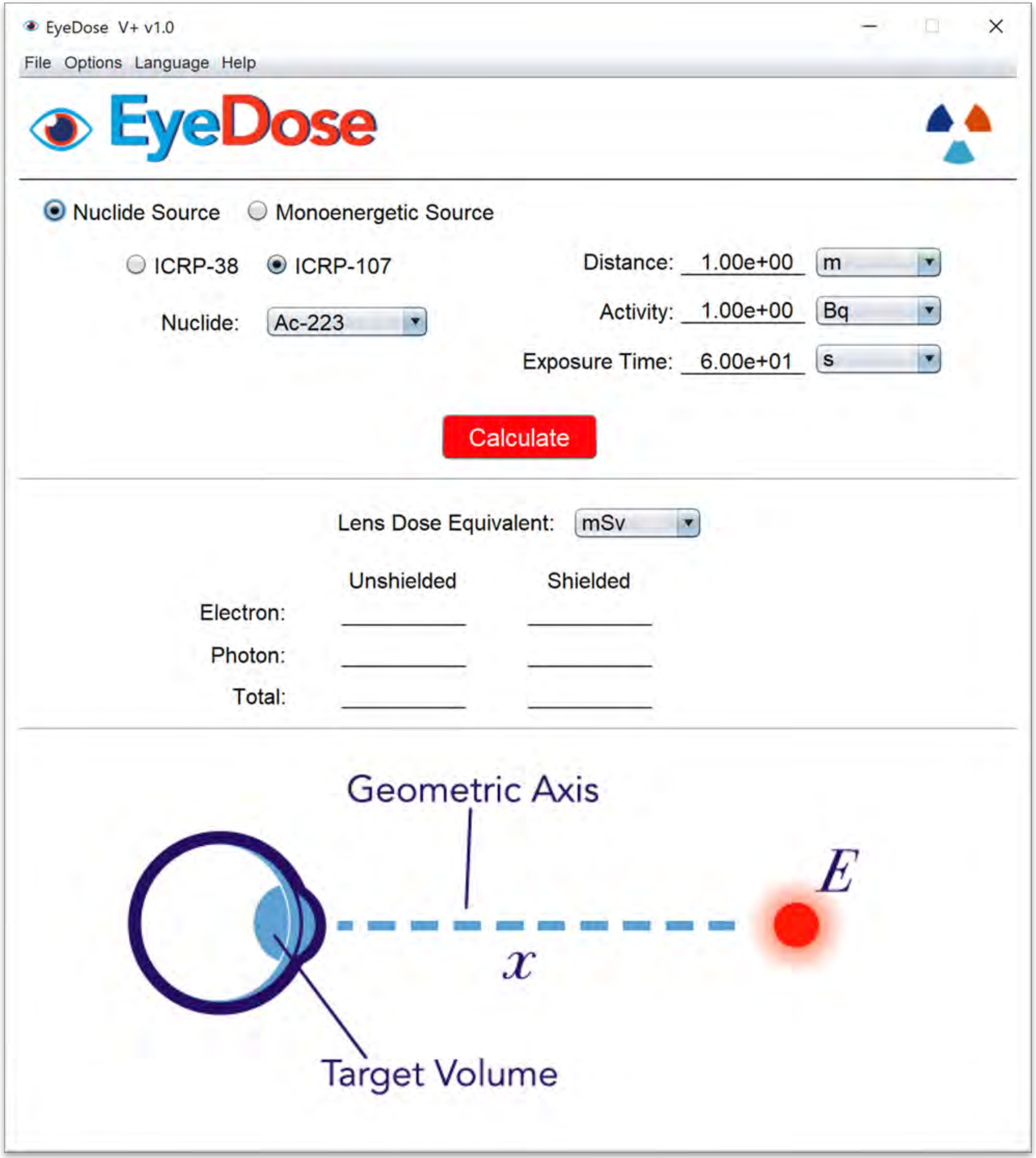


varSKIN+

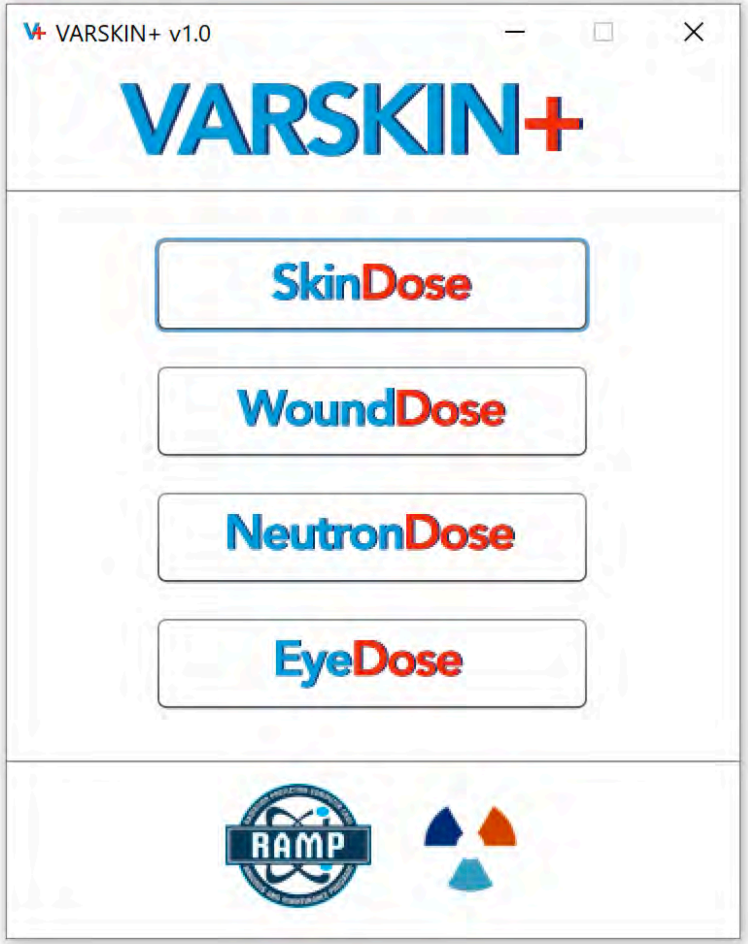
EYE DOSE

RENAISSANCE CODE DEVELOPMENT

Colby Mangini, PhD. CHP

OUTLINE

- Technical Basis
  - Using VARSKIN
- Eye Dosimetry
  - Photon Dose
  - Electron Dose
- V&V
- Examples

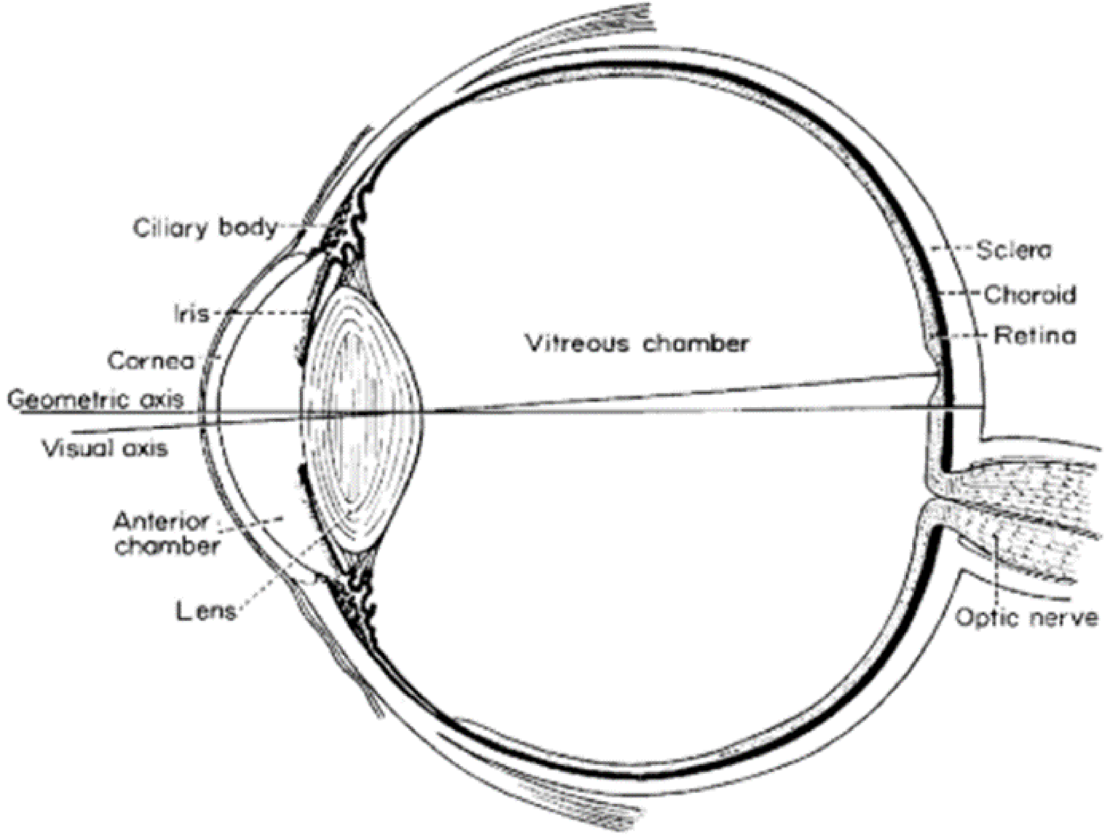


REGULATORY BASIS FOR EYEDOSE

- In the United States from 10 CFR 20.1201 (1991):
  - 150 mSv/yr
- Internationally from ICRP 118:
  - 20 mSv/yr averaged over 5 consecutive years, not to exceed 50 mSv in any single year
- Many nations adopted the new ICRP recommendations, causing a renewed interest in eye dosimetry
  - Some VARSKIN (NRC approved code) users wanted to use code to estimate eye dose

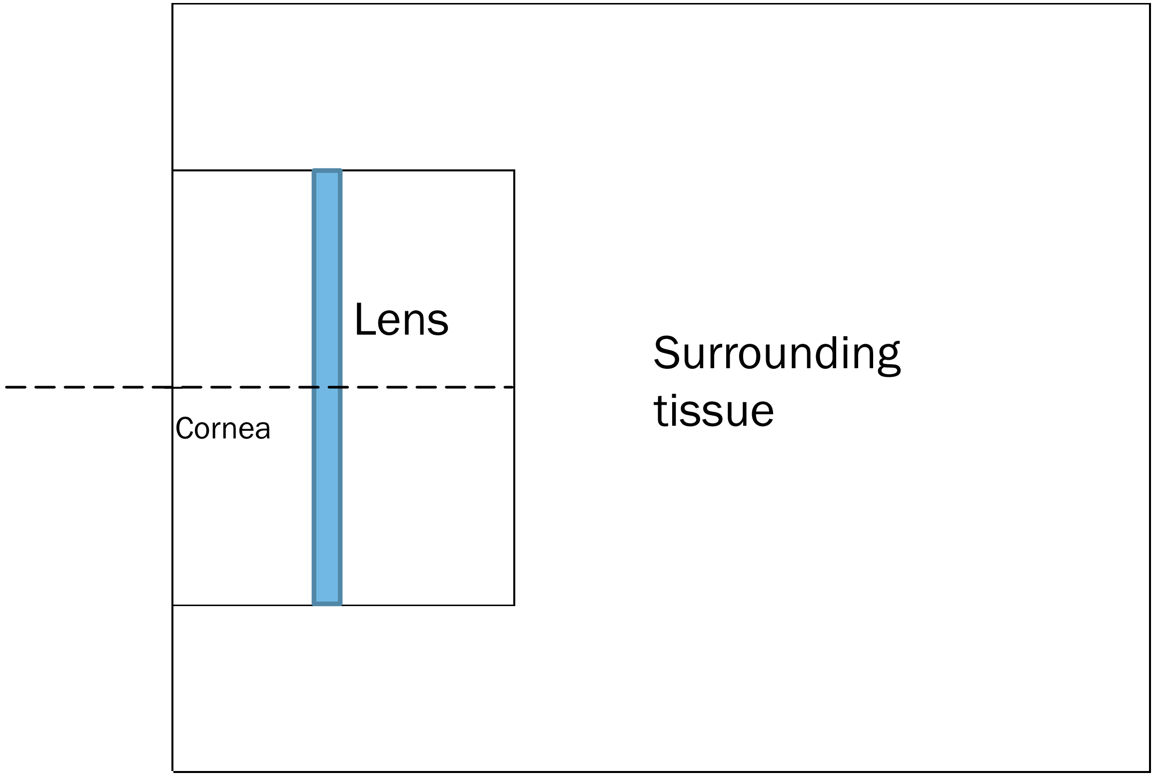
SENSITIVITY BY STRUCTURE

- In order of decreasing sensitivity (Rohrschneider, 19
  - Lens
  - Conjunctiva
  - Cornea
  - Uvea
  - Retina
  - Optic Nerve
- Assumption: Protect the lens and protect the eye

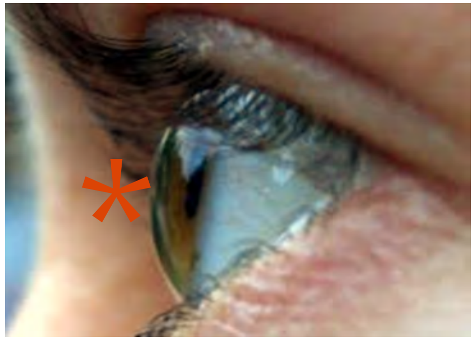


PRIOR TO EYEDOSE

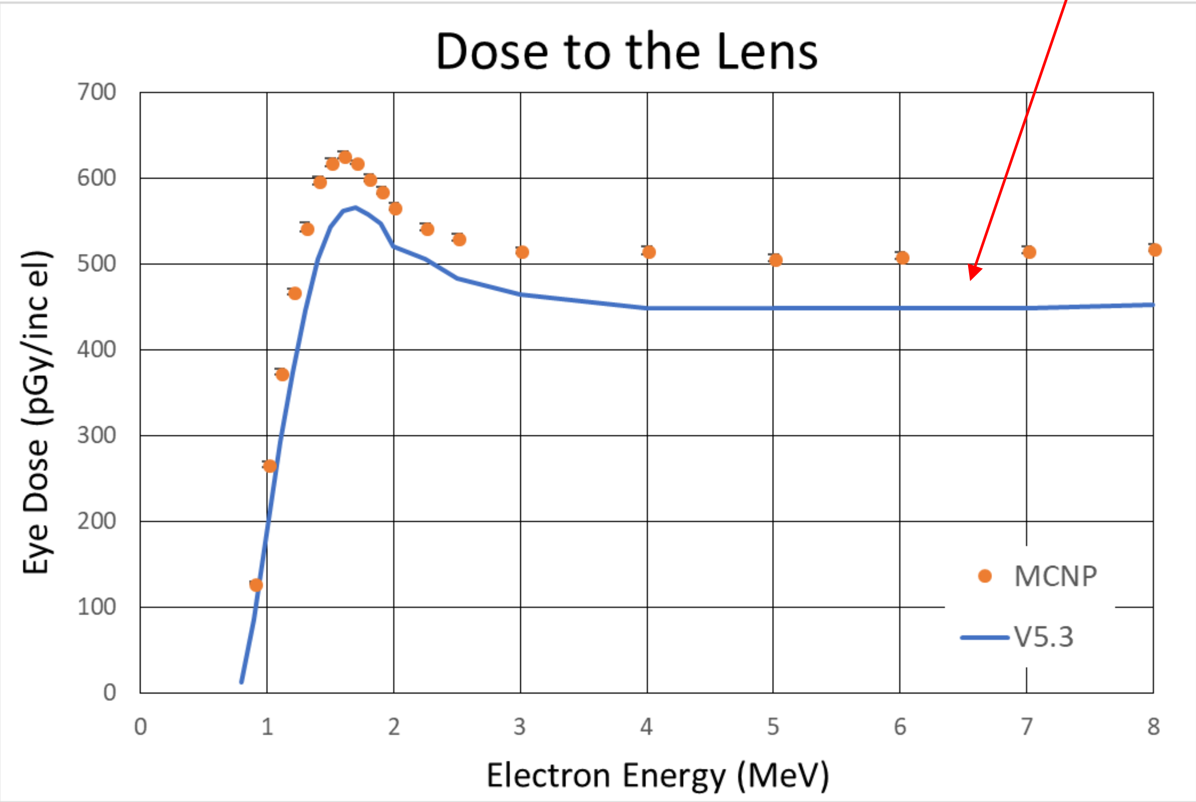
- We compared VARSKIN 5.3 to Monte Carlo simulation (MCNP6)
- Using a simplified eye model with cornea, lens, and surrounding tissue all assumed to be of unit density
  - to be closest to VARSKIN assumptions
- Point sources located along centerline from contact to 20 cm
- Dose estimated per incident electron
  - to normalize for geometry
  - cross-sectional area of 1 cm^2 with 20 mm thickness, centered at a depth of 3 mm

