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Monte Carlo calculation of the k_Q quality conversion factor for the SNC600c ionization chamber for electron beam reference dosimety

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1 Purpose of this report

This report provides calculated values of the beam quality conversion factor k_Q for the Sun Nuclear Corporation ionization chamber model SNC600c, for electron beams, as a function of the beam quality specifier R_{50}. The k_Q conversion factor accounts for the change in chamber response for a given beam quality, with respect to the beam in which it has been calibrated, usually a ^{60}Co reference field.

2 Method

The values of k_Q are derived from EGSnrc Monte Carlo simulations of the SNC600c ionization chamber, following the procedure published by Muir and Rogers [1].

2.1 Principle

The k_Q calculation method relies on the ratio of the dose to water, D_w, to that of the corresponding dose to the cavity air of an ionization chamber, D_{ch}. We calculate this ratio for a ^{60}Co reference field and for each electron beam quality Q, specified by R_{50}. We obtain k_Q for each beam quality by comparing the dose ratio to that obtained in the reference ^{60}Co field:

$$k_Q = \frac{(D_w/D_{ch})_Q}{(D_w/D_{ch})_{^{60}Co}}.$$

2.2 Monte Carlo simulation

We calculate both the dose-to-water D_w and the dose-to-chamber D_{ch} with the `egs_chamber` application, which is part of the EGSnrc toolkit for the Monte Carlo simulation of radiation transport [2, 3].

EGSnrc relies on the Monte Carlo method to sample the physical mechanisms relevant to the passage of individual electrons and photons through matter, including scattering interactions, generation of secondary particles, energy deposition events, etc. This sampling process is repeated for a very large number of independent source particles, until a precise average converges for the quantity of interest, here the dose to either a volume of water or to the chamber cavity air.

We sum up all energy deposition events in the region of interest to obtain the total energy deposited therein. The dose is simply that figure divided by the mass of the region of interest.

2.3 Particle sources

In all simulations we model the incident beam with a spectral point source of particles at 100 cm SSD, collimated to a 10×10 cm^2 square field on the surface of the water phantom. We do not include air above the water phantom in our simulations because it has already been taken into account in generating the various spectra.

For the ^{60}Co reference field calculations we use photons sampled from the tabulated spectrum published by Mora et al. [4]. For electron beams we sample electrons from tabulated spectra corresponding to various beam qualities, as specified by R_{50}, covering a range typical of radiotherapy applications. We use the spectra listed in Table 1, which are taken from References [1] and [5]. The value of R_{50} in each case has been determined directly from Monte Carlo calculated water depth-dose profiles.

TABLE 1 Original accelerator model, nominal energy and spectrum beam quality R_{50} of the electron spectra used for the SNC600c ionization chamber k_Q calculations.

Accelerator model	Nominal energy (MeV)	R_{50} (cm)
Elekta Precise	4	1.79
	8	3.28
	12	4.91
	18	6.99
	22	8.58
Elekta SL75-5	5	2.11
	10	4.15
	14	6.03
Varian Clinac 2100C	6	2.64
	15	6.49

2.4 Dose to SNC600c ionization chamber

We use the egs++ geometry library [6], which is part of the EGSnrc toolkit, to build a computational model of the SNC600c ionization chamber, shown in Figure 1. Physical dimensions and composition of the chamber components are based on specifications provided by Sun Nuclear Corporation. For dimensions missing from the technical drawings, we rely on direct to-scale drawing measurements in a vector illustration program. The volume of air in the chamber cavity is 0.6137 cm^3.

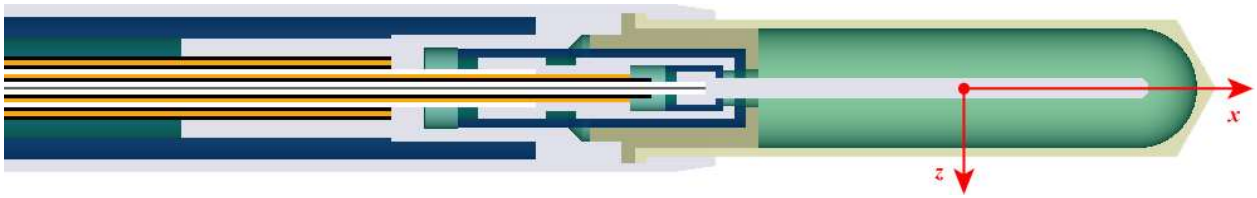

FIGURE 1 The SNC600c chamber egs++ model for EGSnrc Monte Carlo k_Q calculations. This section view reveals the internal structure of the chamber thimble and stem. Axes overlayed in red show the chamber orientation. The geometry is cylindrically symmetric around the x-axis. The axes origin corresponds to the point of measurement, which is 1.3 cm from the chamber tip.

