SRS: Detector Selection

Sonja Dieterich, PhD
Detector selection for SRS/SBRT encompasses an enormous amount of material. Dozens of detectors are available; each has several distinct characteristics to consider.

I have 30 minutes to cover it all.

This lecture will provide you with basic tools to research which detector is right for your project.

Always do a literature search.

Never hesitate to call/email a colleague/the MedPhys list.
WHAT IS A SMALL FIELD FROM A CLINICAL PERSPECTIVE?
Small Field Targets

• SBRT (typically on linac with MLC):
  – Lung metastases are smallest treated tumor
  – lower limit 2 cm x 2 cm PTV
  – Equivalent to 4 MLC leaf pairs (except HD MLCs)

• SRS (in CNS, typically cones):
  – Trigeminal neuralgia/functional Tx (Ø 4 mm)
  – Largest brain met ~40 mm in diameter
  – Human Vertebral body: 28 mm (H) x 45 mm (W)
Smallest Field at Commissioning

- **Linac with MLC:**
  - ~2000: 4 cm x 4 cm
  - ~2006: 3 cm x 3 cm
  - ~2010: 2 cm x 2 cm
  - ~2012: 0.5 cm x 0.5 cm

- **Cones:**
  - GK: ...........4 mm – 16 (18) mm
  - BrainLab: .....4 mm – 50 mm
  - CK: ............4 mm – 75 mm (across all SADs)

- **AAPM TG-106:** ≤ 4 cm x 4 cm
- **4 cm x 4 cm** **VERY** different from 0.5 cm x 0.5 cm!
DETECTORS FOR SMALL-FIELD REFERENCE DOSE METRY
Length of Reference Chamber in FFF


- Ask: Dose flatness sufficient for Farmer-type chamber?
  1) Cross calibrate a short chamber with Farmer-type chamber
  2) Use Farmer with mathematical correction
What chamber characteristic has the largest influence on reference dosimetry for small, no-flattened fields?

<table>
<thead>
<tr>
<th>%</th>
<th>1. Current stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>1%</td>
<td>2. Ratio of stem/volume</td>
</tr>
<tr>
<td>0%</td>
<td>3. Polarity</td>
</tr>
<tr>
<td>14%</td>
<td>4. Chamber diameter</td>
</tr>
<tr>
<td>85%</td>
<td>5. Chamber length</td>
</tr>
</tbody>
</table>
What chamber characteristic has the largest influence on reference dosimetry for small, no-flattened fields?

- Current stability
- Ratio of stem/volume
- Polarity
- Chamber diameter
- **Chamber length**
- e) Kawachi demonstrated a 1.3 % effect on relative dosimetry for a Farmer chamber in a 6 cm diameter FFF beam.
- d) The diameter is perpendicular to the beam; very large integrating pancake chambers could be used for relative dosimetry.
- a)-c) have much smaller influence on reference dosimetry than chamber length.
Small Reference Chamber Selection

• Irradiation conditions are different from typical reference conditions

• Small volume chambers have higher ratio of stem to irradiated volume

• Characteristics needed:
  – Stability of current as function of (continuous) irradiation time
  – Current as function of voltage
  – Current as function of polarity

Reference:
**Tomo Reference Dosimetry with A1SL**

### Table II

Exradin A1SL ionization chamber dose measurements, alanine dose measurements, and global correction factors. Associated uncertainties are expressed with a coverage factor $k = 2$.

<table>
<thead>
<tr>
<th>Field</th>
<th>A1SL $[M_Q \cdot N_{D,x,Q_0} \cdot k_{Q,Q_0}]$ (Gy)</th>
<th>Alanine dose (Gy)</th>
<th>Global correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>m&amp;l</td>
<td>19.90±0.17</td>
<td>19.54±0.34</td>
<td>$k_{Q_{mef,Q}} = 0.982\pm0.019$</td>
</tr>
<tr>
<td>Pcsr</td>
<td>2.023±0.021</td>
<td>1.981±0.035</td>
<td>$k_{Q_{pceo,Q}} = 0.980\pm0.020$</td>
</tr>
<tr>
<td>Lung clin treatment</td>
<td>15.98±0.15</td>
<td>15.670±0.028</td>
<td>$k_{Q_{lueo,Q}} = 0.981\pm0.020$</td>
</tr>
<tr>
<td>H &amp; N clin treatment</td>
<td>1.647±0.015</td>
<td>1.620±0.030</td>
<td>$k_{Q_{hueo,Q}} = 0.984\pm0.020$</td>
</tr>
</tbody>
</table>

