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Feasibility of using a dose-area product ratio as beam quality specifier for photon beams with small field sizes

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ABSTRACT

Purpose: To investigate the feasibility of using the ratio of dose-area product at 20 cm and 10 cm water depths ($DAPR_{20,10}$) as a beam quality specifier for radiotherapy photon beams with field diameter below 2 cm.
Methods: Dose-area product was determined as the integral of absorbed dose to water (D_w) over a surface larger than the beam size. 6 MV and 10 MV photon beams with field diameters from 0.75 cm to 2 cm were considered. Monte Carlo (MC) simulations were performed to calculate energy-dependent dosimetric parameters and to study the $DAPR_{20,10}$ properties. Aspects relevant to $DAPR_{20,10}$ measurement were explored using large-area plane-parallel ionization chambers with different diameters.
Results: $DAPR_{20,10}$ was nearly independent of field size in line with the small differences among the corresponding mean beam energies. Both MC and experimental results showed a dependence of $DAPR_{20,10}$ on the measurement setup and the surface over which D_w is integrated. For a given setup, $DAPR_{20,10}$ values obtained using ionization chambers with different air-cavity diameters agreed with one another within 0.4%, after the application of MC correction factors accounting for effects due to the chamber size. $DAPR_{20,10}$ differences among the small field sizes were within 1% and sensitivity to the beam energy resulted similar to that of established beam quality specifiers based on the point measurement of D_w.
Conclusions: For a specific measurement setup and integration area, $DAPR_{20,10}$ proved suitable to specify the beam quality of small photon beams for the selection of energy-dependent dosimetric parameters.

1. Introduction

In recent years, the use of small beams (field sizes smaller than 2 cm × 2 cm) in routine radiotherapy techniques has increased steadily. Nevertheless, small beam dosimetry is still challenging. The determination of absorbed dose to water, D_w, in narrow photon beams is particularly demanding, if the traditional approach of measuring D_w with a point-like detector placed on the beam axis is followed. Even the use of high resolution detectors with sensitive volume of the order of tenths of mm^3 or less does not ensure a reliable D_w measurement in the absence of lateral electronic equilibrium [1]. When used in small field sizes, point-like detectors can exhibit large response variations (even more than 10%) depending on the detector material and construction details near the sensitive volume. These variations generally result in underestimation (in the case of small volume ionization chambers) or overestimation (in the case of solid state detectors) of both D_w and output factors [2,3]. As a consequence detector specific correction factors [4] are required for accurate D_w measurement in small beams. Previous work in this field has focused on the evaluation of such correction factors, either using direct Monte Carlo calculation or, experimentally, taking a given detector as reference, and results for the most widely used detectors have been reported in literature [1,5–14]. However, as no D_w primary standards exist for field sizes smaller than 2 cm, discrepancies among published data are difficult to solve [15,16]. Moreover, the positioning of point-like detectors in narrow beams is also very critical for the measurement accuracy, since errors larger than 1% can occur even for uncertainties on the detector position as low as a few tenths of mm [17].

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The above difficulties have raised interest in a different approach, based on measuring an integral quantity as reference quantity for small beam dosimetry, in analogy with the concept of dose-area product used for measurements in free space in diagnostic radiology [18], and extending the concept to measurements performed in a material medium like in a water phantom [19–21]. For radiotherapy dosimetry application, the dose-area product (*DAP*) is defined as:

$$DAP = \int_A D_w(x,y)dxdy \tag{1}$$

where *A* is an area, in a plane perpendicular to the beam central axis, larger than the beam size at that plane, and corresponding to the active area of the detector used for the *DAP* measurement. A proper *DAP* detector should have a flat sensitive volume with cross-sectional area larger than the radiation field. Large-area plane-parallel ionization chambers (LACs) have been shown to be adequate *DAP* detectors [22,23]. In very small field sizes, positioning a *DAP* detector on the beam central axis is less critical than positioning a point-like detector. In addition, measurement of the integral dose is expected to be less detector dependent, if compared with the point-dose measurement by point-like detectors [24]. In fact, the latter requires corrections that strongly dependent on beam shape, detector type, and off-axis position in the small field. Conversely, even in the case of a composite clinical field, Monte Carlo calculations in [24] showed that differences in response among point-like detectors substantially diminish, if the detector signal is integrated over the whole radiation field. The Laboratoire National Henri Becquerel (LNE-LNHB) recently developed a calorimeter for absolute measurement of *DAP* in small field sizes, making this quantity available for transfer from the calibration laboratory to the user's beam [25,26]. Then, in the scenario of a small beam dosimetry based on *DAP* references, defining the beam quality specifier in terms of DAP to link the calibration to the user's beam becomes an attractive possibility.

