Development of an accurate Monte Carlo model of the standard Clinac 6MV beam

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Purpose Monte Carlo (MC) models of radiotherapy beams can be used as a comparison benchmark for other dose calculation methods. In any such comparison process, the degree to which an identified deviation represents an actual error will depend upon the accuracy of the benchmark. As part of an ongoing dosimetric study, we have sought to model the standard Varian Clinac 6MV beam as accurately as possible with the BEAMnrc MC code.

Methods In order to insure the reproducibility of our results, the accelerator head geometry was modeled exactly as specified by the manufacturer, with only the electron source parameters and jaw positions varied. Similarly, the widely available Eclipse 'Golden Beam' data was used for open field comparisons with a target matching criteria of 1% of local dose or 1 mm distance-to-agreement for all depths $\geq D_{max}$ and field sizes ranging from 3x3 to 40x40 cm^2. Except for target bremsstrahlung settings, all other transport parameters were left at their default values. Simulations were run for varied monoenergetic electron energy [5.6:0.05:6.2] MeV, Gaussian intensity distribution FWHM [0.0:0.05:0.25] cm, and beam divergence [0.0:0.2:1.2]°.

Results As has been previously established in the literature, matching was found to be strongly dependent on electron beam energy, intensity FWHM, and choice of bremsstrahlung settings. However, as matching approached the target criteria, results became increasingly sensitive to beam divergence as well. It was also found that when using the default bremsstrahlung settings, accuracy better than ~2% was unobtainable. Under the specified parameter resolution, matching of all points within 1.4%/1.0mm was achieved when using the NRC bremsstrahlung cross section, the higher termed Koch and Motz bremsstrahlung angular sampling, and electron beam parameters of 5.9MeV, 0.1cm, and 0.8°.

Conclusion Under the listed constraints, significant improvements (e.g. matching ~ 1%/1mm) in Golden Beam modeling are not likely achievable.

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Innovation/Impact

Reproducibility We believe this beam modeling study to be innovative because it provides a standard set of parameters that can be used by other BEAMnrc users wishing to model a 6MV Clinac (2100/2300 iX, DX, C/D, EX, cX) beam, arguably one the most common beams in current use. Table 1 lists many, if not all, of the currently published source parameterizations of this beam. Using the default transport settings we were unable to achieve accuracy better than approximately 2% of local dose with any of these source parameterizations. This is likely due, at least in part, by the fact that in many of these studies either the model geometry, or the target data set, or both were different than in our own. In the early stages of our modeling procedure, it would have been invaluable to have known exactly what geometry, transport, and source parameterizations would provide good agreement with a standard open field data set.

Matching Criteria Another important piece of information that is not always explicitly provided is the way matching accuracy is defined. Table 2 lists several MC beam modeling studies and their respective matching results. As we intend to use our model in the recalculation of highly modulated rotational therapy treatments, it was important from the outset for the uncertainty of our model to be a single, well defined value for all points deeper than the build-up region. Our approach was that in order to assign a matching result to a given parameterization, *all* points in the selected data must fall within the stated accuracy threshold.

Other Methodology Details

Transport Parameters It has been stated in the literature that the higher termed Koch and Motz bremsstrahlung angular sampling setting is necessary for accurate results. In addition to this we have found that only the NRC and NIST total bremsstrahlung cross sections, combined with the higher order angular sampling will yield a single parameter set, across all selected field sizes, with matching better than ~ 2%. As the matching criteria window is tightened, small field depth-dose and deeper, large field profiles become the most difficult to match. The slight beam hardening effects seen with these two bremsstrahlung setting combinations are able to shift the smaller field depth-dose enough to provide better matching. We are currently studying which of these two setting is the most optimal as well as how results for each of six possible combinations trend across source parameterizations and field size.

Monte Carlo Data Processing Figure 1 is displays the depth-dose and profile matching for the largest, and most sensitive, field size, 40x40 cm^2. All MC data was first smoothed by an one-dimensional second order adaptive Savitzey-Golay filter and then by an averaging filter set to the width of the ion-chamber used for the Golden Beam data measurements (6 mm).

Year	Author(s)	Clinac Model	Energy	Energy FWHM	Intensity Model	Diameter or FWHM
1997	Liu *et al*	2100 C	6.5 MeV	0%	circular	4 mm
2001	Fix *et al*	2300 C/D	6.05 MeV	0%	pencil beam	n/a
2001	Harmann-Siantar *et al*	not specified	6.2 MeV	0%	circular	2 mm
2002	Ding	21 EX	6.02 MeV	17%	Gaussian	1.2 mm
2002	Sheik-Bagheri and Rogers	not specified	5.7 MeV	3%	Gaussian	2.0 mm
2003	Keall *et al*	21 EX Commissioning Data	6.2 MeV	3%	Gaussian	1.3 mm
2005	Cho *et al*	2100 C/D	6.2 MeV	3%	Gaussian	1.0 mm
2007	Pena *et al*	2100 C/D	6.25 MeV	0%	Gaussian	1.5 mm
2011	Chibani *et al*	2100 C/D	6.3 MeV	0%	Gaussian	1.4 mm
2013	this study	Eclipse Beam Data	5.95 MeV	0%	Gaussian	1.5 mm

Table 1 *List of Monte Carlo 6 MC Varian Clinac beam modeling studies and their respective electron beam parameterizations. Though a specific linac model was not provided by Harmann-Siantar et al and Sheik-Bagheri and Rogers, they are included here as they are both highly cited studies of Varian 6X beams.*