We do not take machine tolerances into account in the model, i.e., tolerances are not reflected in the reported uncertainties. We expect a ratio quantity such as k_Q to be rather insensitive to such small variations in chamber geometry. Likewise we do not model the thin layer of Sherwin-Williams POLANE® T paint on the thimble shell, and instead extend the thimble wall material (G347B graphite) to the full specified 7.05 mm outer diameter of the thimble shell.

For k_Q calculations the chamber model is further inscribed in a $30 \times 30 \times 30$ cm^3 water phantom, with its point of measurement on the central beam axis, at various distance below the water surface. For ^{60}Co reference conditions the chamber is positioned 5 cm below the water surface. For any other specific electron beam quality R_{50} the point of measurement is positioned at the reference depth d_{ref} prescribed by the TG-51 protocol [7]:

$$d_{\text{ref}} = 0.6R_{50} - 0.1 \text{ (cm)}.$$

2.5 Dose to water

The dose to water is calculated in a $30 \times 30 \times 30$ cm^3 water phantom. We tally energy deposited in a disk-shaped water region 0.025 cm thick and 2 cm in diameter; its volume is 0.078530 cm^3. This dose scoring disk is centered on the central beam axis, at either 5 cm depth for the ^{60}Co field, or at the reference depth d_{ref}, defined above, for electron beams (i.e., centered on the same location as the point of measurement of the chamber).

2.6 Materials

For the purpose of radiation Monte Carlo simulations, materials are considered homogeneous blends of their constituent atoms, with no crystalline order or molecular structure. Therefore only the bulk density and the mass fraction of the constituting elements are significant. The mean ionization energy I of the material also plays a role through the density effect parameter, which we obtain from the NIST stopping-power and range tables for electrons [8]. Listed in Table 2 and Table 3 are the composition and properties of all materials used in the SNC600c ionization chamber simulations.

It is worth noting that for the G347B graphite resin material, we use the bulk density of the material 1.990 g/cm^3 to calculate the density effect parameter, instead of the microscopic grain density of 2.265 g/cm^3 which normally applies for pure graphite [9]. This is because G347B comprises 17.2% hydrogen and oxygen atoms, and we have no practical way to assess the density at the microscopic level. However, we did check that using a density effect parameter based on a 2.265 g/cm^3 grain density has a negligible impact on the calculated k_{Q} values for the SNC600c chamber.

TABLE 2 Density, mean ionization energy I and elemental composition of organic compounds used in SNC600c Monte Carlo simulations.

			Mass fraction (%)					
Material	Density (g/cm^3)	I (eV)	H	C	N	O	Cl	Ar
air	0.0012048	85.666		0.0124	75.5267	23.1782		1.2827
G347B	1.990	76.4	3.4	82.8		13.8		
PE	0.930	57.4	14.3711	85.6289				
PEEK	1.300	75.3	4.2	79.2		16.6		
PVC	1.406	57.4	4.8380	38.4360			56.7260	
water	1.000	75.0	11.1894			88.8106		

TABLE 3 Density, mean ionization energy I and elemental composition of metallic compounds used in SNC600c Monte Carlo simulations.

			Mass fraction (%)										
Material	Density (g/cm^3)	I (eV)	C	Mg	Al	Si	Ti	Cr	Mn	Fe	Ni	Cu	Zn
aluminum 6061	2.70	189.1		1	96.8	0.6	0.15	0.2	0.15	0.7		0.15	0.25
copper	8.96	322										100	
steel	8.06	317.7	0.1			0.7		18	1	71.2	9		

2.7 Monte Carlo transport parameters

By default we turn on most EGSnrc advanced physics options for the simulation of the SNC600c ionization chamber, since they allow for the most accurate simulations and only incur an incremental computational cost. Not all such processes contribute to chamber response at MeV energies. We use kinetic energy cutoffs of 10 keV for electrons and photons, so processes below this energy threshold are not simulated. For reference, we list below the EGSnrc input block for Monte Carlo transport parameters. Further explanations about the meaning of these parameters can be found in the EGSnrc manual [3].

```
:start MC transport parameter:
    Global ECUT                    = 0.521
    Global PCUT                    = 0.010
    Spin effects                   = On
    Brems angular sampling         = KM
    Brems cross sections           = NRC
    Pair angular sampling          = KM
    Bound Compton scattering       = On
    Radiative Compton corrections  = On
    Photoelectron angular sampling = On
    Atomic relaxations             = On
    Photon cross sections          = xcom
:stop MC transport parameter:
```

2.8 Variance reduction techniques

Variance reduction techniques (VRTs) are strategies to increase the rate of convergence of a Monte Carlo calculation. This is achieved by imposing a statistical bias in the random sampling of particle interactions, applied in such a way as to leave intact the overall physics of the simulation.

We resort to three VRTs in SNC600c chamber simulations: 1) temporary phase-space scoring on a surface enclosing both the water disk and the ionization chamber model; 2) photon cross-section enhancement with a factor of 32, within a 1 cm envelope around the scoring region; and 3) range-based electron Russian roulette with a survival probability of 1/64 and a rejection medium set to PE. More information about such VRTs and the meaning of their parameters can be found in the egs_chamber publication [2].

