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 2011 to February 2013. More detailed scientific information can be found in the publications listed in Section 8.

2 Facilities

2.1 X-ray Facilities

The 50 kV, 300 kV and 420 kV x-ray facilities have been operating throughout the period.

A detector system for measuring x-ray spectra has been commissioned and used to measure the spectra of therapy and protection level qualities for the existing x-ray tubes/generators. Measured spectra show good match to calculated spectra, validating the use of calculated spectra in the derivation of correction factors applied to the primary standards.

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 1 m. The next resource is planned to take place in 2013.

The Nordion Gammacell 220 self-shielded ^{60}Co irradiator was resourced in June 2011, to give a dose rate at that time of ~230 Gy / min.

A holder will be installed in the Gammacell 220 irradiator in 2013 to enable routine irradiations of dosimeters at temperature between -60 ºC and +60 ºC. 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

The Elekta clinical linac multileaf collimator was upgraded to a model MLCi2 in 2012, giving improved interleaf leakage and the capability, with its interdigitating leaves, to deliver more complex field shapes. Flattening Filter Free (FFF) photon beams have been commissioned at 6 MV and 10 MV according to Elekta's default specification. In this setup the electron beam energy is boosted from the value normally used to generate flattened beams, the boost being chosen so that the beam quality parameter, $PDD_{10\ cm}$, takes the same value for FFF and flattened beams. Additional, non-energy boosted unflattened beams (referred to as FFFv) will be set up and commissioned: these are expected to be comparable to those produced in, for example, Varian TrueBeam machines. Preliminary results indicate that measurements and modelling of these FFFv beams enables a more direct validation of the Monte Carlo model, and is consistent with the results previously obtained for flattened beams.

The research linac was decommissioned in 2012 and part of the building is currently being refurbished for the installation of an Elekta Agility clinical linac. Handover is scheduled to be by June 2013. This is a joint venture between NPL and Elekta, with time on this second machine being shared equally between the partners. The Agility radiation head includes an interdigitating, 160 leaf MLC with a 5 mm projected leaf width and a maximum field size 40 cm x 40 cm. A full range of flattened and FFF beams will be commissioned and tuned to match the beams of the existing linac.

2.4 HDR brachytherapy afterloader

The Nucletron microSelectron-v1 classic HDR ^{192}Ir afterloader, which is currently installed at NPL, will no longer be supported by the manufacturer after 31 December 2013. A final Nucletron microSelectron-v1 classic HDR ^{192}Ir source has been ordered for the 2013 HDR brachytherapy calibration service.

A new Flexitron HDR ^{192}Ir afterloader has been installed at NPL in 2012 and the re-commissioning of NPL's air kerma standard for the new source type (Flexisource HDR ^{192}Ir) is now under way. It is planned that NPL's HDR brachytherapy calibration service will be based on the ^{192}Ir Flexisource from 2014 onwards

3 Calibration Services

The decommissioning of the research linac means that NPL is no longer able to provide industrial dose level electron beam irradiation services.

Source geometry factors for six different HDR ^{192}Ir brachytherapy source types currently in use in hospitals have been determined for a Standard Imaging (SI) 1000 Plus well-type ionisation chamber (with Model 70010 source holder), which has been calibrated with a Nucletron microSelectron-v1 classic HDR ^{192}Ir source . These factors are required if the ^{192}Ir source type used in the hospital is different from that used for the calibration of the well chamber at the standards laboratory and accounts for any change in well chamber response due to geometric differences between the sources (as described in the IPEM UK Code of Practice for HDR ^{192}Ir dosimetry). Source geometry factors are now being disseminated in the calibration certificates for SI 1000 Plus well chamber calibrations carried out at NPL.

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

4 Air Kerma Standards

4.1 50 kV and 300 kV Free Air Chambers

The low and medium energy free air chamber primary standards have been compared at the low/medium crossover radiation quality for the therapy and protection level series, with agreement at the 0.2% level.

4.2 Primary Standard Cavity Chambers

The new 5 cc cavity standards #1 and #2 were used in the therapy level Co-60 facility. Various in-beam measurements were performed enabling recombination, polarity and stem scatter correction factors to be calculated. Monte Carlo models of the 5 cc chambers using measured and certified internal radii have been set up and various corrections have been calculated from the models. Preliminary results indicate that agreement between old and new cavity chambers is better than 0.3% in Co-60.

