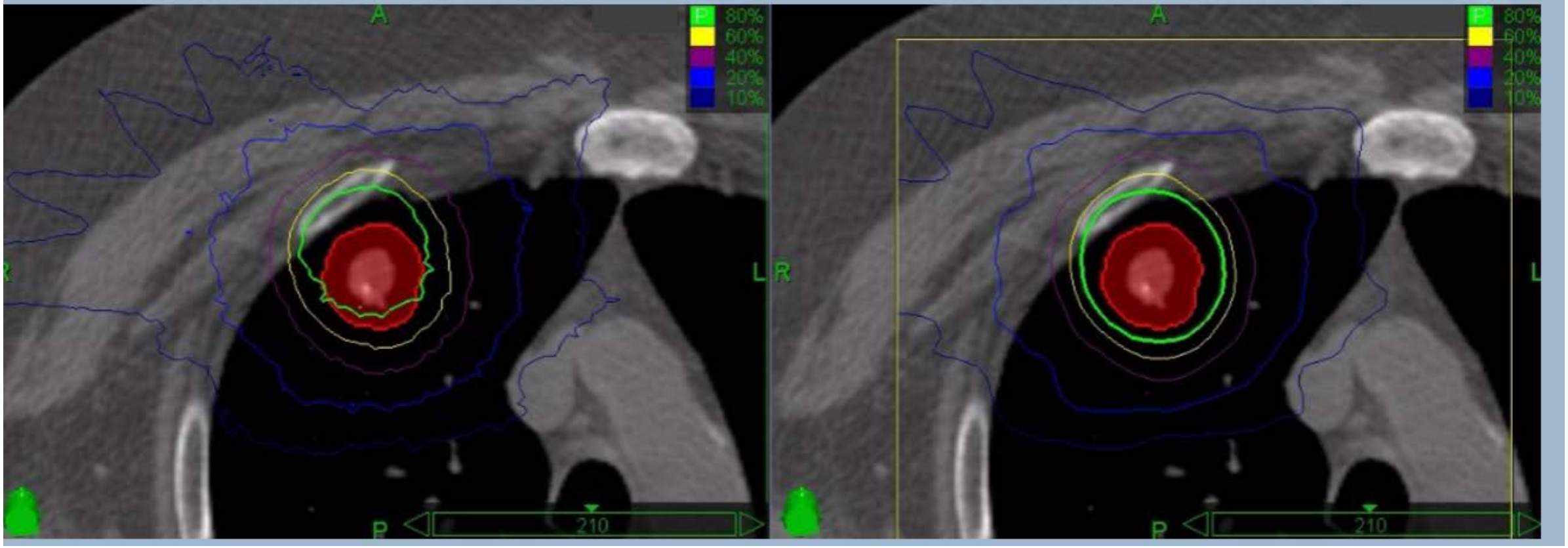
What is the difference between the two plans shown here?



- They are actually the same plan (same beam arrangement, same MU, etc.). The difference lies in the algorithm used for dose calculation. The left panel shows the plan calculated with Monte Carlo. The right panel shows the plan calculated with pencil beam and the simple equivalent path length (EPL) method for heterogeneity correction.
- Since they are the same plan, neither is better than the other. But the Monte Carlo plan will be closer to the actually delivered dose.

