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On the impact of ICRU report 90 recommendations on k_Q factors for high-energy photon beams

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Abstract

Purpose: To assess the impact of the ICRU report 90 recommendations on the beam-quality conversion factor, k_Q, used for clinical reference dosimetry of megavoltage linac photon beams.

Methods: The absorbed dose to water and the absorbed dose to the air in two ionization chambers representative of those typically used for linac photon reference dosimetry, a graphite- and a plastic-walled chamber, are calculated at the reference depth in a water phantom using Monte Carlo simulations. Depth-dose calculations in water are also performed to investigate changes in beam quality specifiers. The calculations are performed in a cobalt-60 beam and MV photon beams with nominal energy between 6 MV and 25 MV using the EGSnrc simulation toolkit. Inputs to the calculations use stopping-power data for graphite and water from the original ICRU-37 report and the new proposed values from the recently published ICRU-90 report. Calculated k_Q factors are compared using the two different recommendations for key dosimetry data and measured k_Q factors.

Results: Less than about 0.1 % impacts from ICRU-90 recommendations on the beam quality specifiers, the photon component of the percentage depth-dose at 10 cm, $\%dd(10)_{\mathrm{x}}$, and the tissue-phantom ratio at 20 cm and 10 cm, TPR^{20}_{10}, are observed. Although using different recommendations for key dosimetric data impact water-to-air stopping-power ratios and ion chamber perturbation corrections by up to 0.6 % and 0.4 %, respectively, we observe little difference ($\leq$0.14 %) in calculated k_Q factors. This is contradictory to the predictions in ICRU-90 that suggest differences up to 0.5 % in high-energy photon beams. A slightly better agreement with experimental values is obtained when using ICRU-90 recommendations.

Conclusion: Users of the addendum to the TG-51 protocol for reference dosimetry of high-energy photon beams, which recommends Monte Carlo calculated k_Q factors, can rest assured that the recommendations of ICRU report 90 on basic data have little impact on this central dosimetric parameter.

Keywords: ICRU 90, Reference dosimetry, Beam quality conversion factors

1 Introduction

The International Committee on Radiation Units (ICRU) recently published report 90 (ICRU-90) recommending changes to key dosimetry data which will affect reference as well as clinical dosimetry.[1] The report recommends an increase of the mean ionization energy, I, for graphite from the ICRU-37[2] value of 78 eV to 81 eV and for water from 75 eV to 78 eV. Moreover, it concludes that for graphite, the crystalline density of 2.265 g/cm^3 should be used to determine the density correction while using the bulk density, usually less than 1.8 g/cm^3 in the actual simulation.

Reference dosimetry protocols[3,4] are based on linear accelerators calibrated in terms of dose to water via

$$D_{\mathrm{w}} = M\, k_Q\, N^{\mathrm{Co-60}}_{\mathrm{D,w}}, \tag{1}$$

where the fully corrected reading, M, of an ion chamber with a cobalt-60 absorbed dose to water calibration coefficient, $N_{\mathrm{D,w}}$, requires the beam quality conversion factor, k_Q, to account for differences in ion chamber response in cobalt-60 compared to high-energy linac beams.

The 2014 addendum to the AAPM TG-51 protocol for high-energy photon beam dosimetry[5] recommends Monte Carlo (MC) calculated k_Q factors from the publication of Muir and Rogers.[6] The quantities for which ICRU-90 recommend new values enter directly in the calculation of the electron stopping powers and hence could potentially impact MC-calculated k_Q factors. In fact, ICRU-90 predicts that the change in determination of absorbed dose to water is between 0.2 % and 0.5 % for low- to high-energy photon beams when using graphite-walled chambers for dosimetry of linac photon beams. The changes predicted by ICRU-90 are made only by considering changes in water-to-air mass stopping power ratios recalculated in the work of Andreo et al.[7] Here we investigate the impacts using fully modeled ionization chambers. Therefore, the aim of this work is to recalculate k_Q factors for representative chambers to investigate the impact of ICRU-90 recommendations of key dosimetric data.

The potential effect on the beam quality specifier $\%dd(10)_x$ is also investigated for 6 MV and 25 MV photon beams of an Elekta Precise linac. This quantity could be affected by changes in the mass stopping power of water since the maximum dose, D_{max}, can be influenced by electrons generated in the linac head or in the buildup region in the phantom. The impact on the tissue-phantom ratio TPR^{20}_{10} is also investigated.

