiti, D Shipley, R Thomas, A Kacperek, P Regan and H. Palmans, "Water equivalence of various materials for clinical proton dosimetry by experiment and Monte Carlo simulation," Nucl. Instrum. Meth. A **619** 344-347, 2010

M. M. Aspradakis*, J. P. Byrne*, H. Palmans, J. Conway*, K. Rosser*, J. A. P. Warrington*, S. Duane, "Small field MV photon dosimetry", IPEM Report 103, IPEM, 2010

A. M. Bidmead*, T. Sander, S. M. Locks*, C. D. Lee*, E. G. A. Aird*, R. F. Nutbrown, A. Flynn*, "The IPEM code of practice for determination of the reference air kerma rate for HDR Ir-192 brachytherapy sources based on the NPL air kerma standard", Bidmead, A M*, Sander, T, Locks, S M*, Lee, C D*, Aird, E G A*, Nutbrown, R F, Flynn, A*. Phys. Med. Biol., 55, (11), 3145-3159, 2010

J. Helt-Hansen, A. Miller, P. Sharpe, B. Laurell, D. Weiss, G. Pageau "D_μ - a new concept in low energy electron dosimetry " Radiat. Phys. Chem. **79** 66–74, 2010

C. P. Karger, O. Jäkel, H. Palmans and T. Kanai, "Dosimetry for Ion Beam Radiotherapy," Phys. Med. Biol. **55**(21) R193-R234, 2010

C. Kessler, P. J. Allisy., D. T. Burns, S. Duane, J. Manning, R. Nutbrown, “Comparison of the standards for air kerma of the NPL and the BIPM for 60Co γrays”, Metrologia, 47, Tech. Suppl., 06004, 2010

D. Kirby, S. Green, H. Palmans, R. Hugtenburg, C. Wojnecki and D. Parker, “LET dependence of GafChromic films and an ion chamber in low-energy proton dosimetry” Phys. Med. Biol. **55** 417-433, 2010

H. Palmans, R. A. S. Thomas, S. Duane, E. Sterpin and S. Vynckier, “Ion recombination for ionisation chamber dosimetry in a tomotherapy unit,” Med. Phys. **37** 2876-2889, 2010

J A D Pearce and G A Bass "Determination of beam quality index, $TPR_{20/10}$, on the NPL Elekta linac" NPL Report IR 22, 2010

J A D Pearce, D R Shipley and S Duane "Re-establishing the absorbed dose primary standard for photon beams on the NPL clinical linac", NPL Report: IR 24, 2010

T. Schmitz, M. Blaickner, C. Schütz, N. Wiehl, J. V. Kratz, N. Bassler, M. H. Holzscheiter, H. Palmans, P Sharpe, G. Otto and G. Hampel, “Dose calculation in biological samples in a mixed neutron-gamma field at the TRIGA reactor of the University of Mainz,” Acta Oncol **49**(7) 1165-1169, 2010

S. Galer, L. Hao, J. Gallop, H. Palmans, K. Kirkby, A. Nisbet, “Design concept for a novel SQUID-based microdosimeter,” Radiat. Prot. Dos. 143(2-4) 427-431, 2011

R. Herrmann, O.Jäkel, H. Palmans, P. Sharpe and N. Bassler, “Dose response of alanine detectors irradiated with carbon ion beams,” Med. Phys. 38(4) 1859-1866, 2011

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 - 25 MV γ-rays: ^{60}Co	γ-rays: ^{60}Co	beta: ^{90}Sr, ^{106}Ru	electrons: 4 - 22 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- 5 Gy/min	0.2 kGy/min	1 - 50 Gy/min	4 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