An empirical relationship for determining photon beam quality in TG-21 from a ratio of percent depth doses

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A key component of the Radiological Physics Center's (RPC) on-site dosimetry review visits are photon beam calibrations for which determination of the energy of the x rays is a key element. The ratio of ionizations, TPR_{20}/TPR_{10}, for a $10\ cm\times 10\ cm$ field at depths of 20 and 10 cm for a constant SCD is used as a quantitative measure of beam quality in the Task Group 21 protocol. The RPC has measured both TPR_{20}/TPR_{10} and the corresponding ratio of percent depth dose (D_{20}/D_{10}) at a constant SSD for 685 photon beams (4–25 MV) for most makes and models of accelerators. A strong correlation between TPR_{20}/TPR_{10} and D_{20}/D_{10} is presented which allows the determination of the TPR ratio from the measurement of the ratio of percent depth doses. An analysis of the uncertainty introduced in the TG-21 factors ($\bar{L}/\rho$, P_{wall}, P_{repl}) caused by the spread in the measured data and translated into the determination of the TPR ratio results in an insignificant error ($<0.3\%$). This empirical relationship provides an alternate technique for quantifying the beam quality defined in the TG-21 protocol without surrendering any loss of precision in output calibration. This technique may be found by those who calibrate at a fixed SSD to be an easier and quicker method. [S0094-2405(98)00507-0]

Key words: photon energy, photon calibration, dosimetry, ionization ratio

I. INTRODUCTION

The Radiological Physics Center (RPC) has, since 1969, performed on-site dosimetry review visits to institutions participating in cooperative clinical trials funded by the National Cancer Institute. The RPC's policy is to implement the American Association of Physicists in Medicine (AAPM) Task Group 21 (TG-21)'s published protocol for the calibration of high-energy photon and electron beams.[1] A key element of the photon beam calibration is determination of the effective x-ray beam energy. The manufacturers normally specify the photon beam energy as the nominal electron energy at the vacuum window. The photon spectrum generated depends on the target, and electron energy but the beam is also degraded by the flattening filter and any beam-shaping or modifying devices. Beam quality is reflected in its penetrating ability (i.e., depth-dose characteristics) and quantified by the ratio of doses at various depths. The TG-21 protocol quantifies beam quality by the ratio of ionization (dose) measured at 20 cm and 10 cm depth in water at a constant source-to-chamber distance (SCD) for a $10\ cm\times 10\ cm$ field at the chamber (TPR_{20}/TPR_{10}). Accurate knowledge of the quality of the beam is crucial for performing a TG-21 calibration since many of the TG-21 factors ($\bar{L}/\rho$, P_{repl}, P_{wall}, $\bar{\mu}_{en}/\rho$) are a function of the beam energy. In the TG-21 protocol, the IR is related to the nominal accelerating potential of the accelerator (NAP), but the NAP may or may not be related to the actual incident electron energy. We will not use NAP further in this discussion.

In 1979, Brahme and Svensson[2] were the first to quantitate megavoltage photon beam quality using the ratio of the absorbed dose (or ionization) at depths of 10 and 20 cm at a constant source-to-surface distance (SSD). This technique was then incorporated into the Nordic Association of Clinical Physicists calibration protocol[3] in 1980 and was the first protocol to recommend quantifying megavoltage x-ray beam quality from the ratio of ionization readings at a constant SSD. The subsequently published AAPM TG-21 protocol[1] recommended that beam quality be quantified by the ratio of ionization readings at 20 and 10 cm depths at a constant SCD. These recommendations were based on data published by Cunningham and Schulz.[4] The International Atomic Energy Agency (IAEA) protocol[5] (Technical Report Series No. 277) published in 1987 allows the protocol user to determine the beam quality from a ratio of ionization readings at 20 cm and 10 cm in water, either at a constant SSD of 100 cm (D_{20}/D_{10}) or a constant SCD (TPR_{20}/TPR_{10}). The IAEA presented a limited number of TPR_{20}/TPR_{10} vs D_{20}/D_{10} data using unreferenced published depth-dose data. Although there is agreement in the physics community that the ratio of ionization at depths of 20 and 10 cm is a proper qualifier of photon beam quality for calibration purposes, different ratios

TABLE I. Machine make and model of accelerators measured by the Radiological Physics Center.

