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Contents

1. Progress Report Department 'Dosimetry for Radiation Therapy and Diagnostic Radiology'

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1.1. Dosimetry for External Radiation Therapy

1.1.1. ^{60}Co irradiation facility for the calibration of dosimeters

1.1.1.1.1 Replacement of ^{60}Co source

At the end of October 2010 the ^{60}Co source in the irradiation facility used for the calibration of dosimeters has been replaced by a source identical in construction, but with higher activity. The new source had an activity of about 300 TBq at the time of installation and produced an absorbed dose rate of about 1.5 Gy/min under reference conditions.

Until the end of the year 2010 the commissioning and justification of the radiation field produced by the new source has been finished. Since beginning of the year 2011 the new source is routinely used for the calibration of dosimeters.

1.1.2. PTB electron accelerator facility for radiotherapy dosimetry

1.1.2.1 New water calorimeter with cylindrical phantom

A new water calorimeter has been designed to be applicable for the direct determination of D_W in various non-standard radiation fields, for example in radiation fields realized by the superposition of IMRT radiation fields from different angles or in tomotherapy radiation fields. The water phantom of the calorimeter has a cylindrical shape with the cylinder axis aligned horizontally. The new water calorimeter will be operated at 4°C; the temperature stabilization system is designed similarly to that of PTB’s so-called transportable water calorimeter. The calorimeter will be assembled and put into operation by the end of the year.

1.1.2.2 Calorimetric determination of D_W in 3 cm x 3 cm photon beams (JRP7-project)

The calorimetric measurements for the determination of D_W and for corresponding k_Q factors for ionization chambers in 6 MV and 10 MV photon radiation fields of 3 cm x 3 cm size were performed at one of PTB’s new Elekta Precise medical accelerators. The measurements were completed in March 2010.

The field size at the 10 cm depth inside the water phantom of the calorimeter was limited to 3 cm × 3 cm using a fixed external collimator made of lead. This collimator was mounted in front of the radiation head of the accelerator. During the experiments, the output of the accelerator was normalized to a transmission monitor chamber which was mounted in front of the water calorimeter’s radiation entrance window. For the calorimetric determination of D_W, the influence of the heat transport occurring during and after the measurements in the 3 cm x 3 cm radiation field is of major concern. To study the effects due to the heat transport experimentally, many sequences of four consecutive irradiations with drift periods of 130 s in between were performed for 60 s and 120 s irradiation times, and several calorimetric detectors with temperature sensors having different lateral positions relative to the central axis of the radiation beam were applied. Corresponding heat transport calculations and the determination of heat conduction correction factors k_C for the different measurement conditions were performed on the basis of the finite-element method using a 3-dimensional geometry model, taking into account the calorimetric detector including the real position of the temperature sensors as well as the measured lateral and depth-dose distributions of the 3 cm x 3 cm radiation fields. The calculated correction factors k_C vary between 0.991 and 0.962. Figure 1 presents a comparison of the uncorrected results of calorimetric measurements and the results of the heat conduction calculations. The data shown are the ratios of the first and the second irradiation as a function of the position relative to the central axis of the field. These ratios are mainly affected by the superposition of the heat conduction effects of the consecutive irradiations. The calculated data are in good agreement with the experimental ones, which proves that the calculated correction factors k_C can be adequately used for the calorimetric determination of absorbed dose to water and, hence, for the determination of the k_Q factors for ionization chambers.

For the determination of the k_Q factors, the NE2561 ionization chamber was mounted inside the water phantom of the calorimeter at the same depth in water as the calorimetric detector was positioned before.

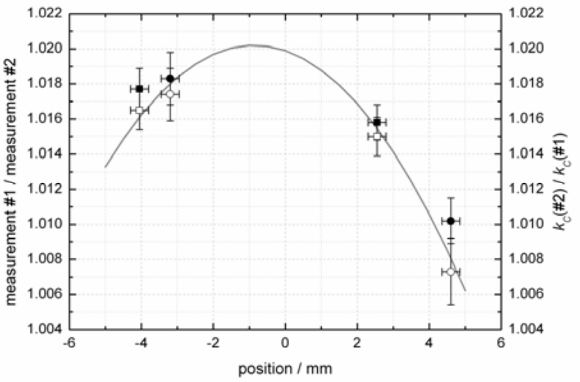


Figure 1: For the case of 10 MV photons and for 120 s irradiation time, the solid line shows the ratio of the calculated correction factors k_C of the second and the first irradiation, $k_C(\#2)/k_C(\#1)$, as a function of the position relative to the central axis of the field. The ratios of the mean values of calorimetric results of the first and the second irradiation obtained from different experiments, together with their standard uncertainties are also shown. The results obtained with different detectors are represented by different symbols.

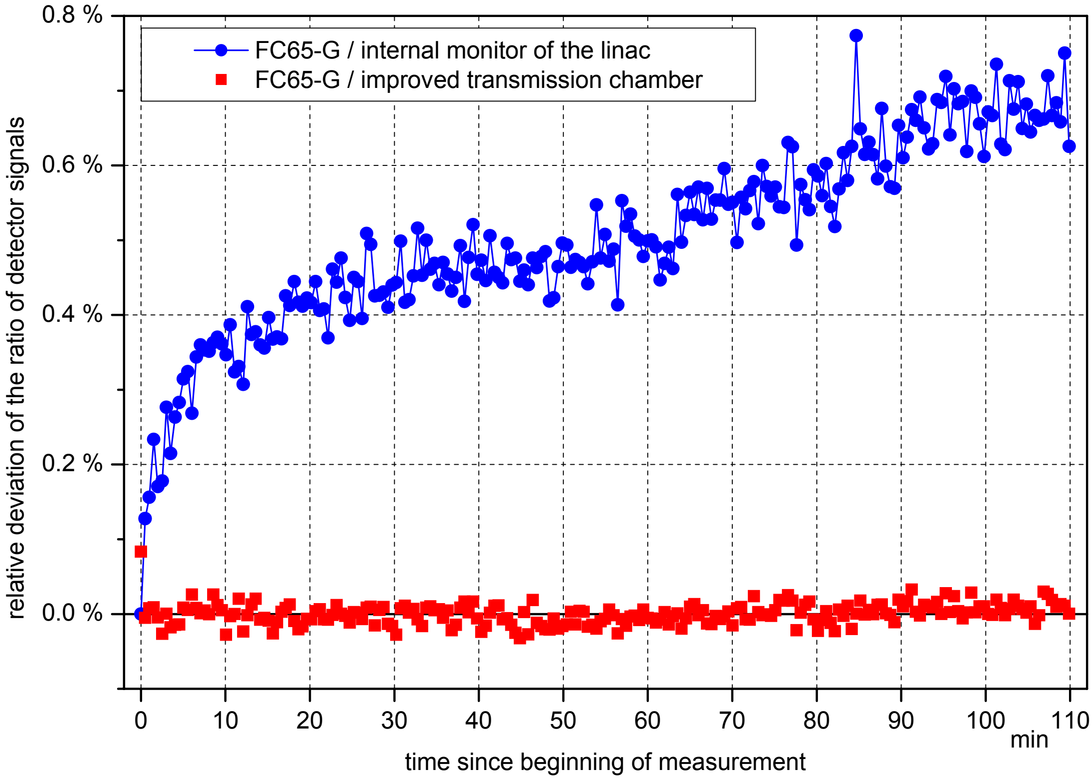
The readings of the chamber were corrected for polarity and recombination effects during the irradiations.

The investigation proved that water calorimetry can be applied to determine k_Q factors of ionization chambers in high-energy photon radiation with beam sizes down to 3 cm x 3 cm. A relative standard uncertainty of less than 0.4% is achievable for k_Q. However, within the standard uncertainties of the experimental method, no dependence of the k_Q factors on the size of the radiation field was observed.

1.1.2.3 Investigation and construction of dose rate monitor

The usability of the internal monitor of the Elekta Precise linear accelerators of PTB for high-precision dosimetric measurements has been investigated. It was found that when comparing the internal monitor signal with primary or reference-class secondary standards, the response of the internal monitor might change by about 1 % over a period of several hours (see the following figure).

An external transmission monitor chamber was constructed whose response is stable well below 0.1 % (see the following figure) and which is now used routinely for high-precision dosimetric measurements which aim at uncertainties in the order of a few tenths of a percent.