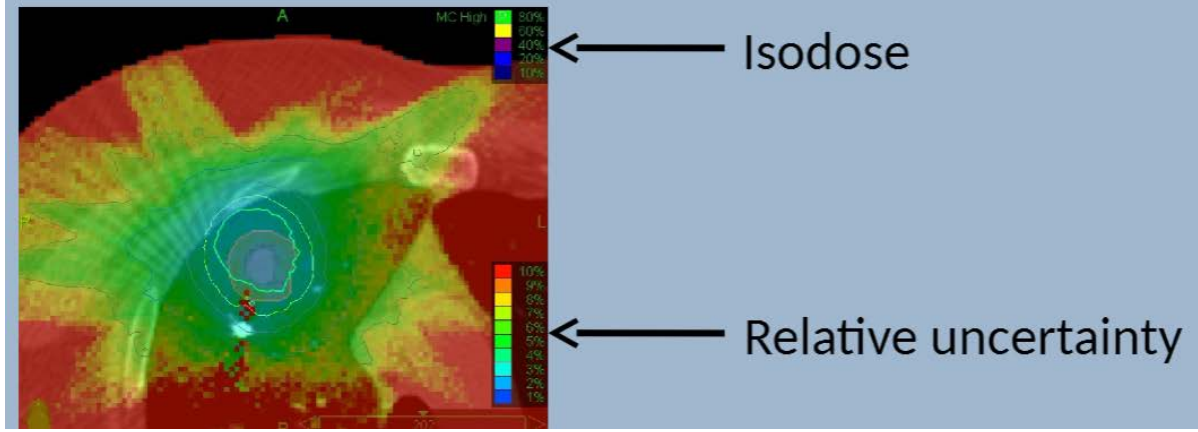
- Equivalent path length (EPL) method assumes electronic equilibrium therefore its calculation is incorrect in that region.
- Monte Carlo algorithm handles electronic disequilibrium very well. At the posterior boundary of the tumor in this case, scatter dose is highly reduced because it is coming from the much less dense lung tissue. This effect is smaller on the anterior portion of the tumor because it is close to the chest wall. Monte Carlo calculates this difference correctly.

Why are the isodose lines on the MC plan jittery?

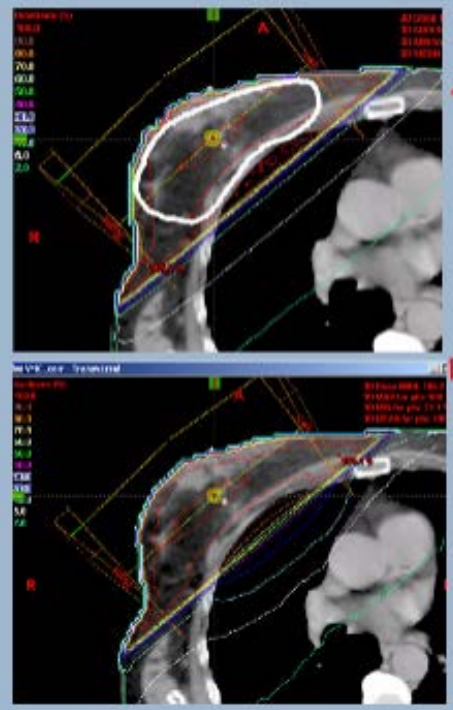
- Monte Carlo is a stochastic method. (You could just stop there) The dose that it generates is a sum of a finite number of dose deposition events that are generated stochastically. Just like in any statistical experiment, you can make the final dose distribution smoother by increasing the number of particles used in the MC simulation, but it will increase the computation time.

What statistical uncertainty is adequate for clinical treatment plans?

- In Monte Carlo plans, each voxel has different statistical uncertainty
- Usually, statistical uncertainty is set on the D_{max} voxel
- TG-105 recommends 2% statistical uncertainty on D_{max} voxel
- $\sigma \approx \sqrt{D}$, however the relative uncertainty is $\sigma/D \approx 1/\sqrt{D}$. Thus the low-dose region has higher relative uncertainty even though the absolute uncertainty is smaller.

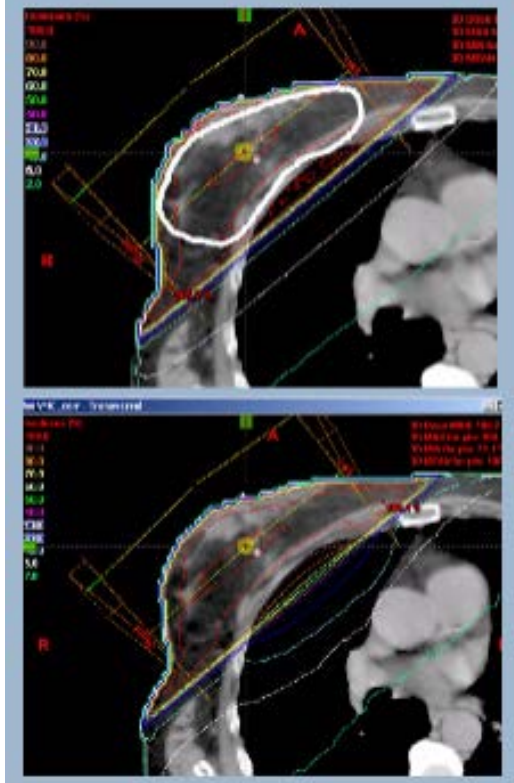


These two plans were calculated with different dose calculation algorithms. What algorithms are likely to have been used here?