### Table I

Relative uncertainty contributions to ionization chamber and alanine measurements with coverage factor $k = 2$. Positioning uncertainty is 0.2% in $f_{mea}$ and 0.4% in helical deliveries.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>Uncertainty type</th>
<th>A1SL (%)</th>
<th>Alanine (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration coeff</td>
<td>B</td>
<td>0.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Ambient conditions (P, T)</td>
<td>B</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Positioning</td>
<td>B</td>
<td>0.2 or 0.4</td>
<td>0.2 or 0.4</td>
</tr>
<tr>
<td>Repeatability</td>
<td>A</td>
<td>0.1–0.7</td>
<td>0.6–0.8</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>A and B</td>
<td>0.87–1.0</td>
<td>1.7–1.8</td>
</tr>
</tbody>
</table>

These values find agreement with previous investigations with alanine dosimetry\(^4,5\) but differ from other works where absorbed dose is measured with radiochromic film,\(^17\) further studies would be desirable to assess the magnitude of this correction.
The Dilemma:

- Gago-Arias publication (Alanine, A1SL) & IROC Houston findings agree on 2% correction
- Manufacturer practice and Zeverino publication (radiochromic film)
DETECTORS TO MEASURE OUTPUT (TOTAL SCATTER) FACTORS
Experimental Setup Consistency I

- Beam lasers/optical CAX indicators are not exactly on central axis
- Detector manufacturing uncertainties
- Method:
  - Do cross-profile scan
  - Set detector to maximum profile in either direction
  - Repeat cross profile scan
  - Aim for 0.1-0.2 mm
Experimental Setup Consistency II

- 3rd party device
- mMLC with backup jaws
- Jaw settings change field geometry
- Set jaws to reflect clinical plans

Das et al, MedPhys 35 (1)
Detector Selection for Output Factor

- In water
- Measure at depth (5 cm or 10 cm) because $d_{\text{max}} = f(\text{field size})$
- Personal experience: diodes
  - $\sim 1$ mm diameter
  - Good size down to 5 mm beam
    - Some diode models degrade with dose
    - Energy-dependence
  - Daisy-chain at 4 cm x 4 cm for 10 cm x 10 cm reference field
OF: Which Diode is “Best”?

Dieterich & Sherouse, MedPhys 38 (7)
Other Suitable Detectors

- Micro-chambers
- Diamond Detectors
- Film
- TLD/OSLD
- Gel (Alanine, BANG, Fricke …)
- …

Do all of these give the same OF values?
Detector Response

- Francescon, Cora, Cavedon, Med Phys (2008) 504

- OF ( = $s_{c,p}$) for 3 smallest CK cones:
  - 2 micro-chambers, PTW60012 diode, diamond detector
  - Measurements
  - Monte Carlo simulation

- MC:
  - Dependency of OF on FWHM of electron beam
  - Correction factors for detector response
MC-OF as Function of Electron-Beam FWHM

Table IV. Measured and MC-simulated $s_{c,p}$ for the four detectors and for the 5, 7.5, and 10 mm collimators, for the various FWHM of the Gaussian spatial distribution of the electron source.

<table>
<thead>
<tr>
<th>Coll 5 mm</th>
<th>Measured $s_{c,p}$</th>
<th>Simulated $s_{c,p}$</th>
<th>Simulated $s_{c,p}$</th>
<th>Simulated $s_{c,p}$</th>
<th>Simulated $s_{c,p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A16</td>
<td>0.614</td>
<td>0.669</td>
<td>0.643</td>
<td>0.611</td>
<td>0.585</td>
</tr>
<tr>
<td>PinPoint</td>
<td>0.613</td>
<td>0.661</td>
<td>0.636</td>
<td>0.607</td>
<td>0.582</td>
</tr>
<tr>
<td>Diode</td>
<td>0.710</td>
<td>0.757</td>
<td>0.732</td>
<td>0.704</td>
<td>0.679</td>
</tr>
<tr>
<td>Diamond</td>
<td>0.613</td>
<td>0.677</td>
<td>0.639</td>
<td>0.609</td>
<td>0.580</td>
</tr>
</tbody>
</table>

| Coll 7.5 mm | A16 | 0.801 | 0.809 | 0.808 | 0.799 | 0.792 |
| PinPoint    | 0.798 | 0.805 | 0.802 | 0.795 | 0.789 |
| Diode      | 0.852 | 0.757 | 0.850 | 0.843 | 0.842 |
| Diamond    | 0.815 | 0.833 | 0.818 | 0.813 | 0.803 |

| Coll 10 mm | A16 | 0.859 | 0.874 | 0.870 | 0.860 | 0.857 |
| PinPoint   | 0.858 | 0.867 | 0.865 | 0.860 | 0.857 |
| Diode     | 0.895 | 0.909 | 0.896 | 0.890 | 0.886 |
| Diamond   | 0.871 | 0.889 | 0.876 | 0.872 | 0.866 |