3 Results

Table 4 gives the Monte Carlo derived dose ratios for the ^{60}Co reference field and for other beam qualities, specified by the value of R_{50}. For each electron beam we calculate the values of k_Q by dividing the dose ratio by the ^{60}Co result. The k_Q results are plotted in Figure 2 as a function of R_{50}, and fitted to obtain

$$k_Q = 0.8604 + 0.1206\, R_{50}^{-0.5635},$$

with a root mean square deviation of 0.12%. The fit does not include data points above $R_{50} = 6.5$ cm because our simulations lack photon contamination, which is known to play a role at high energy [1]. Table 4 also provides the value of $k'_Q = k_Q/k_{ecal}$, where $k_{ecal} = 0.8991$ is the extrapolated value of k_Q when $R_{50} = 7.5$ cm in the equation above.

TABLE 4 Monte Carlo simulation data for the SNC600c k_Q calculation. The quality for electrons beams (other than ^{60}Co) is given by R_{50} in cm. Values of k_Q are obtained by dividing each dose ratio by the ^{60}Co value, and $k'_Q = k_Q/k_{ecal}$ with $k_{ecal} = 0.8991$. The numbers in brackets give the statistical uncertainty on the last two digits. The reported statistical uncertainties arise solely from the finite number of source particles in the simulation, and *do not* include any uncertainty related to the construction of the chamber. Single-CPU simulation time is reported for information only.

Beam quality	d_{ref} (cm)	D_w/D_{ch}	k_Q	$k'_Q = k_Q/k_{ecal}$	CPU time (hours)
^{60}Co	5.000	1.11661 (41)			48
1.79	0.974	1.05781 (12)	0.94734 (23)	1.05365 (26)	291
2.11	1.166	1.04953 (11)	0.93993 (22)	1.04541 (25)	324
2.64	1.484	1.03765 (11)	0.92929 (22)	1.03357 (25)	371
3.28	1.868	1.02958 (11)	0.92206 (22)	1.02554 (25)	401
4.15	2.390	1.02138 (12)	0.91472 (22)	1.01737 (25)	422
4.91	2.846	1.01667 (12)	0.91050 (22)	1.01268 (25)	448
6.03	3.518	1.00915 (13)	0.90376 (23)	1.00519 (25)	442
6.49	3.794	1.00740 (13)	0.90220 (23)	1.00344 (25)	461
6.99	4.094	1.00509 (13)	0.90013 (23)	1.00114 (25)	465
8.58	5.048	0.99760 (15)	0.89342 (23)	0.99368 (26)	461

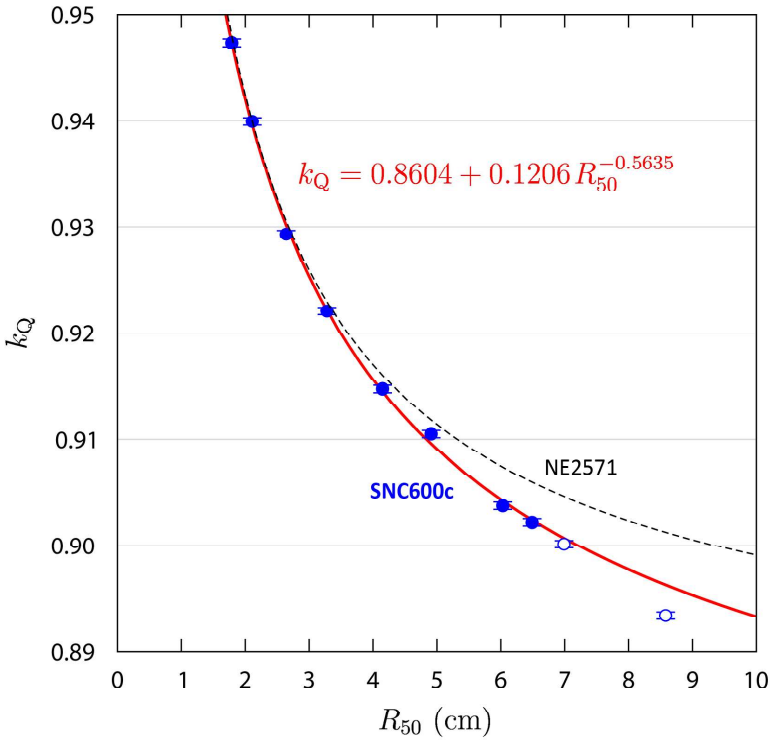

FIGURE 2 Plot of the k_Q values for the SNC600c chamber, as a function of electron beam quality R_{50}. Error bars represent the statistical uncertainties arising from the Monte Carlo simulation. The power law expression shown on the graph provides the best fit, discounting the data points for $R_{50} > 6.5$ cm (open symbols). Also included as a dashed line for comparison is the best fit from Ref. [1] for the NE2571 chamber (with its waterproofing sleeve, and also discounting data for $R_{50} > 6.5$ cm).

4 References

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