Dosimetric impact of implementing kernel hardening and material-specific kernels in the convolution/superposition method

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Introduction

The purpose of this study is to investigate the dosimetric impact of implementing two improvements to the convolution superposition (C/S) method generally ignored in traditional implementations of the algorithm.

First, the impact of taking into account spectral changes in the photon beam in the energy deposition kernel (EDK) calculation, called the "components method," was investigated. Traditional C/S implementations use a single polyenergetic kernel that reflects the spectrum at a single location (e.g. d_{max} on CAX). This approximation ignores spectral changes with depth, field size, and off-axis distance and can thus lead to dose calculation inaccuracies.

Second, the impact of implementing material-specific kernels, rather than performing density scaling of water kernels for heterogeneity correction, was investigated. It has been shown that the density scaling approximation can lead to dose calculation inaccuracies near material interfaces, such as lung/tissue interfaces.[1] For metal implants, the C/S method using density scaling has been shown to underestimate the backscatter dose upstream of the implant and overestimate the dose downstream of the implant.[2] Implementation of material-specific kernels, that fully describe the dose distribution resulting from photon interactions in non-water equivalent materials, has the potential to improve the accuracy of the C/S method for patients with metal implants.

Impact of kernel hardening

Methods: The effect of depth, field size, and off-axis distance on the primary photon spectrum of a Varian Clinac 2100 6MV photon beam was investigated by performing BEAMnrc Monte Carlo simulations. Our accelerator model consists of the target, primary collimator, flattening filter, and jaws, and has been previously validated against measurements.[3] In order to investigate the dosimetric impact of taking these spectral changes into account in the EDK convolution calculation, depth dose curves for our 6MV photon beam were calculated using two different implementations of the collapsed cone C/S method (Mobius Medical Systems, Houston, TX):[4] one using a single polyenergetic kernel reflecting the surface spectrum ("single kernel" method) and one that represents the ideal case where all the spectral changes of the photon beam are fully taken into account. For the ideal case, a full convolution calculation using a monoenergetic kernel is performed for each energy bin ("components" method).[5] Depth doses were calculated for various field sizes (5x5, 10x10, and 20x20 cm²) in a 30x30x30 cm³ water phantom.

Results: Figure 1 illustrates how the primary photon spectrum changes for different depths, field sizes, and off-axis distances in a water phantom for our 6MV photon beam. Figure 2 compares the percent depth dose (PDD) curves calculated using the "single kernel" and the "components" method in water. The "components" method resulted in a harder PDD curve (i.e., larger PDD value at a given depth) than the "single kernel" method. The PDD value was 2.1% to 5.8% larger at a depth of 25 cm and 1.0 to 2.5% larger at a depth of 10 cm for the "components" method, with the discrepancy being larger for smaller field sizes.

References

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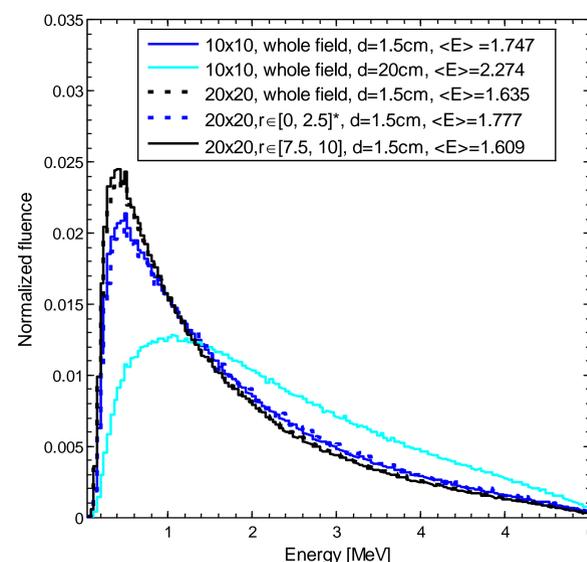
Figure 1: Normalized primary photon spectra for a clinical 6-MV photon beam taken at various locations in a water phantom. The mean energy of the spectrum *<E>* is given in MeV. * Indicates that the beam spectrum was taken over an annular region with an inner radius of r = 0 cm and an outer radius of r = 2.5 cm.
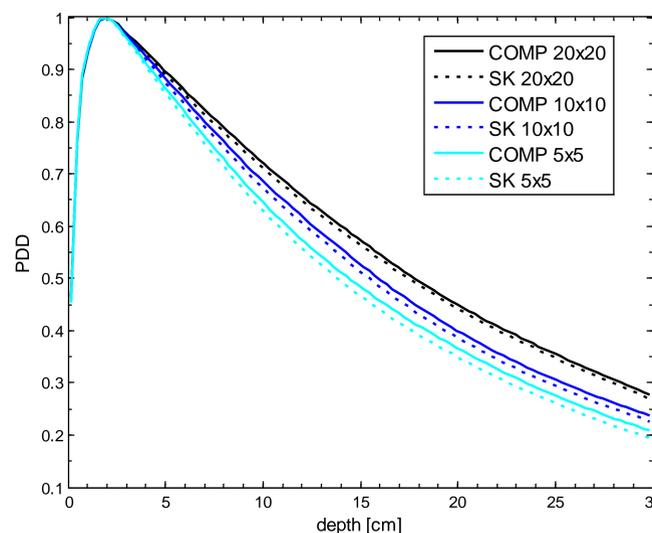
Figure 2: Percent depth dose curves for 6MV photon beam incident on a water phantom calculated using a single polyenergetic kernel ("SK") and the components method ("COMP") for 5x5, 10x10 ,and 20x20 field sizes.

