# Progress Report Department 'Dosimetry for Radiation Therapy'

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## 1 PTB electron accelerator facility for radiotherapy dosimetry

Construction of the PTB electron accelerator facility for radiotherapy dosimetry is proceeding. The topping-out ceremony of the building, now structurally complete, was celebrated on February 15th, 2007. Meanwhile, the building´s infrastructure is being installed. The new building will carry the name Glocker Bau honouring Richard Glocker (1890 -1978), student of C. W. Röntgen and an outstanding pioneer in the application of high energy X-rays for therapy.

The building will house two ELEKTA-Precise linacs covering the energy range between 4 MeV and 25 MeV and providing 6 photon beam qualities and 10 electron beam qualities. One of the clinical linacs will be used for primarily for the realization of the unit of absorbed dose to water by water calorimetry. The other one, equipped with a multileaf collimator, IMRT-facilities and portal imaging, is primarily dedicated to dosimetry under non-reference conditions.

Beyond that, a two-stage linear accelerator designed by ACCEL Instruments will be installed for basic metrological research. Its electron beam energy can be varied continuously from 0,5 MeV to 50 MeV. The system includes beam current transformers allowing to measure the charge imparted to the experiments with a relative uncertainty of less than 0,1 % (k=1) and electron spectrometers with energy resolution of less than 10 keV.

Installation of the three accelerators is planned to begin in September 2007. The clinical accelerators are expected to become operational still in 2007, whereas commissioning of the research accelerator will take until spring 2008.

## 2 Absorbed Dose Standards

### *2.1 Primary standard water calorimeter*

At PTB, a primary standard water calorimeter is available that realizes the unit of absorbed dose to water in $^{60}$Co radiation under reference conditions with a relative measurement uncertainty of 0.2 %. Calibration factors for ionization chambers determined by use of the new primary standard deviate by about 0.2 % from the calibration factors deduced with the previous Fricke-based standard. The corresponding key comparison for $D_W$ has been performed at BIPM in autumn 2005. The water calorimeter is routinely operated at least every few month for the quality assurance of the new primary standard.

### *2.2 PTB's $^{60}$Co reference field*

The spectral properties of the “new” $^{60}$Co beam were determined by means of Monte-Carlo calculations which were benchmarked by comparing calculated and measured depth-dose curves. The results support another project aiming at the development of a beam quality parameter for $^{60}$Co beams (co-operation with Univ. of Oldenburg, preliminary results published in Phys. Med. Biol. 52 (2007), N137-N147).

### *2.3 Calorimetric determination of $k_Q$ factors for NE 2561 and NE 2571 ionization chambers in 5 cm × 5 cm and 10 cm × 10 cm radiotherapy beams of 8 MV and 16 MV photons.*

The determination of calibration factors $N_{D,w,Co}$ of ionization chambers in $^{60}$Co radiation are based on the primary standard water calorimeter at PTB. A further calorimeter – the so-called “transportable” water calorimeter – could now be used at PTB’s linear accelerator to determine the calibration factors $N_{D,w,Q}$ of NE 2561 and NE 2571 ionization chambers at 8 MV and 16 MV photon radiation. For both beam qualities $Q$, the energy dependent correction factors $k_Q = N_{D,w,Q}/N_{D,w,Co}$ were determined for these chambers in a 10 cm × 10 cm radiation field. The experimentally determined $k_Q$ factors of a single ionization chamber yields a standard measurement uncertainty of less than 0.3 %. To investigate if the $k_Q$ factors are dependent on the beam size, additional calorimetric measurements and chamber calibrations were also performed in a 5 cm × 5 cm radiation field.

### *2.4 Application of water calorimetry in different radiotherapy beams*

At PTB, efforts are being made to extend the application possibilities of water calorimetry for radiotherapy dosimetry in various irradiation conditions and in various radiotherapy beams. In a first step, the different water calorimeters available at PTB were successfully operated in 70 kV, 100 kV and 150 kV medium energy x-rays, in a scanned 280 MeV carbon ion beam and in close proximity to a 350 GBq $^{192}$Ir-brachytherapy source. The calorimetric experiments were performed for each of these applications. The study of the wide range of heat transport phenomena occurring in the calorimeters during and after the irradiations for the various irradiation conditions is under way.

