How lack of in vivo dosimetry decreases safety and efficiency in brachytherapy

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Disclosure

Patent for RADPOS Dosimetry System

Objectives

- To present rationale for in vivo dosimetry in brachytherapy
  - increased safety
  - efficiency
- To discuss challenges in clinical implementation of in vivo dosimetry program
- To review currently available commercial systems for online in vivo dose measurements
### Rationale for in vivo dosimetry in brachytherapy

“To err is human” – *Alexander Pope, An Essay on Criticism, Part II*, 1711

- Errors and dose misadministrations in radiotherapy can result in:
  - Underdosing (geographic miss) of the tumor
  - Overdosing of healthy organs

- Magnitude of errors range
  - from a few percent to lethal doses
  - from a couple of millimeters to complete misses of the tumor

- Many brachytherapy procedures are performed without the safeguards of Record and Verify systems

- In vivo dosimetry is the only way to know what dose was actually delivered to the tumour and organs at risk, OAR
Safety Reports Series No. 17 (2000)
30% of cases are incidents in brachytherapy

ICRP Publication 97 (2005)
Prevention of High-Dose-Rate Brachytherapy Accidents

ICRP Publication 98 (2005)
Radiation Safety Aspects of Brachytherapy for Prostate Cancer using Permanently Implanted Sources
Types of errors in brachytherapy

- Equipment errors
  - mechanical errors
  - control unit failure
  - computer
  - source cable
  - applicators

- Procedure problems

- Human errors

*U.S. NRC NUREG-2170 (2017)*
Examples of incidents in HDR brachytherapy related to human errors

- Human errors
  - treatments given to wrong patients
  - incorrectly prescribed / delivered doses or repeated treatments to the same patient.
  - Treatments given to a wrong site (e.g. wrong orifice treated)
  - Errors during treatment planning (e.g. reverse order of entry of dwell positions; applicator diameter confused with radius; wrong dwell steps; wrong catheter length)
Causes of human errors

- Complex, high pressure work environment in brachytherapy
- Combined with how the human brain works

Prospective Memory
Prospective Memory

- Prospective memory involves remembering to perform an action at the appropriate time (McDaniel & Einstein, 2000).

- Depends on:
  - How the human brain works
  - Complexity of work environment

- Brachytherapy setting
  - requires multi-tasking
  - frequent interruptions and distractions
Prospective Memory - vulnerability

- Brachytherapy workers carry a particularly high load on their prospective memory
  - risk of errors

  - Eliminating or minimizing the interruptions during procedures could help to reduce load on prospective memory and therefore human errors.

  - In some cases, in vivo dosimetry would have prevented propagation of certain errors to multiple fractions/patients and therefore improve safety and efficiency in brachytherapy.
Recent (2018) incident in North America: impact on safety and efficiency of brachytherapy process

- HDR cervix treatments
  - wrong catheter LENGTH
    - geographic miss of the tumor
    - overdose of healthy tissues

- Investigation
  - 25 patients possibly affected over a period of time
  - patients informed
Negative impact of error on safety and efficiency:

- Incident Impact
  - Patients
    - Affected Patients
    - Prospective Patients
  - Hospital
Impact on safety and efficiency: Affected Patients

- Impact on affected patients – Quality of Life
  - Treatment compromised
    - Failure of tumor control?
    - Overdosed OAR complications?
  - Additional close follow-ups of identified patients
  - Additional diagnostic and pathological tests ordered on periodical basis
  - Emotional impact - anxiety and anger
Impact on safety and efficiency: Prospective Patients

- Impact on prospective new cervix patients – Quality of Life
  - HDR treatments of future cervix cancer patients suspended till further notice
    - Prospective patients had to travel to other centres
      - Extra cost and inconvenience for these patients
Impact on safety and efficiency: Cancer Centre

Impact on cancer centre

- Extra workload and related cost
  - Close follow-ups of identified patients
  - Additional diagnostic and pathological tests ordered for affected patients on periodical basis

- Suspension of HDR treatments of cervix cancer till further notice
  - Loss of funding for the involved centre

- Reputation
Conclusions / lessons learned

There are many lessons learned, but in the context of this lecture:

*Routine, adequate in vivo dosimetry would*

- *limit the number of patients / tx fractions affected by this error*
- *Improve safety and efficiency in brachytherapy*
ICRP 86 (2000) – “adequate in vivo dosimetry would prevent most of accidental exposures”
What does “adequate” mean?