Year	Author(s)	Depth Dose Fall-off	Profile Plateau	Build-up	Penumbra	MC Statistical Uncertainty
1995	Lovelock *et al*	1% of D_{10}	2-3% of D_{CAX}	n/s	n/s	n/s
1999	Libby *et al*	1%[b]	1%[b]	n/s	n/s	n/s
1999	Ma *et al*	2% of D_{max}	n/s	n/s	n/s	< 1%
2001	Hartmann-Siantar *et al*	2% of D_{local}	1% of D_{local}	n/s	n/s	n/s
2002	Sheikh-Bagheri and Rogers	1.5% of D_{local}	2% of D_{local}	n/s	n/s	~ 0.7%
2003	Keall *et al*	1% of D_{max}[c]	1% of D_{max}[c]	n/s	n/s	< 2%
2005	Cho *et al*	1.5% of D_{local}[d]	2%*	3% of D_{local} or 1 mm	2 mm	< 1.5%
2007	Pena *et al*	0.5% of D_{max} or 1 mm	0.5% of D_{max} or 3 mm	n/s	n/s	n/s
2011	Chibani *et al*	1% of D_{local}	1% of D_{local}	n/s	1% of D_{local} or 0.5 mm	~ 0.3%
2013	this study	1% of D_{local}	1% of D_{local}	not used	1% of D_{local} or 1 mm	~ 0.6%

Table 2 *List of Monte Carlo beam modeling studies and their respective matching criteria. n/s: not specified*

[a]Output factors were not used for parameterization but cited as a result.

[b]The percent difference weighting was not clearly specified.

[c]The slope of a linear fit of the deviations was used.

[d]~ 95% of point were within 1% of local dose, 100% of points were within 1.5%.

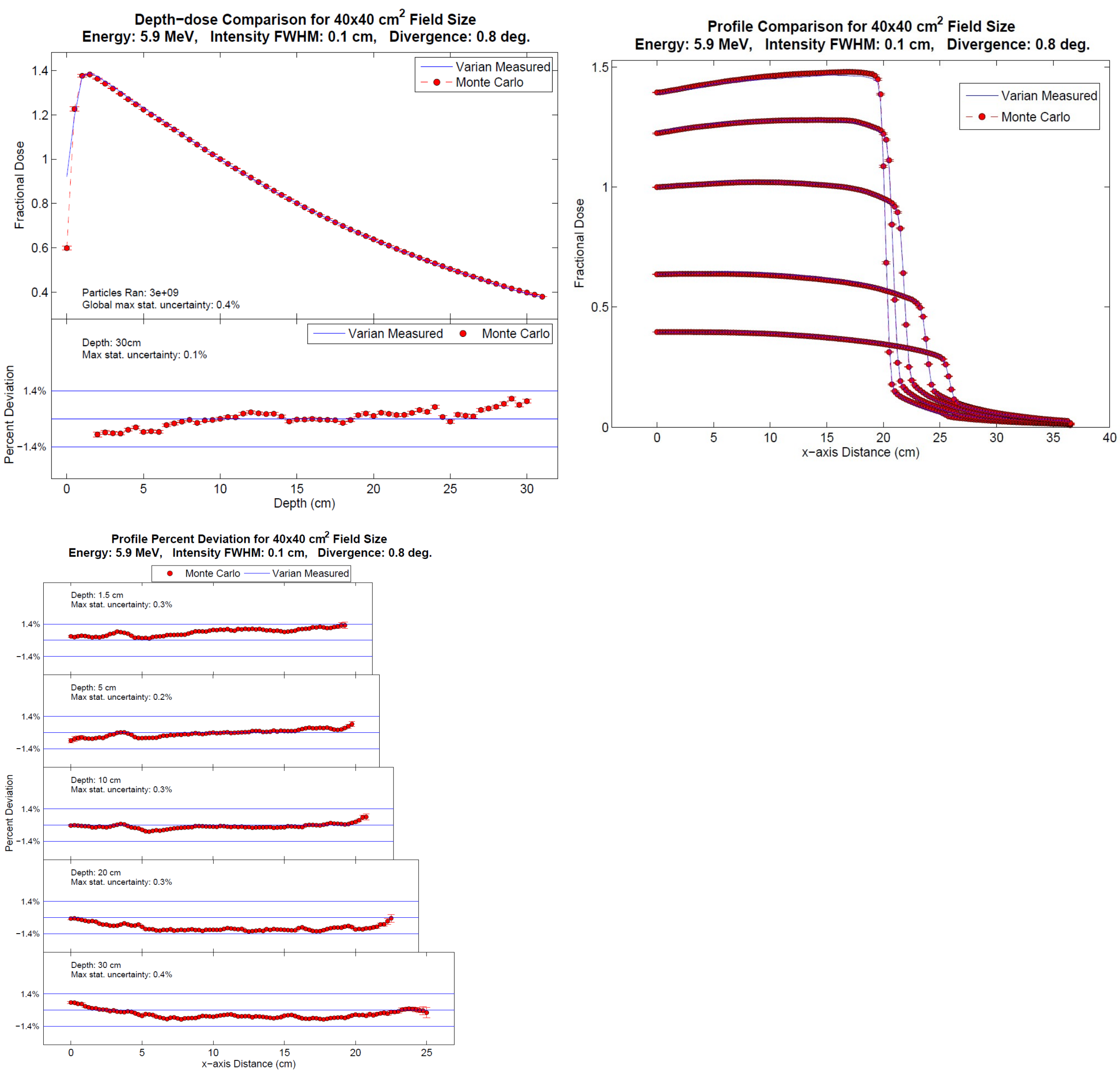

Figure 1 *Example depth-dose and profile matching plots.*