Composite field dosimetry

Hugo Bouchard, PhD, MCCPM

Senior Research Scientist

Radiation dosimetry group

National Physical Laboratory

May 2014
Overview

1. Introduction
   – Dosimetry protocols
   – IAEA formalism
2. Single IMRT beams
   – Quality correction factors
   – Beam decomposition method
   – Gradient effects and volume averaging
   – Other effects
3. Composite IMRT beams
   – Theorem for composite IMRT beams
   – Experimental evidence
4. Calibration: PCSR
   – TPS calibration
   – Addendum to the IPEM UK code of practice
1. INTRODUCTION
Clinical radiation dosimetry

• Clinical reference dosimetry protocols
  – Generation 1
    • HPA 1960 (\(\gamma\)), 1964 (\(\gamma\)), 1969 (\(\gamma\)), 1971 (e-), 1975 (e-)
    • AAPM 1966 (e-), 1971 (\(\gamma\)), 1975 (\(\gamma\))
    • NACP 1972 (\(\gamma\) + e-)
    • *ICRU #10b 1962 (\(\gamma\)), #14 1969 (\(\gamma\)), ICRU #21 1972 (e-)
  – Generation 2
    • HPA 1980 (\(\gamma\) + e-)
    • AAPM TG-21 1983 (\(\gamma\) + e-)
    • IAEA TRS-277 1987 (\(\gamma\) + e-)
    • *ICRU 1984 (e-)
  – Generation 3
    • IPEM 1990 (\(\gamma\))
    • AAPM 1999 (\(\gamma\) + e-)
    • IAEA 2001 (\(\gamma\) + e- + p+)
    • IPEM 2003 (e-)  

*Strictly speaking not a protocol
Clinical radiation dosimetry


• Standard beams
  – 3rd generation
  – Linac or cobalt
  – Reference conditions of TG-51 or TRS-398 (or IPEM...)

• Nonstandard beams
  – 4th generation
  – New machines: Tomotherapy, Cyberknife, Gammaknife, etc.
  – Modulation, small fields (non-compliant with TG51/TRS398)
Clinical radiation dosimetry

- Nonstandard beam protocols (generation #4)
- Generalized absorbed dose to water-based approach (IAEA WG)

\[
D_w = N_{Dw} Q_{Dw} \cdot M_c \\
\times k_{Q_{msr}} Q_0 \\
\times k_{Q_{pcsr}} Q_{msr} \\
\times k_{Q_{clin}} Q_{pcsr}
\]

Standard-lab field

Definitive calibration

Machine reference field

TPS calibration

Plan class specific reference field

Clinical field
2. SINGLE IMRT BEAMS
What is a nonstandard field?

- A field or beam is nonstandard if it is either modulated or small over a plane of interest with half-width comparable to the e-range.
What is a nonstandard field?

- A field or beam is nonstandard if it is either modulated or small over a plane of interest with half-width comparable to the e-range.
- The opposite of a flat broad beam!

Flat broad beam  Modulated beam  Small field
What’s wrong with IMRT fields?

- Med. Phys. 31 (9): September, 2004

Capote et al.

Same conclusion: $D_w = C_Q^{IMRT} \cdot N_{D,w}^Q \cdot M_c$  

with $C_Q^{IMRT} \equiv \left[ \frac{L}{\rho} \right]^w_a \left[ \frac{P_{fl} P_{gr} P_{wall} P_{cel} P_{stem}}{Q_{IMRT}} \right]$
Quality correction factors

- What phenomena are responsible for these corrections?
  - Volume averaging
  - Gradient (displacement) effect (effective point of measurement)
  - Electron fluence perturbation caused by MLC and/or chamber

\[
D_w = N_{D,w}^Q \cdot M_c
\]

\[
D_w = N_{D,w}^{Q_{ref}} k_{Q_{NS} \cdot Q_{ref}} \cdot M_c
\]

\[
k_{Q_{NS} \cdot Q_{ref}} = \frac{\left[ \left( \frac{L}{\rho} \right)_a \right]^w P_{fl} P_{gr} P_{wall} P_{cel} P_{stem} }{Q_{nonstandard}}
\]
Perturbation factors