Varian[a]	Siemens[b]	Philips[c]	GE/Orion[d]	AECL/ Theratronics[e]	Mitsubishi[f]/Scanditronix[g]
Clinac 4	Mevatron 6	SL75	CGR Orion	Therac 6	Mitsubishi EXL-8
Clinac 4/100	Mevatron 12	SL75/5	Sagitaire	Therac 20	Mitsubishi EXL-22
Clinac 6	Mevatron 20	SL75/10	Saturne III	Therac 25	Microtron 6
Clinac 6/100	Mevatron 67	SL75/14	Saturne 40		Microtron MM22
Clinac 600C	Mevatron 77	SL75/20	Saturne 43		
Clinac 12	Mevatron 74	SL20			
Clinac 18	Mevatron 80	SL25			
Clinac 1800	Mevatron 6300				
Clinac 20	Mevatron 6700				
Clinac 2100C	Mevatron MD				
Clinac 2300C	Mevatron MD2				
Clinac 2500	Mevatron KD				
	Mevatron KD2				

[a]Varian Associates, Palo Alto, CA.
[b]Siemens Medical Corp., Iselin, NJ.
[c]Philips Medical Systems Linear Accelerators, Shelton, CT.
[d]General Electric (CGR)USA/Orion Research, Inc., Boston, MA.
[e]AECL/Theratronics International Ltd., Kanata, Ontario, Canada.
[f]Mitsubishi International Corp., Philadelphia, PA.
[g]Scanditronix, Inc., Essex, MA.

are used in different protocols (SSD vs SCD).[6] An institution, depending on its techniques for gathering dosimetry data and calibrating its x-ray beams, may have more reliable data at a constant SSD or constant SCD. In most instances, dosimetry data are measured at a fixed SSD and then converted, using formulas found in BJR-17,[7] to isocentric data. The conversion formulas must account for effects due to the inverse-square law, changes in beam divergence and changes in scatter with field size. These effects represent the experimental and theoretical differences observed between fixed SSD and fixed SCD depth dose data and may introduce some degree of uncertainty in the calculated isocentric data as compared to the measured fixed SSD data. Using the more reliable data in either case should therefore reduce uncertainty in the subsequent determination of machine output.

The RPC is in the unique position of having made a large number of consistent measurements at more than 500 institutions, on most makes and models of linear accelerators, with energies ranging from 4 to 25 MV. The purpose of this paper is to (1) present a correlation between D_{20}/D_{10} and $\mathrm{TPR}_{20}/\mathrm{TPR}_{10}$ measured on 685 x-ray beams, (2) compare these data with those published by the IAEA and the accepted calculating technique in the British Journal of Radiology (BJR)#17;[7] and (3) assess the magnitude of any possible uncertainty in beam calibration introduced by using our D_{20}/D_{10} data to determine the $\mathrm{TPR}_{20}/\mathrm{TPR}_{10}$ used in TG-21.

II. MATERIALS AND METHODS

The $\mathrm{TPR}_{20}/\mathrm{TPR}_{10}$ and D_{20}/D_{10} data were measured on 45 different models of therapy units during the RPC on-site dosimetry review visits since TG-21 was published. The therapy units are shown in Table I. Photon energies ranged from 4 to 25 MV.

Measurements were made in a water phantom using a Farmer-type 0.6 cm^3 ion chamber [NEL 2571, NEL 2505/3A (Nuclear Enterprises, Ltd., Fairfield, NJ) or PTW N23333 (PTW/Nuclear Associates, Carle Place, NY)] with a Keithley model 602 (Keithley Instruments Inc., Cleveland, OH) electrometer. All measurements, even though they were gathered over a period of time, were made in a consistent and reproducible manner.

III. RESULTS AND DISCUSSION

The measured ionization ratio ($\mathrm{TPR}_{20}/\mathrm{TPR}_{10}$) as a function of the measured D_{20}/D_{10} is plotted in Fig. 1. Data for 685 photon beams with energies ranging from 4 MV to 25 MV are presented. A linear regression analysis of the data yielded a straight line (dark solid line) described by the following equation:

$$\mathrm{TPR}_{20}/\mathrm{TPR}_{10} = 1.2661(D_{20}/D_{10}) - 0.0595. \tag{1}$$

The coefficient of determination, r^2, of the fit is 0.992, indicating a good modeling of the data. The thin solid lines represent $+/-$ twice the standard error of estimate within which 96% of the data fall. The open triangle symbols, representing the data presented in the IAEA Technical Reports Series No. 277,[5] all fall within one standard error of estimate of our fit. The IAEA data, although limited, therefore agree with our extensive set of measured data and resulting regression fit. Andreo *et al.*,[8] in generating the IAEA data, derived a third-order polynomial relationship, between $\mathrm{TPR}_{20}/\mathrm{TPR}_{10}$ and D_{10}/D_{20}, but from a limited set of unreferenced published data. In addition, Andreo *et al.*'s TPR data were not measured, but calculated from percent depth dose data. The large number of measured TPR and percent depth dose data presented here, as compared to the Andreo group's or IAEA's data, results in a simple linear relationship that fits the data more precisely and reliably. It is clear from our data that one

