Progress in Radiation Dosimetry at PTB

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PTB electron accelerator project

A new electron accelerator facility for radiotherapy dosimetry is under construction. The facility is intended to meet all experimental requirements for photon and electron dosimetry, from basic metrological research to clinical applications. Clinical and basic metrological research section are designed each to serve two independent experimental areas.

The clinical section covers the energy range between 4 MeV and 25 MeV. Two ELEKTA-Precise linacs provide 6 photon beam qualities and at least 9 electron beam qualities. One of the clinical linacs will be used for the realization of the unit of absorbed dose to water by water calorimetry. The other one, fully equipped with multileaf collimator and IMRT, is dedicated to dosimetry under non-reference conditions.

Heart of the basic metrological research section is a two-step linear accelerator system, designed by ACCEL Instruments. The electron beam energy can be varied continuously from 0,5 MeV to 50 MeV. The instrumentation 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.

At present, the construction site preparation is in progress. Construction of the new building starts mid term this year. Facility operation is planned to begin in 2007. The total cost, machines plus new building, is 14 Mio €.

New ^{60}Co irradiation facility

In July 2004 the new irradiation facility for ^{60}Co gamma radiation was put into operation. It was developed and constructed at PTB with special attention to the stability (reproducibility) of the properties of the radiation field. The radiation field has been fully characterized by the beginning of 2005. The new irradiation facility is mainly used for the realization and dissemination of the unit of absorbed dose to water.

Realization of the unit of absorbed dose to water in ^{60}Co fields

The water calorimeter is now in operation as the new PTB primary standard for absorbed dose to water in ^{60}Co-radiation. After the delivery and implementation of the new ^{60}Co-source, caloric measurements have been performed for about 5 months. Several detectors prepared either as the H_2-system or as the N_2-system, both offering a zero heat defect, were used for the measurement. This way, the radiation field of the new ^{60}Co-source was calibrated in terms of absorbed dose to water for reference conditions within a combined standard uncertainty (k=1) of about 0,21 %.

From previous investigations concerning the heat defect of different chemical systems (H_2-, N_2- and H_2/O_2-system) which had been performed at the old ^{60}Co-facility with a much lower dose rate, it was concluded to make no separate allowance for the uncertainty related to the heat defect. The scatter of the experimental results for the H_2-system seemed to be caused exclusively by the statistical uncertainties of the caloric measurements. This is in contrast to new results indicating a standard uncertainty for the assumed zero-heat defect of the H_2- and N_2-system of 0,14 %. One reason behind this conclusion is the fact that the results of one detector, nominally prepared as the H_2-System, offered, for whatever reason, a response constantly about 0.3 % higher than the mean response of other detectors. Measurements with this detector were performed to an accumulated dose of more than 10 kGy. Therefore, it has to be checked for newly prepared detectors if their response relative to the mean response of the previous detectors is within the range of the stated uncertainty. Nevertheless, caloric measurements using the H_2/O_2-system show that the measured ratio of the response of the H_2/O_2-system to the mean value of the H_2- and N_2-system is in good agreement to the value predicted by the model.

Reference fields at the (old) electron accelerator

The provision of reference radiation fields at the electron accelerator of the PTB (Philips SL 75-20) has been completed in 2004. The accelerator was optimized in view of the long term stability of the properties of its radiation fields by stabilizing the temperature of the microwave resonator and the frequency of the magnetron, and by controlling the microwave power dependent on the energy of the beam. The characteristics of 6 electron reference fields with nominal energies between 6 MeV and 20 MeV and 4 photon reference fields with nominal generation potentials between 8 MV and 18 MV have been determined in detail.

A beam monitor system suitable for the application of the water calorimeter in the high-energy photon reference fields available at the linear accelerator has been established and characterized. It is now used for the experimental determination of beam quality correction factors k_Q for several types of ionization chambers, the respective measurements have been started.