The results of this investigation were presented at the "11th International Congress of the IUPESM - Medical Physics and Biomedical Engineering World Congress 2009" in Munich from 8–12 September 2009.

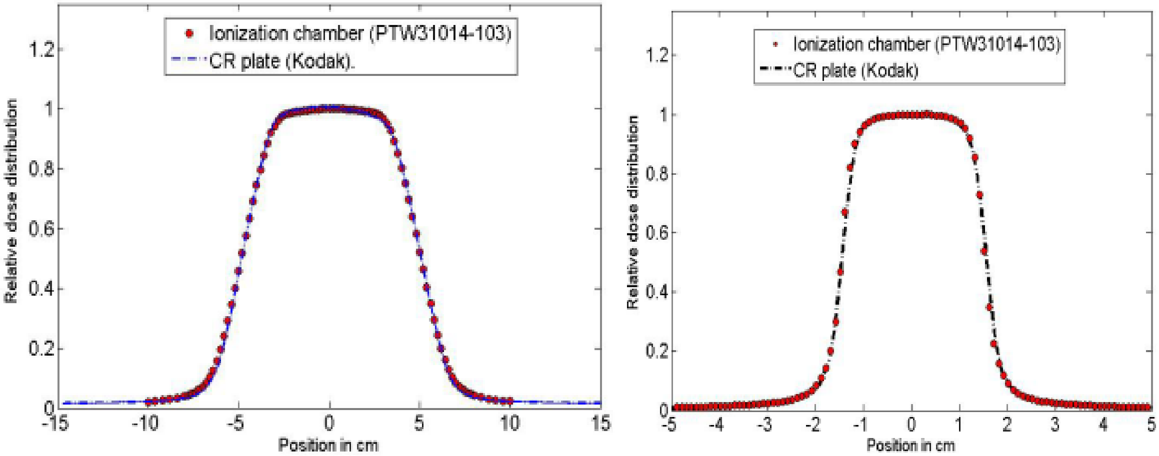
1.1.2.4 Calorimetric determination of k_Q factors for reference conditions

For the investigation of D_W in small radiation fields, k_Q factors for reference conditions have been determined already for 6 MV and 10 MV beams. The water calorimeter is now used to determine k_Q factors for all photon energies available at PTB's medical electron accelerator, ranging from 4 MV up to 25 MV.

1.1.2.5 Investigation of storage foil system (JRP7-project)

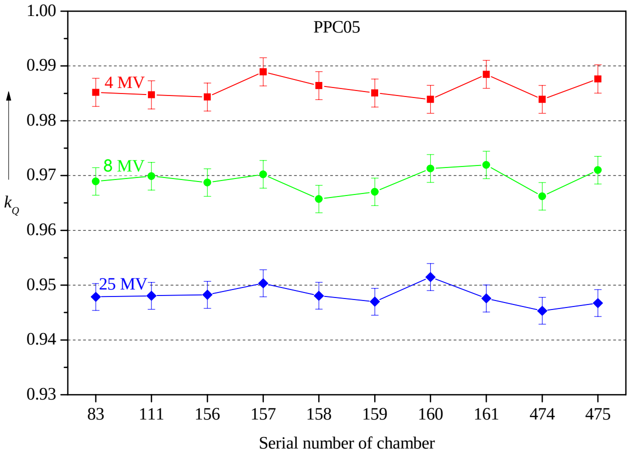
The application of a Computed radiography (CR) system for dose verification in (small and irregularly shaped) photon beams was investigated. The system used was of type KODAK 2000RT. It comprises storage phosphor plates (CR plates) and a laser scanner connected to a PC running acquisition and analysis software.

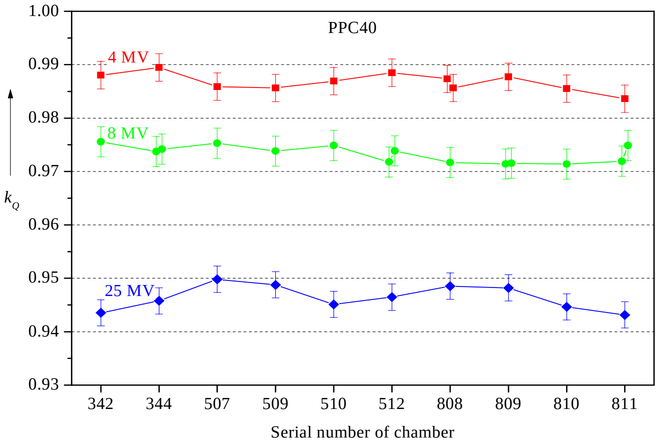
The variation of the response of the CR plates with several influence conditions, among them the time delay between irradiation and read-out (signal decay), the influence of light exposure, the influence of temperature, and the influence of the spectral properties of the photon radiation have been investigated in detail. Finally an analysis procedure has been developed which allows dose measurements in high-energy photon beams with an uncertainty of about 3 % ($k = 2$). In the following figures beam profile measurements using the storage foil system are shown, which are compared with measurements using a small volume ionization chamber in the ^{60}Co 10 cm × 10 cm beam and in a 6 MV 3 cm × 3 cm beam.



These investigations have been supported by the European Union in the framework of the iMERA joint research project "External Beam Cancer Therapy". The results were presented at the "International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS)" held at IAEA in Vienna from 9–12 November 2010; a publication is just being prepared.

1.1.2.6 Experimental determination of beam quality correction factors for plane-parallel chambers in photon beams





In order to examine the chamber-to-chamber variation of the beam quality correction factors (k_Q) for plane-parallel ionization chambers in high-energy photon beams, individual k_Q-factors were determined for each of ten plane-parallel chambers of types IBA PPC05 and IBA PPC40, respectively.

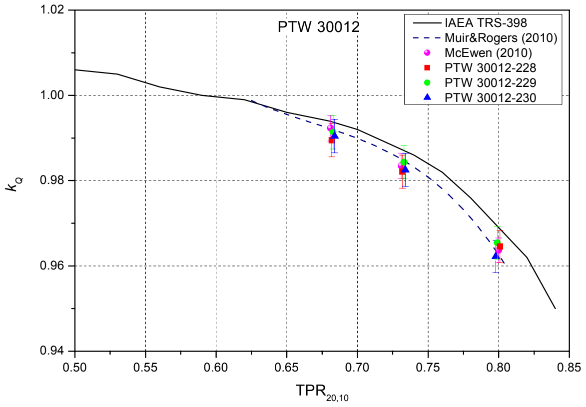
The measurements were performed in the 4 MV, 8 MV, and 25 MV photon beams available at one of the Elekta Precise linacs of PTB under the usual reference conditions specified in IAEA TRS-398.

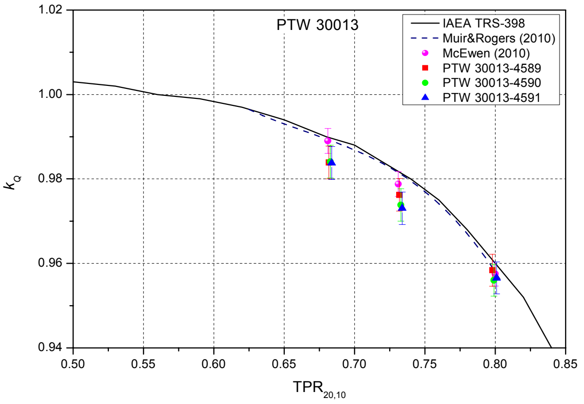
It was found that the variation of the individual beam quality correction factors was not larger than 0.7 % for both chamber types and all beam qualities (see the following figures). From these results it is concluded that chamber-type specific beam quality correction factors could be given for plane-parallel chambers in high-energy photon beams, allowing for the application of the same formalism of absorbed dose measurements as with cylindrical chambers.