Impact of material-specific kernels

Methods: The EGSnrc user-code EDKnrc was used to simulate energy deposition kernels for photon energies ranging from 100 keV to 8 MeV with 10 million histories each. The simulation geometry consisted of 24 spheres and 48 cones, the geometry used by Mackie *et al.* (1988),[6] and consisted entirely of the material of interest (e.g., bone or titanium). In order to investigate the dosimetric impact of implementing these kernels, a water phantom with a 4x4x4 cm³ titanium cavity, representing a simplified hip prosthesis geometry, was used. The depth dose for this heterogeneous geometry was calculated using both a traditional C/S implementation that performs density scaling of water kernels and a novel implementation using titanium kernels for photon interactions occurring in the titanium cavity. The depth dose was calculated for a field size of 10x10 cm² for our clinical 6MV photon beam.

Results: Figure 3 illustrates the differences between various 1.5 MeV monoenergetic, material-specific kernels. In comparison to water, it can be seen that the bone and titanium kernels deposit more dose in the backward (θ = 180º) and lateral (θ = 90º) directions and less dose in the forward direction (θ = 0º). Figure 4 compares PDD curves calculated using density scaling of water kernels and material-specific kernels for the simplified titanium implant geometry. Implementation of material-specific kernels resulted in a 1.5% higher dose upstream of the implant (i.e., higher backscatter dose) and 5.9% lower dose downstream of the implant.
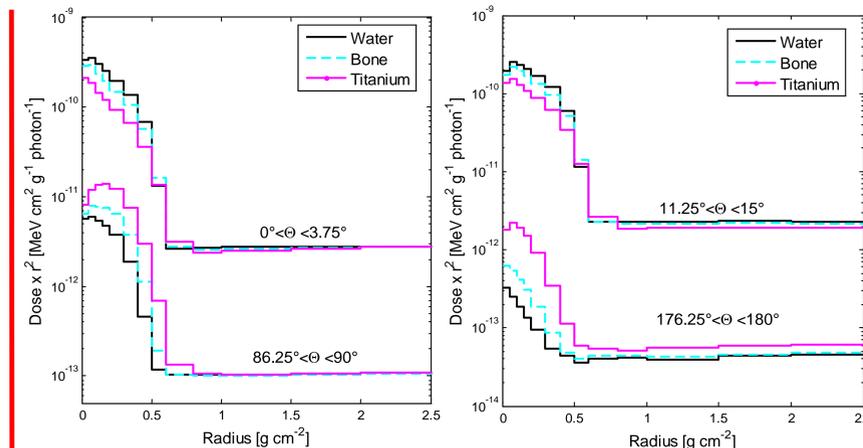
Figure 3: Comparison of water, bone, and titanium monoenergetic kernels for 1.5 MeV incident photons. Shown is the radial dose distribution at selected angular intervals, where θ = 0º is the forward direction, θ = 90º is the lateral direction, and θ = 180º is the backward direction.
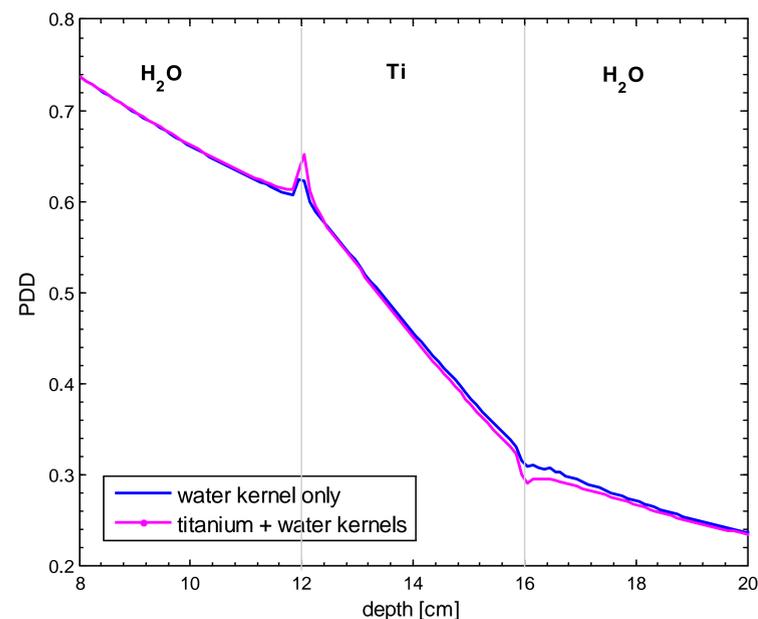
Figure 4: PDD curves for the simplified titanium implant geometry (titanium region extends from z=12 cm to z=16 cm) comparing dose calculated using traditional density scaling of water kernels ("water kernel only") and novel implementation of material-specific kernels ("titanium + water kernels").

Conclusions

➢ Beam hardening with depth has a more dominant effect on the primary photon spectrum than beam softening with greater field size and off-axis distance

➢ Taking into account these changes in photon spectrum in the kernel calculation resulted in a harder PDD curve in water

➢ Implementation of a depth-hardening kernel correction has the potential to affect beam modeling parameters obtained in the treatment planning system commissioning process and thus the overall accuracy of the system.

➢ In comparison to water, higher *Z*, higher density material kernels show more energy deposition in the backward and lateral directions and less in the forward direction

➢ Implementation of metal-specific kernels resulted in better modeling of backscatter and re-buildup phenomenon at the metal/tissue interfaces, reducing dosimetric errors associated with traditional C/S using density scaling of water kernels.

➢ Metal-specific kernels have the potential to improve dose calculation accuracy for patients with metal implants

Support

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