SRS Uncertainty: Linac and CyberKnife Uncertainties

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Linac/CyberKnife Technological Uncertainties
Linac Mechanical/Radiation Isocenters

TG-142 Mechanical Tolerance Limits for SRS/SBRT

<table>
<thead>
<tr>
<th>Procedure</th>
<th>SRS/SBRT Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation/Mechanical Isocenter</td>
<td>±1 mm from baseline</td>
</tr>
<tr>
<td>Collimator Rotation Isocenter</td>
<td>±1 mm from baseline</td>
</tr>
<tr>
<td>Gantry Rotation Isocenter</td>
<td>±1 mm from baseline</td>
</tr>
<tr>
<td>Couch Rotation Isocenter</td>
<td>±1 mm from baseline</td>
</tr>
<tr>
<td>Laser Localization</td>
<td>1 mm</td>
</tr>
<tr>
<td>Collimator Size Indicator</td>
<td>1 mm</td>
</tr>
<tr>
<td>Couch Position</td>
<td>1 mm/0.5º</td>
</tr>
<tr>
<td>Table Top Sag</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Independent errors are added in quadrature: 2 mm!
CK Mechanical Isocenter

Fig. 3. The stack isostat is mechanically mounted on the base frame of the imager system. The isocrystal at the tip of the post defines the coordinate system reference of the CyberKnife® system. The robot is going through the path calibration process (Sec. III B 1), with the beam laser scanning the isocrystal.

CK Mechanical Isocenter: Robot Pointing

- Linac CAX laser light intensity on isocrystal
- Robot runs automated grid pattern for highest light intensity on crystal
- Calibration followed by verification
- Acceptance <0.5mm average rms error per path

<table>
<thead>
<tr>
<th>Point</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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<th>Y</th>
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<th>VV</th>
<th>VZ</th>
<th>VV</th>
<th>ZE</th>
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<td>0.01</td>
<td>0.005</td>
<td>0.001</td>
<td>0.017</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Linac/Imaging Isocenter Match


CK Imaging/Robot Isocenter Match

- Isocrystal defines spatial origin of room coordinate system
- Image of isocrystal on imager center tolerance < 1 mm
Linac Mechanical/Radiation: Winston-Lutz


Frameless SRS: The E2E (modified Winston-Lutz)
Details of E2E test

- Isocentric plan
- Homogeneous Phantom
- Measure shift of delivered 70% isodose line vs. plan
- Tolerance < 1mm

Linac E2E (on TrueBeam)

- E2E result 0.4 – 0.85 mm
- Result is FYI
- No mechanical correction/action performed

CK E2E: The Δ-man Parameter

- E2E for all robot paths for each tracking algorithm (cranial, spine, ...)
- Determine *systematic shift* of E2E
- Result is applied as *global correction*
- Repeat until (nominally) <0.95 mm
- In clinical practice: **E2E ~0.6 mm**
- Adjusts for global systematic mechanical errors

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What is the tolerance of the CyberKnife Isocrystal to Imager Center?

1. **0.5 mm**
2. **1 mm**
3. **2 mm**
4. **1 pixel**
5. **2 pixels**
What is the tolerance of the CyberKnife Isocrystal to Imager Center?

Feedback:
The image of the isocrystal should be within 1 mm of the isocenter.

Slide Location:
Mechanical: Imaging/Robot Isocenter Match (#11)

Reference:
1) AAPM TG-135
2) CK Physics User Guide

Uncertainties Common to All SRS Delivery Systems
Imaging Algorithm Uncertainty

1. **Target Localization Error**: error extracting target position
2. **Target registration error**: mean distance between image data and real patient after registration
3. **Target Positioning error**: Mismatch between intended position and actual position

➢ Methodology of Measuring is the same for all algorithms

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**Target Localization Error**

![Image of target localization error](image_url)
Target Registration Error

• Testing against a “gold standard”
  – E.g. track with fiducials, then edit them out and track on skeletal features

<table>
<thead>
<tr>
<th>Table 1 Validation results using clinical patient data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

Target Positioning Error

• Depends on how you adjust for patient position

• With couch:
  – couch motion accuracy
  – Measure using realistic patient weight!

• With delivery system (CK, VERO, Linac):
  – Robot pointing accuracy
  – Gimbal rotation accuracy
  – MLC shift accuracy
What is the Target Registration Error?

1. Error extracting target position (20%)
2. Mean distance between image data and real patient after registration (20%)
3. Mismatch between intended and actual position (20%)
4. Error caused by choosing incorrect fusion algorithm (20%)
5. Uncertainty in couch movement

Feedback:
Mean distance between image data and real patient after registration

Slide Location:
Imaging Algorithm Uncertainty

Reference:
Uncertainties in External Beam Radiotherapy, Chapter 14 Image Guidance to Reduce Setup error
Dosimetry:
Dose Calculation Algorithm

Common MC uncertainty setting: 2% at maximum dose

Why Include Dose Calculation?