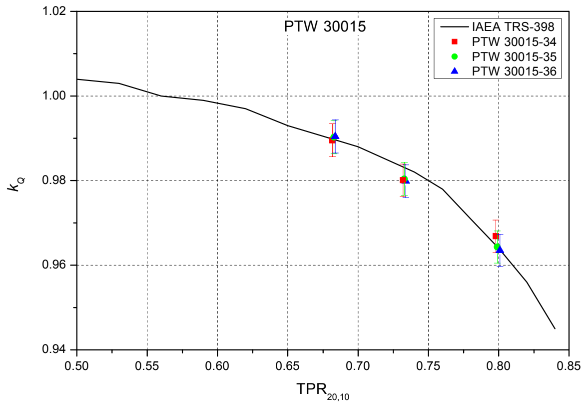
The results of this investigation were presented at the "International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS)" held at IAEA in Vienna from 9–12 November 2010.

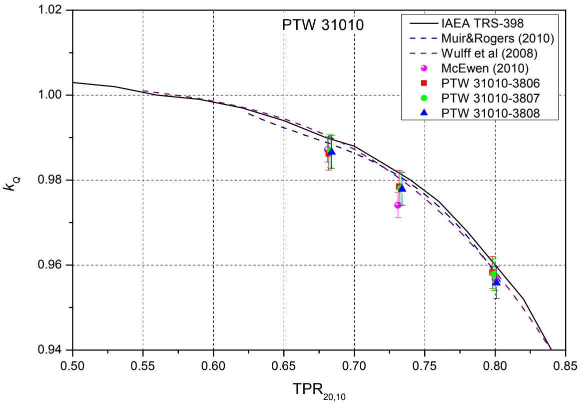
1.1.2.7 Experimental determination of beam quality correction factors for several types of cylindrical chambers (JRP7-project, partially)

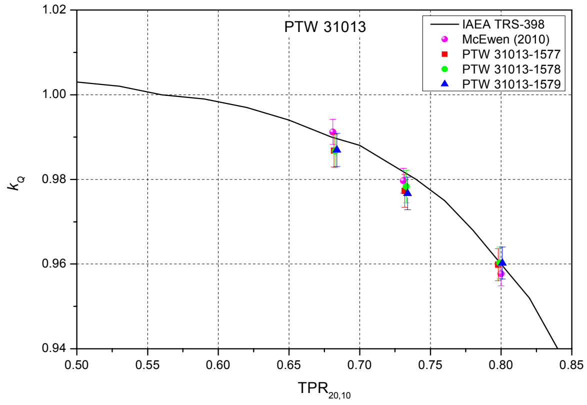
In a research cooperation between PTB and PTW the individual k_Q factors of each 3 chambers of types PTW 30012, PTW 30013, PTW 30015, PTW 31010, PTW 31013 were determined in the 6 MV, 10 MV, and 25 MV photon beams available at the Elekta Precise linacs of PTB. The measurements were done under the reference conditions given in IAEA TRS-398. In the following figures the experimentally obtained k_Q-factors are shown in comparison to the values given in IAEA TRS-398, to the Monte-Carlo calculated values by Muir&Rogers (2010), and Wulff et al. (2008), and to the values obtained experimentally by McEwen (2010) (if available).







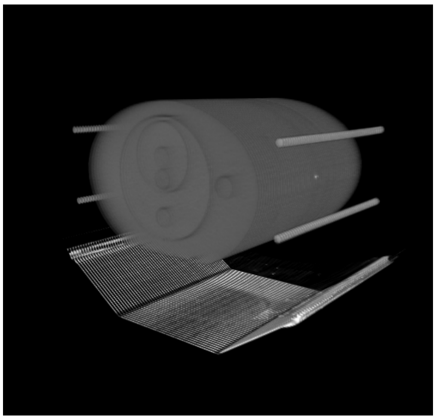




The relative uncertainty of the experimentally determined values is $U = 0.79\ \%$ ($k = 2$). The experimentally determined values will be used in the next update of the German dosimetry protocol DIN 6800-2.

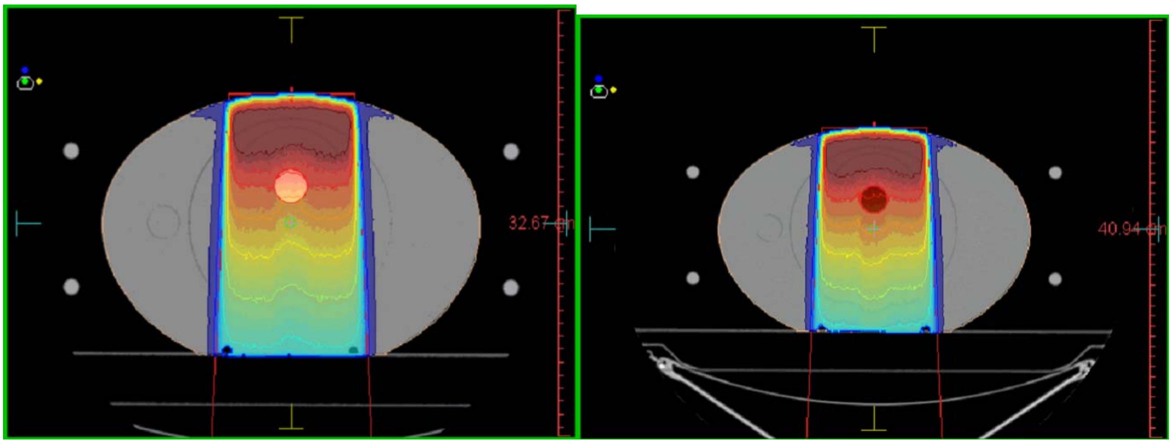
1.1.2.8 Dose measurements in IMRT phantom (JRP7-project)

An “IMRT Head & Torso Freepoint Phantom” (Manufacturer: Computerized Imaging Reference Systems, Inc.) has been bought (see the following picture, left part).



This phantom consists of water equivalent material and allows the insert of different materials (e.g. bone or lung equivalent materials) into several cavities. The dose can be measured using different types of detectors in a free chosen position inside the large circle (see the left picture above)

A CT scan of this phantom (see right part of picture above) was used as input for the treatment planning system and the dose distribution under several irradiation conditions was calculated. As an example the dose distributions in the 10 MV photon beam are shown with a bone-equivalent insert (left side) and lung-equivalent insert (right side) in one of the cavities of the phantom.



The phantom was irradiated in the 6 MV and 10 MV photon beams and the doses measured “behind” the inserts (at the position of the small green circle in the pictures above).

The experimentally obtained ratio of doses behind the lung insert D_{lung} and the bone insert D_{bone} was compared with the ratio of these doses obtained by the treatment planning system; the results are shown in the following table:

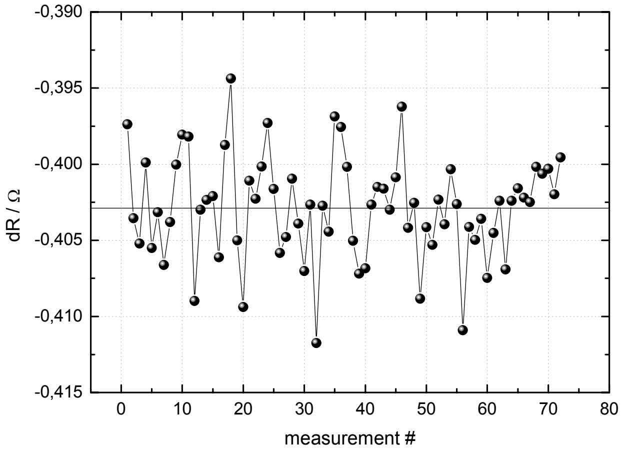
	Dose ratio D_{lung} / D_{bone}	
	6 MV	**10 MV**
Measurement	1.08	1.06
Treatment Planning System	1.11	1.08
Relative deviation	2.8 %	1.9 %

The deviation between the measured and calculated dose ratios is in the order of 2-3 %. More experiments are planned for the future in order to investigate the reason for this deviation.

These investigations have been supported by the European Union in the framework of the iMERA joint research project “External Beam Cancer Therapy”.