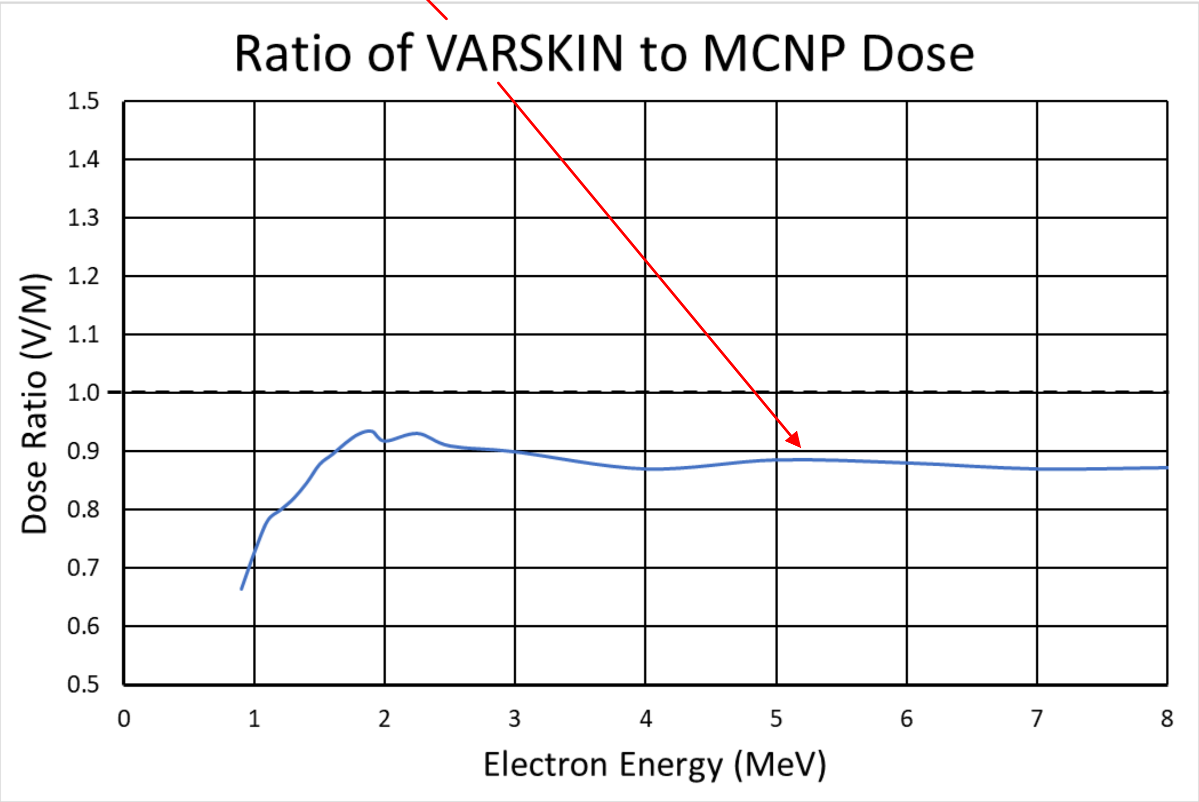


SOURCE ON CONTACT



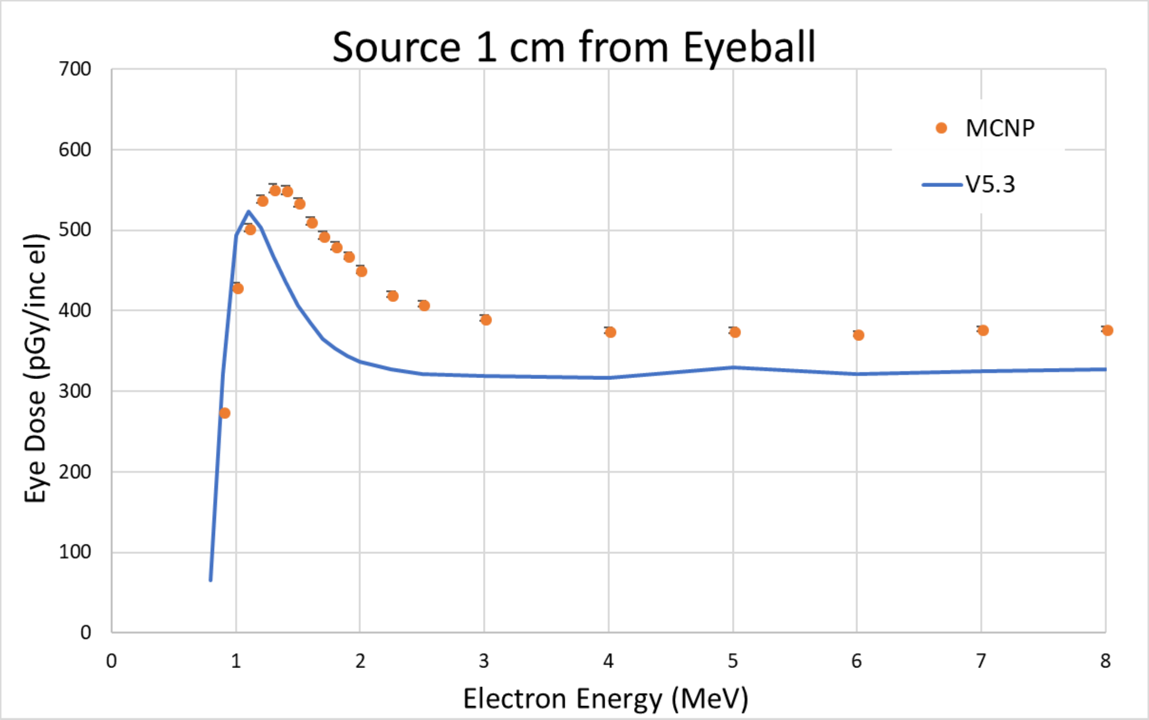
VARSKIN underestimates by at least 10%

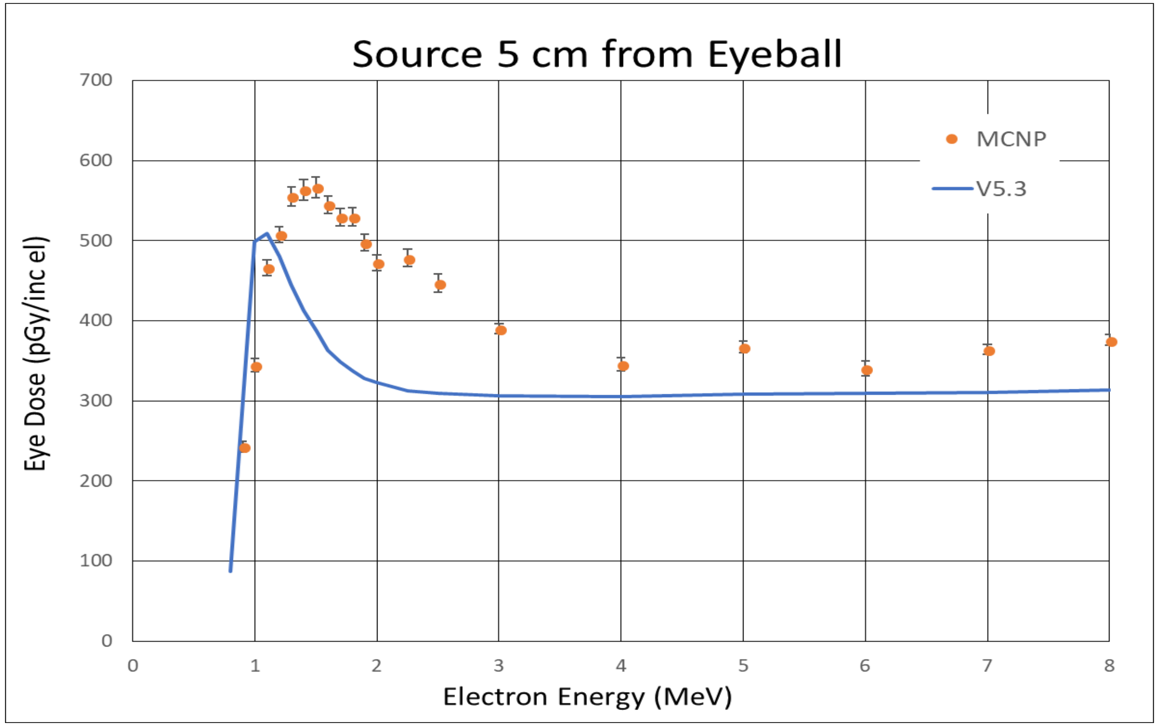




WITH AIR GAP


5
2
1
*
*
*

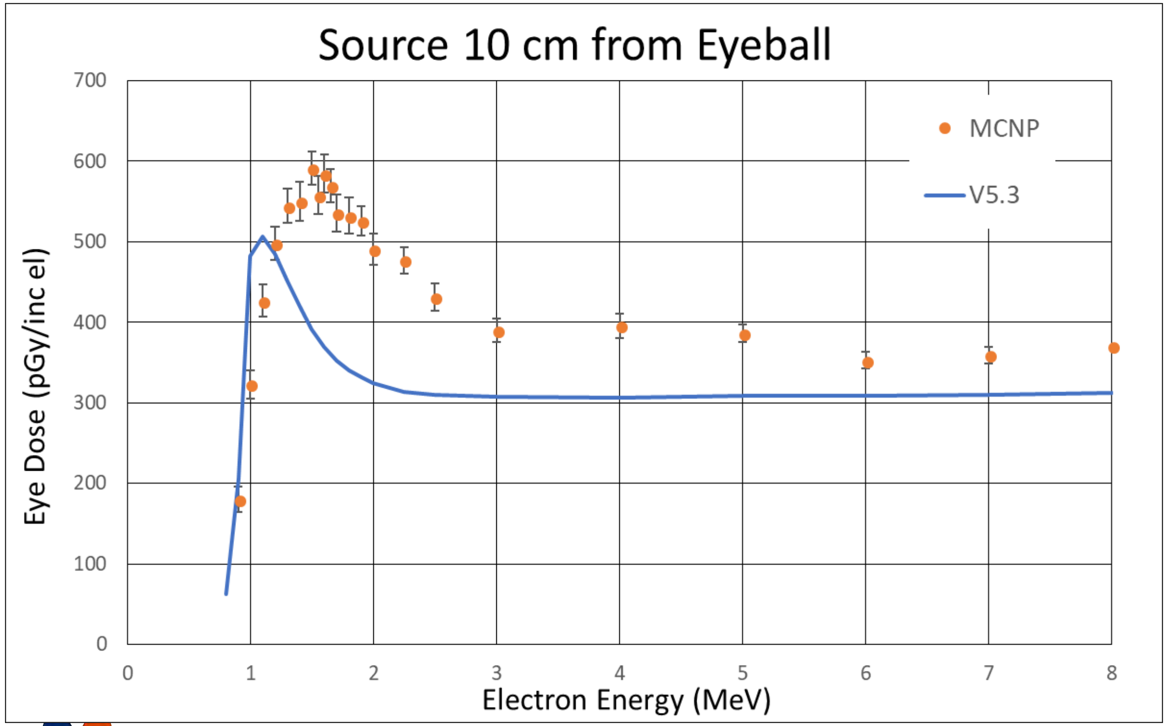

Source 1 cm from Eyeball
Eye Dose (pGy/inc el)
Electron Energy (MeV)
MCNP
V5.3
0
100
200
300
400
500
600
700
0
1
2
3
4
5
6
7
8

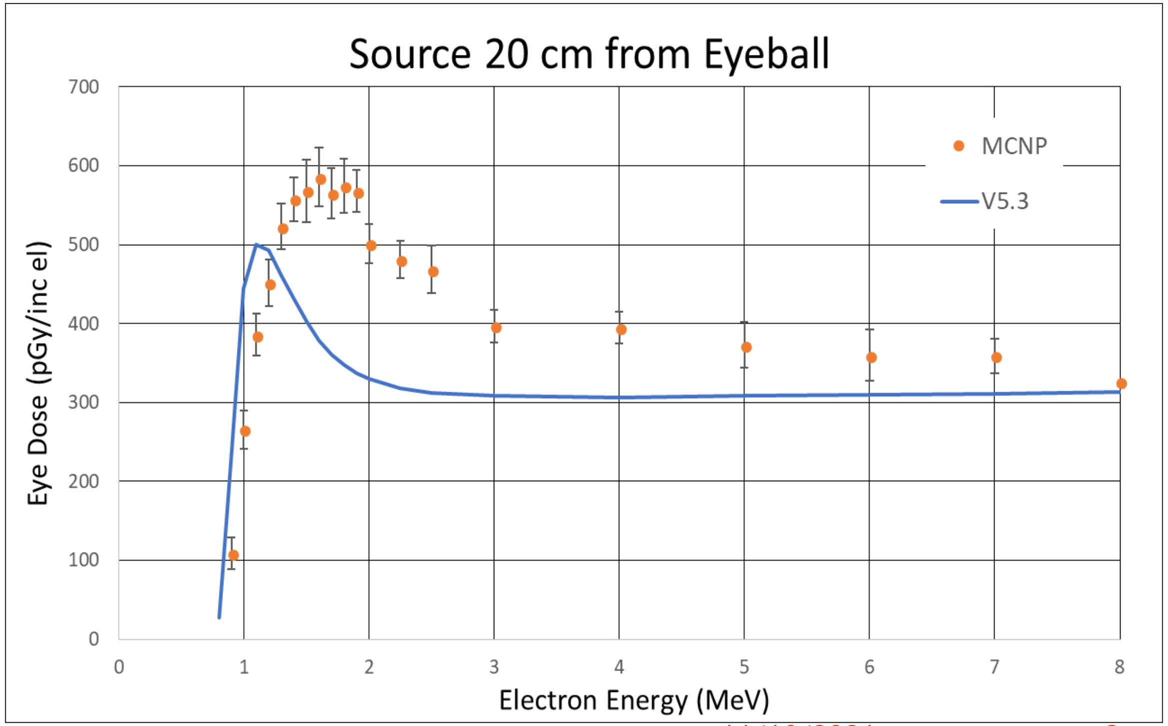

Source 5 cm from Eyeball
Eye Dose (pGy/inc el)
Electron Energy (MeV)
MCNP
V5.3
0
100
200
300
400
500
600
700
0
1
2
3
4
5
6
7
8