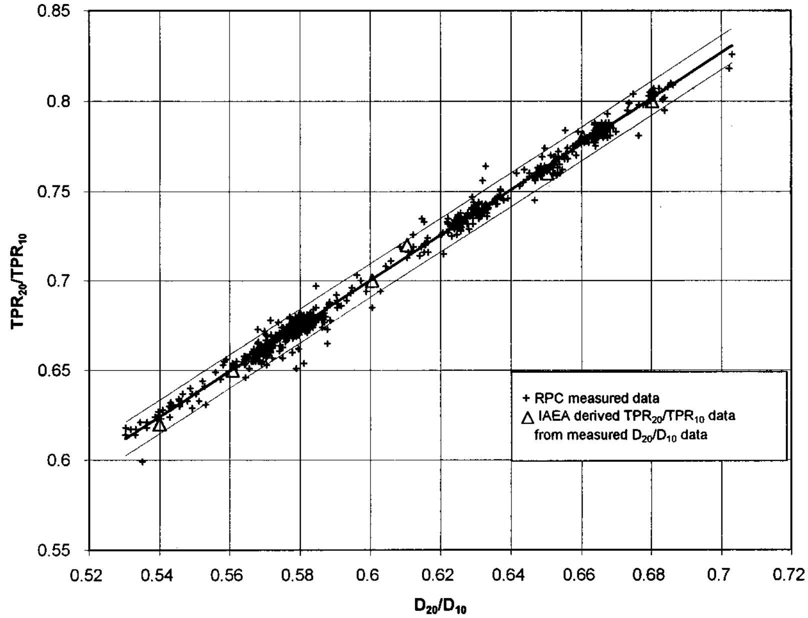

FIG. 1. The correlation of D_{20}/D_{10} ratio to ionization ratio (dark solid line) with specific Radiological Physics Center (RPC) measured data (+) and the International Atomic Energy Agency data (△) indicated. The thin solid lines represent ± twice the standard error of the estimate.

can measure the D_{20}/D_{10} ratio with confidence to precisely characterize the photon beam quality on which the TG-21 calibration factors depend.

IV. EFFECT ON DOSE-CALCULATION VALUE

The values of three factors in TG-21 ($\bar{L}/\rho$, P_{wall}, and P_{repl},) depend directly on the photon beam quality. Any measurement of beam quality, whether it is a D_{20}/D_{10} or TPR_{20}/TPR_{10} ratio, will each introduce a certain amount of uncertainty into the final absorbed-dose calculation. The uncertainty associated with quantifying x-ray beam quality using the D_{20}/D_{10} ratio can be broken into two main components. First, there is the uncertainty in the actual set-up and measurements which should be no different for