A 100 cc cavity standard (intended for HDR brachytherapy) has been characterised metrologically in preparation for final assembly and commissioning.

5 Absorbed Dose Standards

5.1 Graphite Calorimetry

Electron / Photon calorimeter

Commissioning of the new graphite calorimeter as the primary standard of absorbed dose is still in progress, initially in flattened photon beams and at measurement depths scaled from the depths in water of 5 $g.cm^{-2}$ (4MV to 10 MV) and 7 $g.cm^{-2}$ (15 MV to 25 MV), as specified in the Code of Practice currently recommended for use in the UK by IPEM. The commissioning will be extended, as time permits, to include a selection of unflattened beams and a measurement depth scaled from 10 $g.cm^{-2}$ in water (at all energies from 4MV to 25 MV), in anticipation of a possible future extension to the UK CoP. Nine electron beam qualities ranging over energy from approximately 4 MeV to 22 MeV, as recommended in the IPEM's electron dosimetry CoP, will also be commissioned.

Measurements made in isothermal mode using the new calorimeter, have a standard deviation of 0.2% or better. The calorimeter can also be used for the measurement of a temperature rise in quasi-adiabatic modes, but operation in isothermal mode offers significant advantages in both measurement procedures and in the analysis: In quasi-adiabatic measurements, about twelve to fifteen short-duration (<20 s) irradiations per hour may be taken whereas in isothermal mode it is possible to take as many as thirty (with a square-wave, one-minute-on, one-minute-off cycle). Perturbations and correction factors for use in most of the beam qualities are being finalised, together with the appropriate uncertainty budgets.

HDR brachytherapy calorimeter

A novel graphite calorimeter for absorbed dose rate measurements close to high dose rate (HDR) ^{192}Ir brachytherapy sources has been designed, built and tested at NPL. The graphite calorimeter allows a more direct calibration of HDR ^{192}Ir sources in terms of absorbed dose rate to water at a distance of 1 cm, $\dot{D}_{\mathrm{w,1cm}}$, compared to the current air kerma-based calibration method, where $\dot{D}_{\mathrm{w,1cm}}$ is determined as the product of the measured reference air kerma rate (RAKR) and the dose rate constant, Λ, resulting in overall standard uncertainties of up to 5%.

The calorimeter measures the absorbed dose rate to graphite in a ring-shaped core at a distance of 2.5 cm from the source. This quantity is then converted to the quantity of interest by applying Monte Carlo calculated perturbation correction factors and a graphite-to-water conversion factor.

The new absorbed dose standard was operated in two different operating modes, quasi-isothermal or quasi-adiabatic, and $\dot{D}_{\mathrm{w,1cm}}$ was measured directly with relative standard uncertainties of 0.7% and 1.0%, respectively (Sander *et al.*, 2012). Two Nucletron microSelectron-v1 classic HDR ^{192}Ir brachytherapy source were calibrated with the calorimeter in terms of $\dot{D}_{\mathrm{w,1cm}}$. The RAKR of both sources was also measured with NPL's HDR ^{192}Ir air kerma primary standard. Combining the measured $\dot{D}_{\mathrm{w,1cm}}$ and RAKR resulted in an experimentally determined dose rate constant for the Nucletron microSelectron-v1 classic HDR ^{192}Ir source, which compared well with published dose rate constants within stated uncertainties (Selbach *et al.*, 2012). By using the new calorimeter, the relative standard uncertainty of the dose rate constant could be reduced to around 1%, compared to 5% when using experimental methods based on TLD measurements.

5.2 Absorbed dose to water

The UK reference standard of absorbed dose to water for high-energy photon beams remains a set of three type 2611 ionisation chambers, whose calibration in terms of absorbed dose to graphite has been converted to one in terms of absorbed dose to water. Similarly, for electron beams, the reference standard is a set of Scanditronix NACP-02 and PTW Roos parallel-plate ionisations chambers, with a similar conversion to dose to water.

The same chambers will be used with both old and new primary standard calorimeters to support the changeover. In particular, these chambers will be used during the accelerator dosimetry key comparison measurements scheduled to be made at NPL in Autumn 2013.

An IPEM Working Party, with representation from NPL, is preparing an addendum to the existing high-energy photon beam CoP to support reference dosimetry in TomoTherapy beams.