## 3 Comparisons

### *3.1 BIPM key Comparison*

The key comparison between BIPM and PTB for absorbed dose to water (BIPM.RI(I)-K4) has been finished and the results were published (Metrologia 43 06005). The degree of equivalence is $D_{\mathrm{PTB}} = -0.0039$ with an equivalence uncertainty of $U_{\mathrm{PTB}} = 0.0074$. The entry in the CMC-database was updated accordingly. PTB performs now calibrations of ionization chambers in terms of absorbed dose to water with a relative expanded uncertainty of 0.5% ($k = 2$).

### 3.2 EUROMET Comparisons

For the EUROMET project 605 “Beam Quality Specification of High-Energy Photon Beams” the beam quality parameters TPR(20,10) and %*dd*(10)$_X$ were measured (according to their definition) for all of our linac-photon-beams and beam quality correction factors $k_Q$ were determined for 4 ionization chambers. The project is finished and the results are available.

For the EUROMET project 813 “Comparison of air kerma and absorbed dose to water measurements of $^{60}$Co radiation in radiotherapy” 4 ionization chambers were calibrated in terms of absorbed dose to water (and air kerma). The project is not yet finished.

## 4 Clinical Dosimetry for External Radiation Therapy

The $p_{Co}$-perturbation factors for 6 types of parallel-plate chambers (PTW Roos, PTW Markus, PTW Advanced Markus, Scdx-Wellhöfer NACP, Scdx-Wellhöfer PPC05, Scdx-Wellhöfer PPC15) were determined experimentally in cooperation with the German Cancer Research Center and the universities of Tübingen and Freiburg using a large number of chambers of each type. These investigations show that type-specific values for $p_{Co}$ can be given for modern types of parallel-plate chambers. The results were presented at the QANTRM-conference organized by the IAEA in autumn 2006.

## 5 RBE of High-Energy Photon Radiation

For the project “Determination of the RBE for quasi-monoenergetic photon radiation and neutron radiation with high energy” the absorbed dose to water in a quasi-mono-energetic 6-7 MeV photon beam (with very low dose rate) was determined. For this purpose a special plane parallel ionization chamber wit a volume of 3 cm$^3$ was constructed and the necessary correction factors determined experimentally and by Monte-Carlo calculations. Samples of human blood were irradiated with absorbed doses up to 1 Gy; the relative expanded uncertainty ($k = 2$) of the absorbed dose to water is 4.7%. The results (RBE of high energy photon radiation) are not yet available.

## 6 Brachytherapy

### 6.1 Intravascular brachytherapy

The primary standard for the calibration of $^{90}$Sr/$^{90}$Y sources and source trains - a multi-electrode-extrapolation chamber (MEK) has been completed last year. An intercomparison with NIST by means of a $^{90}$Sr/$^{90}$Y-line source, calibrated with the MEK, was performed during 2006. The agreement between NIST and PTB is better than 7%. The source was then send to the NMi, Delft, Netherlands for an further intercomparison. The evaluation of this intercomparison will be completed in the near future.

### *6.2 Conventional brachytherapy*

For $^{192}$Ir- and $^{60}$Co- brachytherapy sources a new calibration facility has been put into operation in 2006. The new system is based on a collimated beam geometry which reduces both, the uncertainties due to scatter in air and radiation protection problems. The source which is to be calibrated is place at the centre of a lead box by means of an afterloading system. With a commercial industrial robot the measuring system is positioned with an uncertainty of less than 0,1 mm on the central axis of the radiation field defined by a diaphragm.

### *6.3 Primary standard for low energy - low dose rate brachytherapy sources*

The new primary standard for the calibration of $^{125}$I- and $^{103}$Pd-prostate seeds, developed at PTB, has been put into operation last year. The standard consists of a large volume extrapolation chamber (GROVEX), suitable to measure the ionisation current produced by low dose rate low-energy photon radiation. Intercomparisons with PTB's primary standard for air kerma as well as an informal intercomparison with NIST calibrated $^{125}$I seeds show an agreement within 1%.

