Level of Accuracy Practically Achievable in Radiation Therapy

David Followill
and RPC staff
August 6, 2013
Sources of Treatment Uncertainty

- Machine functioning
- Radiation dose determination
- Patient specific data for treatment planning
- Radiation dose calculation in the patient
- Transfer of treatment plan to treatment machine
- Day to day variation in the treatment (machine/patient motion/set up)
Modern Treatment Units

1. Modern units for a specific make/model/energy have nearly the same dosimetry parameters.
2. RPC measurements based standard data typically within 1-1.5%
3. QA methodology and equipment have come a long way.

However this does not mean we can become lackadaisical in performing our QA
The RPC has spent the last 45 years trying to minimize the uncertainty in radiation dose delivery and improve the accuracy for the clinical trial participating institutions.
In water phantom reference calibrations indicates a spread in the machine output of ~2.5% for 95% of the data since TG-51 was implemented.

<table>
<thead>
<tr>
<th></th>
<th>REFERENCE CALIBRATION</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PHOTON</td>
<td>ELECTRON</td>
<td></td>
</tr>
<tr>
<td>2000-2006</td>
<td>output 1.004</td>
<td>0.991</td>
<td></td>
</tr>
<tr>
<td></td>
<td>±0.026</td>
<td>±0.022</td>
<td></td>
</tr>
<tr>
<td>2006-2013</td>
<td>output 1.004</td>
<td>1.017</td>
<td></td>
</tr>
<tr>
<td></td>
<td>±0.026</td>
<td>±0.024</td>
<td></td>
</tr>
</tbody>
</table>

Contributing factors
1. T & P
2. $N_{d,w}$
3. $P_{elec}$
4. cables
5. Depth
6. SSD
7. Field size
8. TG-51 factors
9. End effect
10. %dd correction
11. Human error
WARNING!
I KNEW THEY WERE OFF BUT I THOUGHT IT WOULD ALL AVERAGE OUT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>6 MV</th>
<th>6 MV</th>
<th>10 MV</th>
<th>10 MV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RPC</td>
<td>Inst.</td>
<td>RPC/Inst.</td>
<td>RPC</td>
</tr>
<tr>
<td>$K_{TP}$ comparison</td>
<td>1.007</td>
<td>1.002</td>
<td>1.005</td>
<td>1.007</td>
</tr>
<tr>
<td>$(N_{D_{w}})(K_{e})$</td>
<td>5.346</td>
<td>5.336</td>
<td>1.002</td>
<td>5.346</td>
</tr>
<tr>
<td>$P_{pol}$</td>
<td>1.000</td>
<td>1.001</td>
<td>0.999</td>
<td>1.000</td>
</tr>
<tr>
<td>$k_{Q}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.981</td>
</tr>
<tr>
<td>$P_{ion}$</td>
<td>1.002</td>
<td>0.999</td>
<td>1.003</td>
<td>1.002</td>
</tr>
<tr>
<td>$%dd(10)$</td>
<td>1.0655</td>
<td>1/0.662</td>
<td>1.011</td>
<td>-</td>
</tr>
<tr>
<td>$N_{D_{w}}$ (inst)</td>
<td>5.336</td>
<td>5.328</td>
<td>1.002</td>
<td>5.336</td>
</tr>
<tr>
<td>water to muscle</td>
<td>1/0.990</td>
<td>1/1.000</td>
<td>1.010</td>
<td>1/0.990</td>
</tr>
<tr>
<td>product</td>
<td>1.032</td>
<td>1/0.979</td>
<td>1.020</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(1.027)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>6 MeV</th>
<th>6 MeV</th>
<th>9 MeV</th>
<th>9 MeV</th>
<th>12 MeV</th>
<th>12 MeV</th>
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</thead>
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<td>RPC/Inst.</td>
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<td>Inst.</td>
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<td>1.002</td>
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<td>1.007</td>
<td>1.002</td>
<td>1.005</td>
</tr>
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<td>$(N_{D_{w}})(K_{e})$</td>
<td>5.346</td>
<td>5.336</td>
<td>1.002</td>
<td>5.346</td>
<td>5.336</td>
<td>1.002</td>
</tr>
<tr>
<td>$N_{D_{w}}$ (inst)</td>
<td>5.336</td>
<td>5.328</td>
<td>1.002</td>
<td>5.336</td>
<td>5.328</td>
<td>1.002</td>
</tr>
<tr>
<td>$P_{gr}$</td>
<td>1.008</td>
<td>0.987</td>
<td>1.021</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>measure depth</td>
<td>1.5</td>
<td></td>
<td></td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>%dd(dref)</td>
<td>1/0.960</td>
<td>1/0.979</td>
<td>1.020</td>
<td>-</td>
<td>-</td>
<td>1/0.996</td>
</tr>
<tr>
<td></td>
<td>(1.034)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(1.013)</td>
</tr>
</tbody>
</table>
Now one of the hottest topics – output factors (OPF)

