The Monte Carlo method in Diagnostic Radiology Dosimetry

P Andreo, Professor of Medical Radiation Physics (em)
Karolinska University Hospital and Karolinska Institute, Stockholm, Sweden
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Need for accurate dosimetry

- Accuracy dosimetry requirements had generally not been considered ‘essential’
- “Only through the monitoring of doses, inappropriate radiation levels can be discovered and corrected” (Wagner 1991)

Awareness of the importance of patient dose contributed by radiology procedures led to the development of the IAEA TRS-457 CoP (2007)
Reference Dosimetry for Diagnostic and Interventional Radiology

- incident air kerma
- entrance surface air kerma
- air kerma–area product
- air kerma–length product
- CT air kerma index

From ICRU-74 (2005)
Reference Dosimetry for Diagnostic and Interventional Radiology

\[ M_{\text{air}, Q} \times N_{K, \text{air}, Q} \times B_{\text{air}, Q} \times [\mu_{\text{en}}(Q)/\rho_{\text{w,air}}] \Rightarrow D_{w, Q} = M_{\text{air}, Q} N_{K, \text{air}, Q} B_{\text{air}, Q} \left[ \mu_{\text{en}}(Q)/\rho_{\text{w,air}} \right] \text{prim+backs} \]
Quantities to be calculated

\[ D_{w,Q} = M_{\text{air},Q} N_{K_{\text{air},Q}} B_{\text{air}}(Q,f,\text{SSD}) \left[ \mu_{\text{en}}(Q,f,\text{SSD}) / \rho \right]^{\text{prim+backs}}_{w,\text{air}} \]

- Both backscatter factor and mass energy-absorption ratio depend on beam quality, field size and source-surface distance.

- Backscatter factor defined as

\[ B_{\text{air}}(Q,f,\text{SSD}) = \frac{K_{\text{air},Q}}{K_{\text{air},Q}^\text{w}} \]

- \((\mu_{\text{en}}/\rho)_{w,\text{air}}\) includes backscatter spectra

- Difference with low-energy kV RT, where \(B_w\) is a ratio of \(K_w\)'s in water and in air. \((\mu_{\text{en}}/\rho)_{w,\text{air}}\) is free-in-air (FIA)
Monte Carlo calculated data

1. Both quantities require MC-calculated backscatter spectra

\[
B_{\text{air}}(Q, f, SSD) = \int_{0}^{k_{\text{max}}} \left[ k[\Phi_k]_{\text{air}} \right] \frac{[\mu_{\text{en}}(k)/\rho]_{\text{air}}}{[\mu_{\text{en}}(k)/\rho]_{\text{air}}} \, dk
\]

\[
[\mu_{\text{en}}(Q)/\rho]_{\text{prim+backs}} = \int_{0}^{k_{\text{max}}} \left[ k[\Phi_k]_{\text{surface}} \right] \frac{[\mu_{\text{en}}(k)/\rho]_{w}}{[\mu_{\text{en}}(k)/\rho]_{\text{air}}} \, dk
\]
Monte Carlo calculated data

2(a) $B_{\text{air}}$ database built for spectra from monoenergetic photons

Backscatter factors at the surface of 15 cm thick water
Lines: Benmakhlouf et al (2011)
Monte Carlo calculated data

2(b) \((\mu_{en}/\rho)_{w,\text{air}}\) database built for spectra from monoenergetic photons

\((\mu_{en}/\rho)_{w,\text{air}}\) at the surface of a 15 cm thick water phantom

LEFT: dashed - incident monoE photons FIA (independent of field size)
solid - surface spectra for two field sizes

RIGHT: surface spectra values normalized to incident spectrum (FIA)

From Benmakhlouf et al (2011)
Monte Carlo calculated data

3(a) Backscatter data for kV spectra obtained convolving incident spectrum with $B_{\text{air}}$ from monoE database

In addition to the large change with field size, note the variation with kV for a given HVL and field

From Benmakhlof et al (2011)
Monte Carlo calculated data

3(b) $(\mu_{en}/\rho)_{w,\text{air}}$ data for kV spectra obtained convolving spectrum with monoE database

Much smaller dependence with field size, but still significant variation with kV for a given HVL and field

From Benmakhlouf et al (2011)
Influence of phantom material

Backscatter in PMMA and water data differ substantially (too often ignored)

Backscatter factors at the surface of 15 cm thick PMMA phantom (data for water included)

Correction for phantom material

Relative to backscatter from water

\[ f_{m,Q} = \frac{\left( B_{\text{air},Q} \right)_{m,15}}{\left( B_{\text{air},Q} \right)_{w,15}} \]

\[ (B_{\text{air},Q})_{m} = (B_{\text{air},Q})_{w,15} \cdot f_{m,Q} \]

PMMA phantom material correction factor, \( f_{m,Q} \), for 15 cm thick phantom

From Benmakhlouf et al (2013)
Correction for phantom thickness

Smaller dependence on thickness, but significant for paediatric radiology

Thickness correction factor, $f_{t,Q}$, for water phantoms as a function of phantom thickness

Lowest lines of each set (largest correction) are for the highest HVL

From Benmakhlouf et al (2013)

$$f_{t,Q} = \frac{\left( B_{\text{air},Q} \right)_{m,t}}{\left( B_{\text{air},Q} \right)_{m,15}}$$

$$(B_{\text{air},Q})_{m,t} = (B_{\text{air},Q})_{w,15} f_{m,Q} f_{t,Q}$$
Organ dose conversion coefficient

\[ c_{\text{organ}, R} = \frac{D(\text{organ})}{R} \]

- \( R \) is a quantity measured or calculated for the clinical situation, such as \( K_{\text{air}, i} \), \( K_{\text{air}, e} \), \( P_{KA} \) or \( C_K \)
- \( R \) choice depends on clinic preference
- Derived from anatomical phantom MC simulations

✓ Strictly applicable only to the quantity, radiological procedure and organ(s) they were calculated for
✓ Ignores patient-to-patient differences

From ICRU-74 (2005)
Other MC calculations-2

Benchmark (or calc complementary data) for kV spectra analytical models

From Omar et al (2019)
Conclusions

• Need for accuracy in diagnostic and interventional dosimetry properly acknowledged

• Monte Carlo calculations play important role
  ▪ MC codes require accurate low-energy photon transport simulation

• Most dosimetry recommendations include MC-data

• Other Monte Carlo applications in x-ray dosimetry
  ▪ Organ dose conversion coefficients
  ▪ kV spectra calculations
  ▪ Design of x-ray tubes