Roles of *in vivo* Dose Verification in Brachytherapy

AAPM 2017
Denver

Kari Tanderup, PhD
Aarhus University Hospital
Denmark

Aarhus University Hospital

Disclosures

- **Research funding**
  - **Danish Research Council**
  - **Danish Cancer Society**
  - **Varian Medical Systems**
  - **Elekta (*in vivo* dosimetry in brachytherapy)**

Planning, prescription and delivery

Process

Implantation

↓

Dose planning

↓

Approval of plan

↓

Treatment

ICRU89 definitions

Planning aim

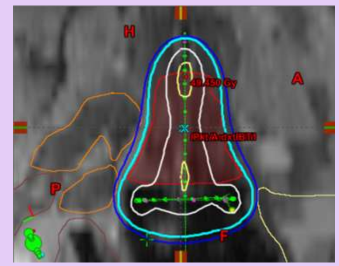
↓

Prescribed dose

↓

Delivered dose

Example

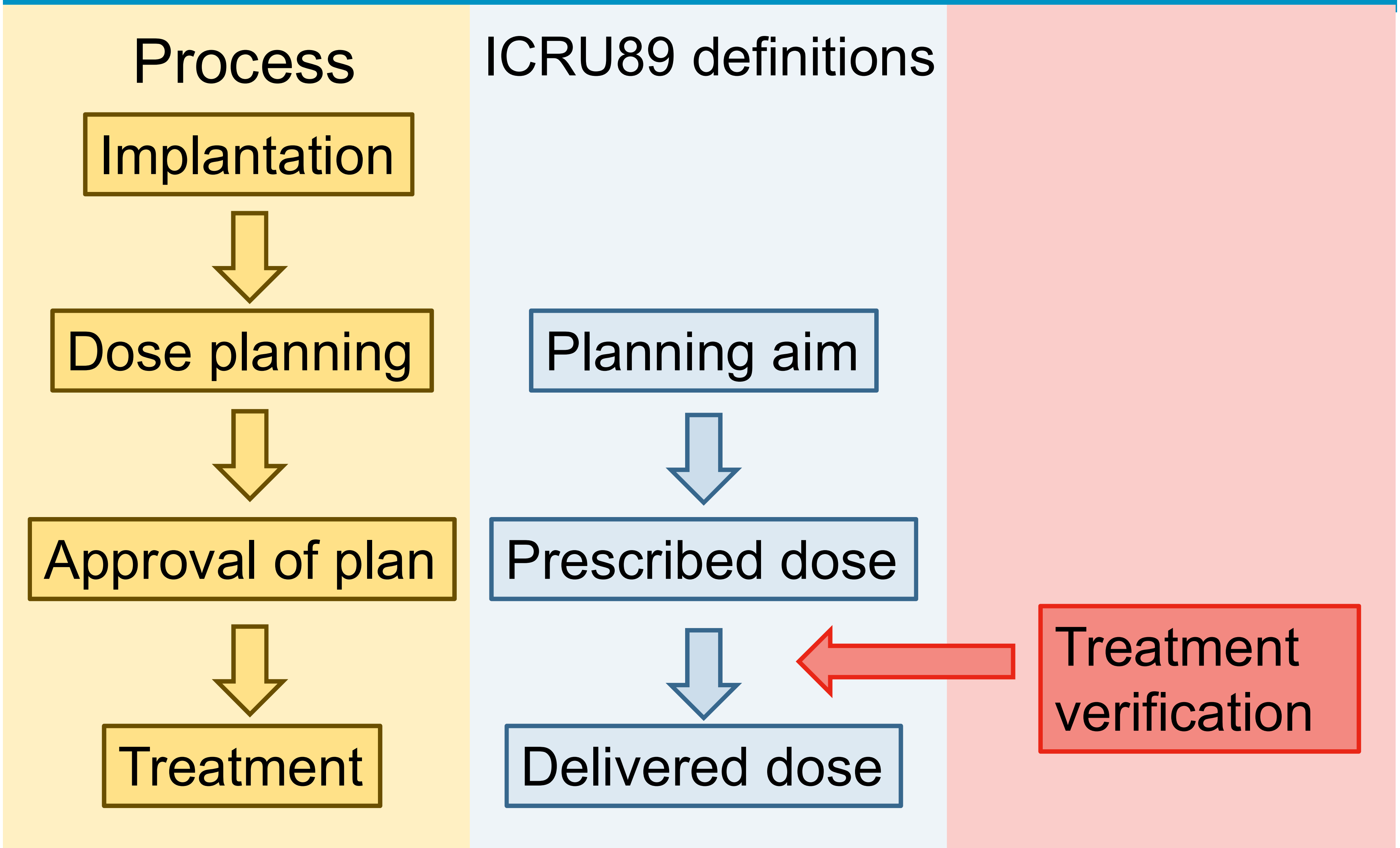


Planning aim cervix
CTV_{HR}: ≥85 Gy

Small tumour, well covered:
92.5Gy

Reduced dose due to swelling during PDR:
90.5Gy

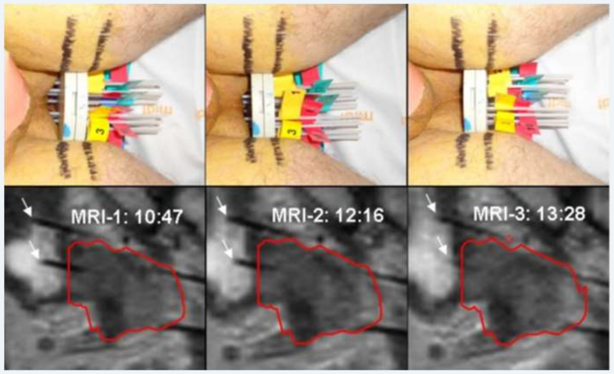
Planning, prescription and delivery



Dosimetric and geometrical treatment verification

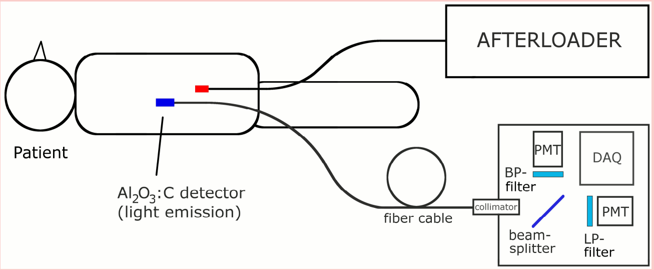
Geometric verification:

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



Dosimetric verification:

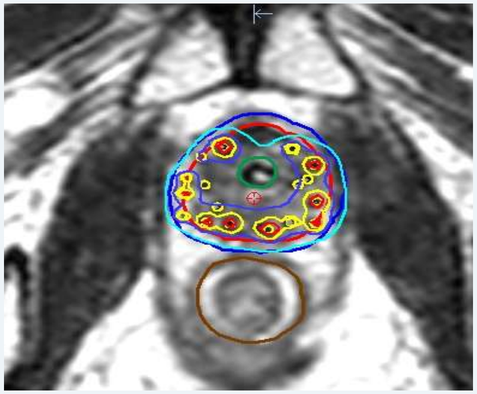
- Purpose
  - Dose to Target or OAR
- Methods
  - In vivo dosimetry



Hybrids of dosimetric and geometrical verification

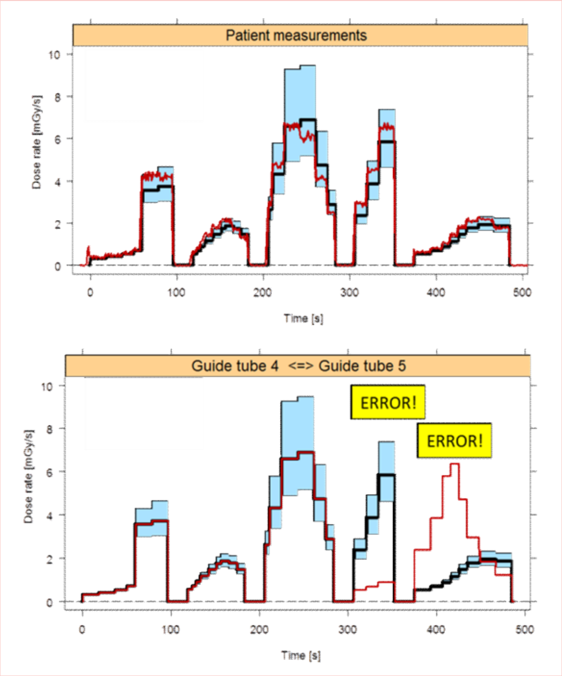
Geometric verification

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

QUALITY ITEM	# Errors	DETECTABILITY	
Nu	R)	IVD	IMAGING
Sc		✓	
Af		✓	
Af		✓	
Pa			✓
Co		✓	
Int	1	(✓)	✓
Ap	4	✓	✓
Ap	5	✓	
Sc		✓	
Interchanged guide tubes		✓	
Recording of dose		✓	
Other (e.g. defective catheter)	7	?	?

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

Results of questionnaire after GEC ESTRO treatment verification seminar, Brussels 2014

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, swopped 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**

*F Guedea et al, **"Patterns of care for brachytherapy in Europe: Updated results"**, Radiotherapy and Oncology 97 (2010) 514–520.

** Estelle Spasic, Institute Curie, Paris, personal communication

Why is in vivo dosimetry not systematically used?