5.3 Proton Dosimetry

The construction of a dedicated primary standard graphite calorimeter for dosimetry in therapeutic proton and ion beams has been finalised. 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 first tests of the new calorimeter were performed in-house in photon beams and off-site in a flattening-filter-free photon beam. The calorimeter was then used extensively in the low-energy clinical proton beam of the Clatterbridge Cancer Centre to confirm measurements performed with an earlier prototype as well as in a carbon ion beam at the Southern National Laboratories (LNS) of the Italian National Institute of Nuclear Physics (INFN) in Catania, Sicily.

The conversion between absorbed dose to graphite and absorbed dose to water has been further investigated for both low-energy clinical proton beams and carbon ion beams, since this is an essential step in applying a graphite calorimeter as a primary standard for absorbed dose to water. For protons, 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%. Similar work for protons was performed for different types of water-equivalent plastics (Al-Sulaiti *et al.*, 2012). An experiment was performed for a low-energy carbon ion beam, resulting in fluence corrections less than 0.5%, consistent with an earlier performed Monte Carlo study (Lühr *et al.* 2011).

Alanine has continued to be used to measure dose in a neutron field at a reactor for BNCT of liver (Schmitz *et al.*, 2011). Also, an alanine based dosimetry audit for scanned proton and carbon ion beams has been designed and tested in collaboration with a number of European partners. A paper on the audit method has been submitted for publication. NPL has contributed to the use of radiochromic film for the spectral characterisation of laser induced proton beams (Kirby *et al.*, 2011).

A number of prototype micro-calorimeters based on the Inductive Superconductive Transition Edge Detector technology have been produced with graphite absorbers diameters between 5 and 25 µm. An experimental setup was created to connect the cryostat of the calorimeter to the microbeam line at the Surrey Ion Beam Centre, where irradiations with MeV protons were performed. In these experiments no degradation of the I-V characteristics was observed, which demonstrates the radiation hardness of the devices.

5.4 Small and composite field dosimetry

Since the publication of IPEM Report 103 “Small Field MV Photon Dosimetry” (Aspradakis *et al.*, 2010) NPL has supported knowledge transfer in this rapidly developing area in three ways. A one day meeting on small field dosimetry was held at NPL in May 2012. Most of the authors of Report 103 contributed invited talks to the meeting and a few stayed on for a second day to deliver hands-on practical training in small field dosimetry for a strictly limited number of participants. A series of invited talks were given at a summer school on *Stereotactic Radiotherapy with Emphasis on Dosimetry*, organised by the Australian College of Physical Scientists and Engineers in Medicine. Finally, the small field dosimetry has been introduced as a new element of the Practical Course on Reference Dosimetry held annually at NPL.

A graphite absorbed-dose calorimeter for IMRT applications has been built at NPL and tested in these small fields. The calorimeter comprises a small (5 mm diameter) spherical core inside a 1 mm thick spherical graphite jacket, with 1 mm thick vacuum gaps, enclosed inside a small PMMA vacuum assembly. Modelling of this calorimeter using the EGSnrc electron and photon Monte Carlo transport code and then extending the modelling to other geometries, has led to a design for a second calorimeter with a slightly larger cylindrical core which is expected to give better results in the types of geometry in which these beams will be used, and which will be built during 2013. A third calorimeter, aimed at being used in the measurement of Dose-Area Product, is being designed. Dose-Area Product is potentially a more appropriate quantity for use in small fields as it removes some of the issues, such as high dose gradients and the absence of charged-particle equilibrium, which are otherwise associated with the use of small fields.

Two studies on the measurement of ion chamber correction factor in composite fields using alanine dosimetry have been published (Gago-Arias *et al.* 2012, 2013)

A method to infer the beam quality index from a measurement in non-reference conditions was improved (Palmans 2012) and a paper was published that addresses a wide-spread misconception concerning the dosimetry of such composite fields; it reveals in an intuitive as well as formal way that in spite of the dose distribution delivered by a composite reference field being uniform, that the charged particle distribution throughout the irradiated volume is not constant (Bouchard *et al.* 2012).

5.5 Alanine Dosimetry

Based on an accumulation of results showing systematic differences between alanine dosimetry and machine parameters, NPL now recommends that alanine dosimeters irradiated in high dose industrial electron beams are corrected to the maximum temperature achieved during irradiation, not the mean temperature, as recommended previously. This was also confirmed by measurements made using an adiabatic high dose calorimeter with an ABS absorber. The effect of this change increases with dose and can reach 5% at doses of 70 kGy.

