Hot Topics in SRS: Small Field Dosimetry & Other Treatment Uncertainties

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Lecture in Two Parts

- SRS Dosimetry
- Other Uncertainties

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SRS DOSIMETRY
Outline

1. What is a Small Field?
2. Small Field Reference Dosimetry
3. Output Factors/Total Scatter Factors
4. PDD/TPR
5. OAR and volume averaging of detectors
6. Dose rate dependence

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WHAT IS A SMALL FIELD?
Small Field Targets

- **SBRT** (typically on linac with MLC):
  - Lung mets are smallest tumor treated
  - 2 cm x 2 cm PTV lower limit
  - 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 Measured 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!
SMALL-FIELD REFERENCE DOSIMETRY

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Reference Dosimetry: The IAEA concept

Alfonso et al, Med Phys (2008), 5179 ©Sonja Dieterich
TG-51 in FFF Beams

- CyberKnife and Tomotherapy
- Linacs:
  - Siemens (Bayouth 2007)
  - Elekta (Georg 2009)
  - Varian (Vassiliev 2006)
- Kalach & Rogers, Med Phys 30 (2003) 1546
- TG51 is using %dd(10)_x

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Length of Reference Chamber in FFF

- Dose flatness sufficient for Farmer-type chamber?
- Option 1: cross calibrate a short chamber with Farmer-type chamber
- Option 2: Use Farmer with mathematical correction
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:

Assessment of small volume ionization chambers as reference dosimeters in high-energy photon beams

M Le Roy, L de Carlan, T Dlaunay, M Donois, P Fournier¹, A Ostrowsky, A Vouillaume¹ and J M Bordy
Independent Output Check

- Absolutely necessary before treating a patient!
- Too many misadministrations based on reference dosimetry gone wrong
- E.g. use TLD service
- Peer review

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OUTPUT (TOTAL SCATTER) FACTORS
Experimental Setup Consistency I

- Beam lasers 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

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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
  - ~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)
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

Table 2. The RPC-measured and institution treatment planning system-calculated small field size dependence output factor values for Elekta machines. The values in square brackets and parentheses beneath each energy for each field size value are the average absolute percent differences and standard deviations of the values, respectively. For each energy and field size, the number of measurements (accelerators) is also shown.

<table>
<thead>
<tr>
<th>Field Size (cm × cm)</th>
<th>Elekta 6 MV RPC</th>
<th>Institution</th>
<th>Elekta 10 MV RPC</th>
<th>Institution</th>
<th>Elekta 18 MV RPC</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 × 10</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>6 × 6</td>
<td>0.936</td>
<td>(0.010)</td>
<td>0.937</td>
<td>(0.004)</td>
<td>0.940</td>
<td>(0.002)</td>
</tr>
<tr>
<td></td>
<td>[0.5%] (n=18)</td>
<td></td>
<td>[0.7%] (n=6)</td>
<td></td>
<td>[0.3%] (n=5)</td>
<td></td>
</tr>
<tr>
<td>4 × 4</td>
<td>0.878</td>
<td>(0.015)</td>
<td>0.890</td>
<td>(0.009)</td>
<td>0.891</td>
<td>(0.010)</td>
</tr>
<tr>
<td></td>
<td>[1.3%] (n=22)</td>
<td></td>
<td>[0.6%] (n=6)</td>
<td></td>
<td>[0.4%] (n=5)</td>
<td></td>
</tr>
<tr>
<td>3 × 3</td>
<td>0.842</td>
<td>(0.012)</td>
<td>0.857</td>
<td>(0.003)</td>
<td>0.852</td>
<td>(0.005)</td>
</tr>
<tr>
<td></td>
<td>[0.9%] (n=17)</td>
<td></td>
<td>[0.6%] (n=6)</td>
<td></td>
<td>[0.6%] (n=4)</td>
<td></td>
</tr>
<tr>
<td>2 × 2</td>
<td>0.796</td>
<td>(0.010)</td>
<td>0.796</td>
<td>(0.009)</td>
<td>0.802</td>
<td>(0.008)</td>
</tr>
<tr>
<td></td>
<td>[1.6%] (n=17)</td>
<td></td>
<td>[1.3%] (n=6)</td>
<td></td>
<td>[2.4%] (n=4)</td>
<td></td>
</tr>
</tbody>
</table>

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## 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></td>
<td>See Next Slide</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**
OF of mMLC is function of linac!