Point source assumption starts breaking down for 5 mm collimator!
**OF Correction Factor \( F_{\text{corr}} \)**

- Detector response: \( F_{\text{corr}} = \text{OF (MC)} / \text{OF (measured)} \)
- Combine detector response with (small) FWHM correction to get \( s^{*}_{c,p} \)

<table>
<thead>
<tr>
<th>TABLE III. Estimated values of ( F^{<em>}_{\text{corr}} ) and ( s^{</em>}_{c,p} ) for the 5, 7.5, 10 mm collimators, for the four detectors.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm</td>
</tr>
<tr>
<td>( F^{*}_{\text{corr}} )</td>
</tr>
<tr>
<td>A16</td>
</tr>
<tr>
<td>PinPoint</td>
</tr>
<tr>
<td>Diode</td>
</tr>
<tr>
<td>Diamond</td>
</tr>
<tr>
<td>Mean ( s^{*}_{c,p} )</td>
</tr>
</tbody>
</table>
Dosimetry: Variation in $S_{c,p}$

- Vicenza study for several detectors results in low uncertainty of OFs (if all corrections apply)
  

- Gel measurement strong indication for correct calculation of OF correction factor
  
  Pantelis Med Phys (2008) 2312

Figure 20-2. Example of rapidly decreasing output factor with decreasing field size from CyberKnife® data. Composite data from several centers, measured by means of diode detectors and normalized to the 60 mm collimator output factor.
2012 Update with 9 Detectors

- MC differs from TRS-398
- Effects of correction for several collimator systems

Francescon et al, PMB 57 (2012) 3741

Table 1. Values of $k_{Q_{\text{iso}},Q_{0}}$ calculated by Monte Carlo simulation of the CyberKnife system and a reference Cs:60 beam. For comparison, $k_{Q_{\text{iso}},Q_{0}}$ extracted from TRS-398 using a hypothetical 100 × 100 mm² TPR20/10 converted using the method of Sauer (2009) from the measured TPR20/10 at 60 mm circular field size is shown, together with the difference between these two calculations.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>$k_{Q_{\text{iso}},Q_{0}}$</th>
<th>$k_{Q_{\text{iso}},Q_{0}}$ (TRS-398)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTW 30006 Farmer</td>
<td>1.000</td>
<td>0.993</td>
<td>+0.7%</td>
</tr>
<tr>
<td>PTW 31014 PinPoint</td>
<td>0.990</td>
<td>0.995</td>
<td>−0.5%</td>
</tr>
<tr>
<td>Exradin A12 Farmer</td>
<td>1.006</td>
<td>0.997</td>
<td>+0.9%</td>
</tr>
<tr>
<td>NE 2571 Farmer</td>
<td>1.003</td>
<td>0.995</td>
<td>+0.8%</td>
</tr>
<tr>
<td>PTW 31010 Semiflex</td>
<td>0.990</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Fig. 3. Relative total scatter factors difference normalized to Monte Carlo [Araki (Ref. 8)]. The y-axis represents the relative total scatter factor difference normalized to Monte Carlo [Francescon et al. (Ref. 5)]. The y-axis represents the relative total scatter factor difference normalized to Monte Carlo.
Heads-Up: Upcoming IAEA report (Seuntjens lecture)

- IAEA Small Field Dosimetry Working Group
- Establishing correction factors for a range of detectors
- Not published yet
**Meanwhile: To correct or not correct?**

- *Brachytherapy (AAPM TG-43 U1)*: Recommended consensus value is equally weighed average of separately averaged MC and experimental values.

- *SRS Detector Correction factors*: Depth of data for detector/beam combination not available yet.

- Inofficial “reasonable approaches”:
  1. Measure OF using 2 detectors with known beam/detector correction factors and average.
  2. Measure OF using 2 detectors with known opposite energy dependency and average.
Until IAEA or AAPM recommendations on detector correction factors are published, what would be a prudent approach to making small field OF corrections based on the literature?

1. Any single peer-reviewed publication for a specific beam/detector is acceptable
2. Under no circumstances should corrections be made
3. Do my own MC simulation for a correction factor
4. Measure the same fields with two detectors for which correction factors are published, compare and average the corrected factors
5. Average all published correction factors for that detector in any beam
Until IAEA or AAPM recommendations on detector correction factors are published, what would be a prudent approach to making small field OF corrections based on the literature?