20
*

15
*

10
*


Source 10 cm from Eyeball
Eye Dose (pGy/inc el)
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
Electron Energy (MeV)
MCNP
V5.3


Source 20 cm from Eyeball
Eye Dose (pGy/inc el)
700
600
500
400
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200
100
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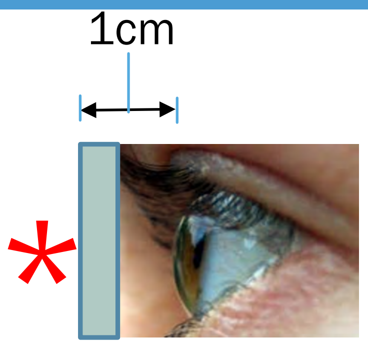
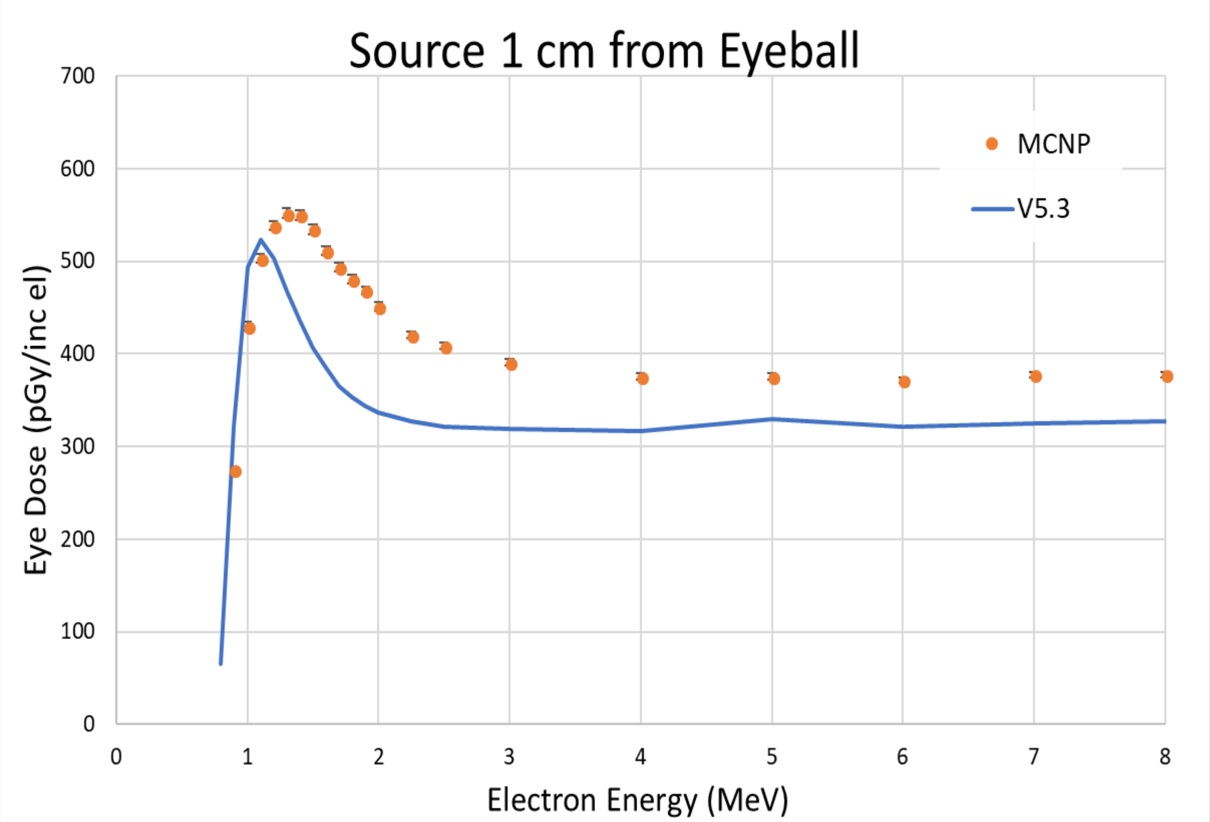
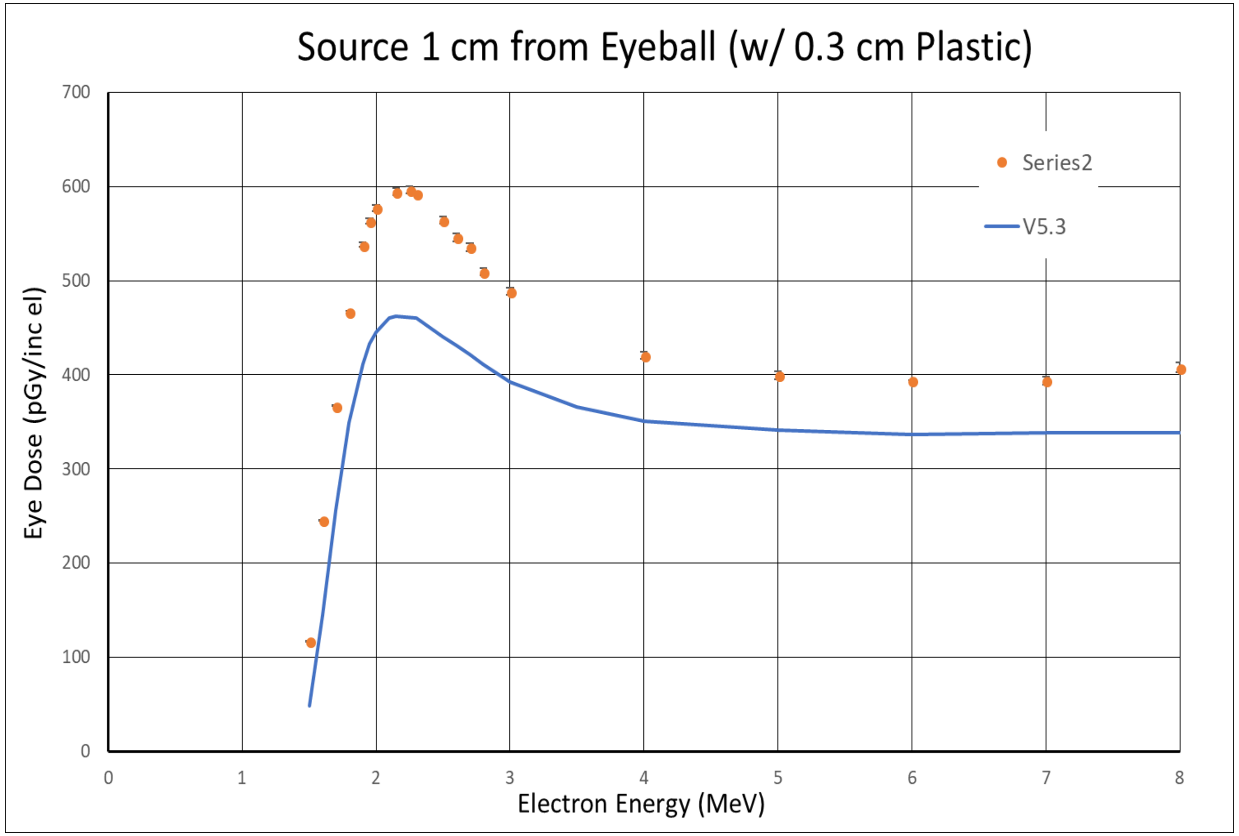
6
7
8
Electron Energy (MeV)
MCNP
V5.3

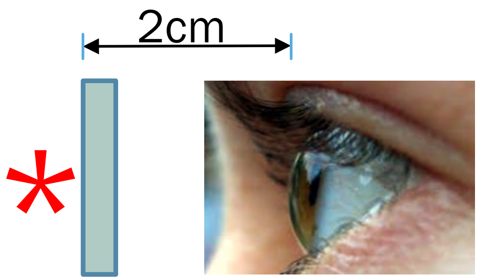
1 CM GAP WITH PLASTIC

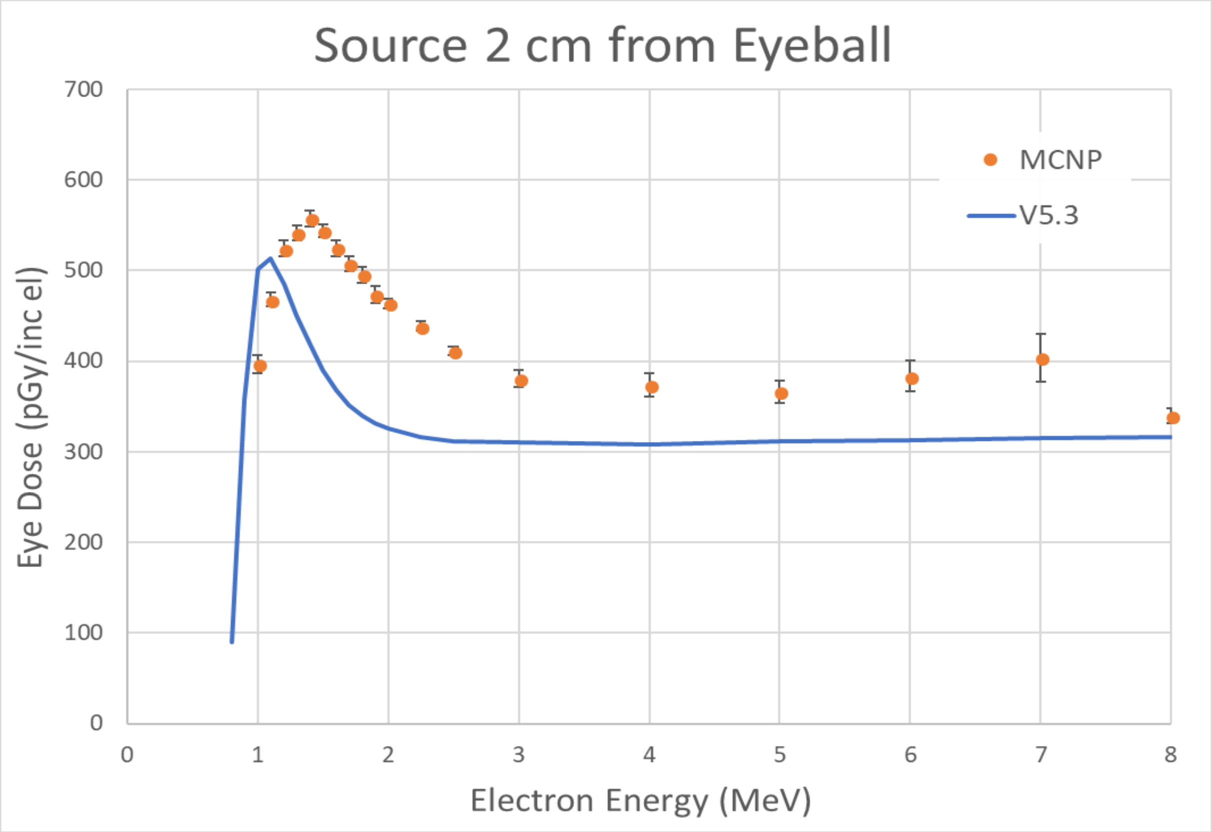


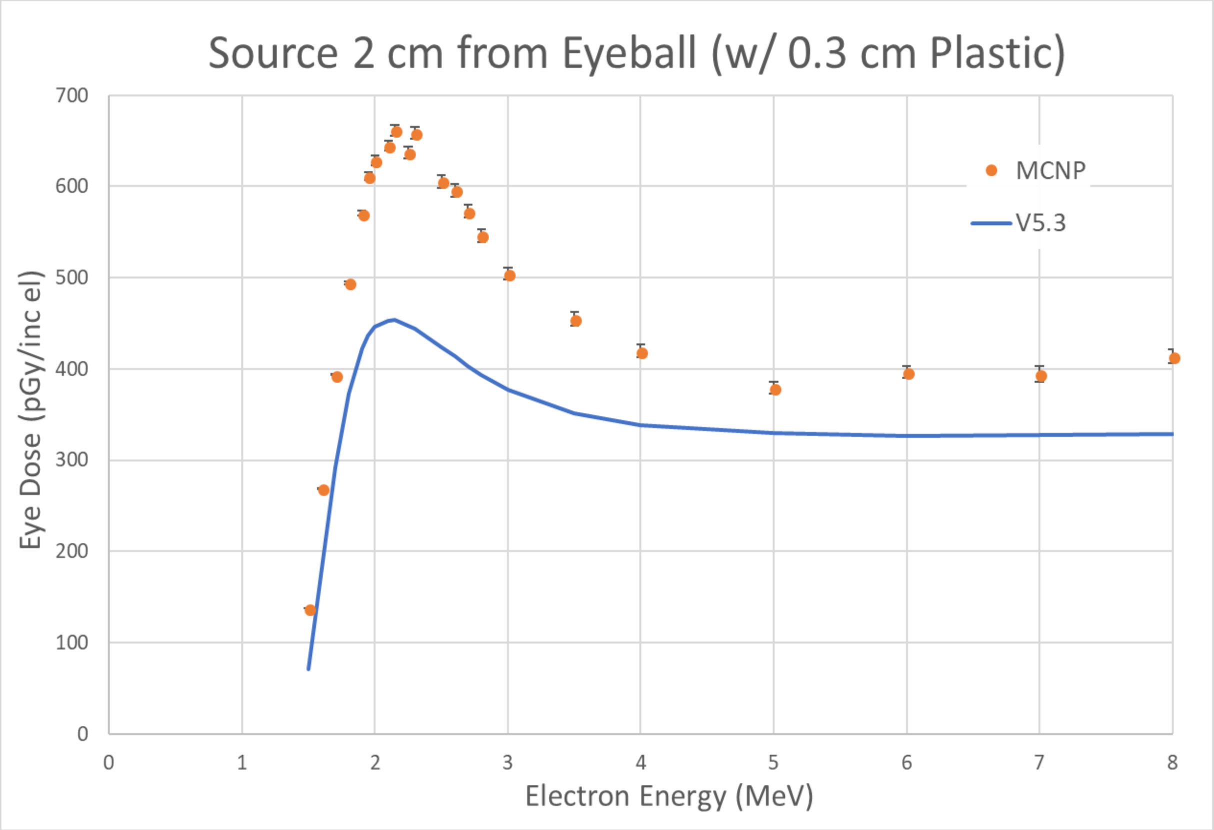




2 CM GAP WITH PLASTIC

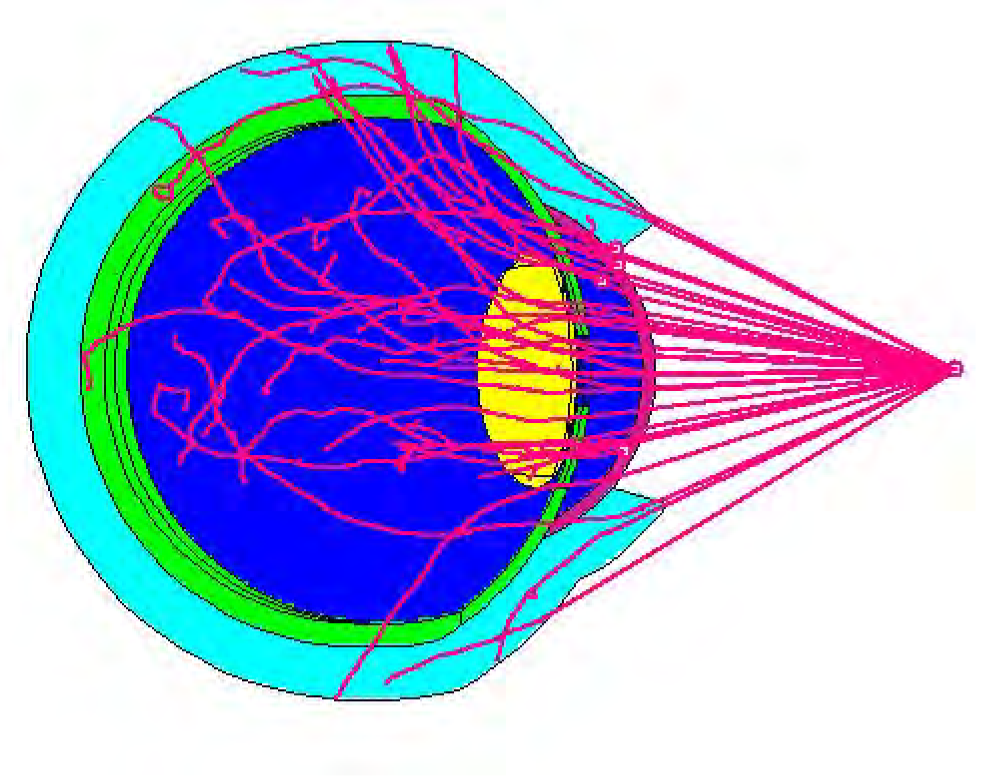






MONTE CARLO METHODS

- “Random walk” physics simulator
  - Average behavior of the typical particle
- Gold standard in particle transport
  - MCNP6, EGS, GEANT, etc.
- Pros
  - Customizable geometries
  - Multiple particle transport
  - Multiple energy
- Cons
  - Time intensive
  - Steep learning curve
  - Output files difficult to interpret