### *6.4 Primary standard for absorbed dose to water for X-radiation below 50 ke**V***

A graphite extrapolation chamber is used as a primary standard for the absorbed dose to water for energies below 50 keV. The underlying idea is to apply a conversion factor, obtained by Monte-Carlo calculations, to the measured ionization current within the chamber to convert the charge collected in the measuring volume for a certain plate separation to the collision kerma at zero plate separation. First estimates indicate that the uncertainty is of the order of 1% ($k$=1).

## 7 Alanine Dosimetry

### *7.1 Uncertainty budget*

In order to determine the repeatability in the dose range down to 2 Gy, comprehensive series of measurements were carried out. The hope was that by adapting the amplitude of the reference substance to the range of doses below 10 Gy and by a modification of the holder for the reference substance it would be possible to reduce the measurement uncertainty. Unfortunately it turned out that without an increase in the measurement time, the uncertainty could not be reduced any further. The development of *the measurement- and analysis method* for *alanine* was therefore regarded as being completed. A graphical user interface for the analysis software was built. The uncertainty budget was subjected to a revision and the result published (Phys. Med. Biol. 51 (2006) pp 5419-5440).

The uncertainty is estimated in two steps. In the first step, the uncertainty of the so-called dose-normalised amplitude $A_D$ is determined. The latter is the result of an analysis method which was developed at the PTB on the basis of a method invented by the NPL. By means of an appropriate normalisation, $A_D$ obtains the unit Gy. The repeatability of $A_D$ turned out to have a constant value of 20 mGy over the range from 2 Gy to 25 Gy, which corresponds to a relative standard uncertainty of 1% at 2 Gy and 0.1% at 20 Gy, respectively. Further contributions to the uncertainty budget are due to the uncertainties of the mass of the probes, the irradiation temperature, the repeatability of the irradiations and the uncertainty of the primary standard. In a second step, the uncertainties of the calibration parameters are determined. Both (uncertainty of $A_D$ and uncertainties of the calibration parameters) are required to estimate the uncertainty of the determined dose.

### *7.2 Other developments in ESR-Dosimetry*

In addition, investigations of the response of the alanine dosimeter with respect to high-energy photons and electrons and of the possible influence of different materials surrounding the alanine probe during irradiation were carried out. Also, home-made alanine probes were used with success as well. Further more, possible alternatives to alanine as a detector material were investigated. An enhanced sensitivity, and thus a reduction of the uncertainty for low doses, will probably be obtained by using lithium formate monohydrate instead of alanine. The measurement- and analysis procedures would have to be adapted only slightly for this purpose.

## 8 Publications:

Anton, Mathias: Development of a secondary standard for the absorbed dose to water based on the alanine EPR dosimetry system. In: Applied Radiation and Isotopes 62 (2005), Nr. 5, p. 779 - 795

Anton, Mathias: Uncertainties in alanine/ESR dosimetry at the Physikalisch-Technische Bundesanstalt. In: Physics in Medicine and Biology 51 (2006), Nr. 21, p. 5419 - 5440
URL: dx.doi.org/10.1088/0031-9155/51/21/003

Anton, Mathias: A correction for temporal evolution effects in alanine dosimetry. In: Anton, Mathias (Hrsg.): Alanine dosimetry for clinical applications : proceedings of the 216th PTB-Seminar. Bremerhaven : Wirtschaftsverl. NW, 2006 (PTB-Bericht PTB-Dos-51), p. 35 - 40. - ISBN 3-86509-526-7 ; ISSN 0172-7095

Anton, Mathias ; Selbach, Hans-Joachim: Measurement of dose distributions in alanine using EPR imaging. In: Bruker Spin Report 157/158 (2006), p. 48 - 51

Burns, D. T. ; Allisy-Roberts, P. J. ; Desrosiers, M. F. ; Nagy, V. Yu. ; Sharpe, P. H. G. ; Laitano, R. F. ; Mehta, K. ; Schneider, Manfred K.-H. ; Zhang, Y.: CCRI supplementary comparison of standards for absorbed dose to water in Co-60 gamma radiation at radiation processing dose levels. In: Radiation Physics and Chemistry 75 (2006), Nr. 9, p. 1087 - 1092
URL: dx.doi.org/10.1016/j.radphyschem.2006.02.003