A new water calorimeter has been set into operation, which can be used as a transportable instrument for measurements in the high-energy photon and electron radiation fields of a hospital as well as in proton- or heavy-ion beams. The temperature stabilization system of this calorimeter consists of six actively cooled aluminium plates covered in a sandwich structure of polystyrene. The water phantom of the calorimeter is surrounded by this structure from all sides, leaving open only the region of the radiation entrance window. The outer edge length of the almost cubic housing is about 60 cm. Currently, this water calorimeter is used for the determination of k_Q-values of different ionization chambers in the photon fields of the PTB linear accelerator.

Parallel plate chambers

Perturbation factors p_{Co} were experimentally determined for 3 modern types of plane parallel chambers (Roos, Markus, Advanced Markus) in cooperation with the Universities of Freiburg and Tübingen and the German Cancer Research Center (DKFZ) in Heidelberg. The perturbation factors, which are needed for the use of plane parallel chambers in electron dosimetry without any cross-calibration, will enter into the revised version of the German dosimetry protocol (DIN 6800-2).

A data base for the results of the comparison measurements, which german radiotherapy clinics have to pass in regular intervals ("Messtechnische Kontrollen"), has been set up. This data base is now used to get an overview on the quality of dosimetry in radiotherapy departments in Germany, and to identify (and solve) problems related to dosimetric measurements.

Brachytherapy for intravascular applications:

The prototype of a $^{90}Sr/^{90}Y$ secondary standard for intravascular brachytherapy, which was finished about two years ago, has been extended to provide now PTB's $^{90}Sr/^{90}Y$-reference radiation field for area sources. The reference field is characterized by the three-dimensional absorbed dose rate distribution in a volume of about 30 mm in diameter and 10 mm depth in water equivalent material (RW3). The reference field is suited for the calibration of ß-dosemeters for intravascular brachytherapy.

A primary standard for the calibration of $^{90}Sr/^{90}Y$ sources and source trains - a multi-electrode-extrapolation chamber (MEC) - is now in test operation and will be completed this year. A intercomparison with NIST by means of a $^{90}Sr/^{90}Y$-line source, calibrated with the MEC, is in preparation and will be performed until falls 2005.

Conventional brachytherapy

Three-dimensional distributions in terms of absorbed dose rate to water were determined for ^{192}Ir - and ^{60}Co- brachytherapy sources in a water phantom at radial distances between 0,6 cm and 10 cm from the center of the source. Special pinpoint ionization chambers of water equivalent material (RW1 and RW3) were developed at PTB for these measurements.

Primary standard for low energy - low dose rate brachytherapy sources.

A new primary standard for the calibration of ^{125}I- and ^{103}Pd- prostate seeds has been developed at PTB. The standard consists of a large volume extrapolation chamber, suitable to measure the ionisation current produced by low dose rate low energy photon radiation. A preliminary intercomparison with NIST calibrated ^{125}I seeds has been performed last year with an agreement of about 1%.

Primary standard for absorbed dose to water for X-radiation

PTB's graphite extrapolation chamber for the determination of absorbed dose to water for X-radiation has been significantly improved during the last year, resulting in a significant increase of the reproducibility of the extrapolation measurements. An improvement of the the underlying physical model, now including effects of Auger electrons, has lead to a much better agreement with the results of MC simulations.

Alanin dosimetry

A secondary standard for D_w has been established, based on the electron paramagnetic resonance (EPR) of irradiated alanine. Positioning devices as well as measurement and data analysis procedures have been developed which allow to measure D_w with a reproducibility better than 0,5% (k=1) in the dose range between 5 Gy and 50 Gy.

Alanine pellets are measured simultaneously with a reference substance which is provided by Bruker, Germany. The EPR amplitude of alanine is thus measured relative to that of the reference. This allows to effectively compensate for changes of the spectrometer sensitivity, which may be caused by thermal drifts of the measurement electronics or by changes of the humidity or temperature of the ambient air. These influences have been studied in a series of experiments.