- Perturbation factor calculation
  - Monte Carlo method: "chain" of scoring volumes
    - L A Buckley and D W O Rogers, Med. Phys. 2006

\[
\begin{align*}
&k_{Q_{SS, Q_{ef}}} = \\
&\left[ \frac{\left( \frac{L}{\rho} \right)^w}{P_{fl} P_{gr} P_{wall} P_{cel} P_{stem}} \right]_{Q_{ref}}
\end{align*}
\]

Nonstandard beams
Electrons enter cavity sideways

Some electrons escape the cavity

Electrons entering cavity mainly from front
Electrons are produced in cavity
Some electrons escape the cavity

Beam crossing cavity

Beam not crossing cavity

Electrons enter cavity sideways
Some electrons escape the cavity
Sparse cavity

Number of electrons produced in cavity is less than water
Electron range in cavity is higher
Electrons can exit cavity more easily
Fluence is lower
Dose is smaller than water cavity

Beam crossing cavity

Beam not crossing cavity

Number of electrons cavity enter is slightly higher (less backscattering)
Electron path is higher
Fluence is higher
Dose is higher than water cavity
Dense cavity

Beam crossing cavity

- Number of electrons produced in cavity is higher
- Electron range in cavity is lower (mostly absorbed locally)
- Electrons can exit cavity less easily
- Fluence is higher
- Dose is higher than water cavity

Beam not crossing cavity

- Electron path is smaller
- Number of electrons entering cavity is lower (more backscattering)
- Fluence is lower
- Dose is lower than water cavity
What’s wrong with IMRT fields?

• Any beam modulation or restriction changes these distinctive contributions:
  1. Absorbed dose from beam area which projection crosses cavity
  2. Absorbed dose from beam area which projection does not cross cavity
The beam decomposition method

• Effect of density
  – Avoid modulating or restraining the perturbation zones

• Effect of volume size
  – Volume averaging
  – The size of cavity is limiting!!
3. COMPOSITE IMRT BEAMS
Composite IMRT beams $k_Q$ factors

- Do quality correction factors add-up?
Theorem for composite IMRT beams

- Theoretical approach on IMRT $k_Q$
  - Symmetrical measurement conditions
Theorem for composite IMRT beams

- Theoretical approach on IMRT $k_Q$
  - Concept of VSC and dosimetric equivalence

\[ k_Q \equiv k_Q \]
Theorem for composite IMRT beams

- Theoretical approach on IMRT $k_Q^*$

  The $k_Q^*$ factor of a VSC associated with a PCSR

\[
\begin{align*}
\frac{1}{2} m_1(x,z) &+ \frac{1}{2} m_2(x,z) \\
+ \frac{1}{2} m_1(-x,z) &+ \frac{1}{2} m_2(-x,z)
\end{align*}
\]

**Theorem.** If a cylindrical composite delivery produces a uniform dose distribution in a cylinder $V_{cyl}$ concentric to the phantom and fulfills the two following conditions: 1) for any beam the dose modulation function is the same in $V_{cyl}$ for any position along the beam axis, and 2) for any beam the dose gradient in the beam direction is constant and independent of the position; then its associated VSC beam produces no lateral dose gradient in $V_{cyl}$. 
Theorem for composite IMRT beams

- For any PCSR, we have this very nice property!

**Composite beam delivery**

**Virtual Symmetric Collapsed beam**

\[ k_Q \equiv k_Q \]
Experimental evidence


(a) axial  
(b) coronal  
(c) sagittal

Radiation: a 6 MV photon beam from a Varian® Clinac™  
6 EX linear accelerator


IMRT $k_Q$: Chung et al 2012

- IMRT $k_Q$ factors
  - Experimental observations during the design of PCSR fields by Chung et al (2012)

$$k_Q \rightarrow 1 \text{ if dose is homogeneous}$$
4. PCSR CALIBRATION
The future of IMRT plan calibration: PCSR beams

• What is a Plan Class Specific Reference field?
  – A PCSR is an ideal delivery meant to represent a class of treatment
  – Uses modulation and composite beams
  – Planned with same objectives as class of plans
  • Uniform dose in PTV-like volume
  • Constraints on OAR doses
  – Site-specific: prostate, head & neck, etc.