- Every fraction?
- Once a week?
- First fraction only?

**We need to define what “adequate” means!**

*ESTRO’s basic philosophy includes routine in-vivo dosimetry as an important part in Quality Control of radiotherapy*

*In vivo dosimetry is required by law in some countries*
Routine in vivo dosimetry program in brachytherapy

What is needed?

- Robust dosimetry system
  - small detectors with high S/N ratio
  - minimally intrusive to the patient
  - fast and reliable, real-time dose readout
### Types of detectors used for in vivo dosimetry

- TLD
- OSL
- Diodes
- MOSFETs
- PSD
- RL

- **off-line (passive) dosimetry**
- **on-line (real-time) dosimetry**
Diode system

- Measures rectum and bladder dose
- A five-diode rectum probe
- Two types of single bladder probes
## Advantages and disadvantages of diodes

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>High sensitivity (18000× equal volume ion chamber)</td>
<td>Temperature dependence</td>
</tr>
<tr>
<td>Real time on-line readings</td>
<td>Energy dependence</td>
</tr>
<tr>
<td>Efficient (fast) in use</td>
<td>Angular dependence</td>
</tr>
<tr>
<td>Waterproof</td>
<td>Different detectors for photon and electron beams</td>
</tr>
<tr>
<td>Durable</td>
<td>Radiation damage – change of sensitivity with accumulated dose</td>
</tr>
<tr>
<td></td>
<td>Cumbersome cables on most systems</td>
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</tbody>
</table>
Mobile MOSFET system

Two physical detector sizes:
- standard (8 x 2.5 x 1.3 mm³)
- microMOSFETs (3.5 x 1 x 1 mm³)
  - Suitable for brachytherapy

Two detector active volumes (sensitivities):
- Standard (0.2 x 0.2 x 5·10⁻⁴ mm³)
- High (0.2 x 0.2 x 1·10⁻³ mm³)

Cygler and Scalchi AAPM Summer School 2009

J. E. Cygler, AAPM 61st Annual Meeting, July 14-18, 2019, San Antonio, Texas
TU-L-SAN4-0 4:30 PM - 6:00 PM: Optimizing Safety and Efficiency in Brachytherapy
RADPOS*
Time-resolved dosimetry system

- Combination of microMOSFET dosimeter and electromagnetic positioning sensor
- Simultaneous measurements of dose and spatial position
- Software allows sampling dose and position manually/automatically
- Real-time treatment verification tool
  - Patient and/or organ motion
  - Accuracy of delivered dose
- Suitable for brachytherapy

## Advantages and disadvantages of MOSFET detectors

<table>
<thead>
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<th>Advantages</th>
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</tr>
</thead>
<tbody>
<tr>
<td>- Instantaneous readouts (on-line dosimetry)</td>
<td>- Finite life expectancy</td>
</tr>
<tr>
<td>- Very small active volume</td>
<td>- Energy dependence</td>
</tr>
<tr>
<td>- Dual detectors eliminate most correction factors</td>
<td>- Some (2.5%) angular dependence</td>
</tr>
<tr>
<td>- No temperature dependence for dual-MOSFET-dual-bias</td>
<td>- Temperature dependence for single-MOSFET-single-bias</td>
</tr>
<tr>
<td>- Waterproof</td>
<td></td>
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<tr>
<td>- Efficient in use (doesn’t consume much time)</td>
<td></td>
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</table>
Exradin W1 Plastic Scintillator

Plastic Scintillator Detector, PSD

Physical probe size is 2.8 mm diameter, 42 mm length

Active volume size is 1.0 mm diameter, x 3.0 mm length

http://www.standardimaging.com/exradin/exradin-scintillator/
In vivo dosimetry with PSD