A detailed study has been carried out of the irradiation temperature coefficient of alanine dosimeters at radiotherapy dose levels. The temperature coefficient for irradiation between 15 ºC and 30 ºC was found to be +0.23% per ºC for doses up to 100 Gy. The irradiation temperature coefficient appears to be dependent on the EPR measurement parameters and, at higher doses, on the dose.

6 Comparisons

The report for comparison of the NPL standard as part of the BIPM.RI(I)-K4 key comparison was published in 2012 (Kessler *et al.*, 2012).

A comparison of the LNHB, NPL and PTB alanine dosimetry systems for absorbed dose to water measurements in gamma-and x-radiation at radiotherapy levels was carried out as part of the EMRP External Beam Cancer Therapy project (Garcia *et al.*, 2012).

A pilot of a comparison of absorbed dose to water standards for mega-voltage therapy electron beams is currently underway involving METAS, NPL and NRCC. The comparison involves shipment of a solid water phantom and NPL alanine dosimeters to each participant. The phantom has cut-outs for a number of different types of ionization chamber and alanine dosimeter pellets.

The pilot will be used as the basis for a formal EURAMET comparison open to all NMIs for electron beam standards.

7 Audits

NPL has been involved with the National Rotational Radiotherapy audit (NRRA) which ran a pilot of 10 centres from June – Aug 2011 and then opened as a national audit to all centres who were treating clinically with Volumetric Modulated Arc Therapy (VMAT) or Tomotherapy from January 2012 to March 2013. This work has been carried out in collaboration with the NCRI Radiotherapy Trials Quality Assurance team (RTTQA), the Royal Surrey County Hospital and the Institute of Physicists and Engineers in Medicine (IPEM). 38 centres have taken part and 45 different systems. This work was submitted to the European Society of Therapeutic Oncology (ESTRO) conference and was given the highest mark of all physics abstracts.

NPL has also worked with the SABR (stereotactic ablative body radiotherapy) consortium QA group to develop an audit for lung SABR techniques in an anthropomorphic phantom using alanine pellets. This work is currently in pilot stage, but will be extended through 2013 to a further 20 centres. This will also form the basis of a collaboration with VSL through the EMRP funding programme.

8 External Reports and Publications (May 2011 – February 2013)

L. Al-Sulaiti, D. Shipley, R. Thomas, P. Owen, A. Kacperek, P. H. Regan and H. Palmans, “Water equivalence of some plastic-water phantom materials for clinical proton beam dosimetry,” Appl. Radiat. Isotop. 70 1052-1057, 2012

H. Bouchard, J. Seuntjens and H. Palmans, “On charged particle equilibrium violation in external photon fields,” Med. Phys. 39(3) 1473-1480, 2012

G. Budgell, J. Berresford, M. Trainer, E. Bradshaw, P. Sharpe and P. Williams “A national dosimetric audit of IMRT” Radiotherapy and Oncology **99** (2011) 246–252

D T Burns, P J Allisy-Roberts, M F Desrosiers, P H G Sharpe, M Pimpinella, V Lourenço, Y L Zhang, A Miller, V Generalova and V Sochor “Supplementary comparison CCRI(I)-S2 of standards for absorbed dose to water in ^{60}Co gamma radiation at radiation processing dose levels”, Metrologia **48** (2011) Tech. Suppl. 06009

S. Duane, M. Aldehaybes, M. Bailey, N. D. Lee, C. G. Thomas and H. Palmans, “An absorbed dose calorimeter for IMRT dosimetry,” Metrologia 49(5) S168-S173, 2012

A. Gago-Arias, J. Pardo-Montero, R. Rodríguez-Romero, P. Sánchez-Rubio, D. M. Gonzalez-Castaño, L. Nuñez, H. Palmans, P. Sharpe, F. Gómez, “Correction factors for A1SL ionization chamber dosimetry in TomoTherapy: machine-specific, plan-class and clinical fields,” Med. Phys. 39(4) 1964-1970, 2012

A. Gago-Arias, E. Antolín, F. Fayos-Ferrer, R. Simón, D. M. González-Castaño, H. Palmans, P. Sharpe, F. Gómez and J. Pardo-Montero, “Correction factors for ionization chamber dosimetry in CyberKnife: machine-specific, plan-class and clinical fields,” Med. Phys. 40(1) 011721 (10pp), 2013