The positioning of the alanine probe and the reference sample has an important influence on the achievable reproducibility. Therefore, much effort has been devited to the optimisation of a holder for both pellets and the reference substance. Results of the latest (yet unpublished) development are promising, a reproducibility of better than 0,3% (k=1) is likely to be achievable in the dose range between 5 Gy and 25 Gy.

Alanine probes of different suppliers have been compared. For the time being, best results were obtained using alanine pellets with paraffin as a binder as supplied by Harwell Dosimeters (UK). Other binders induce a stronger damping in the resonator. Therefore, inhomogeneities (varying concentration of the binder) of probes within the same batch have a weaker influence on the spectrometer sensitivity if paraffin is used as a binder. With the present set-up and Harwell probes, the precision is limited for lower doses by unavoidable noise and an individual background of unirradiated probes which induce an uncertainty of 10-20 mGy (k=1).

The results (apart from the last stage of the development of the positioning device) have been published in Applied Radiation and Isotopes (M. Anton, Development of a secondary standard for the absorbed dose to water based on the alanine EPR dosimetry system, Appl. Radiat. Isot. 62, 2005, pp 779-795).

At present, the influence of fading and the possibility of its elimination is under investigation. A further improvement is expected from an optimisation of the amplitude of the reference substance with respect to the dose range.

Air kerma standards

The PTB operates primary standard measuring devices (free-air and cavity ionisation chambers) for the realization of the unit of air kerma for x-rays (10 kV - 400 kV) and γ-rays (^{137}Cs, ^{60}Co). No substantial changes have been made since the last progress report in 2003.

The PTB took part in a multilateral indirect comparison of air kerma standards for medium-energy x-rays with Taiwan (INER) and Australia (ARPANSA) (Lee, J.-H., Kotler, L. H., Büermann, L., Hwang, W.-S., Chiu, J.-H. and Wang, C.-F.: The performance of the INER improved free-air ionization chamber in the comparison of air kerma calibration coefficients for medium-energy X-rays. Radiation Measurements 39 (2005) 1-10). The comparison results showed a satisfactory agreement in the measurements which were within the combined expanded uncertainties (k=2).

A direct comparison was made in 2004 between the air-kerma standards used for the measurement of medium-energy x-rays at the National Physical Laboratory (NPL) and the PTB. The comparison was carried out at the PTB using radiation qualities produced with tube potentials in the range from 40 kV to 300 kV at protection level (ISO 4037 narrow spectrum series), diagnostic entrance level (IEC 61267 RQR series) and diagnostic exit level (IEC 61267 RQA series) and the BIPM reference qualities. The results show the standards to be in excellent agreement to around 0,1% for the diagnostic entrance and BIPM reference qualities. The results at protection and diagnostic exit level are in less good agreement with the worst deviation of 0,55%. Except this value, all other deviations are less than the estimated relative standard uncertainty of the comparison. A report of this comparison is in preparation.

PTB acts as pilot laboratory in the supplementary comparison of NMI air kerma standards for ISO 4037 narrow spectrum series radiation qualities (EUROMET PROJECT 545, MRA-Appendix B Identifier: EUROMET.RI(I)-S3). Seven of the twelve participating countries have finished their measurements. The project is scheduled to be finished by the end of 2005.

Measurement of the mass-energy absorption coefficient of air for 3 kev -10 keV synchrotron radiation

For the first time absolute mass-energy absorption coefficients of photons in air have been measured in the energy range from 3 keV to 10 keV with a relative standard uncertainty below 1%. Monochromatized synchrotron radiation was used to measure both the total radiant energy by means of a cryogenic radiometer and the fraction of radiant energy that is transferred to kinetic energy of electrons by primary photon interactions in air by means of a free air ionization chamber. The values obtained can be used to verify the actual data tables of photon mass-energy absorption coefficients which are exclusively based on calculations and suffer from quite large uncertainties of up to 5%. The publication of this work is in progress.