1.1.3. Calorimetric determination of D_W in hadron beams (JRP7-project)

PTB’s transportable water calorimeter was used at GSI in Darmstadt, Germany in a 300 MeV/u carbon beam in August 2009. By help of the raster scan method, an almost homogenous dose distribution was achieved over an area of about 5 cm x 5 cm by using 18 x 18 spots and a beam width of about 9 mm (FWHM). By repeating the scanning process twice, a total dose of about 2.2 Gy was achieved. The detector of the water calorimeter was fixed at a water depth of 50 mm, i.e. at the plateau region of the corresponding depth dose distribution. During the beam time at GSI, about 70 irradiation measurements were performed with the water calorimeter. The irradiation time for each measurement was about 80 s and eight consecutive measurements with drift periods of about 300 s in between could be performed before the water calorimeter had to be reconditioned. The results of the calorimetric measurements, i.e. the change of the resistance of the thermistors of the detector, are shown in the following figure. The distribution of the data offers a standard deviation of about 0.9%, which is caused both by the calorimetric measurement itself and the reproducibility of the GSI beam scanning system. The mean value of the measured resistance change was used for the calorimetric determination of absorbed dose to water, D_W.



Results of the calorimetric measurements in the 300 MeV/u carbon beam. The resistance change of the thermistors of the detector is shown for each irradiation. The corresponding

In a scanned radiation beam, the influence of heat transport effects on the measurement results could be expected as being serious. Corresponding heat conduction calculations were performed by help of finite-element calculations using the COMSOL 3.5 software package. For the calculations, the realistic time evolution of the scanning procedure, i.e. the positions and the duration of the single spot irradiations as well as the spill sequence of the GSI storage ring, was taken into account. However, because the raster-scan method provides very fast irradiations, the resulting heat conduction effects remain rather small. For the actual irradiation parameters, the calculated correction factor for the influence of the scanned beam was very close to one. Additional calculations have been performed for the influence of the depth dose distribution of the 300 MeV/u ^{12}C beam. Because the calculated dose distribution resulting from the raster-scan method could not be validated experimentally, the influence of an assumed non-uniformity of the dose distribution was considered in further heat transport calculations. This way, a standard uncertainty of about 0.4% was estimated for the combined heat conduction effects due to the scanning procedure and the irradiation of the non-water materials, i.e the glass walls of the detector and the temperature sensors itself.

A relative standard uncertainty of about 0.5% was estimated for the calorimetric determination of D_W. The main contribution to the uncertainty budget stems from the uncertainty for the calculated heat conduction correction. The uncertainty contributions of further correction factors which are also required for the determination of D_W, have been estimated for the perturbation effect of the calorimetric detector to be 0.20% and for the non-uniformity of the dose distribution at the point of measurement to be 0.15%. The correction for the heat defect and its uncertainty (0.14%) was assumed to be the same as for photon radiation. This assumption is based on the results of model calculations for the radiolysis of the chemical system used in detector of the water calorimeter (pure water saturated with hydrogen gas). These calculations predict the heat defect to be zero also for radiation with higher LET. Nevertheless, it should be mentioned that no further experimental investigations on this issue, for example by using calorimetric detectors with different chemical systems, could be performed in the limited time of this project.

After the calorimetric experiment, measurements with two ionization chambers of type NE 2571 were performed directly inside the water phantom of the calorimeter. The same irradiation conditions were applied as for the calorimetric measurements. For one of the chambers, the polarity effect as well as the recombination effect was determined. For the recombination effect, the inverse of the corrected reading of the chambers at three different voltages V were plotted as a function of $1/V^2$ and a linear fit was applied to the data. This way, the correction factor for the recombination effect was determined to 1.003 ± 0.003. It should be mentioned that this value is in very close agreement to the calculated value for continuous irradiation according to TRS-398. The correction for the polarity effect was found to be 0.999 ± 0.002.

The mean value of the corrected reading of both ionization chambers was used to determine the k_Q factor for the NE2571 chamber in the 300 MeV/u carbon beam:

$$k_Q = D_W^{\mathrm{cal}} / M_Q^{\mathrm{ion}} N_{Dw}^{\mathrm{Co}}$$

In the equation, D_W^{cal} denotes the absorbed dose to water measured by the water calorimeter, M_Q^{ion} is the chamber reading in the carbon beam and N_{Dw}^{Co} is the calibration factor of the chamber for ^{60}Co radiation. The k_Q factor and its standard uncertainty were found to be 1.025 ± 0.007. This value is about 1.5% less than the calculated k_Q factor of 1.041 which is tabulated in TRS-398. However, if the 2.8% uncertainty given in TRS-398 for the calculated value is considered, both values are in agreement.

It must be mentioned that the final result achieved within this investigation is solely based on one calorimetric experiment. Furthermore, the assumption was made that the heat defect for the water being used in the calorimeter is negligible for ^{12}C radiation. Further experimental investigations are required before the water calorimeter can be implemented as a primary standard for the determination of D_W in hadron beams.

1.1.4. Comparisons

1.1.4.1 EURAMET 1021

The EURAMET project 1021 “Direct comparison of primary standards of absorbed dose to water in ^{60}Co and high energy photon beams” between BEV, METAS, and PTB is finished. The final report is available from the EURAMET website.

1.1.4.2 BIPM.RI(I)-K6

The measurements for the key comparison BIPM.RI(I)-K6 “Calorimetric Comparison of Absorbed Dose to Water at High Energies” have been done at PTB in the period between 8 March 2010 and 26 March 2010. During these measurements the same ionization chamber was calibrated in the 6 MV, 10 MV, and 25 MV beams available at the Elekta Precise linacs of PTB traceable on the one hand to the BIPM graphite calorimeter, and on the other hand to the PTB water calorimeter. The results of this comparison are just analyzed, and the report will be prepared.

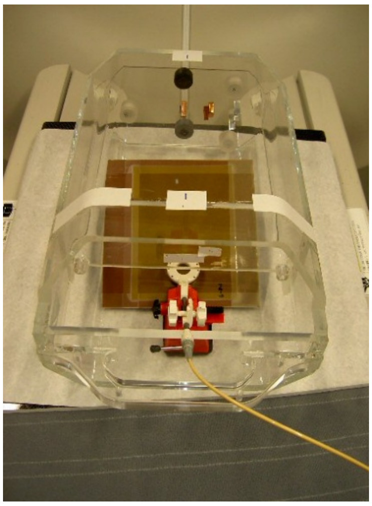
1.1.4.3 EURAMET.RI(I)-S7 intercomparison (JRP7-project)

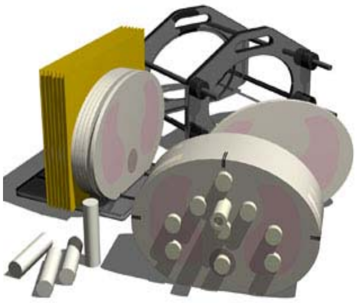
Within the framework of the EMRP / JRP7, a trilateral intercomparison of alanine dosimetry systems was carried out, with the participation of LNHB (leader), NPL and PTB **(EURAMET.RI(I)-S7)**. Irradiations and measurements were compared for 60-Co and 10 MVX or 12 MVX radiation. The results are currently being prepared for publication. Especially the agreement between NPL and PTB is remarkable, deviations were in the range of a few per mille.

1.1.4.4 Intercomparison of measured dose distributions with different detectors for a set of complex dose distributions in a phantom (JRP7-project)

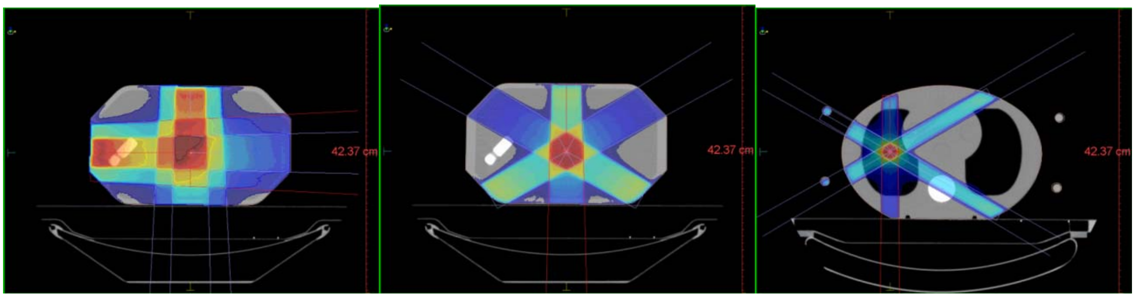
In order to compare the applicability of different types of detectors in small and irregularly shaped photon beams as used in IMRT and to check the precision of treatment planning system under these conditions a comparison between ENEA, STUK, VSL, and PTB was arranged.