Büermann, Ludwig ; Großwendt, Bernd ; Kramer, Hans-Michael ; Selbach, Hans-Joachim ; Gerlach, Martin ; Hoffmann, Michael ; Krumrey, Michael: Measurement of the x-ray mass energy-absorption coefficient of air using 3 keV to 10 keV synchrotron radiation. In: Physics in Medicine and Biology 51 (2006), Nr. 20, p. 5125 – 5150
URL: stacks.iop.org/PMB/51/5125; dx.doi.org/10.1088/0031-9155/51/20/004

Hackel, Thomas: Dosimetrie mit Alanin/Elektronen-Spin-Resonanz : Positionierung von Dosimetersonde und Referenzsubstanz. Bremerhaven : Wirtschaftsverl. NW, 2006 (PTB-Bericht PTB-Dos-52). - ISBN 3-86509-590-9

Kapsch, Ralf-Peter: Dosimetry with ionization chambers. In: Dosimetry for advanced radiotherapy techniques: new and established methods : ESTRO pre-meeting Teaching Course. [s.l.] : ESTRO, 2006, p. 23 - 27

Kramer, Hans-Michael: Wechselwirkung von ionisierender Strahlung mit Materie, Kapitel 7, und . Grundlagen der Dosismessung, Kapitel 8,. In: Angerstein, Wilfried (Hrsg.): Grundlagen der Strahlenphysik und radiologischen Technik in der Medizin. Berlin : Hoffmann, 2005, p. 55 - 90. - ISBN 3-87344-123-3

Kramer, Hans-Michael ; Kapsch, Ralf-Peter: The use of plane-parallel chambers in electron dosimetry without cross calibration. In: International Conference on Quality Assurance and New Techniques in Radiation Medicine: Book of extended abstracts. Vienna : IAEA, 2006 (IAEA-CN-146), p. 486 - 487

Krauss, Achim: The PTB water calorimeter for the absolute determination of absorbed dose to water in $^{60}$Co radiation. In: Metrologia 43 (2006), Nr. 3, p. 259 - 272
URL: dx.doi.org/10.1088/0026-1394/43/3/008; stacks.iop.org/Met/43/259

Krauss, Achim: Heat conduction effects during the calorimetric determination of absorbed dose to water in radiotherapy beams. In: Thermochimica Acta 445 (2006), Nr. 2, p. 126 - 132
URL: dx.doi.org/10.1016/j.tca.2005.08.016

Meghzifene, A. ; Shortt, K. R. ; Czap, L. ; Allisy-Roberts, P. J. ; Kramer, Hans-Michael: Changes to the air-kerma standards of the BIPM and primary standards dosimetry laboratories: implications for IAEA calibrations to SSDL members. In: SSDL Newsletter (2005), Nr. 51, p. 4 - 6
URL: www-pub.iaea.org/MTCD/publications/PDF/Newsletters/SSDL-NL-51.pdf

Nolte, Ralf ; Mühlbradt, Karl-Heinz ; Meulders, J. P. ; Stephan, G. ; Haney, M. ; Schmid, Ernst: RBE of quasi-monoenergetic 60 MeV neutron radiation for induction of dicentric chromosomes in human lymphocytes. In: Radiation and Environmental Biophysics 44 (2005), Nr. 3, p. 201 - 209
URL: dx.doi.org/10.1007/s00411-005-0021-4

Schmid, E. ; Selbach, Hans-Joachim ; Voth, M. ; Pinkert, J. ; Gildehaus, F.J. ; Klett, R. ; Haney, M.: The effect of the β-emitting yttrium-90 citrate on dose–response of dicentric chromosomes in human lymphocytes: a basis for biological dosimetry after radiosynoviorthesis. In: Radiation and Environmental Biophysics 45 (2006), Nr. 2, p. 93 - 98
URL: dx.doi.org/10.1007/s00411-006-0045-4

Schneider, Thorsten ; Kramer, Hans-Michael: A new method for an improved determination of continuous photon fluence spectra for x-ray tube voltages up to 150 kV. In: Radiation Protection Dosimetry 121 (2006), Nr. 4, p. 370 - 375
URL: dx.doi.org/10.1093/rpd/ncl058