Radiation Biology and Nanodosimetry

The greater part of the radio-biological effect of ionizing radiation to cells is initiated by the production of single or double strand breaks within the DNA. From the point of view of radiation physics, damages of that kind are due to the spatial distribution of ionization events in biological tissue. In the case of several ionizations within a small segment of the DNA a double strand break may be caused, and a single strand break in the case of one ionization, as shown in figure 1 below.

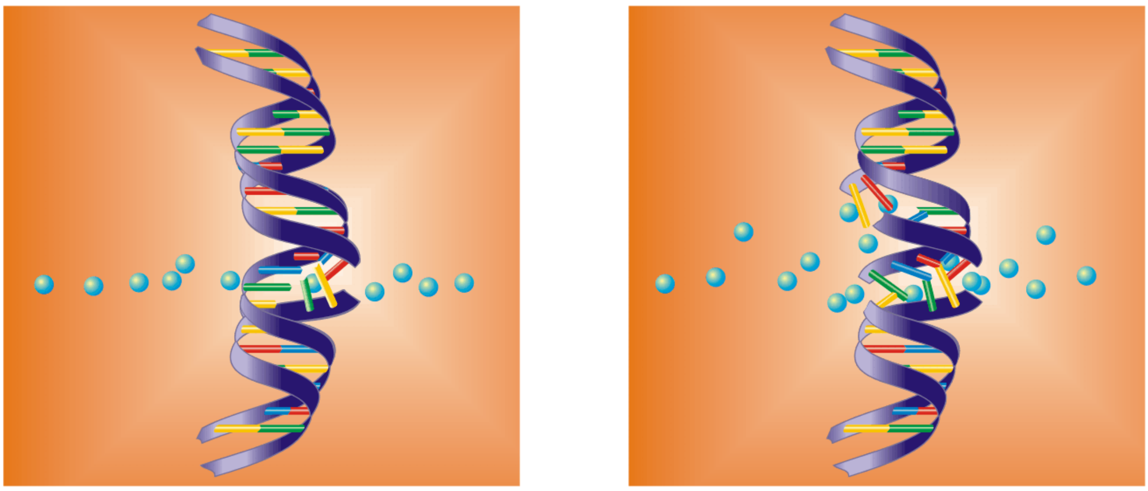

Figure 1: Illustration of a DNA single (left) and double (right) strand break

To prove the correlation between the production of DNA strand breaks and the number of ionization events, the ion production in nanometric cylinders of liquid water by electrons was simulated by using the Monte Carlo method, and compared with the production of single strand breaks within the DNA (see figure 2). It turned out that the ratio of the frequency for producing one single ionization to the energy absorbed within the target cylinder shows an electron-energy dependence which is very similar to that of the yield of single strand breaks within the DNA. In consequence, one is lead to assume that the radiation induced damage of the DNA is strongly correlated to the production of ionization events within nanometric volumes.