2 Method

If one assumes that the average energy lost per Coulomb of charge released by electrons in air is independent of beam quality the k_Q factor can, by definition, be directly obtained as the ratio of the dose to the chamber's sensitive volume, D_{ch}, to the dose to water, D_w, at the reference depth in a water phantom for a beam quality Q and a Co-60 beam[6] with

$$k_Q = \left(\frac{D_w}{D_{ch}}\right)^{Q}_{\text{Co}-60}. \tag{2}$$

Two ionization chamber models are considered in this study: an NE2571 Farmer chamber which has graphite walls and an aluminum central electrode and an Exradin A19 with C552 walls and central electrode. These two chamber types are specifically selected for this work as they are archetypal of two overarching classes of chambers available for photon beam reference dosimetry measurements for which k_Q factors could be impacted by ICRU-90 recommendations - a graphite-walled and a plastic-walled chamber. Since the ICRU-90 recommendations are relevant only for graphite and water calculations results for these representative chambers will demonstrate the impacts of ICRU-90 on k_Q factors.

The EGSnrc Monte Carlo simulation toolkit[8] is used to model the transport of electrons and photons in matter and estimate the energy deposited in regions of interest. Density correction files for water and graphite using ICRU-90 recommended values are obtained using the ESTAR computer program.[9] These files provide not only density corrections, but also the mean ionization energy and the density of the medium. The crystalline density of graphite, used to obtain the density correction, is substituted with a bulk density of 1.7 g/cm^3.

Construction details of the chambers are obtained from manufacturer's specifications and the geometry module of the egs++ library is used to create accurate geometrical chamber models. Calculations of the dose to the air in the chamber and dose to water in a small disc of water at the reference depth use the egs_chamber user-code.[10] Spencer—Attix water-to-air mean restricted mass collision stopping power ratio with a cutoff energy Δ of 10 keV, $\left(\frac{L_\Delta}{\rho}\right)^{\text{water}}_{\text{air}}$, are calculated using the SPRRZnrc user-code.[11] Ion chamber perturbation correction factors, P_Q, which account for effects from the chamber wall, central electrode and the impact of the introduction of an air cavity on the electron spectrum, are calculated with

$$P_Q = \left(\frac{D_{\rm w}}{D_{\rm ch}}\right) \Big/ \left(\frac{L_\Delta}{\rho}\right)^{\rm water}_{\rm air}. \quad (3)$$

Photon beams are simulated using a point source at a source-to-surface distance of 100 cm collimated to 10×10 cm^2 at the surface of a 30×30×30 cm^3 water phantom from tabulated spectra. Muir and Rogers[6] indicate that there is no difference within statistical uncertainties of 0.1 % when beams are simulated using a full BEAMnrc accelerator model compared to using tabulated spectra. Details about the beams simulated here are in table 1. The quantities in table 1 are taken directly from Muir and Rogers.[6] These beams cover the entire range of clinically relevant linac photon beam qualities.

Beam	Nominal Energy (MV)	$\%dd(10)_{\rm x}$	TPR^{20}_{10}
^{60}Co Eldorado 6[12]	-	58.4	0.569
Elekta SL25[13]	6	67.3	0.672
	25	82.8	0.791
Varian Clinac[13]	10	73.8	0.734
	18	81.5	0.785

TABLE 1: Radiation sources and beam quality specifiers (the photon component of the percentage depth-dose at 10 cm, $\%dd(10)_{\rm x}$, and the tissue-phantom ratio at 20 and 10 cm, TPR^{20}_{10}) used for updated k_Q calculations.

The MC simulations are performed by tracking particles until their energy falls below a threshold of 10 keV (PCUT = 0.010 MeV, ECUT = 0.521 MeV) or leave the geometry. However, calculations for a few test cases demonstrate that the impact of following particles to the lower threshold of 1 keV is negligible within statistical uncertainties. No sensitivity to the selection of the photoelectric cross sections for all calculated quantities is observed. To improve the efficiency of the calculations, the variance reduction techniques Russian Roulette and photon cross section enhancement are used. Since the changes proposed in the ICRU-90 report suggest k_Q changes of the order of a few tenths of a percent, simulations are interrupted only when the one sigma statistical uncertainty of the dose falls below a value of 0.01 %.