T. Garcia, M. Anton and P. Sharpe “EURAMET.RI(I)-S7 comparison of alanine dosimetry systems for absorbed dose to water measurements in gamma- and x-radiation at radiotherapy levels”, Metrologia (2012) **49** Tech. Suppl. 06004

C. Kessler, P.J. Allisy, D.T. Burns, S. Duane, J. Manning "Comparison of the standards for absorbed dose to water of the NPL, United Kingdom and the BIPM for ^{60}Co γ rays", Metrologia, 2012, 49, Tech. Suppl., 06008

D. Kirby, S. Green, F. Fiorini, D. Parker, L. Romagnani, D. Doria, S. Kar, C. Lewis, M. Borghesi and H. Palmans, “Radiochromic film spectroscopy of laser-accelerated proton beams using the FLUKA code and dosimetry traceable to primary standards,” Laser Part. Beams 29(2) 231-239, 2011

A. Lühr, D. C. Hansen, N. Sobolevsky, H. Palmans, S. Rossomme and N. Bassler, “Fluence correction factors and stopping power ratios for clinical ion beams” Acta Oncol. 50(6) 797-805, 2011

H. Palmans, “Dosimetry,” In: Proton Therapy Physics, Ed. H. Paganetti (London: Taylor & Francis), 2011, pp. 191-219

H. Palmans, L. Al-Sulaiti, P. Andreo, R. A. S. Thomas, D. R. Shipley, J. Martinkovič and A. Kacperek, “Conversion of dose-to-graphite to dose-to-water in clinical proton beams,” In: “Standards, Applications and Quality Assurance in Medical Radiation Dosimetry – Proceedings of an International Symposium, Vienna 9-12 November 2010 – Vol. 1” (Vienna, Austria: IAEA), 2011, pp.343-355

H. Palmans, “Secondary electron perturbations in Farmer type ion chambers for clinical proton beams,” In: “Standards, Applications and Quality Assurance in Medical Radiation Dosimetry – Proceedings of an International Symposium, Vienna 9-12 November 2010 – Vol. 1” (Vienna, Austria: IAEA), 2011, pp.309-317

H. Palmans, “Small and composite field dosimetry: the problems and recent progress,” In: “Standards, Applications and Quality Assurance in Medical Radiation Dosimetry – Proceedings of an International Symposium, Vienna 9-12 November 2010 – Vol. 1” (Vienna, Austria: IAEA), 2011, pp.161-180

H. Palmans, “Determination of the beam quality index of high-energy photon beams under nonstandard reference conditions” Med. Phys. 39(9) 5513-5519, 2012

H. Palmans, “Comments on ‘The effective depth of cylindrical ionization chambers in water for clinical proton beams’” Phys. Med. Biol. 57(21) 7219-7224, 2012

J.A.D. Pearce, D. R. Shipley and Duane S. "Transfer of the UK absorbed dose primary standard for photon beams from the research linac to the clinical linac at NPL" Metrologia, 2011, **48**(5), 365-374

T. Sander, P. Owen, M. Bailey, S. Duane, H. Palmans, “Design and principles of a graphite calorimeter for brachytherapy,” In: “Standards, Applications and Quality Assurance in Medical Radiation Dosimetry – Proceedings of an International Symposium, Vienna 9-12 November 2010 – Vol. 1” (Vienna, Austria: IAEA), 2011, pp.75-85

T. Sander, S. Duane, N. D. Lee, C. G. Thomas, P. J. Owen, M. Bailey and H. Palmans, “NPL’s new absorbed dose standard for the calibration of HDR 192Ir brachytherapy sources,” Metrologia 49(5) S184-S188, 2012

T. Schmitz, M. Blaickner, M. Ziegner, N. Bassler, C. Grunewald, J. V. Kratz, C. Schütz, P. Langguth, P. Sharpe, H. Palmans, M.H. Holzscheiter, G. Otto and G. Hampel, “Dose determination using alanine detectors in a mixed neutron and gamma field for boron neutron capture therapy of liver malignancies,” Acta Oncol. 50(6) 817-822, 2011

H.-J. Selbach, M. Bambynek, I. Aubineau-Lanièce, F. Gabris, A. S. Guerra, M. P. Toni, J. de Pooter, T. Sander and T. Schneider "Experimental determination of the dose rate constant for selected ^{125}I- and ^{192}Ir-brachytherapy sources", Metrologia **49** S219-S222, 2012

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	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	^{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	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 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
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	absorbed dose to water