• Really no problem with OPFs ≥ 4 x 4 cm²
  - RPC data show 2σ = ~1%

• What about < 4 x 4 cm²?

**Contributing factors**
1. Chamber vol.
2. Cables
3. Field size
4. Depth
5. SSD
6. Human error

From Das et al 2000
TG-155
Small Field Dosimetry Corrections

Situation is even worse if you consider using field sizes less than 0.5 x 0.5 cm²

Francescon et al
2011 data
The Problem is that our Dragon is very small!
Tables of standard small field factors

<table>
<thead>
<tr>
<th>Field Size (cm x cm)</th>
<th>Varian 6 MV</th>
<th>Varian 10 MV</th>
<th>Varian 15 MV</th>
<th>Varian 18 MV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RPC</td>
<td>Institution</td>
<td>RPC</td>
<td>Institution</td>
</tr>
<tr>
<td>10 x 10</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>6 x 6</td>
<td>0.921 (0.013)</td>
<td>0.929 (0.004)</td>
<td>0.946 (0.017)</td>
<td>0.953 (0.016)</td>
</tr>
<tr>
<td></td>
<td>[0.9%] (n=64)</td>
<td>[0.7%] (n=9)</td>
<td>[0.5%] (n=14)</td>
<td>[0.5%] (n=16)</td>
</tr>
<tr>
<td>4 x 4</td>
<td>0.865 (0.018)</td>
<td>0.874 (0.021)</td>
<td>0.900 (0.024)</td>
<td>0.912 (0.030)</td>
</tr>
<tr>
<td></td>
<td>[1.3%] (n=64)</td>
<td>[1.3%] (n=9)</td>
<td>[1.1%] (n=14)</td>
<td>[1.1%] (n=16)</td>
</tr>
<tr>
<td>3 x 3</td>
<td>0.828 (0.017)</td>
<td>0.841 (0.025)</td>
<td>0.867 (0.020)</td>
<td>0.875 (0.025)</td>
</tr>
<tr>
<td></td>
<td>[1.7%] (n=62)</td>
<td>[1.2%] (n=9)</td>
<td>[1.3%] (n=12)</td>
<td>[1.7%] (n=16)</td>
</tr>
<tr>
<td>2 x 2</td>
<td>0.786 (0.019)</td>
<td>0.796 (0.031)</td>
<td>0.817 (0.015)</td>
<td>0.828 (0.019)</td>
</tr>
<tr>
<td></td>
<td>[2.3%] (n=55)</td>
<td>[1.8%] (n=11)</td>
<td>[2.8%] (n=10)</td>
<td>[3.5%] (n=15)</td>
</tr>
</tbody>
</table>

Followill et al 2012

RPC: 0.8 - 2.4%
Institution: 0.4 – 3.8%

It’s HARD!
Wedges – Our **nemesis** yet they should be our friend!