- The top panel was calculated with **Pencil Beam Convolution (PBC)**, which is one of the standard algorithms in Eclipse, for example.
- The bottom panel was done with **Monte Carlo (MC)**, which is widely considered a benchmark for dose calculation algorithms.
- Algorithms that take into account secondary electron transport in 3D, such as Pinnacle's **Collapsed Cone Convolution** or Eclipse's **AAA**, will behave similarly to MC and not to PBC. Their low isodose lines will protrude deeper into the lung such as shown here for the MC plan.

Why do the isodose lines look different in these two plans?

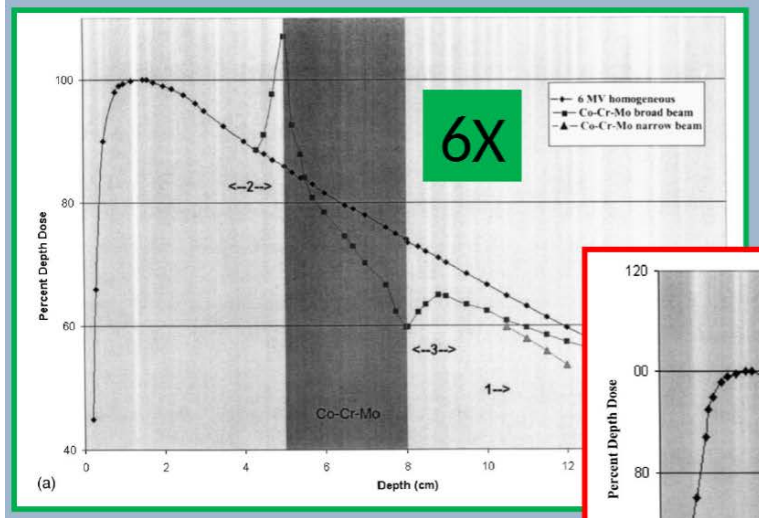


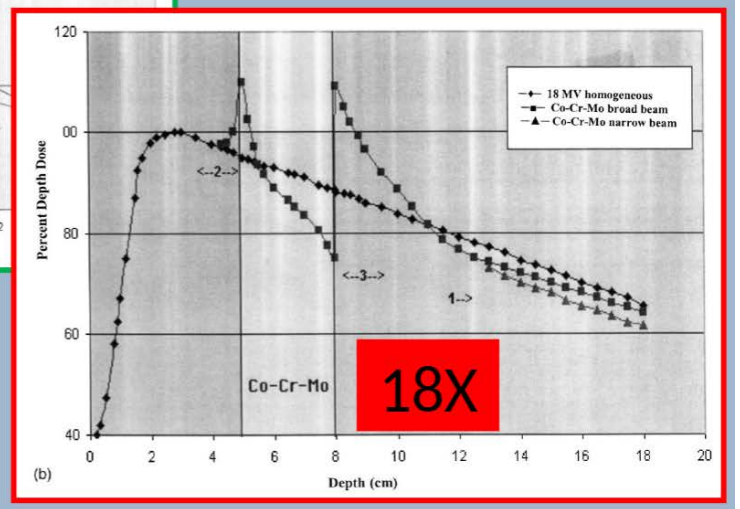
- The PBC plan does not recognize the heterogeneity. The secondary electron transport is not calculated correctly.
- The MC plan transports secondary electron correctly. When the photon energy is released in lung, or close to lung, the secondary electrons it generated can **travel farther in lung** than in tissue (because of lower density).
- If you use higher energy photon, the secondary electrons can travel even further in lung. **The discrepancy between PBC and MC plan will be larger for higher energy photons.**

- These plans use 6X. Will they look more similar or more different if you use 18X?
- How will AAA compare to Pencil beam? More or less accurate in lung?

