Advance of the Austrian Absorbed Dose to Water Primary Standardisation System

Andreas Baumgartner\textsuperscript{a,b,*}, Andreas Steurer\textsuperscript{a}, Franz Josef Maringer\textsuperscript{a,b,c}

\textsuperscript{a}BEV - Bundesamt für Eich- und Vermessungswesen (Federal Office of Metrology and Surveying), Arltgasse 35, 1160 Vienna, Austria.

\textsuperscript{b}University of Technology Vienna, Atominstitut, Stadionallee 2, 1020 Vienna, Austria.

\textsuperscript{c}University of Natural Resources and Applied Life Science, LLC-Laboratory Arsenal, Faradaygasse 3, Arsenal 214, 1030 Vienna, Austria.

Abstract. The Austrian absorbed dose to water primary standardisation system is based on a graphite calorimeter. It was developed at the Austrian Research Center Seibersdorf, based on the design by Domen, and is in operation since 1983. The calorimeter and the corresponding measuring devices are supervised by the Federal Office of Metrology and Surveying (BEV). The BEV is the National Metrology Institute (NMI) and national authority on legal metrology in Austria. The realisation of the unit absorbed dose to water is based upon absorbed dose to graphite measurements. The conversion from absorbed dose to graphite to absorbed dose to water is done by two methods based on the photon fluence scaling theorem. The calorimeter was originally designated for determination of absorbed dose to water in $^{60}$Co gamma ray beams. The progress in radiation therapy within the recent years forced increased demands on high energy photon dosimetry. To meet the needs the application range of our primary standard was extended, to enable field characterisation and calibration of medical accelerators. In order to operate the energy range and application enhancement a set of conversion and correction factors was needed. They were obtained via Monte Carlo simulations with PENELOPE code, and measurements - with the calorimeter itself and ionisation chambers. First of all measurements and simulation studies were carried out for $^{60}$Co gamma rays to achieve a well founded basis. The simulations include calorimeter geometry specific simulations to get radiation quality dependent correction factors. These calculations are constitutive on photon fluence spectra determination of radiation facilities to enable the use of realistic input radiation fields. Furthermore cooperative measurements for the verification of simulation results at accelerators located in Austrian hospitals are in progress. The accomplishment of the BEV high energy calorimetry project was promoted by the Physico-technical Testing Service (PTP), which is a partial legal entity of BEV.

KEYWORDS: dosimetry; graphite-calorimeter; Monte Carlo simulation; primary standard.

1. Introduction

A primary standard based upon an absorbed dose to graphite-calorimeter is used to realize the unit absorbed dose to water at the BEV. The graphite-calorimeter was designed and implemented by Witzani et al [16]. In principle it’s a Domen type calorimeter [2] designed for quasi-adiabatic and quasi-isothermal mode of operation. The calibration of the instrument can be done heatloss-compensated or quasi-adiabatically. The realisation of the unit absorbed dose to water is based upon absorbed dose to graphite measurements with the graphite-calorimeter. The conversion from absorbed dose to graphite to absorbed dose to water is done by two methods based on the photon fluence scaling theorem [13]. These methods are: conversion by calculation and conversion through ionisation chamber measurements.

The calorimeter was originally designated for determination of absorbed dose to water in $^{60}$Co gamma ray beams. The progress in radiation therapy within the recent years forced increased demands on high energy photon dosimetry (i.e. photons generated with accelerators). To meet the needs the application range of our primary standard was extended, to enable field characterisation and calibration of medical accelerators.

* Presenting author, E-mail: andreas.baumgartner@bev.gv.at
2. Materials and methods

In order to operate the energy range and application enhancement a set of energy dependent conversion and correction factors was needed. In addition the graphite-calorimeter and its corresponding phantom had to be adapted to the measurement requirements for high energy radiation fields. The corrections were obtained via Monte Carlo simulations with the PENEOPE® code system [14], and measurements - with the graphite-calorimeter itself and various ionisation chambers.