- Small size (2.8 mm diameter x 42 mm long)
  - can fit into rectal probe
  - can fit into Foley catheter

Exradin W1 Scintillator from Standard Imaging

A detector patch
- The red line represents the dose sensitive region
- Detector elements are spaced every 2 mm

The detectors are mounted on a rectal balloon

Pictures courtesy of S. Beddar

Advantages and disadvantages of plastic scintillators

**Advantages**
- On-line system
- Spatial resolution
- Linear response to dose
- Dose rate independence
- Energy independence
- Easy to produce
- Relatively inexpensive

**Disadvantages**
- Some temperature dependence
- Some radiation damage (~ 2% / kGy)

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Wootton and Beddar, PMB 2013

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![Graph showing normalized measured dose vs detector temperature](image)
In vivo dosimetry with RL detectors: Securidose -BT

- Based on GaN crystal radioluminescence
- Real-time dosimetry system for HDR
- Developed by the universities of Grenoble (UJF) and Lyon (UCBL) and Dosilab Co
- Miniature crystal fits in a brachytherapy needle

https://www.dosilab.ch/en-ch/home
Technical challenges for in vivo dosimetry in brachytherapy

- High dose gradients
- Short treatment distances
- Energy dependence of detector response
- Uncertainties on radiation source parameters
- Shortcomings of dose calculation algorithms

large effect of positioning errors
Barriers to routine in vivo dosimetry

- Cost (?)
  - Equipment – lack of fully integrated systems (?)
  - Staff to perform and analyze measurements
- Efficiency - increased treatment and staff time (?)
  
  Not true for fully integrated system

- Staff resistance (?)
  - Lack of well documented guidelines, protocols and procedures (?)
  - Lack of proper training
  - Extra work load
  - Uncertainty about possibly changing work role in the treatment team
Integrated in vivo dosimetry - SagiNova®

Eases handling of real-time in vivo dosimetry

- Integration of probe connection into treatment delivery unit
- Integrated live monitoring of doses to rectum and bladder at the control console
- Complete data integrated in treatment report
- Warnings displayed if dose limits are exceeded
- Individual definition of dose limits for bladder and rectum

Dosimetry equipment of Eckert & Ziegler BEBIG – SagiNova®

Presentation 2016

http://www.bebig.com/united_states/products/hdr_brachytherapy/new_saginova/
Integrated in vivo dosimetry

http://www.bebig.com/united_states/products/hdr_brachytherapy/new_saginova/

Live monitoring of dose to rectum and bladder including highlighting of high values

Dose Monitoring Displayed on the Control Unit

Dosimeter Measurements (Gy)

- R1: 7.31 Gy
- R2: 10.94 Gy
- R3: 1.29 Gy
- R4: 0.36 Gy
- R5: 0.16 Gy
- B1: 0.41 Gy

Diodes for dose measurement in bladder and rectum

Eckert & Ziegler BEBIG – Saginova®
Presentation 2016
Conclusions

- Errors in brachytherapy dose delivery do happen
- Human errors account for the largest fraction of all errors
- They can affect multiple tx fractions and/or patients
- Errors have negative impact on safety and efficiency of the brachytherapy process
  - result in compromised treatment outcomes
  - consume extra time and resources
- **Routine in-vivo dosimetry** would prevent propagation of errors to multiple tx fractions and/or patients and therefore improve safety and efficiency in brachytherapy
- Commercial in vivo dosimetry systems exist and should be routinely used in brachytherapy
On-line measurements on patients

- Waldhäusl et al, *Radiother. and Onc.* (2005), 77, 310 (diodes, 55 patients)
- Cygler et al, *Radiother. and Onc.* (2006), 80, 296 (single MOSFET, 5 patients)
- Cherpak et al, Brachytherapy, 13, (2014) 169 (RADPOS, 16 patients)

*passive (not on-line) detectors*
Selected references


Selected references cont.


Thank you