The measurements for the comparison took part between 29th November – 3rd December 2010 at PTB. Three different phantoms owned by STUK, VSL, and PTB as shown in the following picture were used.





Complex dose distributions in these phantoms have been calculated with PTB's treatment planning system based on CT scans of the phantoms (see the following picture)



The doses generated during irradiation of these treatment plans were measured at different positions in the phantoms using several types of ionization chambers, diamond detectors, and GafChromic films. The results of this comparison are just analyzed, and the report will be prepared. These investigations have been supported by the European Union in the framework of the iMERA joint research project "External Beam Cancer Therapy".

1.1.4.5 Calibration of secondary standards in small photon beams (JRP7-project)

A comparison between LNE, NPL, and PTB was arranged in order to compare the ability to calibrate secondary standards in small photon beams. An ionization chamber of type Exradin A1SL (owned by LNE) has been calibrated at PTB in the 6 MV and 10 MV 3 cm × 3 cm photon beams. A chamber of type PTW 31010 (owned by PTB) is sent for calibration to LNE. The results of this comparison are not yet available. This investigation has been supported by the European Union in the framework of the iMERA joint research project "External Beam Cancer Therapy".

1.1.5. Alanine Dosimetry

1.1.5.1 Relative Response of the Alanine dosimetry system (JRP7-project, partially)

A main subject of ongoing research is the investigation of the response of the alanine dosimetry system for different radiation modalities.

For high energy photons, k_Q was determined for 6 MVX and 10 MVX photons at the new electron accelerator facilities, referring to the water calorimeter. The response was investigated also as a function of field size, i.e. k_Q was measured in 10 cm x 10 cm reference fields as well as in 3 cm x 3 cm fields. Accompanying Monte Carlo simulations using EGSnrc and spectra produced by the BEAM code were carried out for 10 cm x 10 cm, 3 cm x 3 cm and 1 cm x 1 cm field size. For both Monte Carlo and experimental data, no significant influence of the field size on the response was observed. The measured data agree very well with the ones published earlier by NRC (Zeng et al. 2004). It is suggested to use an average k_Q for alanine for all MVX qualities and field sizes, the value determined from measurements is k_Q=1.004 with a standard uncertainty of 0.004. The value obtained by Monte Carlo simulations is k_Q=1.000 with a statistical uncertainty of 0.003. Further simulations are underway in the framework of a cooperation with the Technical University of Giessen.

First measurements in small fields (1 cm x 1cm) were carried out. The dominating correction turned out to be the volume correction which could be determined with the help of measurements of the dose distribution using a storage foil. Corrections are between 1.003 and 1.06, depending on the actual field. A comparison with measurements using a diamond detector (ENEA, Italy) are under way.

A great amount of work was put in the investigation of a yet unsolved problem. Measurements of k_Q that were performed after April 2010 differ significantly (approximately 0.5%) from the results obtained earlier. The significant drop was also confirmed by colleagues from NPL (P. Sharpe) who kindly supported our efforts to locate the source of the problem.

The relative response of the alanine dosimetry system was also determined for different X-rays and 137-Cs. For 10 MVX, the influence of the surrounding material on the response was also investigated. Different from the Cobalt results published earlier, a systematic deviation of the response was observed. For lung and bone equivalent materials, the difference compared to RW-3 is almost 1%.

In cooperation with METAS (Switzerland), the response for a range of MeV electron beams was determined . Irradiations were carried out by METAS, where the Swiss Fricke dosimetry system served as a primary standard. The results are currently prepared for publication, they confirm results obtained by NRC using a different primary standard (Zeng et al. 2005), which is quite encouraging. As is the case for photons, there is no significant dependence of the response on the energy between 6 MeV and 20 MeV, the average correction is k_E=1.013 with a standard uncertainty of 0.010.

1.1.5.2 Correction for irradiation temperature

Since it is one of the major corrections, the correction for the irradiation temperature was again investigated for two types of pellets (Harwell and GammaService), this time equipped with an improved total least squares straight line fitting algorithm which also takes correlations between x and y data properly into account. The uncertainty achieved for the temperature coefficient c_T=0.181%/K was less than 0.01%/K. Within these limits of uncertainty, no difference between the temperature correction for the two types of probes was discernible, different from what one of the suppliers (GammaService) communicated.

1.1.5.3 Cooperations

The cooperation with the University Hospital Göttingen was continued. Measurements for 192-Ir HDR brachytherapy of the prostate were carried out *in vivo* in the urethra using our specially prepared detectors. Unfortunately, approximately half of the results were useless due to positioning problems with the detector, the other half showed good agreement between planned and measured dose.

The cooperation with the Belgian Beldart project (NuTec Center, Xios Hoogeschool Limburg) was continued as well, a modified version of the data analysis software and the measurement procedure was produced in order to better meet the needs of the QA measurement system that the Belgian partners set up.

A cooperation with the University of Tübingen just started; it is planned to do dose measurements at the blood irradiation facility of the University.

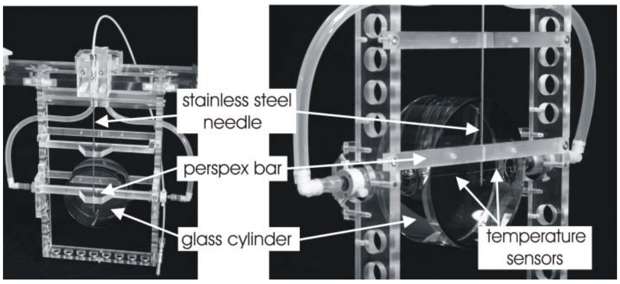
1.2. Dosimetry for brachytherapy

1.2.1. Comparison of secondary standards for measurements of the absorbed dose to water for beta brachytherapy sources.

In 2008 an international comparison of the absorbed dose to water in a water equivalent depth of 1 mm from a ^{106}Ru-area source similar to sources used in the eye tumour brachytherapy was carried out between the three National Metrology Institutes, PTB, NIST and at the VSL (former NMi). The results agreed within the stated combined uncertainties ranging from 3% (PTB,VSL) to 3,5% (NIST). Having completed this comparison, PTB extended this task in 2009 to clinical and manufacturers sites. For this purpose the same ^{106}Ru-area source was calibrated again at PTB using the beta radiation primary standard, the so-called "Multi-electrode Extrapolation Chamber" (MEC), and then sent to the participating partners, being the clinical departments of the Universities Essen and Tübingen and the source manufacturer Eckert & Ziegler BEBIG GmbH, Berlin. At the clinical and manufacturers sites the absorbed dose to water was or respectively will be measured by means of scintillation detector systems, which are traceable to NIST, based, however, on calibration factors determined at least ten years ago. The source will then be returned to PTB in April 2011, where it will be calibrated another time to complete the comparison.

1.2.2. Calorimetric determination of absorbed dose to water for ^{192}Ir HDR brachytherapy sources in near-field geometry (JRP6-project)

The design of the water calorimeter used for the measurements with ^{192}Ir-brachytherapy sources is essentially the same as of the PTB’s primary standard water calorimeter operated in ^{60}Co radiation. The calorimeter is also operated at a water temperature of 4°C and uses the same type of calorimetric detector, but some modifications have been made to ensure that the ^{192}Ir-source can be positioned in close geometry in front of the detector. By help of the afterloader, the source is moved through the teflon catheter into the calorimeter’s outer container and further into the water phantom of the calorimeter, where the teflon catheter is connected vertically to a stainless steel tube. The tube, which has an inner diameter of 1.35 mm and which is closed at one end to stop the movement of the source, can be fixed in vertical direction in a small distance to the parallel-plate glass cylinder of the calorimetric detector by help of a mechanical frame made of Perspex. The frame was adapted such that different distances from 24 mm up to 60 mm between the ^{192}Ir-source and the two thermistors of the calorimetric detector could be realized.



Picture of the calorimetric detector within its frame structure, also showing the additional bars to fix the stainless steel tube at both sides of the detector

The exact geometrical distances between the mid-point of the ^{192}Ir-source and the mid-point of each of the two thermistors were determined by help of an optical telescope.