1

Discuss what is going on with the two PDDs shown in each panel below.
Explain qualitatively the behavior at each interface.
How would these curves be relevant at your clinic?

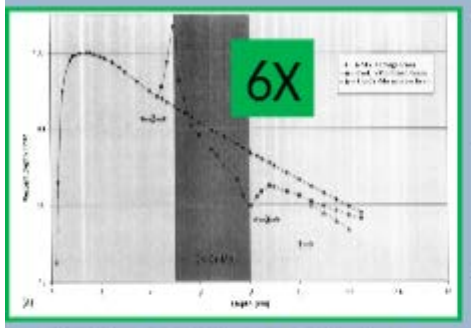




Reft et al., TG-63 (2003)

3

Discuss what is going on with these PDDs.



Z(Co) = 27, Z(Cr) = 24, Z(Mo) = 42
Z_{eff}(Water) = 7.4

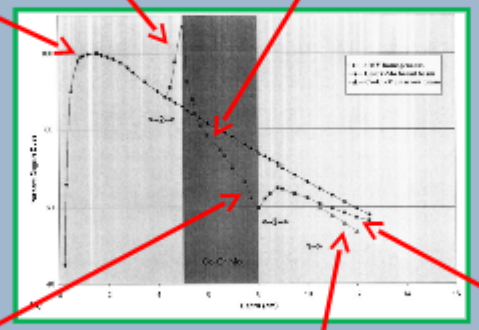
- This panel compares PDD 6X in water and the perturbed PDD that you get when you insert a 3-cm high-Z slab.
- This simulates and quantifies the interface effects due to the presence of hip prosthesis, for example.
- The effective range of the perturbation ≈ range of the secondary electrons in the medium ≈ d_{max}. So you would expect to see non-equilibrium behavior only around the interface ± d_{max}.

4

More back-scattered electrons from metal than from water that it displaces.

At 6X, the dominant interaction is Compton, both in water and in the metal slab. Higher density of metal creates higher attenuation of primary photon beam (steeper slope).

Back-scattered electrons cannot travel too far from the slab, so there is no change in the shallow part of the phantom.



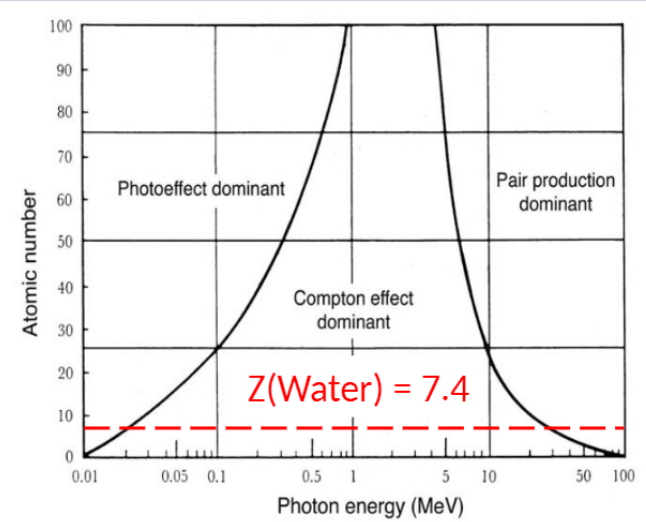
Primary photon beam has passed through longer radiological distance at this point (relative to all water phantom). It has been more attenuated so the new curve is below the all-water curve.

Inside the slab, at distal end, it gets fewer scatter electron from water, so the curve dips down.

Narrow-beam PDD is below broad-beam PDD because it gets less scatter dose.

Follow Up

- Which interaction (PE, Compton, or PP) dominates in water at 6X and 18X? What about high-Z material?