A detailed BEAMnrc model of the NRC Elekta Precise linac, previously validated by Tonkopi et al.,[14] is used as a source of particles for the EGSnrc application DOSXYZnrc to calculate the dose distribution in a 30×30×30 cm^3 water phantom for a 10×10 cm^2 field at a source to phantom surface distance (SSD) of 100 cm. Electrons are transported until their energy falls below 189 keV and photons until their energy falls below 10 keV (ECUT = 0.700 MeV, PCUT = 0.01 MeV). Electron contamination from the linac is included in the calculations, and the dose is scored on the central axis in 1 cm × 1 cm × 0.2 cm voxels, where the 1 cm dimensions are perpendicular to the beam axis and the 0.2 cm dimension is along the beam axis. The effect on $\%dd(10)$ for 6 MV and 25 MV photon beams is demonstrated by analyzing the percentage depth-dose (PDD) curve at a depth of 10 cm.

Rather than comparing results using the ICRU-90-recommended parameters for graphite and water with previous calculations, we also obtain k_Q values using ICRU-37-recommended parameters for these materials. This allows a self-consistent approach to estimate impacts of the new ICRU-90 recommendations where only these differences are considered, although a comparison to previous MC simulations and measurements is also performed.

3 Results

Results comparing calculations using ICRU-37 and ICRU-90 recommendations are presented in table 2. The main result to be taken is that the impact of the recommendations of ICRU report 90 on k_Q values is negligible with a maximum difference of 0.14 %, considering systematic uncertainties on the order of 0.4 % on calculated k_Q factors.[6] The difference in absorbed dose to water is at the level of statistical uncertainties of 0.01 %. This lack of difference is because the reference depth (5 cm for cobalt-60 and 10 cm for MV beams) is in a region of transient charged particle equilibrium. The Spencer—Attix water-to-air mean restricted mass collision stopping power ratio changes by up to 0.6 % in cobalt-60 and 0.4 % in MV beams. Meanwhile, the dose to the chamber is affected by up to 0.4 % for the NE2571 chamber and only about 0.15 % for the Exradin A19. Due to cancellation of effects when taking the ratio of absorbed doses in MV beams to that in cobalt-60, the resulting k_Q factors demonstrate only a small impact for the NE2571 chamber and no impact for the Exradin A19.

Difference (%)										
	Common parameters		NE2571				Exradin A19			
$\%dd(10)_x$	ΔD_w	$\Delta\left(\frac{L_\Delta}{\rho}\right)^{water}_{air}$	ΔD_{ch}	$\Delta(D_w/D_{ch})$	ΔP_Q	Δk_Q	ΔD_{ch}	$\Delta(D_w/D_{ch})$	ΔP_Q	Δk_Q
58.4	0.00	-0.57	0.39	-0.39	0.18		0.13	-0.13	0.43	
67.3	0.00	-0.48	0.33	-0.34	0.14	0.05	0.13	-0.13	0.34	0.00
73.8	0.01	-0.41	0.29	-0.28	0.12	0.11	0.14	-0.13	0.27	0.00
81.5	0.03	-0.37	0.27	-0.25	0.12	0.14	0.15	-0.13	0.25	0.01
82.8	-0.01	-0.35	0.27	-0.28	0.07	0.12	0.12	-0.13	0.21	0.00

TABLE 2: The % difference ($\frac{x_{ICRU-90}-x_{ICRU-37}}{x_{ICRU-90}}$) between calculations that use recommended data from ICRU-90 compared to ICRU-37 for inputs to MC calculations for common parameters (D_w, $\left(\frac{L_\Delta}{\rho}\right)^{water}_{air}$) and for D_{ch}, (D_w/D_{ch}), P_Q, and k_Q for NE2571 and Exradin A19 ion chambers.

Muir and Rogers[6] and Wulff et al.[15] investigate systematic uncertainties in MC calculated k_Q factors. They found that these uncertainties are at the 0.4 % level considering reasonable assumptions. These investigations also looked at the uncertainty in k_Q from potential variation in mean excitation energy, I, for water and graphite. The results of the present work are consistent with these previous investigations and show that the impact of ICRU-90 recommendations are within the estimated systematic uncertainties on calculated k_Q factors.