<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 × 6</td>
<td>0.612</td>
</tr>
<tr>
<td>12 × 12</td>
<td>0.800</td>
</tr>
<tr>
<td>18 × 18</td>
<td>0.859</td>
</tr>
<tr>
<td>24 × 24</td>
<td>0.881</td>
</tr>
<tr>
<td>30 × 30</td>
<td>0.895</td>
</tr>
<tr>
<td>36 × 36</td>
<td>0.904</td>
</tr>
<tr>
<td>42 × 42</td>
<td>0.913</td>
</tr>
</tbody>
</table>

J Med Phys 2007 32(1)

Up to 8% difference for smallest field across accelerators!

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Other Suitable Detectors

- Micro-chambers
- Diamond Detectors
- Film
- TLD
- Gel
- ...

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

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MC-OF as Function of Electron-Beam FWHM

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 III.** Estimated values of $F_{\text{corr}}^*$ and $s_{c,p}^*$ for the 5, 7.5, and 10 mm collimators, for the four detectors.

<table>
<thead>
<tr>
<th></th>
<th>5 mm</th>
<th>7.5 mm</th>
<th>10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F_{corr}^*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A16</td>
<td>1.098</td>
<td>1.021</td>
<td>1.010</td>
</tr>
<tr>
<td>PinPoint</td>
<td>1.107</td>
<td>1.027</td>
<td>1.014</td>
</tr>
<tr>
<td>Diode</td>
<td>0.957</td>
<td>0.966</td>
<td>0.978</td>
</tr>
<tr>
<td>Diamond</td>
<td>1.104</td>
<td>1.006</td>
<td>1.000</td>
</tr>
<tr>
<td>Mean $s_{c,p}$</td>
<td>0.677</td>
<td>0.679</td>
<td>0.679</td>
</tr>
<tr>
<td>±2σ</td>
<td>±0.004</td>
<td>±0.008</td>
<td>±0.008</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)
  (Francescon et al, Med Phys (2008) 504)

- BANG gel measurement strong indication for OF correction factor
  Pantelis Med Phys (2008) 2312

Minimize uncertainty by using correction factors

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

- Includes 9 detectors
- MC differs from TRS-398
- Effects of correction for several collimator systems

( Francescon et al, PMB 57 (2012) 3741 )
Visualizing the Difference

Morin, MedPhys 40 (1), 2013
Heads-Up: Upcoming IAEA report

- IAEA Small Field Dosimetry Working Group
- Establishing correction factors for a range of detectors
- Not published yet
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

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OAR AND VOLUME AVERAGING
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 reference detectors should be

• Ref detector above field
• Works well if above secondary collimation
• Alternate option: place below field detector
• Out of field: too much noise!
OAR Width vs. Detector Size

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

<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>
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

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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.
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
- Effect is smaller than volume-averaging effect
<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

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THE OTHER UNCERTAINTIES

Disclaimer: This section is about the big picture, ongoing research, and ideas.

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## (Selected) SBRT margins from Literature

<table>
<thead>
<tr>
<th>Paper</th>
<th>Target</th>
<th>Type</th>
<th>Motion compensation</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 Rusthoven</td>
<td>Liver</td>
<td>Phase 1 &amp; 2</td>
<td>ABC</td>
<td>5 mm radial</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10 mm cranio-caudal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compression</td>
<td>7 mm radial</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15 mm cranio-caudal</td>
</tr>
<tr>
<td>2006 Dawson</td>
<td>Liver</td>
<td>Phase 1 &amp; 2</td>
<td>Free, breath-hold, compression</td>
<td>&gt; 5 mm</td>
</tr>
<tr>
<td>2010 Timmermann</td>
<td>Lung</td>
<td>Phase 2</td>
<td>Free, breath-hold, compression, gating</td>
<td>≤ 5 mm radial</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>≤ 10 mm cranio-caudal</td>
</tr>
<tr>
<td>RTOG-0813</td>
<td>Lung</td>
<td></td>
<td>Free, breath-hold, compression, gating, tracking</td>
<td>Helical scan:</td>
</tr>
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<td></td>
<td></td>
<td>- 5 mm radial</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- 10 mm cranio-caudal</td>
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<td>4DCT:</td>
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<td></td>
<td>- 5 mm ITV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Other methods per approval</td>
</tr>
</tbody>
</table>

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What is an appropriate margin?