2.1 Measurements

The graphite-calorimeter is in operation since 1983. To ensure the quality and reliability of the Austrian primary standard, the graphite-calorimeter and its corresponding components had to undergo a refurbishment process. This process included a complete check of the hardware components of the calorimeter and the evaluation electronics. After that the graphite-calorimeter response was verified by electric calibrations for the complete temperature working range. Furthermore the modernisation included the development of a newly created LabView® based evaluation program. This program provides automatic non-linear drift extrapolations. The program can be used for all modes of operation and calibration at $^{60}$Co gamma rays as well as high energy photons. Upon completion of the modernisation process measurements were done in the $^{60}$Co gamma ray beam and in medical linear accelerator radiation fields. The BEV measurement capacities regarding irradiation facilities for photon therapy are limited to a Picker $^{60}$Co teletherapy unit. To realize measurements and calibrations at high energy radiation fields the BEV supports cooperation with the hospital Wiener Neustadt.

The measurements with the graphite-calorimeter in the beam of the BEV $^{60}$Co teletherapy unit were realised according to [6], [7],[8], [10], [16]. The measurement setup and conversion factors were taken from [9]. The calorimeter specific correction factors used for the measurements were determined via Monte Carlo Simulations and are described below. With these measurements the BEV reference value for absorbed dose to water was specified and calibrations of secondary standards were done. With use of these results the BEV will participate the international key comparison of absorbed dose to water at the Bureau International des Poids et Mesures (BIPM).

The measurements at the hospital Wiener Neustadt were done in beams of Varian Clinac® accelerators. Fig. 1 gives an overview of the graphite-calorimeter measurement setup at the hospital. The types of used accelerators are: Varian 2300 CD and Varian 2100 C. The nominal accelerator potentials for the generation of photon beams are 4 MV, 6 MV, 10 MV and 15 MV. Electron beams can be provided with the energies of 4 MeV, 6 MeV, 9 MeV, 12 MeV, 16 MeV and 20 MeV. The measurements were done with the graphite-calorimeter and secondary standards (Ionisation chambers: PTW 34001 for electrons and PTW 30012 for photons, electrometer: UNIDOS 10002) calibrated at METAS.

In case of graphite-calorimeter measurements at high energy photon beams the determination of absorbed dose to graphite is done in the quasi-adiabatic mode of operation. The evaluation of the measurements is done according to equation (1).

$$D_{g,\text{adiabat}} = \frac{1}{m_c} \left( \frac{\Delta R}{R} + k_2 \cdot \Delta U \right) \cdot k_1 \cdot k_{\text{gap}}$$

$D_{g}$ ............. absorbed dose to graphite (Gy)
$m_c$ ............. core mass (g)
$\Delta R$ ........... change in resistance (%)
$R$ .............
$k_2$ ............. chart calibration factor (%/V)
$k_1$ ............. quasi-adiabatic calibration factor (mJ/%)
$\Delta U$ ........... difference in voltage (V)
$k_{\text{gap}}$ ......... correction for the effect of the vacuum gaps
The conversion from absorbed dose to graphite to absorbed dose to water is in case of measurements at high energy photon beams is done by calculation according to equation (2). The conversion procedure is based on the photon fluence scaling theorem [13] with use of conversion factors from [8], [11], [15]. The used calorimeter specific correction factors for the measurements were determined via Monte Carlo Simulations and are described below.

\[ D_w = D_g \left( \frac{R_g}{R_w} \right)^2 \left( \frac{\mu_w}{\rho} \right)_{w,g} \cdot \beta_{w,g} \cdot k_{\Delta\mu} \cdot k_p \cdot k_{gc} \]  

\( D_w \) ........ absorbed dose to water (Gy)
\( R \) ............ source to reference point distances in graphite and water (m)
\( \left( \frac{\mu}{\rho} \right)_{w,g} \) ... ratio of the mass energy absorption coefficients of water and graphite
\( \beta_{w,g} \) ...... ratio of the absorbed dose to collision kerma of water and graphite
\( k_{\Delta\mu} \) ........ air attenuation correction
\( k_g \) .......... scaling correction
\( k_{gc} \) ........ correction for the effective measurement depth in graphite

**Figure 1:** Measurement setup of the graphite-calorimeter at the hospital Wiener Neustadt

2.2 Simulation Studies

The realization of the energy range and application enhancement of the graphite-calorimeter was executed in different stages. First of all measurements and simulation studies for the estimation of correction factors were carried out for \(^{60}\)Co gamma rays to achieve a well founded basis. After that simulations concerning higher photon energies were done. For the accomplishment of the simulation studies the Monte Carlo code System PENELOPE-2006® was used to gain application specific correction factors to enable the use of the calorimeter in high energy radiation fields for medical applications. For the verification of the simulation studies measurements with the graphite-calorimeter and with ionisations chambers at the BEV teletherapy unit and at the accelerators of the hospital Wiener Neustadt were carried out.