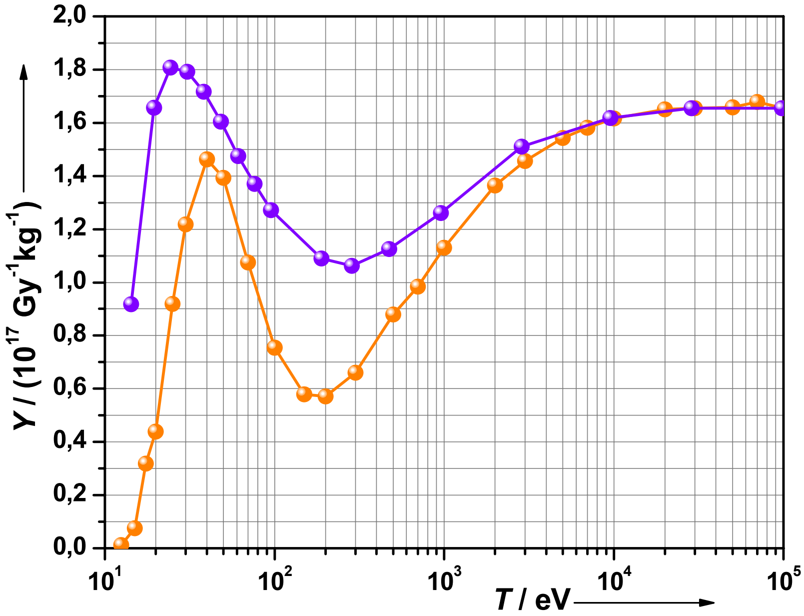

Figure 2: Yield *Y* of single strand breaks in the DNA as a function of electron energy *T*: (●) DNA data of Friedland et al. (1998), (●) ratio of the frequency of a single ionization to the energy absorbed within a nanometric volume of liquid water, normalized to the DNA data

Secondary standard chamber for the personal dose equivalent $H_p(10)$

A secondary standard chamber for photon radiation for measuring an ionisation current, which is directly proportional to the conventionally true value of the personal dose equivalent $H_p(10)$ in a slab phantom, was developed in the PTB, see figure 3. The standard is commercially available from PTW Freiburg since 1999. Up to now 11 chamber were distributed worldwide.

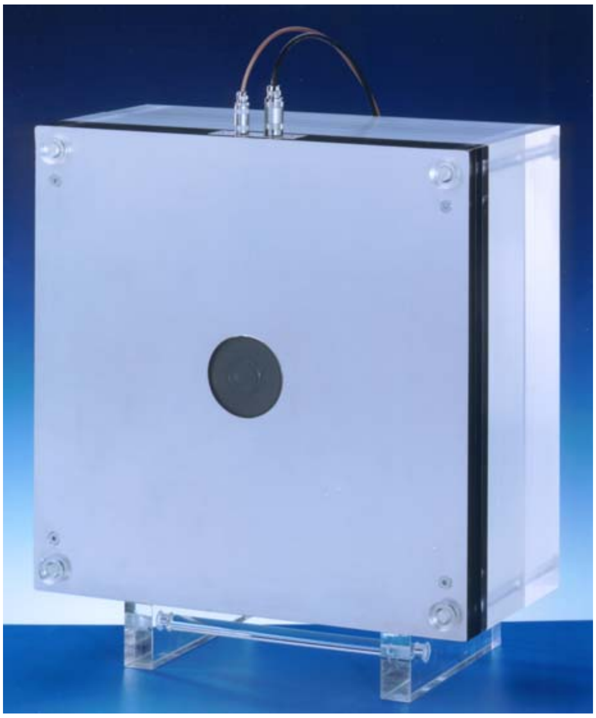

Figure 3: Secondary standard ionisiation chamber for measuring $H_p(10)$ in a slab phantom

The technical data of the $H_\mathrm{p}(10)$ device are the following:

- outside dimensions: 300 mm x 300 mm x 150 mm (same geometry as the ISO water slab phantom)
- made completely of polymethyl metacrylat (PMMA)
- active volume: 10 cm^3
- front surface is covered by an 0,1 mm thick Al plate , with a hole in ist centre in which a PMMA step cylinder (2 mm thick) is fastened.

The chamber was optimized to get a nearly constant response with respect to $H_\mathrm{p}(10)$ for photon energies from 12 keV to 1250 keV and angles of incidence from 0° to 75°. The chamber response for $H_\mathrm{p}(10)$ in the energy range from 13 keV to 250 keV and for angles of incidence between 0° and 75° was within about 15 %, an exception being the lowest photon energy and largest angle where a larger correction was found.

Chamber calibrations can be carried out by the PTB using the radiation qualities according to ISO 4037-1.