Dose calculation uncertainty = spatially shifting isodose lines!
Dosimetry: Commissioning Beam Data

- **All** measured data comes with error bars
- TG-106 states inter-user and equipment repeatability should be <1%
- CK needs 3 (4) sets of data: output factor, TPR, and profiles. (In-air OF data for MC)
- Effects of combined beam data error, processing artifacts, etc. challenging to assess
- Assumption: 1% error each for unconnected data sets

I do not know how to express this as spatial uncertainty

Let’s take a step back and summarize what we have learned so far
## Qualitative Accuracy Comparison of SRS/SBRT

<table>
<thead>
<tr>
<th>Linac</th>
<th>GK</th>
<th>CK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Simpler than linac</td>
<td>Similar to linac</td>
</tr>
<tr>
<td>Commissioning Data</td>
<td>Simpler than linac</td>
<td>Similar to linac</td>
</tr>
<tr>
<td>Patient Positioning</td>
<td>Similar: frame</td>
<td>Similar: IGRT</td>
</tr>
<tr>
<td>Target localization</td>
<td>Similar: frame</td>
<td>Similar: IGRT</td>
</tr>
<tr>
<td>Dose calculation</td>
<td>Similar</td>
<td>similar</td>
</tr>
<tr>
<td>Biological model</td>
<td></td>
<td>Same</td>
</tr>
<tr>
<td>Target Definition</td>
<td></td>
<td>Same</td>
</tr>
<tr>
<td>3D imaging (in-beam imaging)</td>
<td>TBD (CBCT?)</td>
<td>Depends on 2D-3D imaging frequency</td>
</tr>
</tbody>
</table>

## Major Contributors to Uncertainty

<table>
<thead>
<tr>
<th>Type</th>
<th>Uncertainty</th>
<th>Linac</th>
<th>CK</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Mechanical Isocenter</td>
<td>Star shots</td>
<td>Robot pointing</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Collimator</td>
<td>MLC starshot, picket fence, etc</td>
<td>Film/Large chamber</td>
<td>A/B</td>
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<tr>
<td></td>
<td>Imaging Isocenter</td>
<td>Phantom</td>
<td>Isocrystal on imager</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Imaging algorithm</td>
<td>?</td>
<td>Anthropomorphic phantom</td>
<td>B?</td>
</tr>
<tr>
<td>Dosimetry</td>
<td>Beam data</td>
<td>Water tank setup, kQ, detector/beam noise, data processing, detector correction factors ...</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dose calculation algorithm</td>
<td>Algorithm uncertainty</td>
<td>MC uncertainty</td>
<td>A</td>
</tr>
<tr>
<td>Planning (Geneser lecture)</td>
<td>Contouring</td>
<td>Similar for both machines</td>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Treatment</td>
<td>Residual patient motion</td>
<td>Similar for both machines</td>
<td></td>
<td>A/B</td>
</tr>
</tbody>
</table>
Quantitative Accuracy Comparison: It’s Complicated ...

• While Linac SRS accuracy contributing factors are generally similar to CK ...
• ...they combine differently.
• Why?
  – Delta-man concept on CK to determine & adjust systematic mechanical/imaging errors
  – Winston-Lutz vs. E2E concept
  – Intra-fraction imaging & position correction:
    • clinical on CK,
    • under development on linac
• My Dream: measure uncertainty with same test procedure on all three SRS/SBRT modalities

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%

Interobserver variation of brain AVMs on DSA • D. R. Bux et al.
What impact has higher technical targeting accuracy on the required target contouring accuracy?

20% 1. The two are not related
20% 2. The CTV margin can be reduced
20% 3. A fused image set should be used
20% 4. A contouring atlas must be used
20% 5. It leaves less room for contouring uncertainty

Feedback:
The CTV margin depends on the extent of the microscopic disease. A higher technical accuracy means there is more conformality to the tumor contour. Therefore, the tight coverage leaves less room for contouring uncertainties. Using a contouring atlas may help in accurately contouring organs at risk.

Slide Location:
Higher Accuracy means less room for uncertainty (#41)

Reference:
Conclusion

1. Dedicated Radiosurgery machines can delivery dose very accurately to homogeneous phantoms

2. Treatment Planning systems are getting much more accurate
   – In-vivo studies of dose calculation accuracy or anthropomorphic phantom DQA sparse in SRS/SBRT
   – DQA methods have technical limits measuring to accuracy better than 3%/1mm

3. Uncertainties in Radiation Biology, imaging disease, image registration & contouring are now large compared to mechanical & dosimetry uncertainty