In the present paper, the feasibility of expressing the photon beam quality in terms of a *DAP* ratio is explored for field diameters below 2 cm. Specifically the ratio of *DAP* at 20 cm and 10 cm water depths

$$DAPR_{20,10} = \frac{\int_A D_{w,20cm}(x,y)dxdy}{\int_A D_{w,10cm}(x,y)dxdy} \tag{2}$$

is considered in analogy with the traditional $TPR_{20,10}$ beam quality index [27] based on point-dose measurement. We thoroughly investigated the properties of $DAPR_{20,10}$ in 6 MV and 10 MV small photon beams both by Monte Carlo calculation and experimentally, using LACs with different air-cavity diameters and characteristics. Two types of Linacs with different collimator systems were used. The aim of this work was: a) to verify the ability of $DAPR_{20,10}$ to discriminate between qualities of small beams for the purpose of selecting energy-dependent dosimetric data (i.e. ionization chamber calibration coefficient, correction factors); b) to establish appropriate measurement conditions and procedures for the experimental determination of $DAPR_{20,10}$ as a beam quality specifier.

2. Materials and methods

Monte Carlo simulations of 6 MV and 10 MV clinical photon beams were performed in order to investigate the dependence of $DAPR_{20,10}$ on beam energy and field size. Moreover, Monte Carlo calculation was applied to evaluate the influence on $DAPR_{20,10}$ of the area over which *DAP* is integrated (i.e. the detector active area). Measurement setups with fixed source-to-surface distance (SSD) or with fixed source-to-detector distance (SDD) were considered. Additionally, the water-to-air stopping power ratio, $s_{w,air}$, the most important energy-dependent parameter affecting ionization chamber response, was calculated at reference depth as a function of the beam energy and field size, to assess whether the $s_{w,air}$ values are correlated with the corresponding $DAPR_{20,10}$ values. Finally, ratios of ionization signals at 20 cm and 10 cm water depths were measured under various experimental conditions (beam energies, field sizes and measurement setups) by means of LACs with different active areas, and experimental results were compared to those obtained by Monte Carlo calculation.

2.1. Accelerators and photon beams

Accelerators used in this work were a Varian DHX clinical accelerator available at San Filippo Neri Hospital in Rome and a General-Electric (GE) Saturne 43 clinical accelerator at LNE-LNHB. Since reproducibility of jaw positioning was not good enough for small beams (in some cases measurement reproducibility was larger than 1%), only beams shaped by fixed cones were considered for *DAPR* measurement.

The Varian DHX accelerator produces 6 MV and 10 MV photon beams and it is equipped with Radionics stereotactic collimators. These are tapered conical collimators using Cerrobend (27% lead, 50% bismuth, 13% tin and 10% cadmium) as collimating material. A Cerrobend cylinder with central conical opening is inserted into a stainless steel cylindrical housing with length of 12.5 cm and outer diameter of 7.5 cm. Using such cones and a constant 7 cm × 7 cm secondary collimator (e.g. linac jaws) setting, circular beams with diameters of 2.00 cm, 1.50 cm and 1.25 cm at the isocenter are produced. The beams shaped by the stereotactic collimators were used for investigating the properties of $DAPR_{20,10}$ by Monte Carlo simulations and measurements.

For the Saturne 43 accelerator, specifically designed external collimators made of tungsten alloy (D185) with a length of 10 cm and a conically-shaped hole were added to produce 6 MV beams with diameters of 2 cm, 1 cm and 0.75 cm at the reference plane. The alignment was checked optically with a telescope. The entry and exit apertures of the collimator had to be centred on the same axis and the radial dose distribution was checked with EBT3 films. Two additional monitor ionization chambers were mounted on the external collimator in front of the beam defined by the linac jaws. For the three small beams, $DAPR_{20,10}$ was experimentally determined setting an SDD of 100 cm and integrating the absorbed dose over a detector surface of 3 cm diameter.

2.2. Monte Carlo simulations

2.2.1. Varian DHX accelerator

The BEAMnrc code [28] of the EGSnrc Monte Carlo system version V4-r2-4 [29] was used for simulating the 6 MV and 10 MV photon beams produced by the Varian DHX accelerator (Fig. 1). First, square photon beams shaped by the jaws were simulated with the purpose of validating the accelerator model by comparing the calculated and measured dose distributions. The mean energy of the initial electron beam was tuned by comparing calculated and measured percentage depth dose (PDD) curves for the 10 cm × 10 cm field size. A circular, Gaussian spatial distribution was assumed for the electron beam incident on the target. The full width at half maximum (FWHM) of the Gaussian distribution was determined by comparing simulated and measured total scatter factors for the 1 cm × 1 cm field size, according to the procedure proposed by Francescon et al. [30]. Then, the 6 MV and 10 MV stereotactic beams shaped by the Radionics cones were simulated and the corresponding phase-space files (PSFs) generated. To extend the range of beam sizes studied, square fields (side 1.6 cm, 1.0 cm, 0.8 cm and 0.5 cm at the isocenter) defined by the linac jaws were also simulated. The BEAMDP program [31] was used to analyse the phase-space files and to derive the photon beam energy spectra.

The values of the EGSnrc simulation parameters are summarized in table 1. For the BEAMnrc simulations, cutoff energies were set to 10 keV for photons (PCUT) and 700 keV for electrons (ECUT, electron rest mass included). The range rejection (RR) and the directional bremsstrahlung splitting (DBS) techniques were applied to improve the calculation efficiency of photon beam simulations [32,33]. The RR