- Any single peer-reviewed publication for a specific beam/detector is acceptable
- Under no circumstances should corrections be made
- Do my own MC simulation for a correction factor
- **Measure the same fields with two detectors for which correction factors are published, compare and average the corrected factors**
- Average all published correction factors for that detector in any beam


Is the OF Measurement Correct?

- RPC published data sets
  JACMP Vol 13 (5) 2012
- CyberKnife MP has reference data set available in commissioning tool
- “Golden” beam data sets
- Literature
## Typical OF Values for 6MV

<table>
<thead>
<tr>
<th></th>
<th>10 x 10</th>
<th>6 x 6</th>
<th>4 x 4</th>
<th>3 x 3</th>
<th>2 x 2</th>
<th>1 x 1</th>
<th>.5 x .5</th>
</tr>
</thead>
<tbody>
<tr>
<td>**Elekta ***</td>
<td>MLC</td>
<td>1</td>
<td>0.930</td>
<td>0.878</td>
<td>0.842</td>
<td>0.790</td>
<td>N/A</td>
</tr>
<tr>
<td>**Varian ***</td>
<td>MLC</td>
<td>1</td>
<td>0.921</td>
<td>0.865</td>
<td>0.828</td>
<td>0.786</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>BrainLab</strong></td>
<td>mMLC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>See Next Slide</td>
<td></td>
</tr>
<tr>
<td><strong>BrainLab</strong></td>
<td>Cone</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>0.969</td>
<td>0.926</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>CK</strong></td>
<td>Cone</td>
<td>N/A</td>
<td>1</td>
<td>0.997</td>
<td>0.993</td>
<td>0.974</td>
<td>0.911</td>
</tr>
</tbody>
</table>

- *JACMP Vol 13 (5) 2012:
- Elekta field size defined by secondary jaw that included an MLC
- Varian defined by tertiary MLC with jaws set to 10 x 10
- Wilcox and Daskalov, MedPhys 34 (6) 2007 for CyberKnife data

➢ Values depend on **field shape**
➢ Values depend on **normalization field**
Variation of output factors of mMLC (m3) with the make and model of the medical linear accelerator

<table>
<thead>
<tr>
<th>Square field size (mm²)</th>
<th>Output factor of mMLC (m3) installed at</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Siemens primus (H1)</td>
</tr>
<tr>
<td>6 x 6</td>
<td>0.612</td>
</tr>
<tr>
<td>12 x 12</td>
<td>0.800</td>
</tr>
<tr>
<td>18 x 18</td>
<td>0.859</td>
</tr>
<tr>
<td>24 x 24</td>
<td>0.881</td>
</tr>
<tr>
<td>30 x 30</td>
<td>0.895</td>
</tr>
<tr>
<td>36 x 36</td>
<td>0.904</td>
</tr>
<tr>
<td>42 x 42</td>
<td>0.913</td>
</tr>
</tbody>
</table>

*J Med Phys 2007 32(1)*

Up to **8%** difference for smallest field across accelerators!
Independent Output Check

- Absolutely necessary before treating a patient!
- Too many misadministrations based on reference dosimetry gone wrong
- E.g. use TLD/OSLD service
- Peer review
**PDD/TPR in Small Fields**

- Some detector dependence
  - Energy dependence?
  - CAX alignment?
- **PDD very sensitive to water tank/CAX alignment!**
- PDD/TPR conversion does not work well for small fields
- Measure TPRs directly if planning system requires
- Special small-field water tanks for TPR measurements

AAPM TG-106 Accelerator Beam Data Commissioning
OAR and Volume Averaging: Influence of Detector Size
Placement of Reference Detector

- AAPM TG 106:

  The reference detector may be positioned anywhere in the beam where it does not shadow the field detector for the entire area of programmed positions. For very small fields, where the reference detector may shadow the field detector, a time integration method could be used instead of the reference chamber. The field and refer

1) Ref detector above collimator (if available)
2) In water or air above field detector
3) Out of field: not recommended, too much noise (maybe?)
4) Below field detector (Divergence!)
5) Don’t use a reference detector
OAR Width vs. Detector Size

- Fields predominantly penumbra
- Penumbra = f(detector size)

**Table IV.** Comparison of the 80%–20% penumbra measured with EBT film, diode, and ion chamber. The standard deviation for all detectors is within ±0.1 mm.