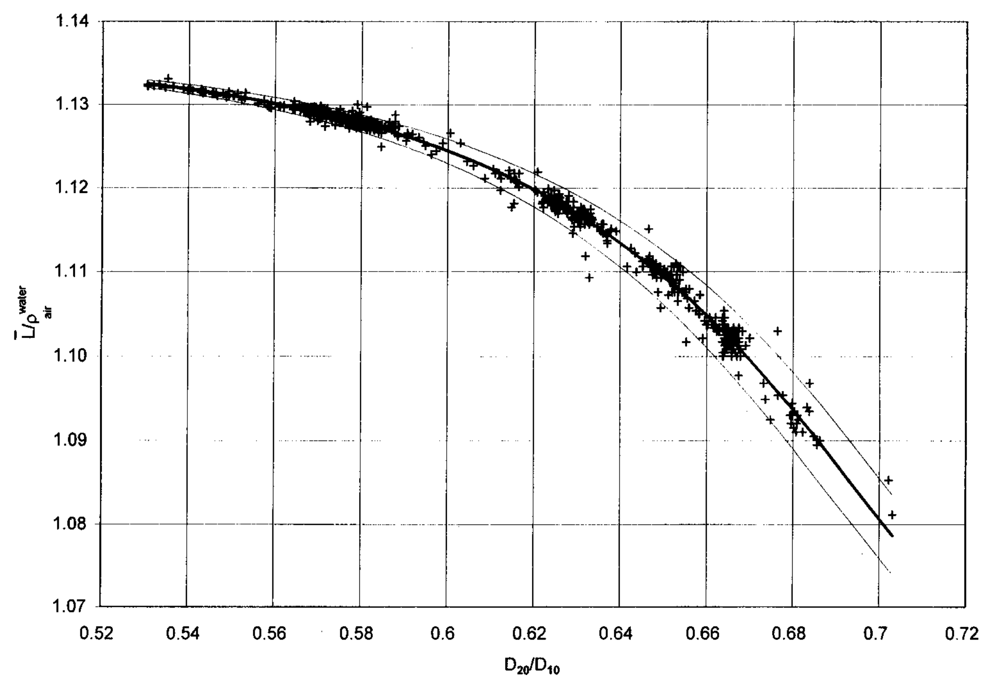

FIG. 2. The mean restricted stopping power ratio determined from the ionization ratio vs D_{20}/D_{10} correlation in Fig. 1 (dark solid line), with specific mean stopping power ratios determined from the RPC D_{20}/D_{10} ratio measured data (+). The thin solid lines represent a spread of ±0.25% in the determination of $\bar{L}/\rho$ from the correlation in Fig. 1.

TPR_{20}/TPR_{10} or D_{20}/D_{10}. Second, the spread in our measured data and the correlation coefficient of the relationship introduce a small amount of error in calculating the TPR_{20}/TPR_{10} ratio from D_{20}/D_{10}. The slope of the fitted line in Fig. 1 characterizes the difference in the uncertainties of the two measured ratios. Therefore, any additional uncertainty introduced in the calculation of absorbed dose from using the D_{20}/D_{10} data is minimized by the strong correlation of the fitted data. P_{wall} and P_{repl} change by less than 0.5% over the range of energies from 4 to 25 MV so any small errors introduced in the TPR_{20}/TPR_{10} will represent minimal uncertainty in calculated dose.

To estimate the uncertainty in $\bar{L}/\rho$ from uncertainty in IR introduced D_{20}/D_{10}, we present the mean restricted stopping power vs the D_{20}/D_{10} ratio (Fig. 2) where $\bar{L}/\rho$ was determined from the TPR_{20}/TPR_{10} ratio for each beam using figures and tables in TG-21. The thick solid line in Fig. 2 is a mapping of the thick solid line of Fig. 1. The effect of uncertainty in the beam quality determination using the D_{20}/D_{10} ratio on the $\bar{L}/\rho$ factor can be seen in the spread of the data in Fig. 2. The two thin solid lines represent a spread of $\pm 0.25\%$ in the calculation of $\bar{L}/\rho$, and they encompass 97% of the data (approximately two standard deviations). The data presented in Fig. 2 show that the uncertainty in $\bar{L}/\rho$ due to the spread in our measured data increases with energy. Any uncertainty in the determination of the TPR_{20}/TPR_{10} ratio from a D_{20}/D_{10} ratio would result in no more than 0.3% uncertainty in the calculation of absorbed dose as a result of the uncertainties in P_{wall}, P_{repl}, and $\bar{L}/\rho$.

V. CONCLUSIONS

In this paper we correlated D_{20}/D_{10} through an extensive set of measurements at a constant SSD to the ratio of TPR_{20}/TPR_{10} used in TG-21. The empirical relationship between the D_{20}/D_{10} ratio and the TG-21 TPR ratio was precisely measured. Specification of photon beam quality by the ratio of D_{20}/D_{10} is an acceptable alternate to specification by the ratio of TPR_{20}/TPR_{10}. To quantify the beam quality by measuring the TPR_{20}/TPR_{10} ratio requires the physicist to move both the chamber and phantom whereas with the D_{20}/D_{10} method one only moves the chamber. Data at the RPC indicates that 75% of the photon beams in North America are calibrated using a fixed SSD technique. We believe that the measurement of a D_{20}/D_{10} ratio would be easier and more convenient for most physicists to measure. The relationship between D_{20}/D_{10} and TPR_{20}/TPR_{10} can be obtained from Fig. 1 of this paper or from Table VIII of the IAEA Protocol.[5] Because of the larger sample size, the data in Fig. 1 and subsequent linear relationship in Eq. (1) are considered more precise than the limited IAEA data. We also demonstrated that the uncertainty in the TG-21 factors resulting from the spread in the measured results in Figs. 1 and 2 translate into an insignificant error (less than 0.3%) in absorbed-dose determination. Therefore, depending on an institution's particular technique and set-up for measuring its dosimetry data, the D_{20}/D_{10} ratio can be an easier and quicker technique for assessing the photon beam quality and calculating the beam output than with TPR_{20}/TPR_{10} measurements. The data in Fig. 1 also provide a redundant check of the beam energy determination.

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