Prostate PCSR
The future of IMRT plan calibration: PCSR beams

• What is a Plan Class Specific Reference field?
  – It is strongly correlated to a clinical delivery...

Prostate PCSR
The future of IMRT plan calibration: PCSR beams

• PCSR dose rates would be used for calculating monitor units rather than reference beam
  – The planned dose rate is typically calculated as

\[ \dot{D}_{plan} = \dot{D}_{cal,msr} \left( \frac{\dot{D}_{TPS,clin}}{\dot{D}_{TPS,msr}} \right) \]

  – One can modify the relation from PCSR calibration

\[ \dot{D}_{plan} = \dot{D}_{cal,msr} \left( \frac{\dot{D}_{cal,pcsr}}{\dot{D}_{cal,msr}} \frac{\dot{D}_{TPS,msr}}{\dot{D}_{TPS,pcsr}} \right) \left( \frac{\dot{D}_{TPS,clin}}{\dot{D}_{TPS,msr}} \right) \]

Dose rate correction
The future of IMRT plan calibration: PCSR beams

• Potential to improve accuracy of plan by reducing the dependence of error on TPS calculation

\[ c = \left[ \frac{\dot{D}_{cal,pcsr}}{\dot{D}_{cal,msr}} - \frac{\dot{D}_{TPS,msr}}{\dot{D}_{TPS,pcsr}} \right] \]

\( c \) is 1 for ideal TPS engine, \( c \) varies with class of plans

• One can show that there is a benefit of using the dose rate correction if and only if

\[ \sigma_{cal,pcsr}^2 - \sigma_{cal,msr}^2 < \sigma_{TPS,msr}^2 + \sigma_{TPS,clin}^2 \]

Should be \( \ll 1\% \)

National Rotational IMRT Audit: \( \approx 2\% \)
The future of IMRT plan calibration: PCSR beams

Primary calibration

![Diagram of primary calibration](image1)

Definitive calibration

![Diagram of definitive calibration](image2)

TPS correction

![Diagram of TPS correction](image3)
IPEM Code of Practice

• Addendum for TomoTherapy (PMB 2014)

\[ D_{msr} = R_{FC,msr} N_{D,w,Q_{Tomo}}^{FC,f_{msr}} \]
\[ D_{pcs} = R_{FC,pcs} N_{D,w,Q_{Tomo}}^{FC,f_{msr}} k_{FC} \]

• Composite correction ignored, i.e. \( k_{FC}^{} = 1.000 \)

Appendix F. Field-dependent corrections for field chambers in TomoTherapy beams

Recommendation

In a pcsr field that provides a region of low dose gradient in the vicinity of the chamber, \( k_{FC}^{} = k_{Q_{msr},Q_{ms}}^{FC,fc,msr} \) for an A1SL chamber can be taken as equal to 1.000. For other chambers, no recommendation is made.

• QI for Tomotherapy must be done properly

\[ QI_{Tomo} = 0.94836 \cdot TPR_{Tomo} + 0.05164. \]
References

• Lilicrap et al., PMB 1990
• Almond et al. Med Phys 1999
• Andreo et al., IAEA 2001
• Capote et al., Med Phys 2004
• Bouchard and Seuntjens, Med Phys 2004
• Alfonso et al., Med Phys 2008
• Crop et al., PMB 2009
• Bailat et al., Med Phys 2009

• Rosser and Bedford, PMB 2009
• Bouchard et al., Med Phys 2009
• Chung et al., Med Phys 2010
• Langen et al., Med Phys 2010
• Chung et al., Med Phys 2012
• Scott et al., PMB 2012
• Bouchard, Med Phys 2012
• Thomas et al., PMB 2014
• ...