2.2.1 Irradiation unit specific simulations

To obtain radiation quality specific correction factors it was necessary to determine the radiation field characteristics of the used irradiation units. This included the Monte Carlo modelling of the BEV \(^{60}\)Co
teletherapy unit and Varian Clinac® accelerators with the use of PENELLOPE-2006® penmain code. The aim of these calculations was determination of the real energy spectra. These spectra were used for the implementation to the sources within the graphite-calorimeter specific Monte Carlo simulations with the aim to obtain the required radiation quality dependent correction factors. The verification of the simulated photon fluence spectra based upon depth dose curves in water. Therefore simulated and measured dose curves and the radiation quality factors ($TPR_{20,10}$) were compared. The measurements were done with a PTW 31003 ionisation chamber for high energy photons. For $^{60}$Co gamma rays was additionally the cylindrical chamber CC01 used.

2.2.2 **Graphite-calorimeter specific simulations**

For the graphite-calorimeter the following radiation quality dependent correction factors are taken into consideration:

- Correction for the effect of the vacuum gaps around the core, $k_{gap}$
- Correction for the deviation of the graphite phantom dimension from the scaling requirements, $k_{gs}$
- Air attenuation correction $k_{air}$
- Correction for the effective measurement depth in graphite, $k_{gc}$

These corrections were determined by the use of the Monte Carlo technique and via measurements for selected high energy photon beam qualities and $^{60}$Co gamma rays. A major component from the set of correction factors applied to the graphite-calorimeter is the correction for the effect of the vacuum gaps around the core, see [1], [3], [4], [12]. This correction accounts for beam perturbation caused by the vacuum- and air gaps around the core and the surrounding graphite calorimeter bodies. For the estimation of the effect were two Monte Carlo geometries used namely a setup in order to the build-up used for measurements, and an idealised setup of the graphite-calorimeter without gaps. For the set up without gaps were these gaps filled with graphite, and the thickness of the graphite plates in front of the calorimeter was reduced to ensure that the depth of graphite from the phantom surface to the middle of the core remains the same. To get a correction for the effect of the gaps energy deposited in the core was scored for the geometry with and without gaps. For $^{60}$Co were first of all simulations with the use of monoenergetic point source under variation of the field size done, the results shall be discussed in chapter 3. For high energy photons the Monte Carlo sources contain the spectral photon fluence distribution of the irradiation units.

As mentioned above the conversion from absorbed dose to graphite to absorbed dose to water is done by methods based on the scaling theorem. Thus the graphite phantom has to be a scaled cube with an edge length of 19.2 cm for $^{60}$Co gamma-rays and due to the larger size of the water phantom 25.4 cm for high energy photons. To study the effect of the deviation from the scaling requirements simulations with the PENELLOPE® code penmain were done. The simulation set up consists of two geometries: an exactly scaled graphite cube and a geometry model of the cylindrical phantom used for the measurements. Both geometries only consist of one material and two bodies namely the core - where the deposited energy is scored - and the surrounding phantom.

The air attenuation correction accounts for the difference in attenuation at the corresponding measurement distances as result for compliance of scaling requirements. For the determination of the air attenuation correction the photon energy fluence was scored at one distance equal to the source surface distance of the water phantom, and at the corresponding scaled source surface distance of the graphite phantom. The usage of tabulated attenuation coefficients for air taken from [5] and equation (3) allowed the calculation of a mean attenuation coefficient for the simulated spectra.

$$
\frac{\mu}{\rho} = \frac{\int_{E_{min}}^{E_{max}} \Psi(E) \cdot \frac{\mu(E)}{\rho} \cdot dE}{\int_{0}^{E_{max}} \Psi(E) \cdot dE}
$$

(3)
With these mean attenuation coefficients the correction factors were estimated according to equation (4).