The influence of the heat transport effects on the measurement results were considered by applying correction factors k_C, which were deduced from heat conduction calculations. Dependent on the measurement position, the irradiation time and the method of data analyze, the calculated k_C factors varied between about 0.978 and 1.082. A standard uncertainty of 0.5 % was estimated for the heat conduction calculations, considering small variations in the finite-element models.

Up to now calorimetric measurements have been performed for two different ^{192}Ir brachytherapy sources, i.e. of type GammMed 12i and of type Nucleotron micro selectron classic. For both types, the dose rate constant Λ, which is the ratio of absorbed dose rate to water at a distance of 10 mm from the source and the reference air kerma rate was determined by extrapolating the results of the calorimetric measurement by help of relative measurements with a plastic scintillator.

1.2.3. High-Dose Rate (HDR) brachytherapy sources

Within a EURAMET joint research project funded from the European Community's Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No. 217257, the PTB has build up a primary standard for the calibration of ^{192}Ir and ^{60}Co HDR brachytherapy sources in terms of absorbed dose rate to water. The standard is based on a modified water calorimeter able to be position a HDR brachytherapy source in close geometry in front of the calorimetric detector. As reported already in 2009 a first HDR source of type GammaMed 12i with an initial activity of 370 GBq has been measured. In the meantime all measurement data and correction factors have been evaluated and determined leading to a calibrated factor for absorbed dose rate to water in 1 cm distance from the source with a combined uncertainty (k=1) of 1,2 %. This includes relative dose rate measurements in different distances from the source by means of an own built scintillation detector system, as the calorimetric measurements could only be performed in distances of 24 mm and 48 mm. Subsequent measurements of the reference air kerma rate of the same source allowed the determination of the dose rate constant Λ, according to the AAPM report TG43. The dose rate constant was determined to :

$$\Lambda = 1{,}0118 \cdot 10^4$$

wit an standard uncertainty of 1,8 % (k=1). The numerical value for Λ is exactly the same as for the MC calculated value given in the literature (Ballester et. al.) for the same source type.

In 2010 a second ^{192}Ir-HDR source of different type (Microselectron Classic) has been investigated in detail. The higher initial activity (550 GBq) of this source allowed to extend the absorbed dose rate to water measurements to a third distance from the source of 60 mm, which resulted in a better extrapolation on the relative measurements with the scintillation detector system and thus to a slightly lower uncertainty. The dose rate constant for the Microselectron Classic source was determined to be:

$$\Lambda = 1{,}01195 \cdot 10^4$$

with a combined uncertainty of 1,7 %.

1.2.4. New afterloading systems for HDR brachytherapy sources.

In 2010 PTB has purchased two new afterloading systems, which were constructed and build by an external manufacturer according to the terms of reference prescribed by PTB. Both afterloading systems were delivered in Oct. 2010 and taken in operation until the end of the year. The advantage of these specially constructed afterloaders is, that in contrast to commercial systems PTB is now able to handle any HDR brachytherapy sources, even ^{60}Co sources from any manufacturer always providing safe radiation protection conditions

1.2.5. Three-dimensional dose rate distribution around ^{192}Ir sources

Within the above mentioned EURAMET joint research project the three-dimensional dose rate distribution around the Microselectron Classic brachytherapy source was measured. The measurement system consists of a 30 cm x 30cm x 30cm Water phantom (PTW MP3-XS) with a motor driven 3 axis positioning system, which allows the detector to be placed in all three dimensions at any desired distance from the source between about 1,5 mm to 100 mm with a special resolution of 0,01 mm. The scintillation detector system used for the measurements is designed as two channel system with a active scintillation channel and a inactive (dummy) channel to be able to correct for the Cherenkov light produced in the light guides. From the tree-dimensional dose rate distribution the radial dose rate function g(r) (according to AAPM TG 43) was also deduced and compared with data published in the ESTRO database for brachytherapy sources. The measured dose rate function is in good agreement to the published data.

1.2.6. Low-Dose Rate (LDR) brachytherapy sources

As stated in the latest CMC list, PTB is now offering calibrations in terms of reference air kerma rate for ^{125}I brachytherapy sources with an uncertainty of 1,8 % (k=2). The used primary standard is a large volume extrapolation chamber, commissioned in 2007. Up to now several calibrations of ^{125}I seeds of three different types from the German manufacturer Eckert & Ziegler BEBIG GmbH have already been performed. The primary standard was also used for calibrations within the EURAMET joint research project to allow the experimental determination of the dose rate constant Λ for a ^{125}I seed of type I.25-S16 from Eckert & Ziegler BEBIG GmbH.

Within the same project PTB has developed a new extrapolation chamber with water equivalent walls, allowing the determination of the absorbed dose to water in 1 cm depth of a water equivalent material (RW1) for the realization of absorbed dose to water in the photon energy range of LDR brachytherapy sources (E< 50 keV). After the determination of all correction factors the new primary standard for absorbed dose to water calibrations was commissioned at the end of 2010. First calibration measurements for a ^{125}I seed of type I.25-S16 were performed in January 2011 and are ongoing for the time being

1.2.7. Three-dimensional dose rate distribution around ^{125}I seeds

PTB has developed a water phantom for three dimensional dose rate distribution measurements around 125I and 103Pd prostate line seeds as well as for the concave Ru/Rh ophtalmic eye applicators. This device was used within the EURAMET joint research project to determine the radial dose rate function and a complete three dimensional dose rate distribution for the above mentioned 125I source of type I.25-S16. The water phantom is equipped with a four axis (2 translational and 2 rotational) positioning unit, which allows in combination with a onsite developed software automatic and complete three dimensional dose rate distribution measurements in spherical coordinates.

1.2.8. Electronic brachytherapy

PTB has purchased a miniature X-ray device from the US – American manufacturer XOFT. The miniature X-ray tube is operated at 50 kV high voltage and a tube current of 0,1 mA. The device is designed to be used in the same way as a common HDR brachytherapy sources. First measurements of the reference air kerma rate produced by the miniature X-ray tube have been carried out in 2010.

Within a research contract between PTB and the Carl Zeiss Meditec AG a second commercially available miniature X-ray device, the Intrabeam system was investigated. Measurements of the spectral photon fluence distribution of the Intrabeam X-ray source have been performed, as well as the manufacturers dosimetry system based on a calibrated soft X-ray ionisation chamber (PTW type 23344) was verified.

1.3. Air kerma and dosimetry for diagnostic radiology

1.3.1. Primary 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 □-rays (^{137}Cs, ^{60}Co). No substantial changes were made since the last progress report in 2009. A new free-air ionisation chamber for low-energy x-rays is under construction. The main application will be the air kerma rate measurements for mammographic radiation qualities. This is due to an improving demand for calibration of dosimeters used in mammography.

1.3.2. Radiation qualities

Since May 2009 new diagnostic radiation qualities according to IEC 61267:2005-11 were established. These are the RQC series, which are used for adjustment of x-ray image intensifier tubes and automatic exposure control. In contrast to the RQR and RQA series which are characterized by aluminium added filtrations the RQC qualities are based on aluminium and copper added filtration. The distributions of the photon fluence spectra as a function of energy were measured with a high purity Germanium detector based spectrometer. Beam characteristics like mean energy and aluminium half value layers and mean correction factors for the primary air kerma standard were calculated based on the measured spectra. A complete list of the PTB radiation qualities now available for clients to calibrate secondary standard dosimeters in terms of air kerma can be downloaded from the following PTB Website: http://www.ptb.de/en/org/6/62/625/pdf/strhlq.pdf .

1.3.3. Comparisons

1.3.3.1 COOMET.RI(I)-K1

PTB acted as pilot laboratory of the COOMET key comparison of the national measurement standards of air kerma for ^{60}Co gamma radiation (COOMET Project 318, MRA-Appendix B Identifier: COOMET.RI(I)-K1). The comparison is finished and published in Metrologia **46**, Technical Supplement 06015 (2009).