It’s not a hard measurement, you just need to take the time to center your chamber accurately (<0.5% rdg change when wedge flipped)

The RPC finds a wedge factor outside our ±2% criterion in a **THIRD** of the sites we visit.
Off Axis Factors can SURPRISE you

Matched machines may have the same dosimetry data but their profiles may be quite different.

### Machine A

<table>
<thead>
<tr>
<th>Position</th>
<th>RPC</th>
<th>Institution</th>
<th>RPC/Inst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cm left</td>
<td>1.036</td>
<td>1.024</td>
<td>1.01</td>
</tr>
<tr>
<td>10 cm left/right</td>
<td>1.060/1.065</td>
<td>1.040</td>
<td>1.02/1.02</td>
</tr>
<tr>
<td>10 cm toward/away</td>
<td>1.059/1.064</td>
<td>1.040</td>
<td>1.02/1.02</td>
</tr>
<tr>
<td>15 cm left</td>
<td>1.080</td>
<td>1.052</td>
<td>1.03*</td>
</tr>
</tbody>
</table>

### Machine B

<table>
<thead>
<tr>
<th>Position</th>
<th>RPC</th>
<th>Institution</th>
<th>RPC/Inst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cm left</td>
<td>1.016</td>
<td>1.024</td>
<td>0.99</td>
</tr>
<tr>
<td>10 cm left/right</td>
<td>1.018/1.013</td>
<td>1.040</td>
<td>0.98/0.97*</td>
</tr>
<tr>
<td>10 cm toward/away</td>
<td>1.019/1.012</td>
<td>1.040</td>
<td>0.98/0.97*</td>
</tr>
<tr>
<td>15 cm left</td>
<td>1.016</td>
<td>1.052</td>
<td>0.97*</td>
</tr>
</tbody>
</table>

OAD 2 $\sigma$

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>3.2%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## On-Site Dosimetry Review Audit

Discrepancies Discovered (Jan. ’05 – April ’13)

<table>
<thead>
<tr>
<th>Discrepancies Regarding:</th>
<th>Number of Institutions Receiving rec. (n = 206)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Review QA Program</td>
<td>152 (74%)</td>
</tr>
<tr>
<td>Photon Field Size Dependence</td>
<td>138 (67%)</td>
</tr>
<tr>
<td>Wedge Factor (WF)</td>
<td>66 (32%)</td>
</tr>
<tr>
<td>Off-axis Factors (OAF)/Beam symmetry</td>
<td>60 (29%)</td>
</tr>
<tr>
<td>Electron Calibration</td>
<td>35 (17%)</td>
</tr>
<tr>
<td>Photon Depth Dose</td>
<td>33 (16%)</td>
</tr>
<tr>
<td>Electron Depth Dose</td>
<td>25 (12%)</td>
</tr>
<tr>
<td>Photon Calibration</td>
<td>16 (8%)</td>
</tr>
</tbody>
</table>
Sort of Disturbing to the RT community when Das et al published their findings on variations between prescribed and planned doses.
Clinical Trial Patient Case Rapid Review

- Rapid review (pre-treatment review) is designed to evaluate the plan prior to treatment to ensure it meets the protocol prescription specifications.

- 56 IMRT Gyne rapid reviews were performed in 2013 (to date)
  - 22 submitted twice (39%)
  - 6 submitted three times (11%)
  - 2 had to submit 4 times.
Sources of Treatment Uncertainty

- Machine functioning
- Radiation dose determination
- Patient specific data for treatment planning
- Radiation dose calculation in the patient
- Transfer of treatment plan to treatment machine
- Day to day variation in the treatment (machine/patient motion/set up)
Benefits of RPC Phantoms

- Independent "end to end" audit
  1. Imaging
  2. Planning/dose calculation
  3. Setup
  4. Delivery
- Uniform phantoms and dosimeters
- Standardized analysis
- Uniform pass/fail criteria
- Allows inst. to inst. comparison
RPC Phantoms