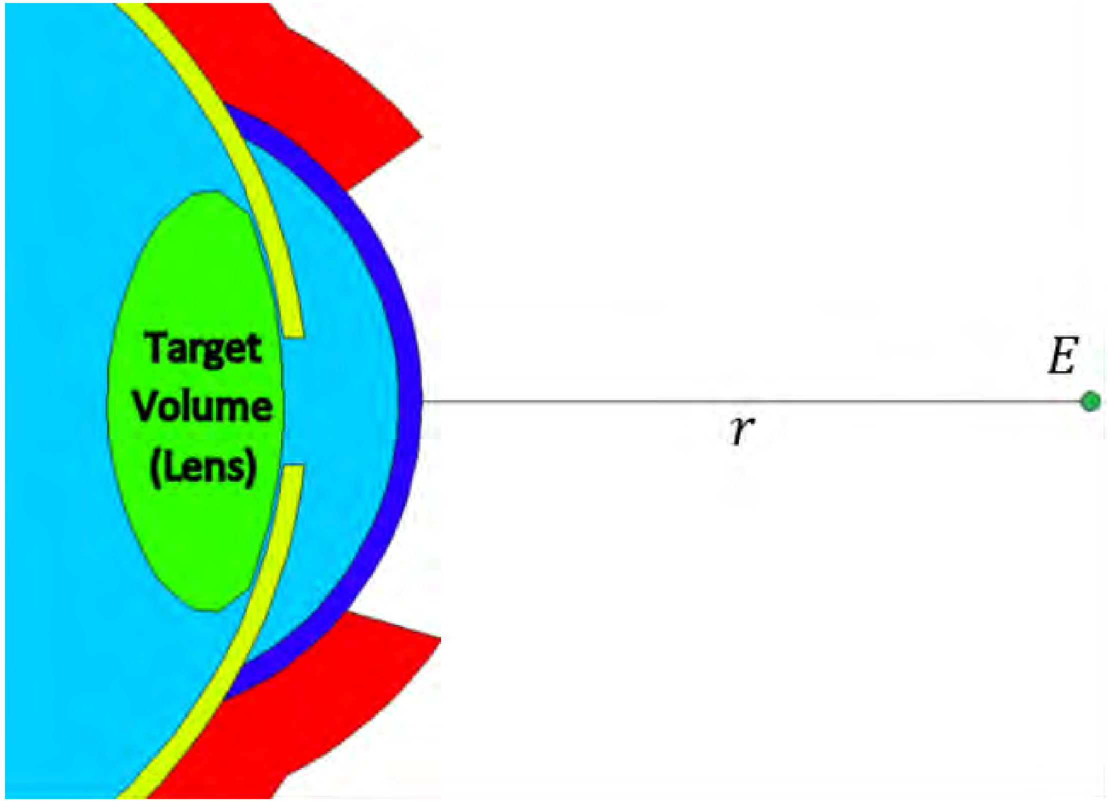


EYEDOSE MODEL

- A set of deterministic equations were developed from a vast array of probabilistic simulations to estimate radiation dose to the lens of the eye
- The equations used in EyeDose were developed through Monte Carlo simulations of monoenergetic radioactive sources placed at varying distances from a stylized eye model
- Account for particle type, energy, source emission rate, and protective eyewear and are valid for:
  - electron energies ranging from 100 keV to 11 MeV
  - photon energies ranging from 7 keV to 11 MeV
  - distances from 0 to 20 meters.
- Additionally, sources emitting particles over an energy spectrum, such as beta sources, are incorporated into this new dosimetry model using both ICRP 38 and 107 data
- The source is assumed to be an infinitely small, isotropic point source located on the geometric axis of the eye
- The target volume is taken to be the entire lens

EYE GEOMETRY

- The source in EyeDose is modeled as an infinitely small, monoenergetic, isotropic point source of energy *E*
- The source is located on the geometric axis of the eye and the distance between the surface of the eyeball and the source is labeled *r*
- The target volume is taken to be the entire lens



PHOTON DOSIMETRY

- The development of the photon model begins with the uncollided fluence equation:

$$\Phi^0(r) = \frac{S_0}{4\pi r^2}$$

- Fundamental equation for absorbed dose to a point in space at some distance *r* from an isotropic source of photons:

$$D^0(r, E) = E\ \Phi^0\ \frac{\mu_{en}}{\rho}\ B\ e^{-\mu r}$$

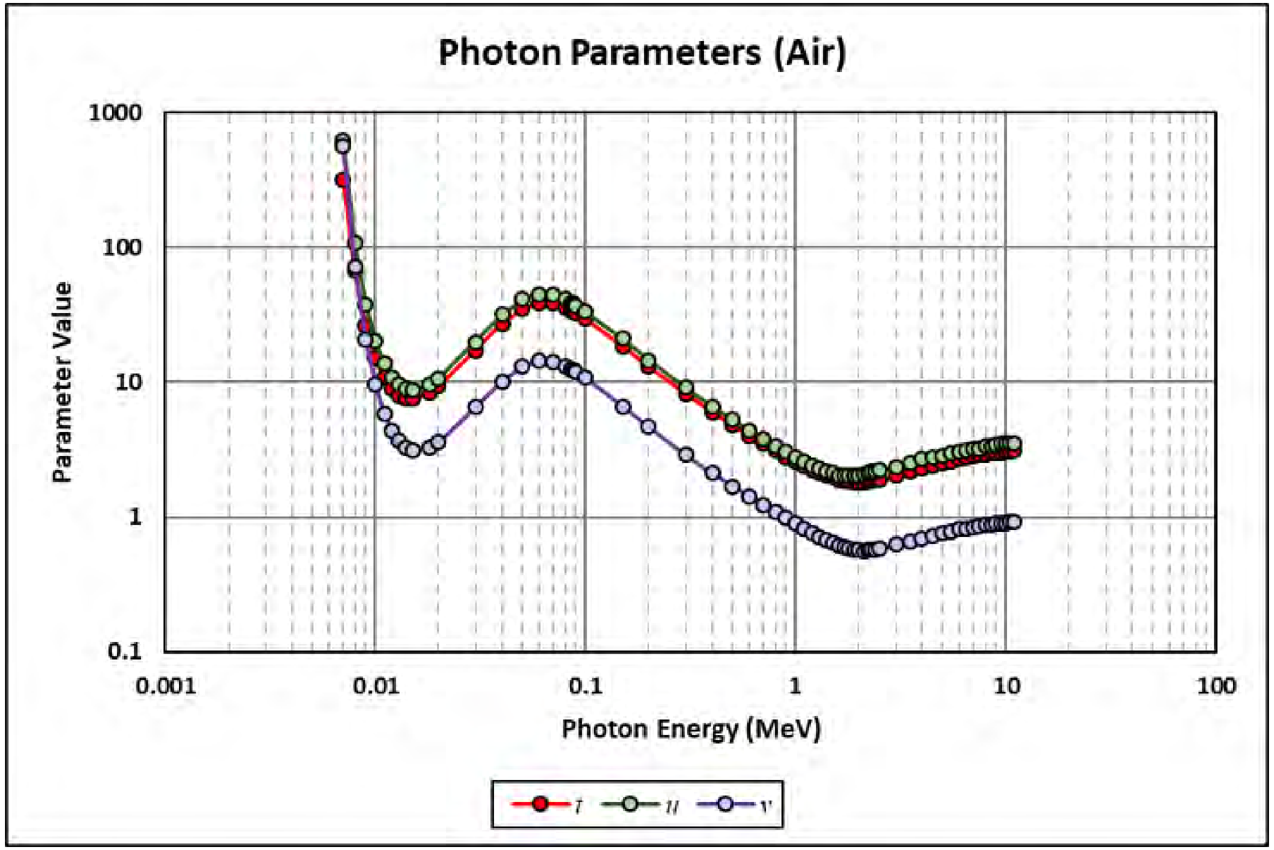
PHOTON DOSIMETRY

- The lens, however, is a complex volume and not a single point
- The probabilistic modeling software MCNP6 was used to determine dose to the human lens over a range of photon energies after passing through, and scattering in, air and the cornea
- The resulting function for determining lens dose from photons of energy *E* emanating from an isotropic source at distance r, is

$$D_{\mathrm{p}}(r, E) = \frac{\exp(-\mu r)}{t r^2 + u r + v} \qquad \left(\frac{\mu}{\rho}\right)_{\mathrm{air}} = \frac{\alpha_0 + \sum_{i=1}^{6} \alpha_i \ln^i E}{1 + \sum_{i=1}^{6} \beta_i \ln^i E},$$

- The parameters *t, u*, and *v* describe the overall shape of the curve and *μ* is the mass attenuation coefficient in air

PHOTON DOSIMETRY

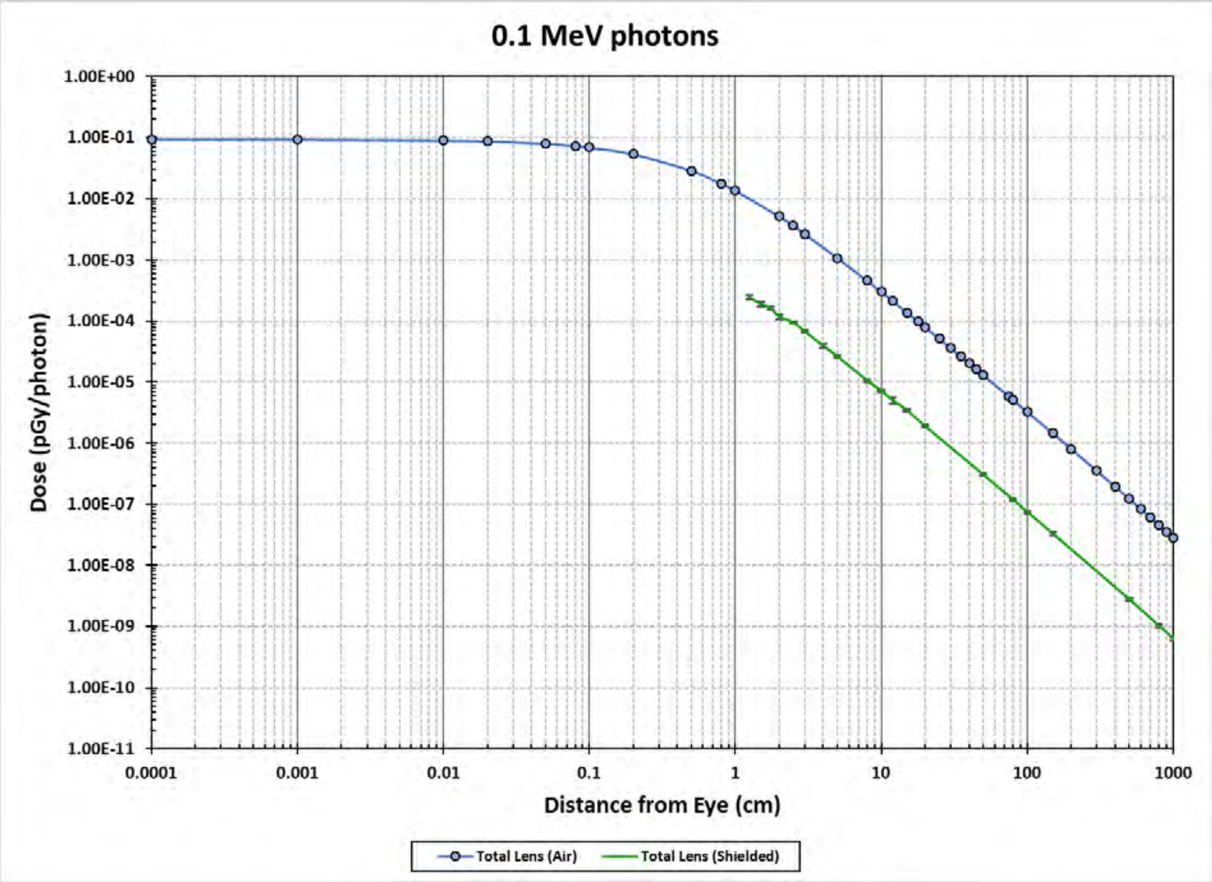


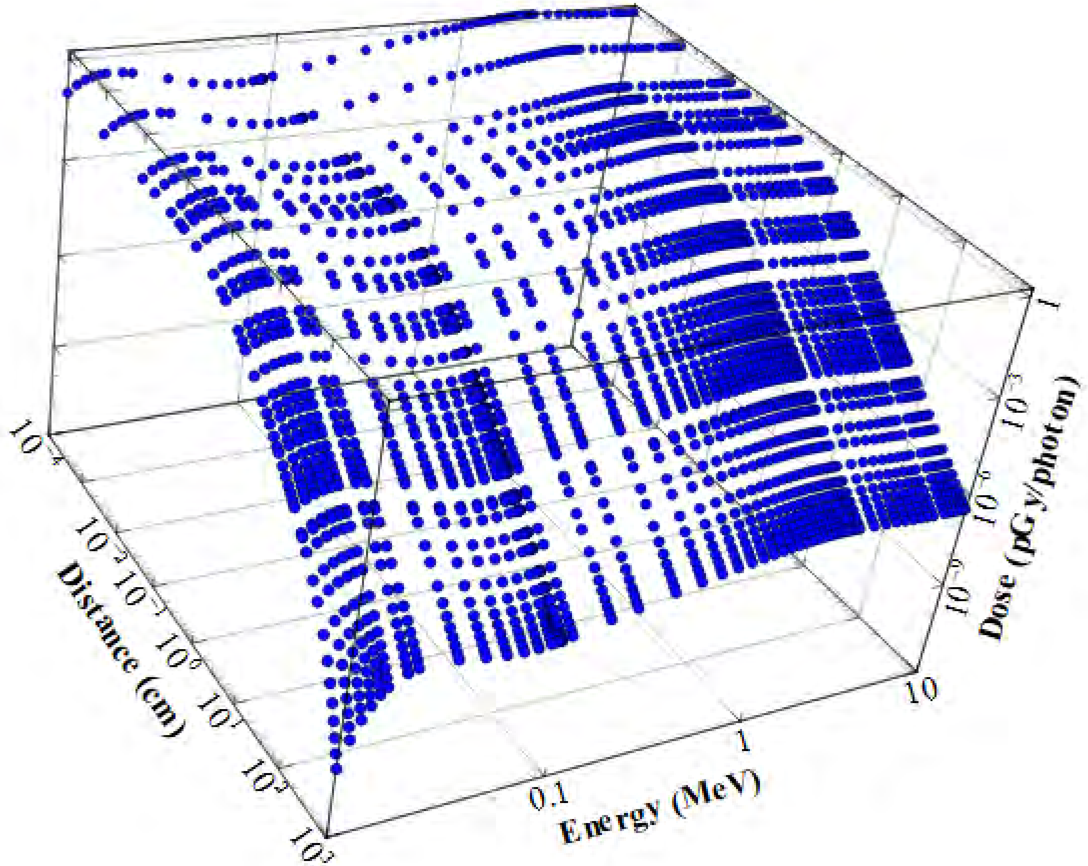
$$t = \exp\left[\frac{\alpha_0 + \sum_{i=1}^{5} \alpha_i \ln^i E}{1 + \sum_{i=1}^{8} \beta_i \ln^i E}\right]$$

$$u = \exp\left[\frac{\alpha_0 + \sum_{i=1}^{9} \alpha_i \ln^i E}{1 + \sum_{i=1}^{7} \beta_i \ln^i E}\right]$$