1.3.3.2 NIST and PTB air-kerma standards comparison for low-energy x-rays

A comparison has been made of the air-kerma standards for low-energy x rays at the National Institute of Standards and Technology (NIST) and the Physikalisch- Technische Bundesanstalt (PTB). The comparison involved a series of measurements at the PTB and the NIST using the air-kerma standards and two NIST reference-class transfer ionization chamber standards. Results were obtained for the reference radiation beam qualities in the range from 25 kV to 50 kV for low energy x rays, including the techniques used for mammography dose traceability. Results are published in J. Res. Natl. Inst. Stand. Technol. **114**, 321-331 (2009Publications

Selbach, H.-J.; Kramer, H.-M.; Culberson, W.: Realization of reference air-kerma rate for low-energy photon sources. Metrologia **45**, S. 422-428 (2008)

1.3.3.3 Comparison for Co-60 dosimetry

PTB participated in EUROMET project no. 813 which covered the comparisons EUROMET.RI(I)-K1 and EUROMET.RI(I)-K4. Results are published in Metrologia **47**, Technical Supplement 06012 (2010).

1.3.3.4 BIPM.RI(I)-K7

In 2010, PTB participated for the first time in the key comparison BIPM.RI(I)-K7 of the air-kerma standards of the PTB, Germany and the BIPM in mammography x-rays. The Draft B report was circulated for comments in February 2011.

1.3.3.5 COOMET project 445

PTB acts as pilot laboratory in the upcoming COOMET 445 comparison of national standards of air kerma for Cs-137 at protection level. Participants are VNIIM (Russia), BelGIM (Belarus), CPHR (Cuba); GEOSTM (Georgia), INSM (Moldova), NSC-'IM' (Ukraine, SMU (Slovakia) and BIM (Bulgaria). The comparison is scheduled to begin in June 2011 and to be finished in April 2012.

1.3.3.6 AFRIMETS.RI(I)- S1

PTB will participate and act as a link laboratory in the AFRIMETS comparison of national air kerma standards for Co-60, Cs-137 gamma radiation and the ISO 4037 x-radiations narrow series qualities N-40, N-100, N-150 and N250. The pilot laboratory is NMISA, South Africa. The comparison is scheduled to start in March 2011 and to finish in November 2012.

1.3.3.7 EURAMET Project 1177

PTB will participate in a new EURAMET comparison of the calibration of KAP meters in terms of air kerma area product which is piloted by the Greek Ionizing Radiation Calibration Laboratory of the Greek Atomic energy Commission (IRCL/GAEC-EIM). The comparison is scheduled to start in April 2011 and to be finished in February 2012.

1.3.4. A new method to measure shielding properties of protective clothing materials

A new experimental method has been developed to measure the attenuation properties of materials used for radiation shielding garments worn by workers and patients during diagnostic x-ray imaging. In particular, the method is well suited for lead-free or lead-reduced composite materials because it includes the measurement of the secondary radiation generated by photon interactions inside the material. The new method is much easier to use than the classically applied "broad beam geometry" and is characterized by significantly lower standard uncertainties. The method was adopted in the German standard DIN 6857-1 and is expected to be adopted in the international standard IEC 61331-1 which is currently under revision.

1.4. Publications

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2. Progress Report of the Department 'Radiation Protection Dosimetry'

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2.1. Pulsed radiation in radiation protection dosimetry

In the past decade the application of pulsed radiation fields has increased considerably. To give an example, currently nearly all radiation fields used for X-ray diagnostics in human and veterinary medicine or in dentistry, and fields produced by accelerators in therapy and science are pulsed. In addition, the use of active electronic dosemeters (AEDs) has also increased greatly. Even for legal radiation protection dosimetry, the radiation protection community has the intention of replacing in some fields the passive personal dosemeters with active (direct reading) dosemeters. Active electronic dosemeters, i.e. personal and also area dosemeters, have many advantages over passive dosemeters. But one disadvantage is that they are limited with respect to high dose rate measurements. This could be of concern in case of accidental exposure, if this is accompanied by high dose rates. Special care is required in pulsed fields, as these have always enhanced dose rates in the short pulse as compared to a continuous field leading to the same dose.

Any dosemeter, and thus also the AED, should measure the dose correctly in case of an accident or unexpected incident, which may result in higher than expected doses and may even exceed the dose limits. Passive dosemeters are capable of this. But is this also the case for AEDs? In a first step to answer this question, which is closely linked to the PTB’s task to type test dosemeters, PTB has done some preliminary investigations, see publications 4 and 10. These indicate the necessity of further investigations which are now on the way.

Therefore, PTB has established a special pulsed X-ray facility which can produced pulsed reference radiation fields with well known parameters like pulse duration, high voltage, dose rate in the pulse, which are all traceable to primary standards and can be adjusted independently.

In parallel, the PTB has initiated international efforts to develop a Technical IEC specification for testing counting dosemeters with respect to the performance in pulsed fields and will also discuss the standardization of pulsed reference fields at the next ISO meeting.

2.2. Cooperation in the field of beta dosimetry of PTB and VNIIM

In 2009, a bilateral comparison for the unit of the absorbed dose rate in 0.07 mm tissue depth for beta radiation was started. In this comparison, radiation fields of the radionuclides Sr-90/Y-90, Kr-85, and Pm-147 are compared by means of an exchange of radioactive sources. This is different to an earlier EUROMET comparison finished in 2007 (www.iop.org/EJ/abstract/0026-1394/44/1A/06003).

All measurements have been finished and a corresponding paper is in preparation.

2.3. Progress in the field of beta dosimetry at PTB

Recent studies indicate a small (or no) dose threshold for cataract induction: 0.5 Gy or smaller instead of 2 Gy (ICRP 103, 2007). Therefore, the dose assessment may become more important. Simulations show that for beta radiation only the quantity $H_p(3)$ adequately estimates the eye lens dose, see Behrens and Dietze: Phys. Med. Biol. **55** (2010) 4074-4062 and Phys. Med. Biol. **56** (2011) 511. For that reason, $H_p(3)$ will be implemented in the primary dosimetry at PTB and subsequently in the beta secondary standard (BSS2) which is available commercially. For the future, a comparison is envisaged. See also the PowerPoint presentation of the 2010 meeting.

2.4. Fifth EURADOS intercomparison of early warning network systems

The PTB had a unique combination of reference measuring sites for the dosimetry of natural environmental radiation. The work in this area will now be stopped.

The combination consists of the Ultra-low Background Underground Laboratory, UDO, and two free-field sites, a floating platform on a lake showing an almost pure cosmic radiation field and a free-field gamma ray irradiation facility. They provide the particular opportunity to precisely quantify the inherent background of the detectors and to calibrate them almost free of any background and traceable to PTB's primary standards. In addition, the sensitivity of the detector systems to small dose rate variations, similar to that caused by a passing overhead radioactive plume was studied under realistic free-field conditions by using a free-field gamma ray irradiation facility.

Every EU member state has installed a network system to detect nuclear accidents with unintentional release of radioactivity. Measured dose rate values are permanently delivered to the EURDEP data base which is operated as a central platform on behalf of the European Commission. These data base makes only sense if the input data are comparable. To accieve this is one of the goals of Working Group on Environmental Monitoring (WG 3) of the European Radiation Dosimetry Group (EURADOS). In this context the working group 3 has performed a fifth intercomparison of these systems in 2009. The use of the same dose quantity, i. e. ambient dose equivalent, is an important presupposition. Dosimetry teams from the following countries attended the 2009 exercise (organisation in brackets): France (IRSN), Italy (ENEA), Netherlands (RIVM), Spain (University of Basque Country), and Germany (BfS). Most of the tested dosimetry systems are already part of national early warning systems, but some other systems were tested to obtain information regarding future upgrading of networks. In total, 60 dosimetry systems from 36 institutions in 18 EU states had participated in these 5 intercomparisons.

One result was that the individual calibrations still showed discrepancies from the reference values up to 30 %, which would be unacceptably high in the case of a real emergency situation. The UDO measurements of some of the tested dose rate show a pronounced deviation from a constant photon energy response (variations of the response by nearly a factor of 2 were observed). This is less that found in other intercomparisons, but still not satisfying. In this intercomparison, all of the tested systems demonstrated their capability to detect small changes in the dose equivalent rate as caused by a radioactive plume. The fifth intercomparison showed that there is a large interest in the research methods of WG 3 and also in the PTB measuring sites for the dosimetry of environmental radiation.