$$k_{\Delta\mu} = \frac{\overline{\mu}}{\rho} \frac{e^{-\frac{\rho}{\mu}} R_g}{e^{-\frac{\rho}{\mu}} R_r}$$

(4)

\(\overline{\mu}\) ..........mean photon energy fluence at reference distance (cm²/g)

\(\rho\) ...........differential photon energy fluence at the defined scoring plane (1/MeV·cm²)

\(\mu(E)\) ......mass attenuation coefficients of air for photons of energy \(E\) (cm²/g)

The correction for the effective measurement depth in graphite accounts for the fact that the required measuring depth in graphite cannot be exactly realized with the graphite-phantom. The phantom is assembled with graphite plates of different thickness and mass densities. Therefore it is necessary to determine depth dose curves in graphite and interpolate the dose values to gain the correction factor for the required measuring depth. This correction factor was determined experimentally with the use of the graphite calorimeter and the CC01 cylinder ionisation chamber at \(^{60}\)Co gamma rays and with the METAS calibrated ionisation chamber based measuring system at high energy photon beams.

3. Results and discussion

The simulation studies were first of all done for a monoenergetic photon emitting point source. The initial energy of the photons was set to be the mean of \(^{60}\)Co gamma lines. The simulations included the correction for the effect of the vacuum gaps around the core and the correction for the deviation of the graphite phantom dimensions from the scaling requirements. The results are plotted in Fig. 2 and show the correction factors with 1σ statistical uncertainty under variation of the field size at the calorimeter core.

**Figure 2:** Correction factors calculated with monoenergetic gamma rays as a function of field radius at the graphite-calorimeter core
Fig. 3 shows the results of the Monte Carlo simulations - with 1σ statistical uncertainty - for the gap correction, scaling correction and the correction for the difference in air attenuation as a function of the radiation quality specifier $TPR_{20,10}$. Within these simulations the spectra of the used irradiation units and the different reference conditions according to the set up were taken into account. The standard reference conditions are: source detector distance 100 cm at a depth of 5 g/cm² water for $^{60}$Co gamma rays, and 110 cm source detector distance at a depth of 10 g/cm² water and respectively the scaled distances and measuring depths in graphite. The tissue phantom ratio ranges from $TPR_{20,10} = 0.562$ ($^{60}$Co) up to $TPR_{20,10} = 0.758$ (15 MV). Because of the different measurement conditions for $^{60}$Co and high energy photon beams the regression does not include the $^{60}$Co simulation results, but only the simulation results for high energy photon beams. The regression of the total correction $c_t$ (product of the different correction factors) unaccounted for the $^{60}$Co results is done with the function described in equation (5).

$$c_t = y_0 + a \cdot e^{b \cdot TPR_{20,10}}$$

(5)

$c_t$…………total graphite calorimeter specific correction factor
$y_0, a, b$…..regression parameter
$TPR_{20,10}$……tissue phantom ratio

Figure 3: Graphite-calorimeter specific correction factors as a function of $TPR_{20,10}$

4. Conclusion

The energy range and application enhancement of the BEV graphite-calorimeter enables the primary standardisation system for the accomplishment of secondary standard ionisation chambers calibration in terms of absorbed dose to water at high energy photon beams.

The over all verification of the implemented correction and conversion factors will be done in the framework of the EURAMET Projekt 1021. This project is proposed for the direct comparison of primary standards for absorbed dose to water of BEV, METAS and PTB in $^{60}$Co and high energy photon beams. The measurement should be carried out in the $^{60}$Co and high energy photon beams of
METAS and PTB. The BEV will transport the graphite calorimeter primary standard to METAS and PTB for operation in the accelerator fields. The proposed photon beam qualities are generated by electrons with energies in the range from 4 MeV to 15 MeV (optional 18 MeV).

Acknowledgements

The accomplishment of the BEV high energy absorbed dose to water calorimetry project was promoted by the Physico-technical Testing Service (PTP), which is a partial legal entity of BEV.

We are grateful to Prim. Univ.-Doz. Dr. Brigitte Pakisch from the hospital Wiener Neustadt for giving us the opportunity of collaboration and to DI Michael Vejda for his support at the Varian Clinac® accelerators.

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