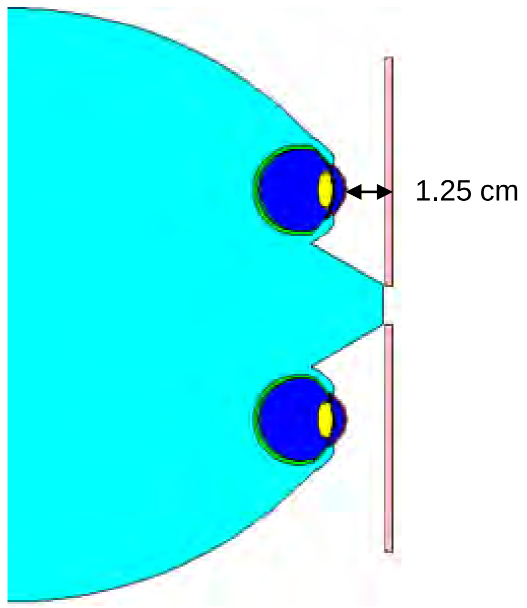
$$v = \exp\left[\frac{\alpha_0 + \sum_{i=1}^{9} \alpha_i \ln^i E}{1 + \sum_{i=1}^{6} \beta_i \ln^i E}\right]$$

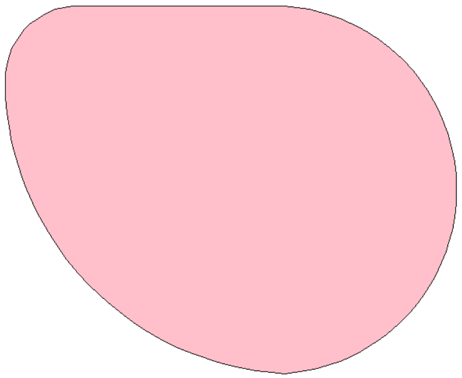
PHOTON DOSIMETRY





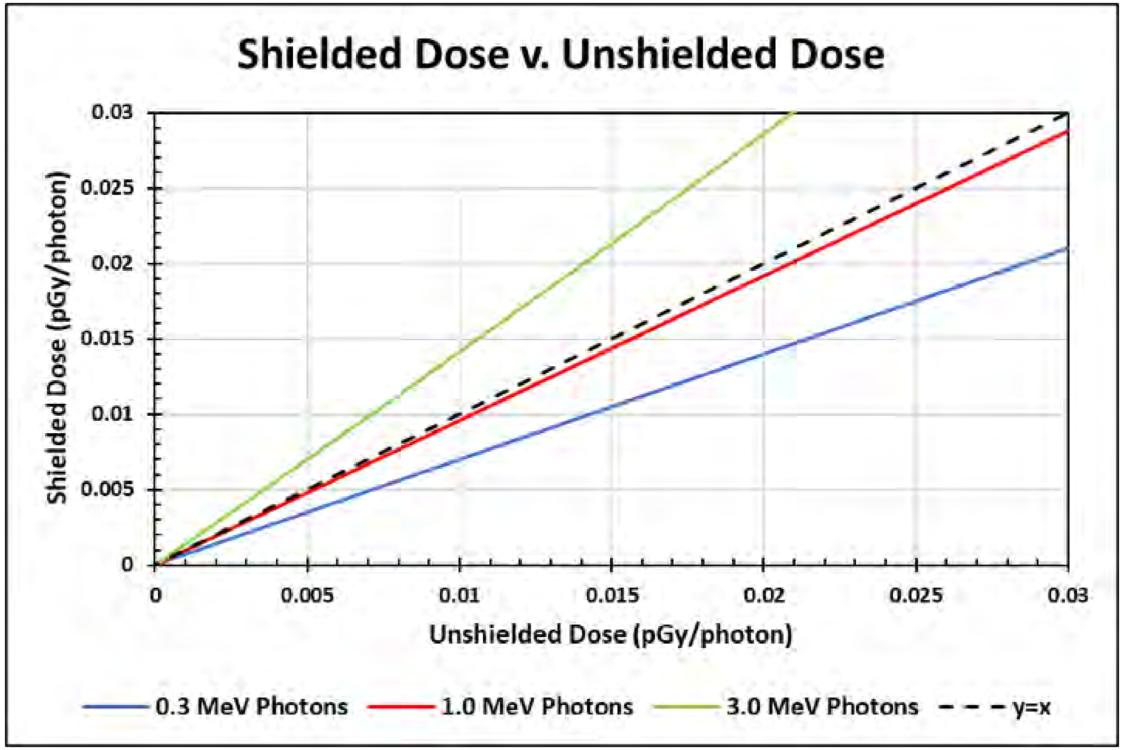
PROTECTIVE GLASSES

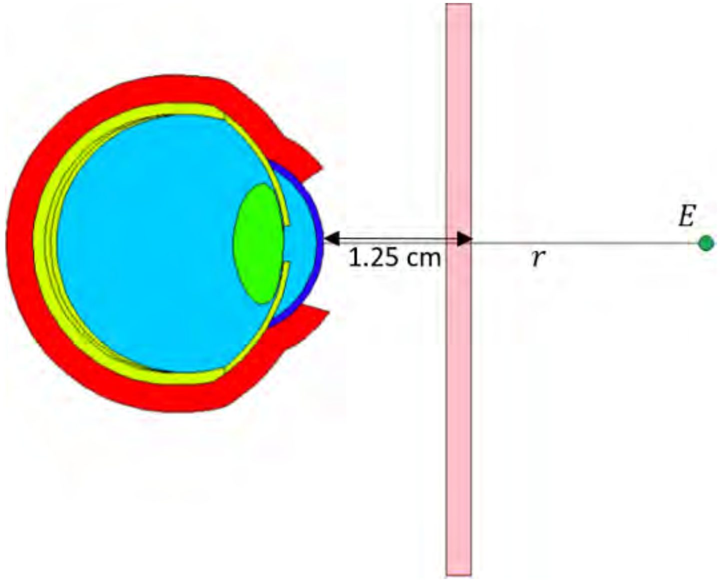




- The shielding used in the model is based on Spackman's "classic" style eyewear
- Adding the lens thickness of 2 mm places its anterior face 1.25 cm from the cornea's surface

PROTECTIVE GLASSES





PROTECTIVE GLASSES

- The concept of the *buildup factor* is extremely useful when estimating the dose after shielding has been introduced,
- Since the buildup factor is the ratio of total fluence to the primary fluence, total fluence can be expressed mathematically as:

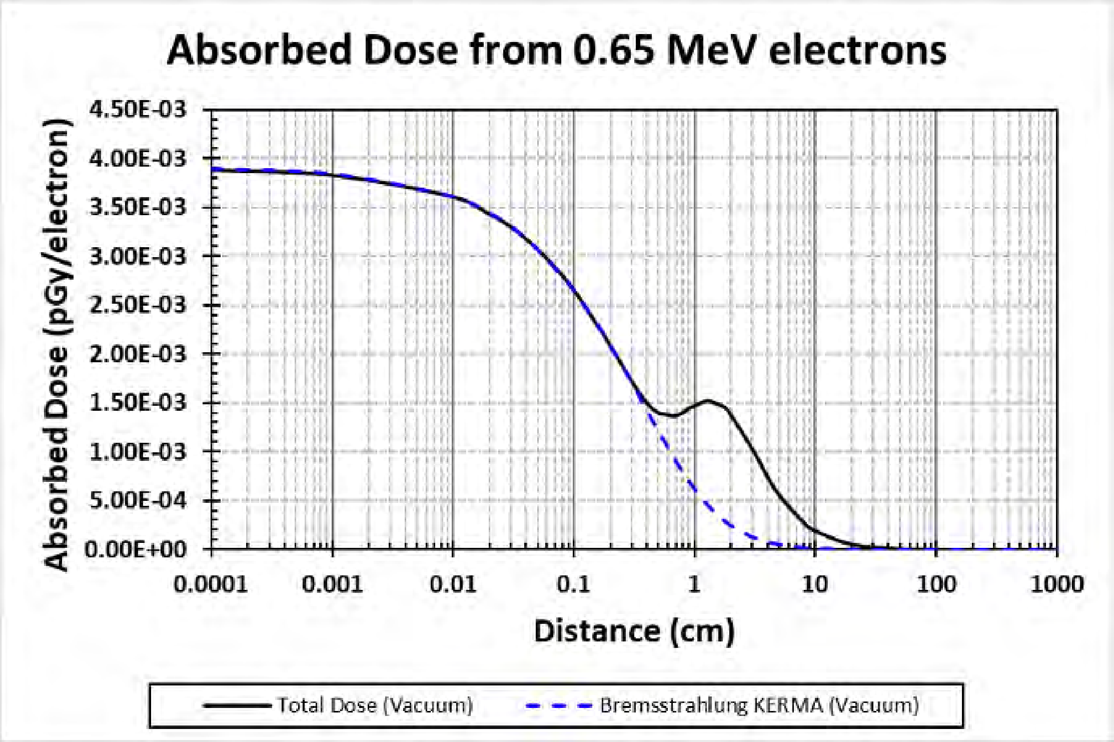
$$\Phi(\mathrm{r}) = B(\mathrm{r})\Phi^{0}(\mathrm{r})$$

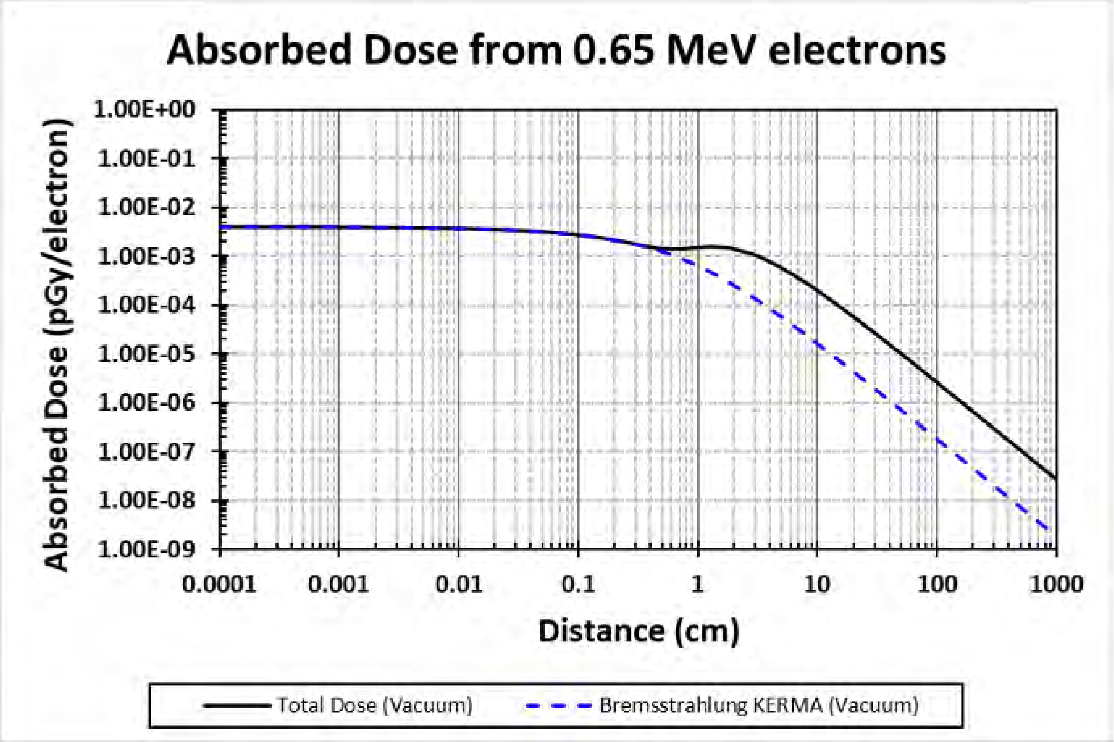
- where $\Phi(r)$ is the total fluence at point *r*, $\Phi^{0}(r)$ is the primary fluence at *r*, and the buildup factor is $B(r)$
- Combining this concept with the equation for dose written as $D=\Phi E(\mu_{ab}/\rho)$, shows that the dose rate at a given point is related to the fluence at that point, and so one may write:

$$D_{\mathrm{sh}}(r,E) = f\left(D_{\mathrm{unsh}}(x,E)\right).$$

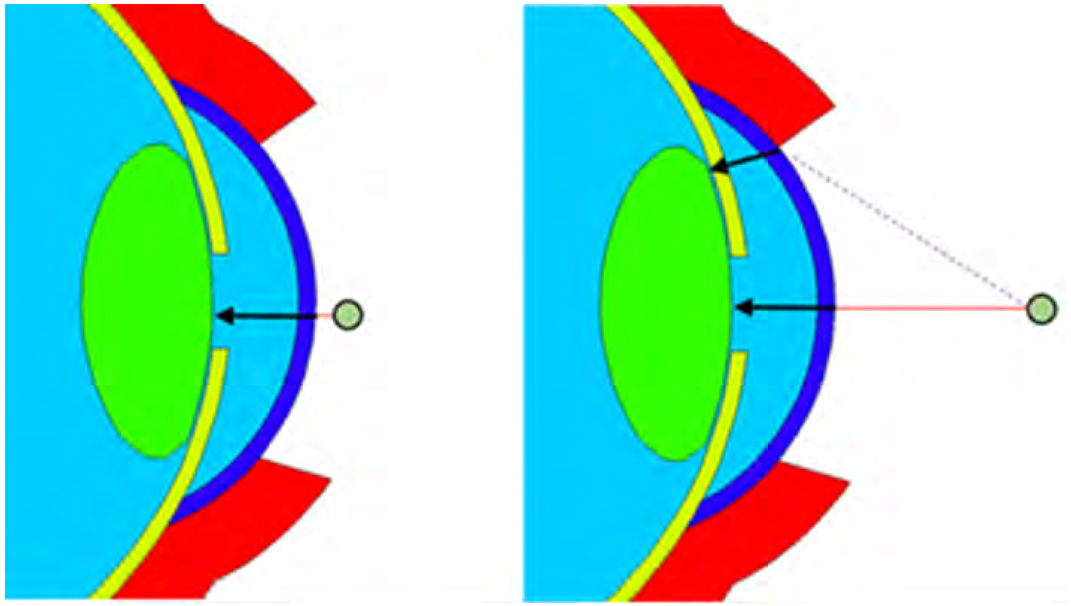
ELECTRON DOSIMETRY

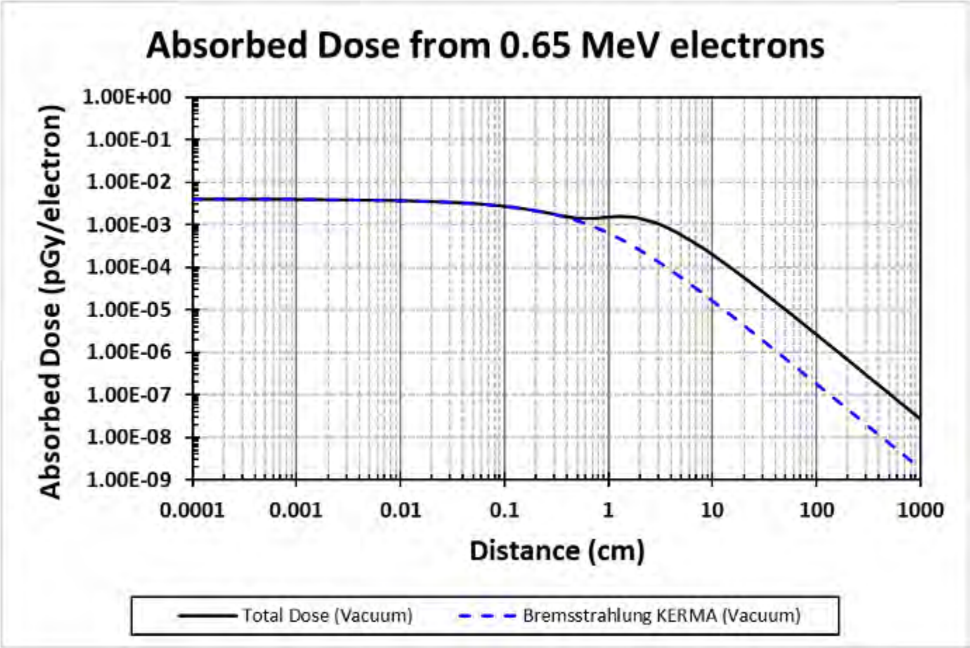
- Understanding the electron model in both shielded and unshielded circumstances first requires the analysis of the unshielded electron model in a vacuum
- Because the bremsstrahlung plays a significant role in electron dosimetry, it must be considered





ELECTRON DOSIMETRY





- This new path opens at around r = 0.3 cm. The electron rays radiating from the source can be considered parallel at about 10 cm, at which point both the bremsstrahlung and direct contribution obey the inverse square law.

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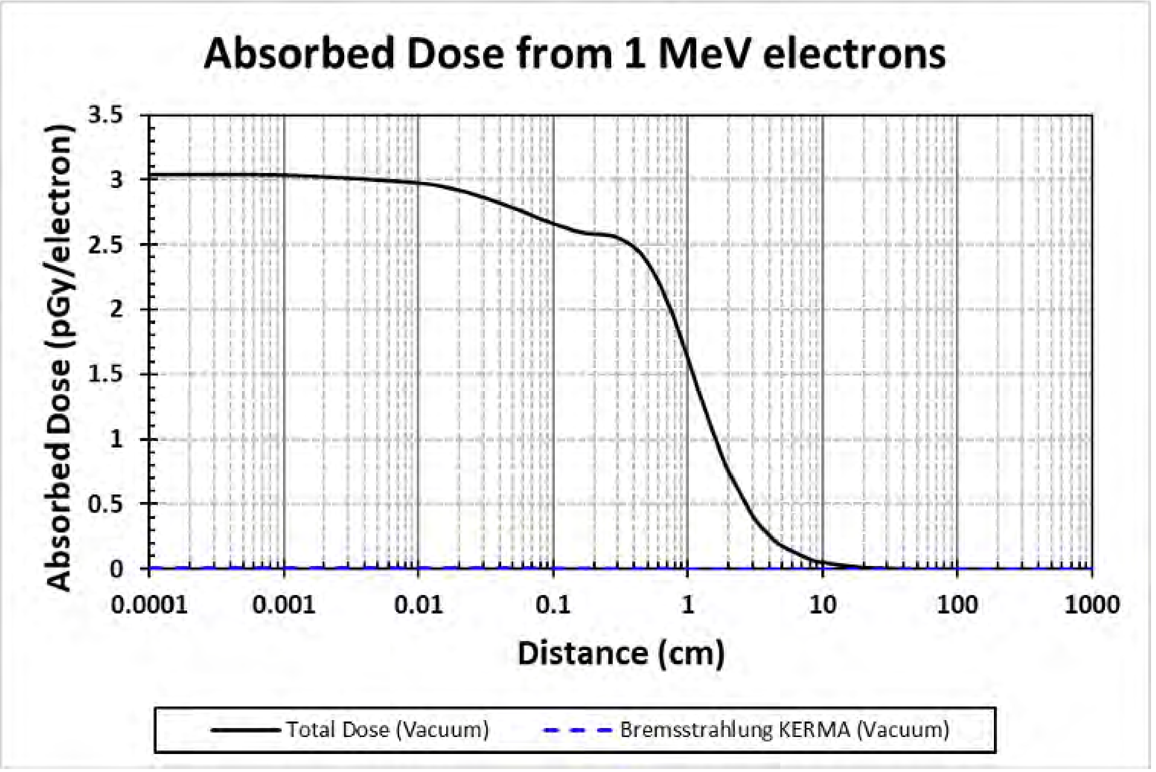
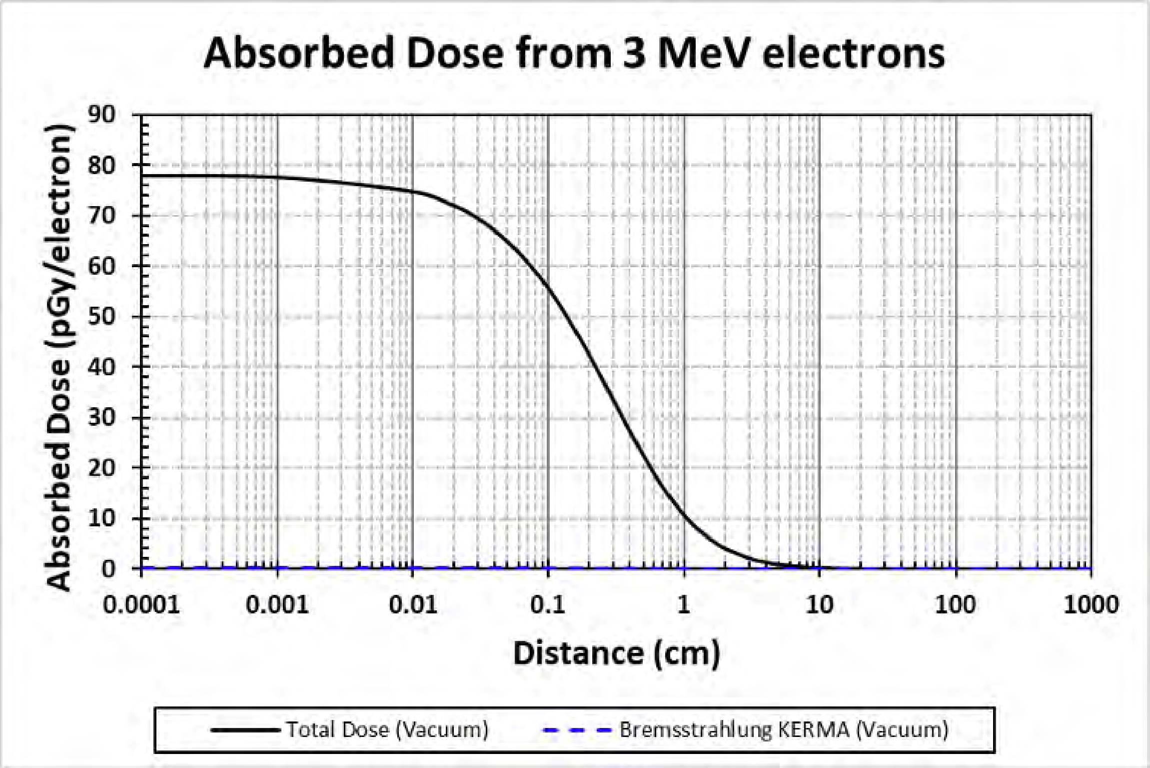
ELECTRON DOSIMETRY





ELECTRON DOSIMETRY

- An empirical model that fits the MCNP probabilistic data for dose due to electron source, bremsstrahlung, and scattered contributions is

$$D_{\mathrm{e,vac}}(r,E) = \frac{\mathcal{B}^{-}(q,s)}{ar^2 + br + c\sqrt{r} + d} + \frac{\mathcal{B}^{+}(q,s)}{tr^2 + ur + v}.$$

- The parameters *a, b, c, d, t, u*, and *v* are all energy dependent shaping parameters and the functions B^{+} and B^{-} are modified hyperbolic tangent functions

ELECTRON DOSIMETRY

- Additional parameters are needed to account for energy degradation in air

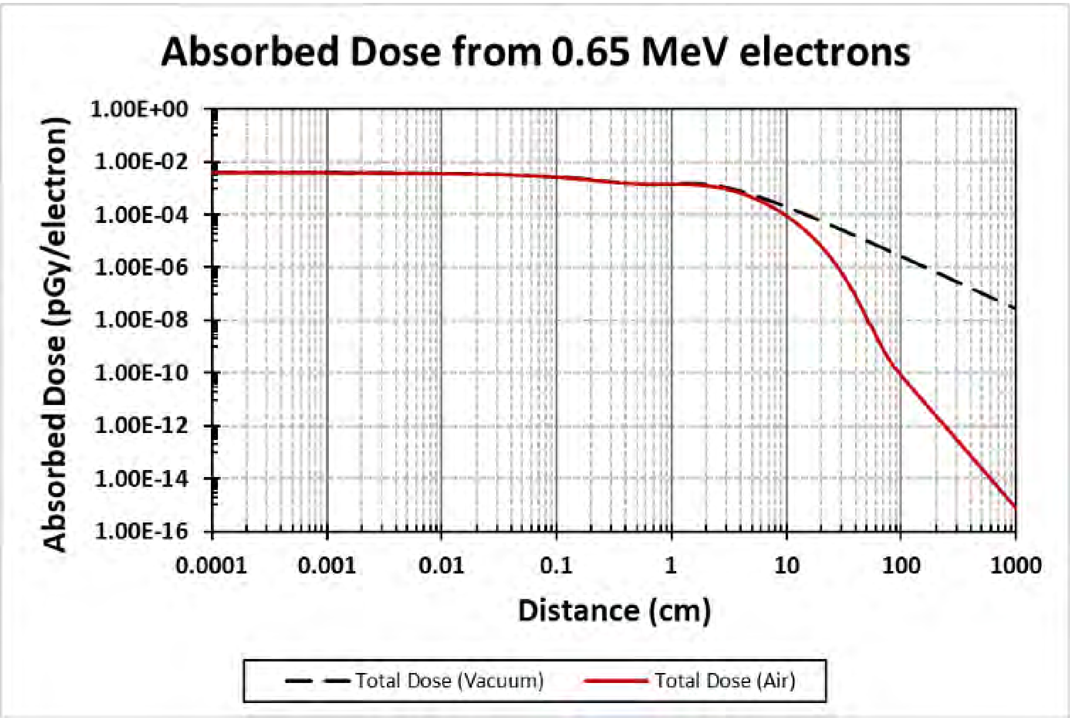
$$D_{\text{air}} = f\left(D_{\text{vac}}, \mu_{\text{e}}(r, E)\right),$$

where $\mu_e(r,E)$ is a function that accurately describes the impact that air has on electron dosimetry.

- Generally, one could write $D_{air}=D_{vac}\ exp(-hr)$, where h behaves similarly to μ for photons. This formulation fails for purposes of this analysis, though, for three reasons.
  - The analysis concerns distances in air up to 10 m
  - The size and shape of the target volume play a significant role in electron dosimetry
  - Bremsstrahlung generated in air is a key component of electron dose

ELECTRON DOSIMETRY

- While traversing through space, the electron fluence undergoes dramatic transformations that are not adequately described by simple exponential decay

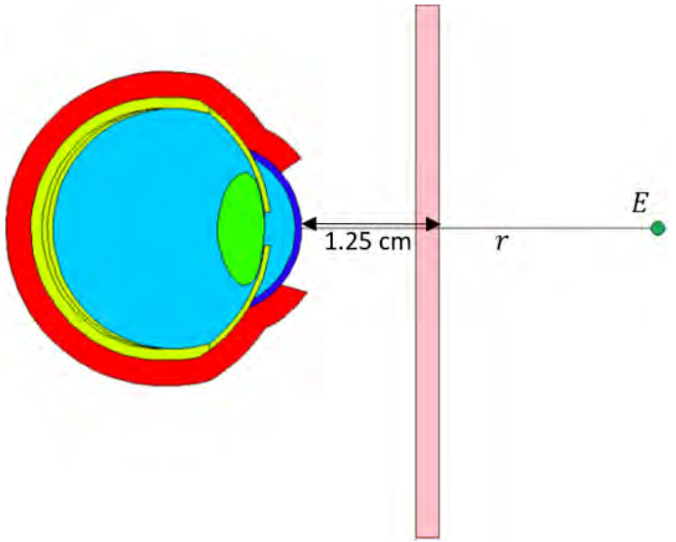


- An empirical expression accounting for the effects of air was derived:

$$D_{\text{air}} = \frac{\mathcal{B}^{-}(q,s)}{ar^2 + br + c\sqrt{r} + d} + \frac{\mathcal{B}^{+}(q,s)\,\mathcal{B}^{-}(m,n)}{tr^2 + ur + v} + \frac{k\,\mathcal{B}^{+}(1000,z)}{(1+r)^j}$$

PROTECTIVE GLASSES

- Incorporating shielding for electrons requires a slight modification of the unshielded D_{air} equation and recalculation of each of the shaping parameters
- Similarly, the shielded electron dose model is:



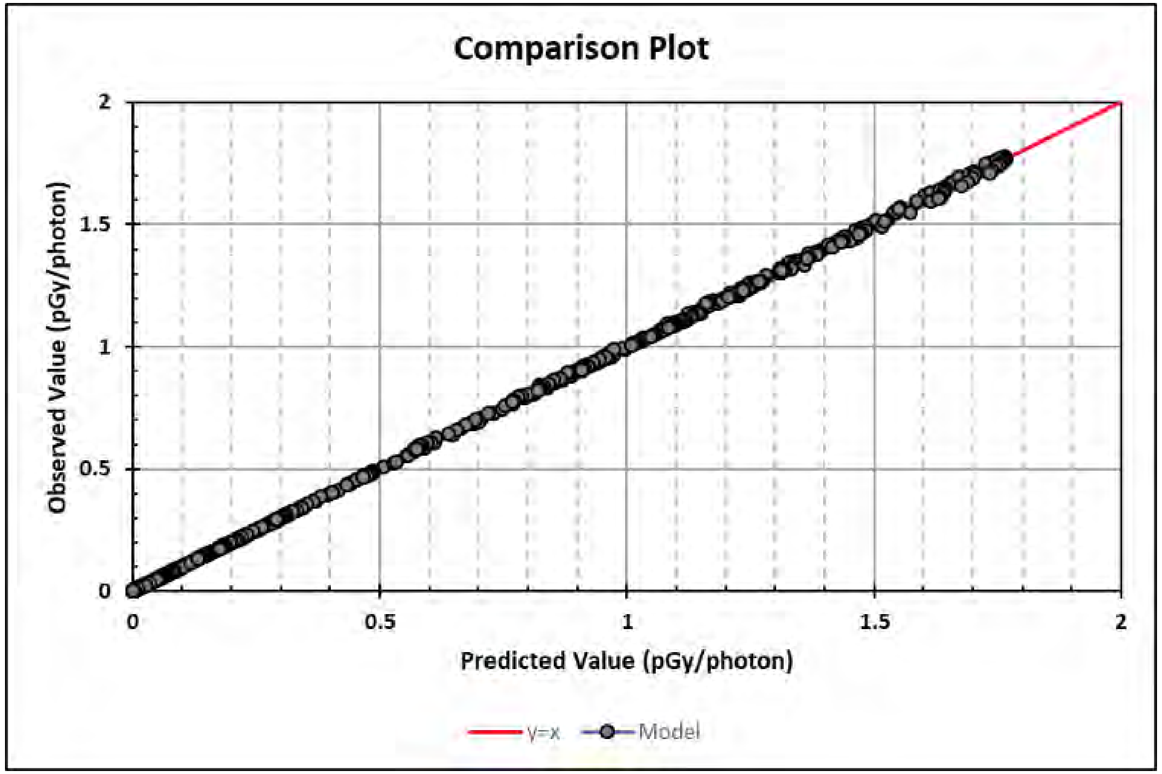
$$D_{\text{sh}} = \left[\frac{\mathcal{B}^{-}(q,s)}{ar^2 + br + c\sqrt{r} + d} + \frac{\mathcal{B}^{+}(q,s)\,\mathcal{B}^{-}(m,n)}{tr^2 + ur + v} + \frac{k\,\mathcal{B}^{+}(1000,z)}{(1+r)^j}\right][\mathcal{B}^{-}(y,0)].$$

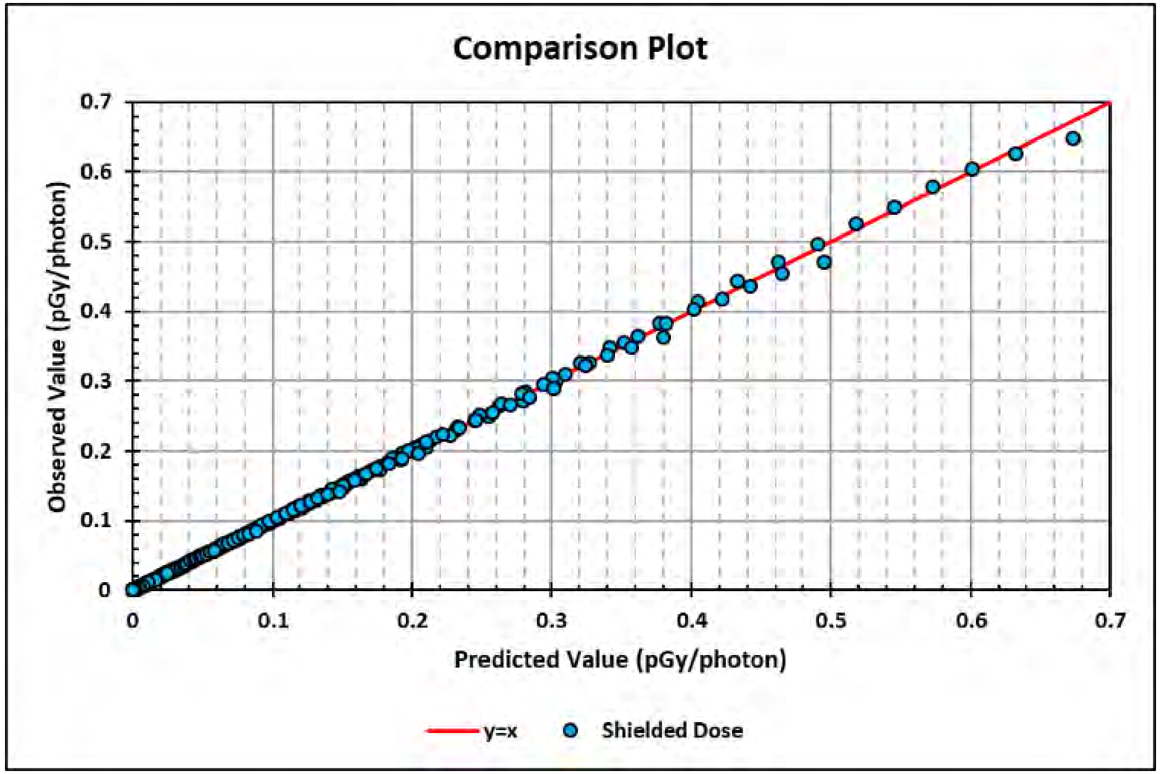
TOTAL DOSE

- In the presence of discrete energy particles (such as Auger electrons, characteristic x-rays or gamma rays) and continuous energy spectra (such as beta radiation or x-ray machines), total dose is given by:

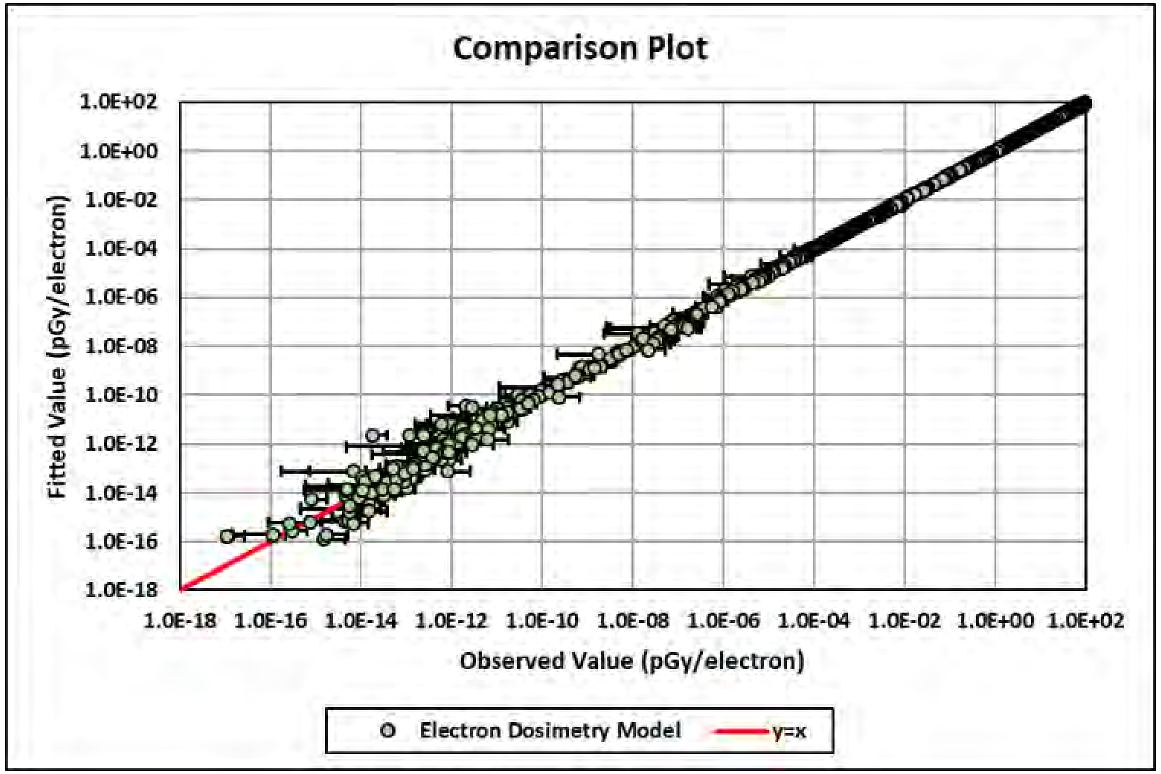
$$\dot{D}_{\text{total}} = \sum_{\substack{discrete \\ photons}} A_i D_{\text{p}}(E) + \sum_{\substack{continuous \\ photons}} A_i \int_E D_{\text{p}}(E) \cdot P_i(E) dE + \sum_{\substack{discrete \\ electrons}} A_i D_{\text{e}}(E) + \sum_{\substack{continuous \\ electrons}} A_i \int_E D_{\text{e}}(E) \cdot P_i(E) dE \,.$$