These results are for two representative ion chamber types specifically selected as examples of the two classes of ion chambers used for reference dosimetry, these being graphite- or plastic-walled chambers. Other graphite-walled chambers used for reference dosimetry measurements only differ from the NE2571 chamber used here in small variations in wall thickness so results will be very similar. There will be no additional impact for other chambers that use plastic walls since the only relevant change from ICRU-90 recommendations for simulations with these chambers is the change in parameters required for water. One other type of chamber, the PTW 30013, commonly used for reference dosimetry measurements uses a combination plastic and graphite wall. However, the thickness of graphite employed for that chamber type is only 0.09 mm compared to the 0.36 mm thick graphite thimble used for the NE2571. Therefore, results for the PTW30013 will fall somewhere between the results for the Exradin A19 and NE2571 and will likely be closer to those for the A19 given the very thin layer of graphite employed. Based on the results in table 2, it is difficult to imagine results for any chamber used for reference dosimetry of MV photon beams differing by more than 0.2 % due to the differences in the recommendations made in ICRU-37 and ICRU-90.

The results for calculations of absorbed dose to the air in the chambers for the NE2571 and Exradin A19 obtained here using ICRU-37 parameters agree within 0.1 % compared to the previous calculations of Muir and Rogers.[6] This is comparable to the statistical uncertainty in the calculations of Muir and Rogers, although other small differences exist between the two sets of calculations (e.g., EGSnrc version, MC transport parameters).

We compare the calculated results for the NE2571 chamber to compiled results from a large comparison of measured results from primary standards laboratories. This data was presented in the publication of Muir et al.[16] and is part of an in-progress report [Stucki, G, private communication (comparison report in preparation)]. A fit to all of the measured data is used for comparison to calculated results. Table 3 shows that, comparing to high-quality experimental k_Q factors for the NE2571 chamber, a small improvement in agreement is observed using ICRU-90 recommended data compared to using the recommendations of ICRU-37 for MC calculations. It also gives values of k_Q factors for the NE2571 and Exradin A19 using both sets of recommendations as a reference.

As an additional result, we calculated the dose to the NE2571 chamber with and without a 1 mm waterproof PMMA sleeve. This allows an estimation of the "sleeve effect" which agrees with experimental and previous MC findings[16–19] of a negligible effect for the Co-60 beam and a 0.25 % effect for the 25 MV beam. These results demonstrate consistency of these calculations with other studies. However, the results presented in tables 2 and 3 do include a water-proofing sleeve for the NE2571 chamber for a realistic simulation.

$\%dd(10)_x$	k_Q			
	NE2571	Exradin A19	NE2571	
	Calculated - ICRU-37		Measurements	Difference (%)
67.3	0.9919	0.9904	0.9936	0.17
73.8	0.9819	0.9800	0.9835	0.16
81.5	0.9682	0.9668	0.9693	0.11
82.8	0.9647	0.9629	0.9666	0.20
	Calculated - ICRU-90		Measurements	Difference (%)
67.3	0.9924	0.9904	0.9936	0.12
73.8	0.9830	0.9801	0.9835	0.05
81.5	0.9696	0.9669	0.9693	-0.03
82.8	0.9658	0.9629	0.9666	0.09

TABLE 3: Comparison of calculated and measured k_Q factors when ICRU-90 or ICRU-37 recommendations are used for inputs to MC simulations. The % difference ($\frac{k_{Q,\text{meas.}}-k_{Q,\text{MC}}}{k_{Q,\text{meas.}}}$) is provided where the results used for comparison are from a compilation of measured results from primary standards laboratories as described in the text. The actual calculated k_Q factors are provided for reference.