Pelvis (10)

Thorax (10)

Spine (8)

H&N (30)

SRS Head (10)

Liver (6)
RPC Phantoms for Protons

prostate phantom

lung phantom

head phantom

spine phantom
Phantom Irradiations per Year

Year

Phantoms Mailed


SRS head
Spine
Liver
Prostate
Lung
H&N
Measurement vs. Monte Carlo

Criteria
3%/2 mm

Varian 6 MV IMRT H&N
Lung Phantom TLD results

Average = 0.967 +/- 2.9%
274 irradiations
Algorithms included:
AAA/Superposition/MonteCarlo
Lung Phantom TLD results

Average = 0.967 +/- 2.9%
274 irradiations
Algorithms included: AAA/Superposition/MonteCarlo

Average = 0.994 +/- 3.3%
30 irradiations
Algorithms included: MonteCarlo
Percent of pixels passing 5%/3mm gamma criteria

- Pinnacle SC: 96%
- Eclipse AAA: 90%
- Eclipse PB: 50%
- XiO SC: 86%
- XiO Clarkson: 52%
- TomoTherapy SC: 85%
- MultiPlan MC: 94%
- MultiPlan PB: 31%
- Corvus PB: 61%
Phantom Accomplishments

- Setting a standard for IMRT use in national and international clinical trials
- Use of heterogeneity corrections for modern algorithms
- Test ability to hit a moving target(s)
- Provide consistent and independent QA evaluation tool
- Testing proton therapy planning and dose calculations
Phantom Results

Comparison between institution’s plan and delivered dose.

<table>
<thead>
<tr>
<th>Phantom</th>
<th>H&amp;N</th>
<th>Prostate</th>
<th>Spine</th>
<th>Lung</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiations</td>
<td>1368</td>
<td>419</td>
<td>176</td>
<td>664</td>
</tr>
<tr>
<td>Pass</td>
<td>1135 (83%)</td>
<td>359 (86%)</td>
<td>119 (68%)</td>
<td>535 (81%)</td>
</tr>
<tr>
<td>Fail</td>
<td>233</td>
<td>61</td>
<td>57</td>
<td>129</td>
</tr>
<tr>
<td>Criteria</td>
<td>7%/4mm</td>
<td>7%/4mm</td>
<td>5%/3mm</td>
<td>5%/5mm</td>
</tr>
</tbody>
</table>
Phantom Statistics

Number of Machines

1 - 2
3 - 4
≥5

Pass Rate

<1
1
>1

Number of Physicists per Machine

Pass Rate

0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
Progress is being Made!
Use of Advanced Technologies in clinical trials?

TRACKING

TPS

IMRT DOSE PAINTING

HETERO CORRECTION

IGRT

KV OR MV

GATING

IMRT

SBRT

Respiratory Control
Pay Attention to the Basics as well
Thoughts to Consider

The goal in radiotherapy is to achieve the golden $\pm 5\%$ dose delivery goal for our patients.

Realistically I believe that there are many good RT sites that deliver well within 5%, but there are many that probably, for some patients, are somewhere between 5-10%.

**Primary reasons**

- Human error
- Don’t understand the complex processes
- Don’t pay attention to QA results
- Resources
Be Willing to Consider an Independent Audit

1. Local physicist at another RT center
2. Physicist at your center/physics group
3. Consulting physicists
4. Former medical physics classmates
5. Radiological Physics Center
Conclusions

1. Take more time and ask questions.
2. Reread the task group report.
3. Read the clinical trial protocol.
4. Be willing to admit you were wrong and learn from your mistakes.
5. Place more responsibility on manufacturers to implement more accurate systems.
6. MLC QA!
7. Use only the most recent heterogeneity correction algorithms (preferably Monte Carlo or Acuros XB).
8. Small field dosimetry – caution, how small can we really go?
9. Implement IGRT for heaven’s sake.
10. Be inquisitive, don’t just believe others at face value.