Roles of *in vivo* Dose Verification in Brachytherapy

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Denver

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Disclosures

- Research funding
  - Danish Research Council
  - Danish Cancer Society
  - Varian Medical Systems
  - Elekta (*in vivo* dosimetry in brachytherapy)
<table>
<thead>
<tr>
<th>Process</th>
<th>ICRU89 definitions</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implantation</td>
<td></td>
<td><strong>Planning aim cervix</strong></td>
</tr>
<tr>
<td>Dose planning</td>
<td></td>
<td>$CTV_{HR} \geq 85\text{ Gy}$</td>
</tr>
<tr>
<td>Approval of plan</td>
<td></td>
<td><strong>Small tumour, well covered:</strong></td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td>$92.5\text{ Gy}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Reduced dose due to swelling during PDR:</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$90.5\text{ Gy}$</td>
</tr>
</tbody>
</table>
Planning, prescription and delivery

**Process**
- Implantation
- Dose planning
- Approval of plan
- Treatment

**ICRU89 definitions**
- Planning aim
- Prescribed dose
- Delivered dose

**Treatment verification**
Dosimetric and geometrical treatment verification

Geometric verification:
- **Purpose**
  - Anatomy in place
  - Source/catheters aligned
- **Methods**
  - Direct measurements
  - Imaging
  - Tracking: EM, MR or optical

Dosimetric verification:
- **Purpose**
  - Dose to Target or OAR
- **Methods**
  - In vivo dosimetry
Hybrids of dosimetric and geometrical verification

Geometric verification

Dosimetric verification

Imaging with dose reconstruction

In vivo dosimetry with geometric information
### Which errors happen during BT?

**U.S. Nuclear Regulatory Commission reports: 2005-2013**

<table>
<thead>
<tr>
<th>QUALITY ITEM</th>
<th># Errors</th>
<th>DETECTABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of HDR/PDR events</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Source calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Afterloader source positioning and dwell time</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Afterloader malfunction</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Patient identification</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Correct treatment plan</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Intra- and interfraction organ/applicator movement</td>
<td>1</td>
<td>✓</td>
</tr>
<tr>
<td>Applicator reconstruction and fusion errors</td>
<td>4</td>
<td>✓</td>
</tr>
<tr>
<td>Applicator length/source-indexer length</td>
<td>5</td>
<td>✓</td>
</tr>
<tr>
<td>Source step size (patient specific)</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Interchanged guide tubes</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Recording of dose</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Other (e.g. defective catheter)</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

**Examples – most (in principle) detectable:**

- Wrong guide tube, 12 cm too short
- Obstructed GYN catheter for HDR (60 Gy to skin between thighs)
- Inverted catheter direction (not detected by planners nor TPS)
- Catheter not fully inserted into tandem
- Radiation therapist pushed “auto radiography” rather than “treatment” button → 9 times the intended dose
- Incorrect target area entered
Have you ever encountered any errors/events or major deviations in brachytherapy delivery?

1. Applicator movement
2. Incorrect connection, wrong catheter length, wrong reconstruction
3. Wrong catheter direction, wrong needle depth
4. Wrong patient, swapped reconstruction
5. None
6. None
7. Incorrect connection, wrong applicator length
8. Incorrect connection, wrong applicator length
9. Incorrect connection, wrong reconstruction, afterloader malfunction, applicator movement
Importance of treatment verification for brachytherapy

- "High" risk of errors (as compared to EBRT):
  - Manual procedures: reconstruction of catheters, applicator afterloader connection, applicator length
  - "Mechanical" equipment: cables, transfer tubes, applicators

- High impact of errors/uncertainties:
  - High dose gradients
  - Hypofractionation

- Challenge: Low patient volume (as compared to EBRT):
  - Investment
  - Expertise (smaller critical mass of experts)
How much is *in vivo* dosimetry utilised?

- **Patterns of care study Europe (2007)**:
  - *in vivo* dosimetry available in 23% of centers
- **French survey of 15 centers by Estelle Spasic (2017)**:
  - *in vivo* dosimetry not performed in any center


** Estelle Spasic, Institute Curie, Paris, personal communication
Why is in vivo dosimetry not systematically used?

Routine rectal diode in vivo dosimetry, Aarhus University Hospital:

 poor sensitivity/specificity to identify errors

FIG. 1. Rectal IVD in PDR $^{192}$Ir cervix cancer BT with tandem ring applicator for BT fractions 1 (BT1) and 2 (BT2). Dashed lines indicate bounds of the 95% prediction interval.