The beam quality specifier is required for reference dosimetry measurements for the selection of k_Q for the clinical beam and could also potentially be impacted by ICRU-90 recommendations. The ratio of PDD curves calculated with ICRU-90 and ICRU-37 recommendations for 6 MV and 25 MV beams are shown in Fig. 1. The one sigma statistical uncertainties are less than 0.02 % beyond the maximum dose depth, indicated by the vertical dashed line. In the buildup region the statistical uncertainty increases to about 0.08 % for the 6 MV beam and 0.05 % for the 25 MV beam at the phantom surface. No statistically significant changes in the PDD curves are observed at depths beyond the buildup region. These simulations from a realistic accelerator model that include contaminant electrons generated in the linac head are likely more sensitive to changes to electron stopping powers recommended by ICRU-90 than if a pure photon beam were considered. The value at 10 cm depth in Fig. 1 demonstrates that the effect on $\%dd(10)$ (including electron contamination) is less than 0.1 % when using ICRU-90 parameters for both beam qualities. Although these results are for $\%dd(10)$, the impact will be similar or less for $\%dd(10)_{\mathrm{x}}$, the component of the percentage depth dose independent of electron contamination, which is the relevant parameter for reference dosimetry beam quality specification. The fact that the dose to water does not change at 10 cm depth in the phantom, as is evident in the second column of table 2, demonstrates that the beam quality specifier TPR^{20}_{10} will not be affected by the suggested changes either since it is obtained from the ratio of doses at 10 cm and 20 cm depth deep enough that transient charged particle equilibrium (TCPE) exists.

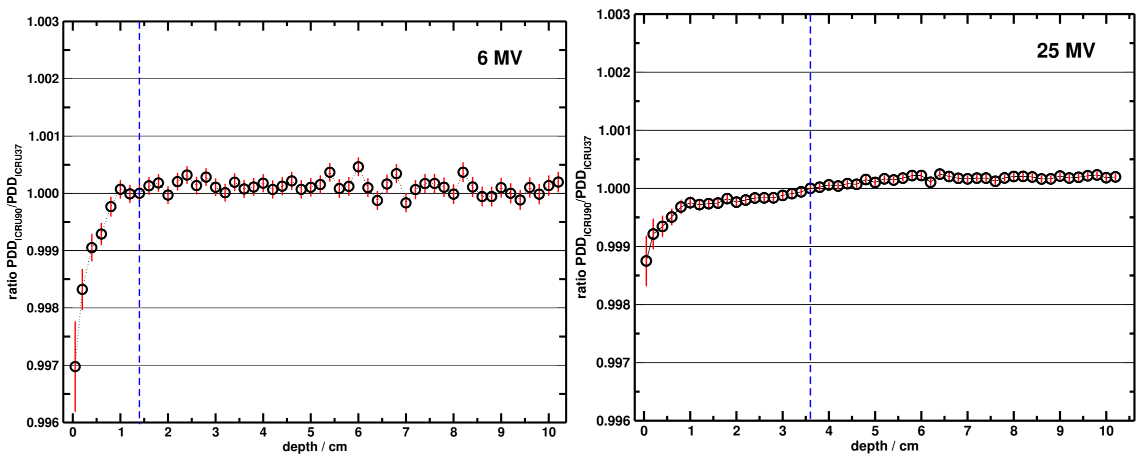

FIGURE 1: Ratios of Elekta Precise PDD curves for 6 MV and 25 MV photon beams for a 10 cm × 10 cm field and an SSD of 100 cm. The vertical dashed line indicates the position of the maximum dose, $\mathrm{D}_{\mathrm{max}}$. The value at 10 cm depth can be used as an indicator for any relative variation in the beam quality specifier, $\%dd(10)$.

4 Conclusions

Comparison with experimental k_Q factors for the NE2571 chamber suggest slightly better agreement with the MC calculated k_Q factors that use the new ICRU-90 recommendations.

The results of this work show that there will be very little change to Monte Carlo calculated beam quality specifiers $\%dd(10)_{\mathrm{x}}$ and TPR^{20}_{10} due to the changes in key dosimetry data recommended in the ICRU-90 report.

The effect on k_Q when changing the mean ionization energy for water and graphite, and using the graphite crystalline density to calculate the density effect correction as recommended by ICRU-90 is at most 0.14 % for high-energy beams, and much less at lower energies. This is contrary to the predictions presented in ICRU-90 that suggest changes between 0.2 % and 0.5 % for low- to high-energy photon beams. Considering that current dosimetry protocols report approximately 0.4 % uncertainties in k_Q factors, the effects observed in this work can be deemed negligible.

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