<table>
<thead>
<tr>
<th>Collimator diameter (mm)</th>
<th>EBT film</th>
<th>Diode</th>
<th>Ion chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.09</td>
<td>2.05</td>
<td>2.4</td>
</tr>
<tr>
<td>7.5</td>
<td>2.21</td>
<td>2.25</td>
<td>2.7</td>
</tr>
<tr>
<td>10</td>
<td>2.55</td>
<td>2.55</td>
<td>2.85</td>
</tr>
<tr>
<td>20</td>
<td>2.66</td>
<td>2.85</td>
<td>3.1</td>
</tr>
<tr>
<td>30</td>
<td>2.74</td>
<td>3.00</td>
<td>3.2</td>
</tr>
<tr>
<td>60</td>
<td>3.47</td>
<td>3.85</td>
<td>4.4</td>
</tr>
</tbody>
</table>

*Medical Physics, Vol. 34, No. 6, June 2007*
Visual Example of Volume Averaging

- Greater divergence of measured penumbra for larger detectors

OAR Volume Averaging

- Wuerfel, MIP 1,1 (2013)
- Volume averaging for finite detector
- FWHM will stay constant
- Choose smallest detector available!
- **Detector**: FWHM = 1:3
- Slow scan speed to increase signal-to-noise ratio
What is the largest Detector:FWHM ratio which should be used for OAR measurements?

1. 1:1
2. 1:2
3. 1:3
4. 1:4
5. 1:5
What is the largest Detector:FWHM ratio which should be used for OAR measurements?

1:1
1:2
1:3
1:4
1:5

Feedback:
a) and b) are too large; significant volume averaging
c) correct answer
d) and e) would be better, but for small fields detectors of this size are not available and S?N ratio becomes problematic

Reference:
OAR: Energy Change Across Field

- Energy spectrum change across fields affects diodes
- Effect most pronounced for LARGE SRS fields

Morin, MedPhys 40 (1), 2013

**Fig. 6.** Dose profile measured at 1.5 cm depth and 80 cm SAD with the 5-mm cone normalized to the dose measured at the center of the field. Error bars are not shown to simplify the visualization. The gamma evaluation used acceptance criteria of 2% and 0.2 mm.

**Fig. 7.** Dose profile measured at 1.5 cm depth and 80 cm SAD with the 60-mm cone normalized to the dose measured at the center of the field. Error bars are not shown to simplify the visualization. The gamma evaluation used acceptance criteria of 2% and 0.2 mm.
Dose Rate Dependence of Detectors (Theory)
A Word on Dose Rate Dependence

• Wuerfel, MIP 1,1 (2013)
• Hypothetical detector:
  – Assume dose rate dependence linear with dose/pulse
  – Max saturation loss at highest dose/pulse
• Assume 2 % saturation loss (large!)
• Effect is smaller than volume-averaging effect
## Summary

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Ionization chamber</th>
<th>Micro Chambers</th>
<th>Stereotactic Diodes</th>
<th>Diamond detector</th>
<th>Plastic Scintillator</th>
<th>Gels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field size</td>
<td>≥ 2 cm x 2 cm</td>
<td>≥ 3 mm x 3 mm</td>
<td>≥ 3 mm x 3 mm</td>
<td>≥ 3 mm x 3 mm</td>
<td>≥ 3 mm x 3 mm</td>
<td>≥ 3 mm x 3 mm</td>
</tr>
<tr>
<td>Energy dependence</td>
<td>Use $k_Q$ to correct energy dependence</td>
<td>Use $k_Q$ to correct energy dependence</td>
<td>Normalize at 4 cm$^2$ for energy dependence</td>
<td>Almost none</td>
<td>Almost none</td>
<td>Depends on gel material</td>
</tr>
<tr>
<td>Drawbacks</td>
<td>Volume effect</td>
<td>Stem and cable effect, S/N ratio</td>
<td>Some models: Aging, dose rate</td>
<td>Weak dose rate dependence; availability</td>
<td>S/N ratio; temperature dependence; cable irradiation</td>
<td>Availability</td>
</tr>
<tr>
<td>Advantage</td>
<td>Familiarity/ Availability</td>
<td>Spatial resolution</td>
<td>Small size, availability</td>
<td>Near ideal</td>
<td>Small size</td>
<td>Spatial resolution</td>
</tr>
</tbody>
</table>
Conclusion

- Small fields require special techniques
- Guidance documents are becoming available
- Detector selection becoming larger (and coming down in price)
- Match detector/equipment to need
- Research detector performance
- Compare measurements to published data