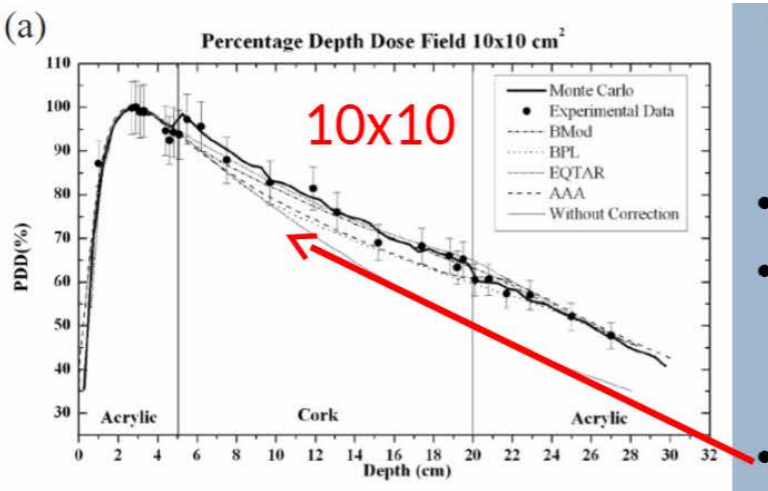


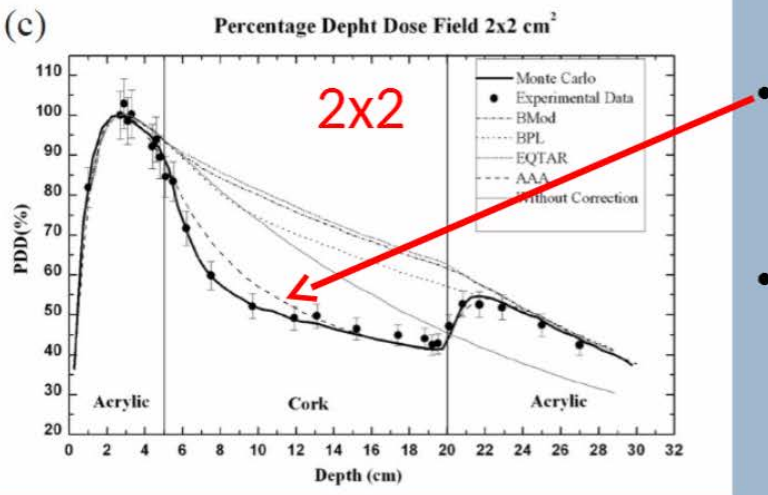
From Podgorsak et al., Radiation Oncology Physics Handbook, IAEA.
Used with permission.

- Photoelectric effect: $\tau/\rho \approx Z^3/E^3$
- Compton scattering: $\sigma/\rho \approx 1/E$
- Pair production: $\pi/\rho \approx Z \log(E)$ above the threshold energy
- So for high-energy photons in high-Z materials, pair production dominates.
- For water, use 25 keV and 25 MeV for boundaries separating the regions where PE, Compton, or pair production is dominant.

For materials with Z ≈ 25 (good enough approximation for implants such as hip prosthesis), use 100 keV and 10 MeV.

- What happens if you insert a low density (lung) slab instead of the high-Z slab shown in the previous slide?





Da Rosa et al., JACMP 11(1), 117 (2010).

What happens to the PDD if you insert a cork slab instead?

- It depends on your field size!
- Basic idea is that there is more scatter dose because electrons can travel farther in cork.
- For large field size, the CAX dose increases in cork because scatter in > scatter out.
- For small field size, the CAX dose decreases in cork because scatter in < scatter out.
- The message is that you have to worry about lateral, in addition to longitudinal, disequilibrium!

At the distal end of the high density slab, the 18X PDD is qualitatively different from 6X PDD. Why?

- The short answer: Pair production!
- At 18X, the competing interactions are Compton and PP.
- PP produces 2 charged particles (electron + positron), both are emitted in the forward direction with respect to the original photon.
- These charged particles have large LET (linear energy transfer) and will transfer most of their energy within short distances from where they are created.
- For 6X, since the main interaction is Compton, the interaction products are mostly photons. Thus, beyond the metal slab, you still get some build up in dose.
- For 18X, due to PP dominance, most of interaction products are mostly charged particles with finite range. There is practically no build up distal to the metal slab.

4

How does a TPS calculate dose distribution?