Beta Secondary Standard BSS 2 at the PTB

The Beta Secondary Standard BSS 2 was developed at the PTB in co-operation with the companies Elektro-, Sondermaschinen- und Werkzeugbau GmbH (ESW) and AEA Technolgy QSA GmbH & Co (AEAT). It is shown in figure 4. Since 1997 the BSS 2 have been produced and sold by AEAT. Up to now about 20 facilities have been distributed worldwide.

Figure 4: Photography of the BSS 2

The BSS 2 realizes reference fields for beta radiation of the nuclides ^{147}Pm, ^{85}Kr and ^{90}Sr/^{90}Y. In these fields the user can calibrate area and personal dosemeters for measurements of the directional equivalent dose $H'(0{,}07)$ and of the personal dose $H_p(0{,}07)$.

Table: Parameters of the BSS 2 secondary standard

Radio-nuclide	**Average beta energy** keV	**Calibration distance** cm	**Nominal absorbed dose rate in tissue** $\dot{D}_t\ (0{,}07)$ mGy/h
with beam flattening filter			
^{147}Pm	60	20	10
^{85}Kr	240	30	150
$^{90}Sr + {}^{90}Y$	800	30	45
without beam flattening filter			
$^{90}Sr + {}^{90}Y$	800	11	500
		20	160
		30	70

The traceability to a Primary Standard is ensured by the calibration of each set of beta sources for the BSS 2 with the primary standard measuring device of the PTB for the performance and the transfer of the unit for the absorbed dose rate for beta radiation in tissue.

Environmental Dosimetry

To investigate environmental radiation at ground level, the PTB maintains several sites: the Ambient Radiation Dosimetry Site ARADOS, the Cosmic Radiation Dosimetry Site (CORADOS), the ARADOS „Free-Field Facility“ and the deep under-ground laboratory UDO.

ARADOS

At ARADOS several proportional counters and ionisation chambers monitor the ambient dose equivalent rate caused by photons, electrons (positrons) and muons. These kinds of detectors are not able to separate the contributions from terrestrial radiation and secondary cosmic radiation. Additional neutron rem counters of the type NM500 and the modified version NM500(X) monitor neutrons which are also part of the secondary cosmic radiation at ground level. The muon detector MUDOS consists of two multi-wire proportional counters separated by a 25 mm thick lead layer which absorbs low energy particles. The two chambers run in coincidence mode from which the coincidence count rate is directly proportional to the muon fluence. By using the in-flight dosimetry system developed at PTB the measured muon fluence is calibrated in terms of $H^*(10)$. This system allows to measure the ambient dose equivalent rate of the charged component of the secondary cosmic radiation.

CORADOS

The platform CORADOS is installed on a small lake close to PTB. The approximate distance to the shore is 100 m and the water depth underneath the platform varies between 2.5 m and 3.5 m. Therefore, the residual ambient dose equivalent rate is mainly due to secondary cosmic radiation. The platform is made of hollow polyethylene blocks with a total area of $5\ \text{m} \times 5\ \text{m}$. The dosimetry equipment is set up in boxes made of polyethylene which are permanently mounted at the platform. During a measurement at CORADOS the muon detector MUDOS monitors the charged component of the secondary cosmic radiation at ARADOS. The response to secondary cosmic radiation is then directly given by the dose rate measured at CORADOS normalised to the MUDOS value. With the measured response to secondary cosmic radiation one is able to subtract the cosmic component with the help of MUDOS. The resulting ambient dose equivalent rate is then due to terrestrial radiation only.

UDO

Calibrations, linearity measurements and inherent background measurements can be performed in UDO. ^{137}Cs sources of different activities are used to provide ambient dose equivalent rates between 15 $nSvh^{-1}$ and 150 $nSvh^{-1}$, which is the range of the environmental dose rate at ground level. From the linearity measurements the calibration factor and the inherent background can be determined directly. The latter can also be measured in UDO itself, since the residual background radiation is approximately 1 $nSvh^{-1}$.