Tanderup, Beddar, Andersen, Kertzsch, Cygler. In vivo dosimetry in brachytherapy, Med Phys 40(7), 2013
Uncertainties

Example of an uncertainty budget for Al₂O₃ detectors


<table>
<thead>
<tr>
<th>Component</th>
<th>RL (%)</th>
<th>OSL (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic reproducibility</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Energy response</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Angular dependence</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Stem effect</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Instrument temperature</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Crystal temperature</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fiber-cable transmission</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Readout uncertainty</td>
<td>7.0</td>
<td>3.6</td>
</tr>
<tr>
<td>Calibration (at 11.2 mm)</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Combined standard uncertainty</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>
“Classical” *in vivo* dosimetry: measurement of organ dose

- Measurement of dose in organs
  - Rectal probes
  - Bladder probes
  - Urethra

- Requires excellent identification and stability of dosimeter

Cygler et al, Radiother Oncol, 80, 2006, 296-301

Fig. 5. Initial pre-plan (●) and measured post-implant (▲) dose rates inside the urethra.
Rethink *in vivo* dosimetry: From organ point dose measurement to overall treatment verification

- **Organ dose measurements not primary objective**
  - Detector point doses are surrogates for organ dose
  - Organ doses are assessed with 3D imaging and DVH reporting
  - (Although dose measurements are relevant under conditions of uncertain dose calculation)

- **Treatment verification primary objective**
  - Monitoring of treatment progression
  - Real-time measurements and instantaneous error detection
What is real-time in vivo dosimetry?

Foot print of source progression!!

Courtesy Gustavo Kertzscher
Dose rate → geometry

- Prostate HDR brachytherapy
- Real-time in vivo dosimetry
- Al2O3 luminescent dosimeter placed in additional needle

Measured and expected dose rates

Jacob Johansen et al, Aarhus University Hospital, 2017
Dose rate → geometry

Dose rate profile of a single needle

Δr: change in height of profile

Expected dose

Measured dose

Δz: change in position of profile

Jacob Johansen et al
Aarhus University Hospital, 2017
What do we need from our *in vivo* dosimetry system?

- **Detectors:**
  - Real-time signal
  - Small size (ability to position detectors inside applicators)
  - High signal and reproducibility
  - As small dependence as possible of:
    - Time (e.g. after-glow)
    - Dose (change in radiosensitivity with dose)
    - Energy
    - Angular
    - Temperature

- **Software:**
  - Dose rate analysis
  - Error detection
### Which detector?

**TABLE III. Characteristics of detectors for IVD in brachytherapy.** The items are rated according to: advantageous (++), good (+), and inconvenient (--).

<table>
<thead>
<tr>
<th></th>
<th>TLD</th>
<th>Diode</th>
<th>MOSFET</th>
<th>Alanine</th>
<th>RL</th>
<th>PSD</th>
<th>(Radioluminescence)</th>
<th>(Plastic scintillator)</th>
<th>(Inorganic scintillator)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>+</td>
<td>+/-</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Energy dependence</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Angular dependence</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Calibration procedures, QA, stability, robustness, size of system, ease of operation</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Commercial availability</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Online dosimetry</td>
<td>-</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Main advantages</td>
<td>No cables, well studied system</td>
<td>Commercial systems at reasonable price, well studied system</td>
<td>Small size, commercial system at reasonable price</td>
<td>Limited energy dependence, no cables</td>
<td>Small size, high sensitivity</td>
<td>Small size, no angular and energy dependence, sensitivity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main disadvantages</td>
<td>Tedious procedures for calibration and readout, not online dosimetry</td>
<td>Angular and energy dependence</td>
<td>Limited life of detectors, energy dependence</td>
<td>Not sensitive to low doses, tedious procedures for calibration and readout, not online dosimetry, expensive readout equipment not available in clinics</td>
<td>Needs frequent recalibration, stem effect, not commercially available</td>
<td>Stem effect</td>
<td>Energy dependence</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Novel developments inorganic scintillators: Large light yield

Ruby-based


How to proceed?

- French survey (2017): 57% of centers are interested in implementing *in vivo* dosimetry for brachytherapy

- Needs for commercial availability of:
  - Robust, sensitive and accurate detectors
  - Software for dose rate analysis and error detection

- Needs for prospective *in vivo* dosimetry for:
  - Avoidance of errors
  - Assessment of frequency and nature of errors

* Estelle Spasic, Institute Curie, Paris, personal communication
As long as we do not look for errors, we do not see errors
As long as we do not look for errors, we do not see errors

\textit{In vivo} dosimetry may enable us to see!