- The short answer is: Dose = TERMA * Kernel
- Note that the (*) sign is not a simple multiplication! It is a convolution sign (you need to know what that means)
- The math answer is: $\mathrm{Dose}(\mathbf{r}) = \int\int\int \mathrm{TERMA}(\mathbf{r}')\,\mathrm{Kernel}(\mathbf{r}-\mathbf{r}')\,d^3\mathbf{r}'$
- Here is what it says:
  - Energy is released by primary photon at point r'. How much energy is deposited there is given by TERMA(r').
  - Secondary electrons that receive this energy travel away from the point where energy is released. As it travels, it deposits the energy along the way. The fraction of energy deposited at point r, from the energy released at point r', is specified by Kernel(r-r'). You multiply this with TERMA(r') to get the dose contribution to point r from point r'.
  - Sum up the contribution from all r' points to get the dose at r.

5

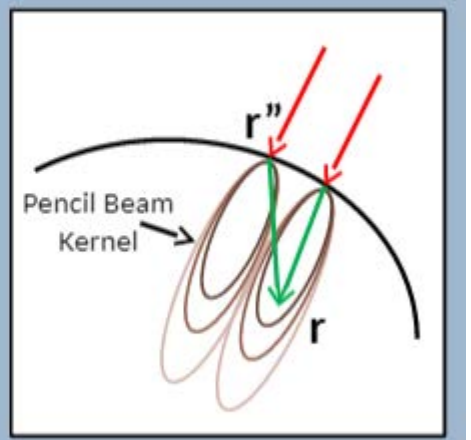
What is the difference between convolution and superposition?

- Convolution: $\mathrm{Dose}(\mathbf{r}) = \int\int\int \mathrm{TERMA}(\mathbf{r}')\,\mathrm{Kernel}(\mathbf{r}-\mathbf{r}')\,d^3\mathbf{r}'$
- Superposition: $\mathrm{Dose}(\mathbf{r}) = \int\int\int \mathrm{TERMA}(\rho\cdot\mathbf{r}')\,\mathrm{Kernel}(\rho\cdot(\mathbf{r}-\mathbf{r}'))\,d^3\mathbf{r}'$
- Convolution method uses the same kernel everywhere. It does not distinguish whether the photon energy is released in muscle or in lung, the energy will be spread out using the same kernel.
- Superposition method uses spatially dependent kernel. The kernel is scaled according to inverse density as shown in the formula above. If the energy is released in lung, it can spread out further away than if the energy is released in lung.
- Superposition equation is obtained by replacing all distances in the convolution equation with radiological distances: $\mathbf{r} \rightarrow \rho \cdot \mathbf{r}$
- Superposition is better because it can handle heterogeneity more accurately. Convolution incorporates transport of secondary electron correctly but it assumes homogeneous medium.

How does Pencil Beam Convolution (PBC) work?

$$\text{Dose}(\mathbf{r}) = \int\int \text{TERMA}(\mathbf{r}'') \frac{|\mathbf{r}''|^2}{|\mathbf{r}|^2} \text{Kernel}_{2D}(\mathbf{r} - \mathbf{r}'')\, d^2\mathbf{r}''$$

- PBC simplifies the original equation by pre-calculating the depth dependence of the kernel.
- Dose contribution is now summed over points on the surface of the phantom instead of the whole volume.
- PBC kernel is a 2D kernel, as opposed to 3D kernel in original convolution formula.
- It handles forward scattering component well but not so much for back and side scattering.



r = dose deposition point
r" = photon interaction point

What is collapsed cone convolution (CCC) algorithm?

- This is used in Pinnacle, among others.
- It a technique to maintain the accuracy of full S/C (somewhat), but speed up the calculation.
- In the original convolution, dose released at a given interaction point needs to be spread out to N^3 other points.
- Instead of using Cartesian coordinates (X,Y,Z), CCC uses spherical coordinates (r,θ,φ).
- CCC divides spheres of each radius into cones that cover the whole sphere. Think of the patches on the soccer ball! Each patch is one cone with the center of the ball being the apex.
- Instead of summing over every points on the ball surface, CCC assigns zero to every point except the center of each patch where it is assigned the total dose from all points in the patch. This is why it is called "collapsed" cone; you collapse the cone into one ray.
- This reduces the number of calculations from N^3 to NM, where M is the number of cones. M is typically about 100, so it is faster.