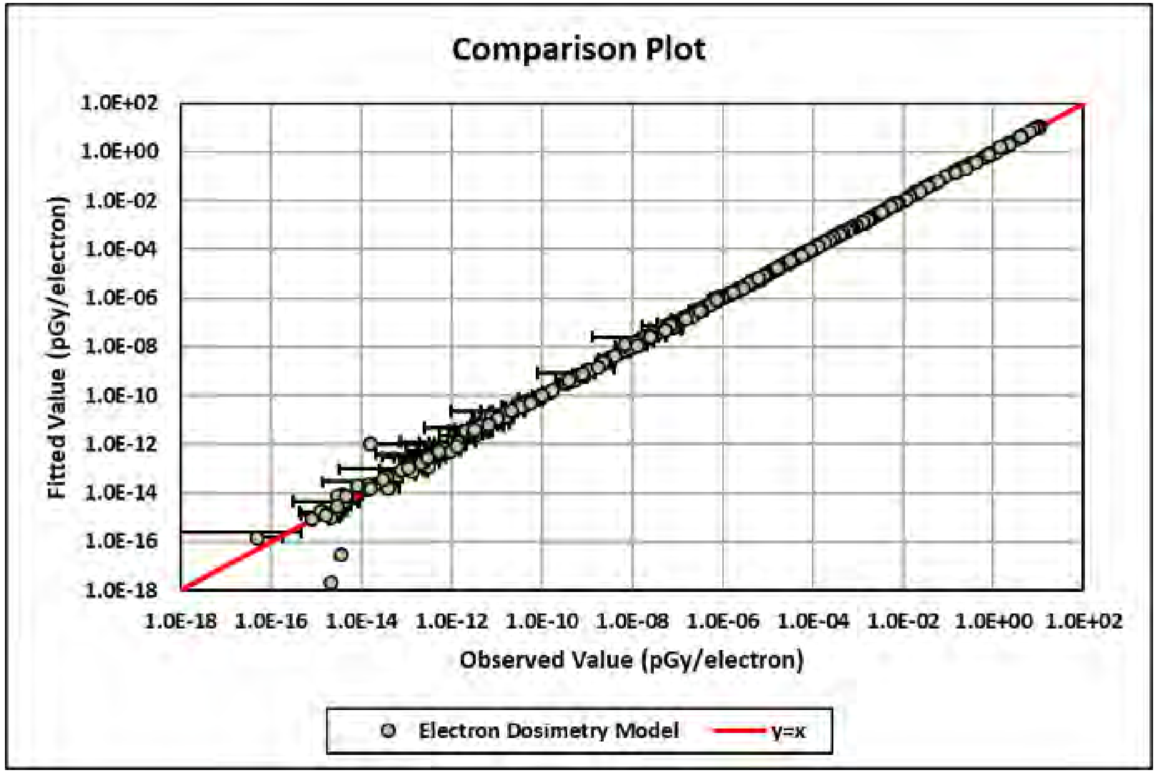
VERIFICATION AND VALIDATION



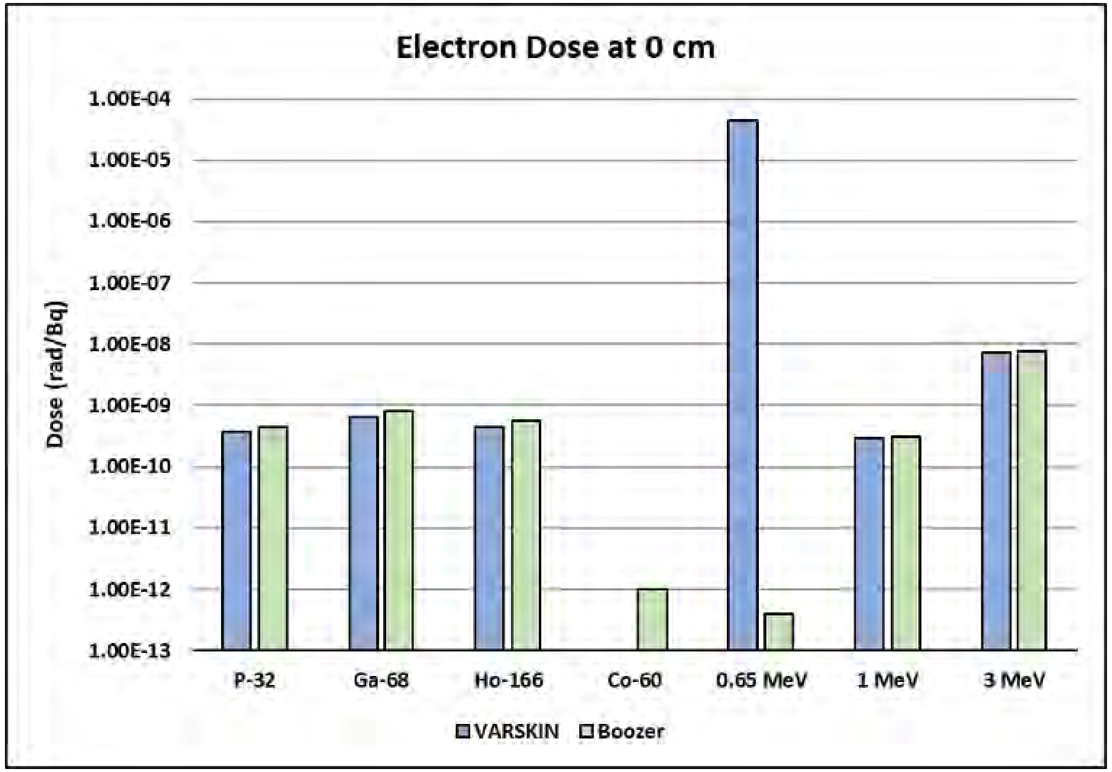


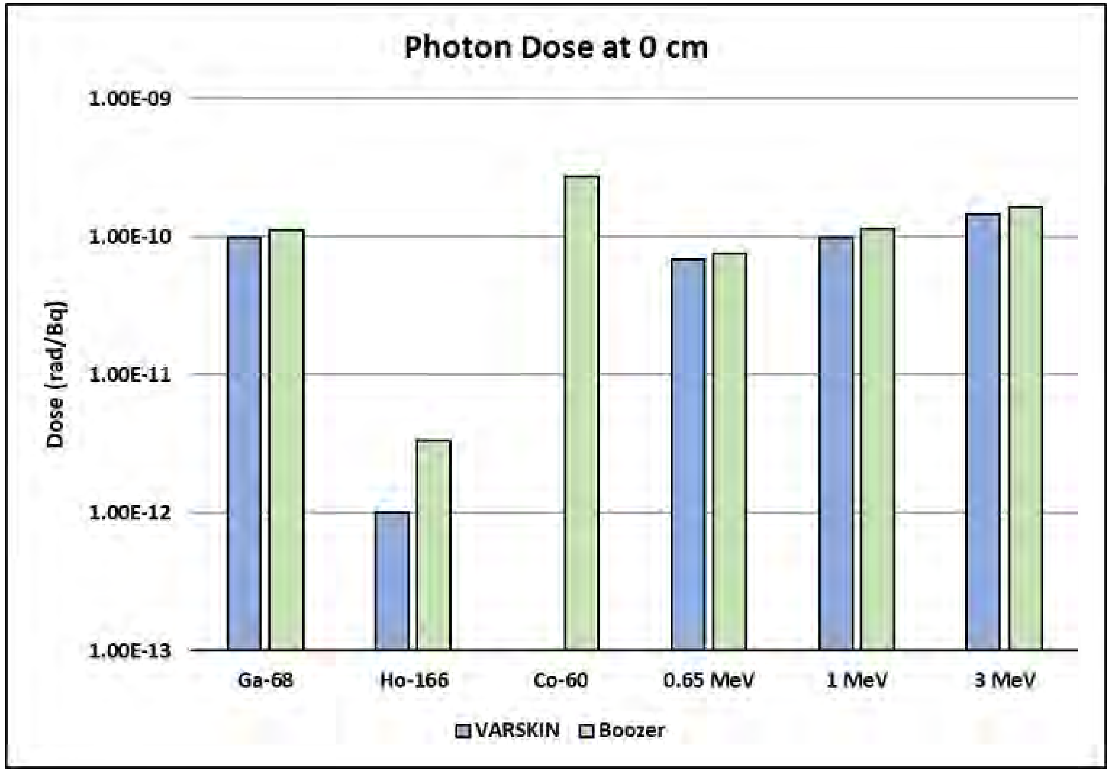
VERIFICATION AND VALIDATION



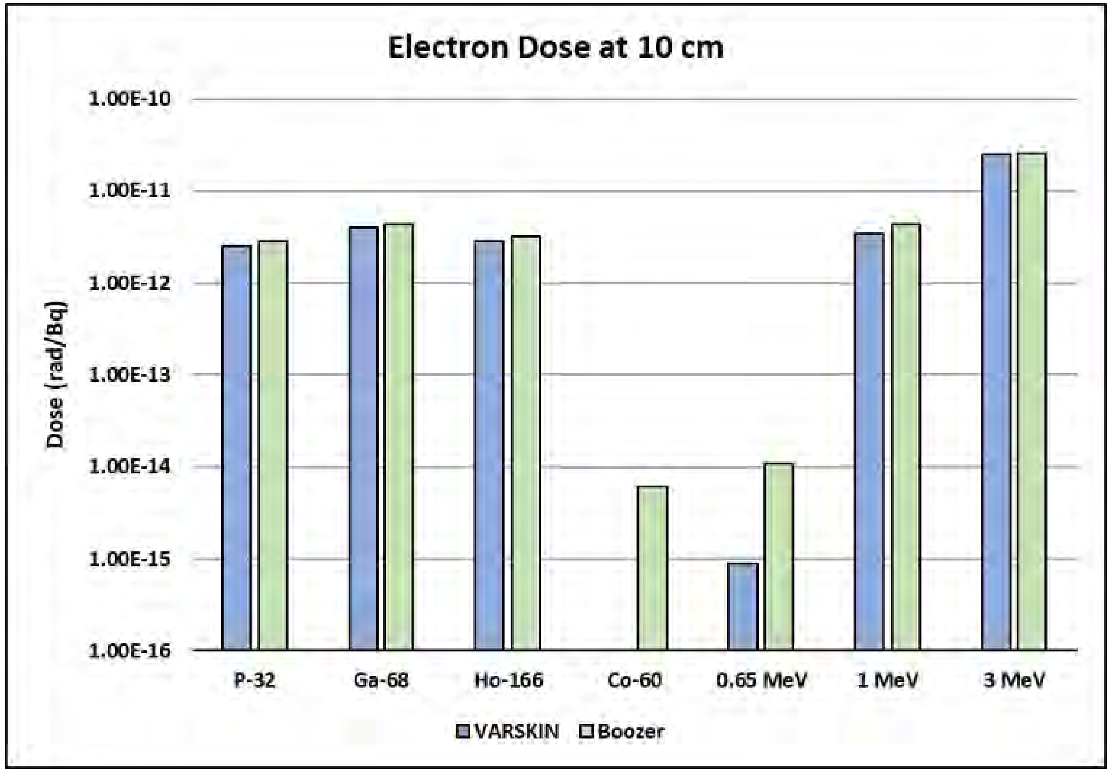


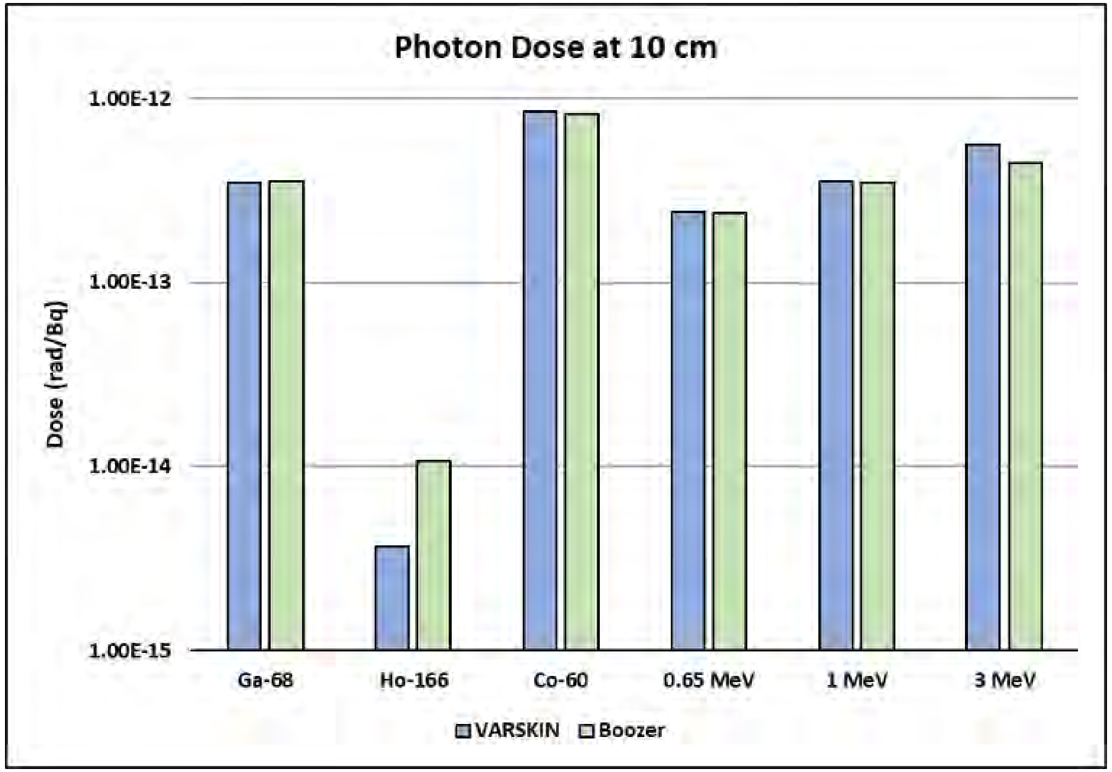
COMPARISON TO VARSKIN





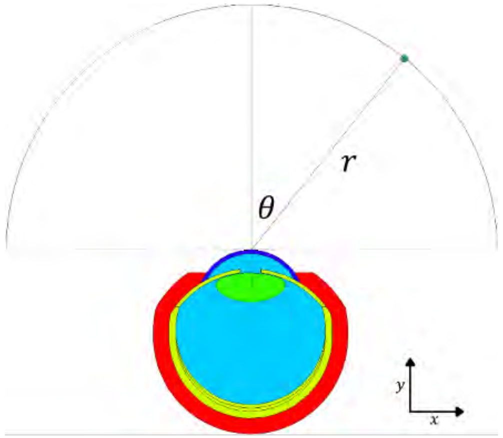
COMPARISON TO VARSKIN

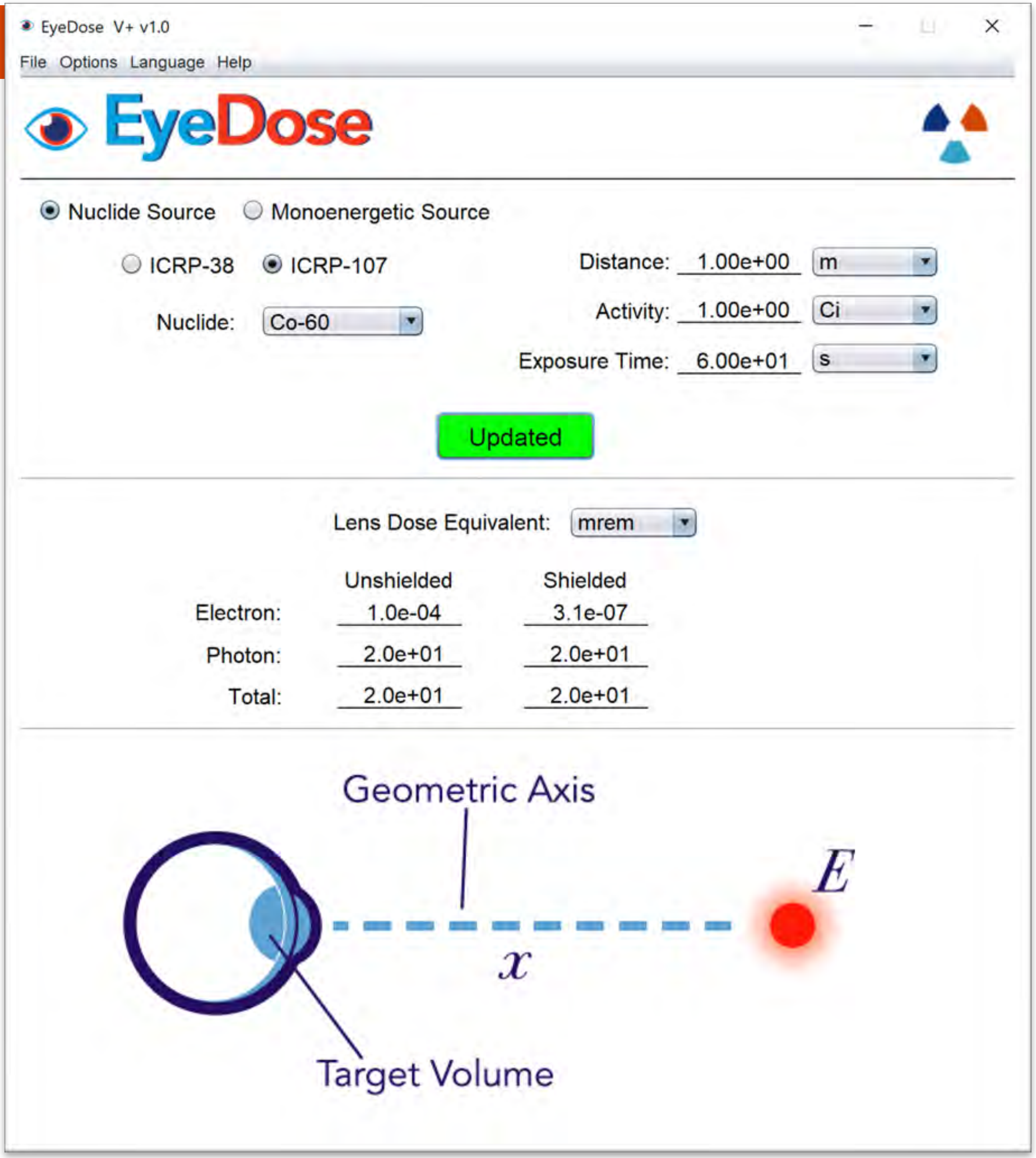




CURRENT LIMITATIONS

- Cannot adjust eye glasses parameters – built directly into the model
- Assumes eyeball being irradiated is staring directly at the source for the entire exposure
  - Sensitivity study shows dependency on off-axis angle and energy
  - The difference between the on-axis and off-axis dose might be within 20 percent provided that θ < 20°





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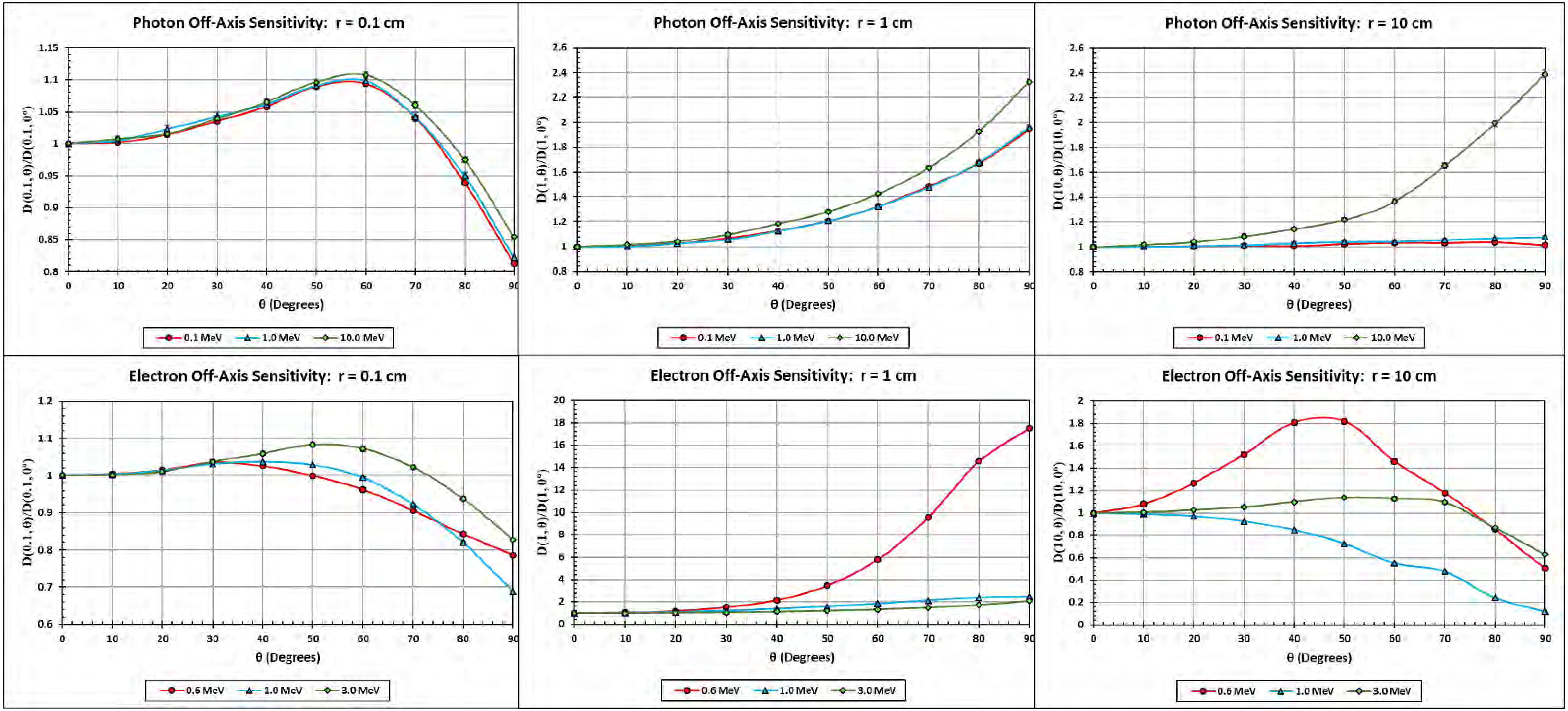
OFF-AXIS SOURCE



QUESTIONS