2.5. Publications

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3. Progress Report of the Department 'Ion Accelerators and Reference Radiation Fields'

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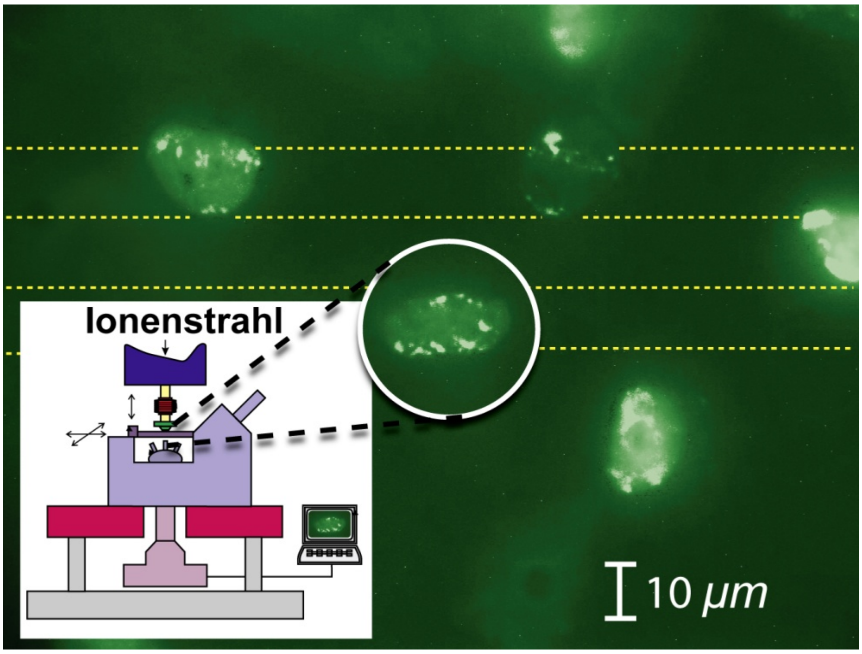
3.1. Radiobiological Effects of Neutrons and Ions

Knowledge of the relative radiobiological effectiveness (RBE) of neutrons and ions is of great interest for radiation protection (Radon, Cosmic Rays) and radiation therapy (Scattered radiation outside the tumor volume). The RBE of 0.565 MeV neutrons for neoplastic transformation of human cells has been measured and compared to the RBEs of α-particles and ^{60}Co γ-rays (Frankenberg-Schwager et al. 2009 RPD 139: 29-39).

Live-cell imaging has been established at the microbeam facility at PTB within an interdisciplinary collaboration with German biological research groups. The fluorescent gene GFP has been coupled to the reporter genes p53BP1 and MDC1 and stably transfected into human cells. The corresponding fluorescence-tagged proteins are involved in the repair of DNA double-strand breaks (DSBs) and are normally distributed in the cell nuclei. After irradiation they accumulate rapidly into bright foci at the sites of DSBs. The group is now imaging online the initial and fast radiation damage responses and measuring the protein kinetics of individual cells after targeted microbeam irradiation with single low- and high-LET particles (Giesen et al. 2011 RPD, doi: 10.1093/rpd/ncq477).



At the microbeam, human cells were irradiated in a pattern of lines with a distance of 10 µm and approx.1 µm between α-particle hits (symbolized by yellow dots). Along the particle track, double-strand breaks of the DNA occur. In the figure, they appear as bright foci, because fluorescence-marked repair proteins accumulate at the damage sites.

3.2. Publications:

Frankenberg-Schwager, M., Spieren, S., Pralle, E., Giesen, U., Brede, H.J., Thiemig, M. and Frankenberg, D.: The RBE of 3.4 MeV a-particles and 0.565 MeV Neutrons relative to ^{60}Co γ-Rays for Neoplastic Transformation of Human Hybrid Cells and the Impact of Culture Conditions
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4. Progress Report of the Department “Fundamentals of Dosimetry”

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4.1. Experimental verification of track structure models

A tracking ion counting nanodosimeter was employed to acquire spatial ionization patterns produced by charged particles in propane gas at 1.3 mbar. Data were taken with 250 MeV, 17 MeV, 5 MeV and 1.5 MeV proton beams, 4.8 MeV alpha particles and electrons from a Sr-90/Y-90 source. For each particle type, the number of ionizations and their location within a wall-less, cylindrical sensitive volume was measured with a tissue-equivalent resolution of about 5 nanometers. Measured ionization frequency distributions as a function of distance from the primary particle track were compared with the results of a dedicated Monte Carlo track structure code.

4.2. Nanodosimetric model of radiation-induced clustered DNA damage yields

The model uses ionization cluster size distributions measured by an ion counting nanodosimeter or simulated by a dedicated Monte Carlo track structure code. It is based on a straightforward combinatorial approach translating ionizations to lesions in a DNA segment. The two model parameters, corresponding to the probability that a single ion detected by the nanodosimeter corresponds to a single strand break or a single lesion (strand break or base damage) in the equivalent DNA segment, were tuned by fitting the model-predicted yields to previously measured double-strand break and double-strand lesion yields in plasmid DNA irradiated with protons and helium nuclei. Model predictions were also compared to both yield data simulated by the PARTRAC code for protons of a wide range of different energies and experimental DSB and non-DSB clustered DNA damage yield data from the literature.

4.3. Effect of a magnetic field on the track structure of low-energy electrons

The track structure of low energy electrons in the presence of a uniform static magnetic field of strength up to 14 T was calculated for a simplified DNA segment model in form of a water cylinder. In the case that no magnetic field is applied, nanodosimetric results obtained with Geant4-DNA were compared with those from the PTB track structure code. The obtained results suggest that any potential enhancement of complexity of DNA strand breaks induced by irradiation in a magnetic field is not related to modifications of the low-energy secondary electrons track structure.

4.4. Check of the scaling procedure of track structures of ionizing radiation in nanometric volumes

Ionization cluster size distributions produced by mono-energetic proton and alpha particle beams in the energy range between 0.1 MeV and 20 MeV were measured at the accelerator facilities of the PTB. The working gases used in this experiment were C_3H_8 and N_2. From the NIST databases for stopping power and mean ionization energy, equivalent cluster size distributions for protons and alpha particles should be obtained for pressures of 0.25 mbar C_3H_8 and 1.2 mbar N_2. Measurements reveal the best agreement with pressures of 0.425 mbar C_3H_8 and 1.2 mbar N_2 for protons and 0.46 mbar C_3H_8 and 1.2 mbar N_2 for alpha particles.

4.5. Effect of a static magnetic field on nanodosimetric quantities in a DNA volume.

Using the Geant4-DNA Monte Carlo simulation toolkit, nanodosimetric track structure parameters were calculated for electrons, protons and alpha particles moving in transverse magnetic fields up to 10 Tesla. Applying the model proposed by Garty et al. [3] the track structure parameters were used to derive the probability of producing a double strand break (DSB). For all primary particles and energy ranges simulated the application of a magnetic field was shown to have no significant effect on the parameters characterizing radiation track structure or the probability of producing a DSB.

4.6. Effect of a magnetic field on the chromosome damage in human lymphocytes induced by irradiation with 28 kV X-rays

Primary human lymphocytes were irradiated with mammography X-rays (28 kV) in the absence and presence of a magnetic field of strength comparable to that used for magnetic-resonance imaging. Chromosomal aberrations in irradiated cells were analysed in Giemsa-stained as well as in multi colour hybridized (mFISH) metaphases to ascertain any change in the RBE due to the presence of the magnetic field. In agreement with data in the literature, a higher rate of dicentric chromosomes as compared to cells irradiated with ^{60}Co γ-rays was found. Furthermore, in the presence of a magnetic field the rate of dicentric chromosomes increased by 30%.

4.7. Publications:

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Bashkirov, V.; Schulte, R; Wroe, A.; Breskin, A.; Chechik, R.; Schemelinin, S.; Garty, G.; Sadrozinski, H; Gargioni, Elisabetta; Großwendt, B.; *Experimental verification of track structure models,* Proc. 2008 IEEE Nuclear Science Symposium and Medical Imaging Conference, ISBN 978-1424427147, IEEE (2009), 2890-2894.

Bug, M.; Gargioni, E.; Guatelli, S.; Incerti, S.; Rabus, H.; Schulte, R.; Rosenfeld, A. B.; *Effect of a magnetic field on the track structure of low-energy electrons: a Monte Carlo study,* Eur. Phys. J. D **60** (2010), 85-92.

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