• Internal margin (IM or ITV):
  – Residual motion, deformation

• Setup margin (SM):
  – Ensures adequate clinical coverage
  – Includes all uncertainties

• Appropriate for hypofractionation

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Type A and B

• Replaces “random” and “systematic”

• Type A evaluation
  method of evaluation of uncertainty by the statistical analysis of series of observations,

• Type B evaluation
  method of evaluation of uncertainty by means other than the statistical analysis of series of observations.

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Margins – not your simple PTV anymore

- Margin recipes based on many fractions:

- Small fraction number in SBRT requires adaptation

- Heijmen et al. adapted v Herk recipe for SBRT:
  - mean random error added to systematic error

- Gordon and Siebers (2007), proposes Alternative Method:
  - systematic $\ll$ random error (AM1)
  - weighted sum of AM1 when Systematic $\ll$ random does not hold (AM1)

Herschtal Margin for SBRT

- Adjusted van Herk formula as lower limit
- Develops method for estimating upper limit
- Derives a model to interpolate between limits
- Verification using MC simulation

Data generation:
- MC to generate displacement data for 10,000 patients (max 0.5% standard error)
- Generate Dose Population Histograms
- Generate data for varying random & systematic errors, number of fractions

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Figure 5. Graphs of margin against $n$ for varying values of $\sigma$ and $\tau$, for $\sigma_p = 1$. 
Radiosurgery Chain of Uncertainty

- Target definition
- 3D Imaging
- Target localization
- Biological model
- Patient positioning
- Mechanics
- Dose calculation (TPS)
- Dosimetric calibration

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TPS Dose Calculation = Spatial Shift!

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Radiosurgery Chain of Uncertainty

- Target localization
- Biological model
- Patient positioning
- Mechanics
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- 3D Imaging
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The Famous “Expert Users” Papers

- X expert users are given the same patient to contour
- Example of AVM (similar numbers in many papers)
- Agreement ratio < 60%
- 50% time absolute positional shift > 2mm

Fig. 3. (a) Agreement ratio, defined as VOA/ECV for all six observers (AR<sub>vo</sub>) was < 60% in all cases. (b) Ratio improved when all possible pairs of observers were compared; however, 76% remained at < 60% of agreement. (c) In about 50%, absolute positional shift was < 2 mm between mutual individually contoured target volumes (TV) and between target volumes and center of mass of originally treated volume (OTV). (d) However, this shift may increase up to 12 mm.
Higher Accuracy Means Less Room for Uncertainty

a) Isocentric, 1 cone
b) Isocentric, 1 cone coverage 96.8%±4%

(c) Dynamic Conf. Arc
d) Dynamic Conf. Arc coverage 78%±4.4%

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Interobserver variation of brain AVMs on DSA • D. R. Buis et al.
More References on the Topic

Delineation of brain metastases on CT images for planning radiosurgery: concerns regarding accuracy

K SIDHU, MD, FRCPC, P COOPER, MD, FRCPC, R RAMANI, PhD, M SCHWARTZ, MD, FRCPC, E FRANSSEN, BSc, MSc and P DAVEY, MD, FRCPC

Interobserver variations in gross tumor volume delineation of brain tumors on computed tomography and impact of magnetic resonance imaging

Caroline Weltens, Johan Menten, Michel Feron, Erwin Bellon, Philippe Demaerel, Frederik Maes, Walter Van den Bogaert, Emmanuel van der Schueren

Target delineation in post-operative radiotherapy of brain gliomas: Interobserver variability and impact of image registration of MR(pre-operative) images on treatment planning CT scans

Giovanni Mauro Cattaneo, Michele Reni, Giovanna Rizzo, Pietro Castellone, Giovanni Luca Ceresoli, Cesare Cozzarini, Andrés José Maria Ferreri, Paolo Passoni, Riccardo Calandrino
Autosegmentation Can Help

- De novo, segmented edit, peer and self-edit
- Segmented edits remained closest to ground truth
...could continue for hours. Dinner?

Dosimetric calibration

Dose calculation (TPS)

Mechanics

Patient positioning

Biological model

Target localization

3D Imaging

Target definition

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Accuracy and precision are NOT interchangeable!

Accurate, but not precise

Precise, but not accurate

Accuracy and precision are NOT interchangeable!

Images: http://en.wikipedia.org/wiki/Accuracy_and_precision
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Precision ≠ Resolution
Repeatability: The closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.

Reproducibility: The closeness of the agreement between the results of successive measurements of the same measurand carried out under changing conditions of measurement.

Both are part of the concept of precision.
Uncertainty: Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

http://physics.nist.gov
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