Routine rectal diode in vivo dosimetry, Aarhus University Hospital:

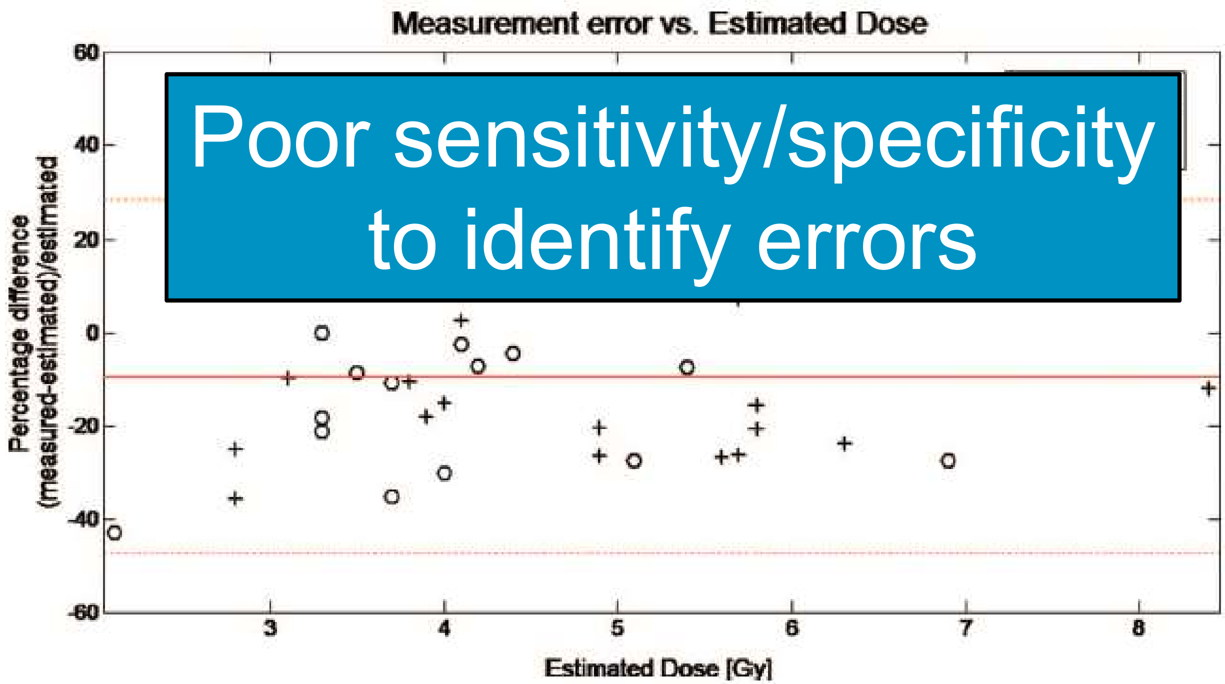


FIG. 1. Rectal IVD in PDR ^{192}Ir cervix cancer BT with tandem ring applicator for BT fractions 1 (BT1) and 2 (BT2). Dashed lines indicate bounds of the 95% prediction interval.

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

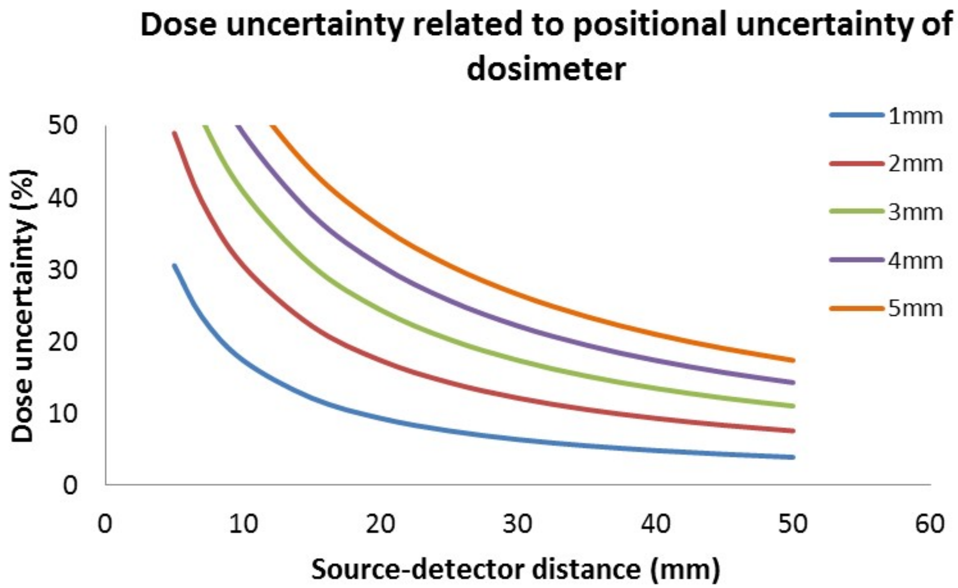
Uncertainties

Example of an uncertainty budget for Al_2O_3 detectors

Andersen et al, Characterization of a fiber-coupled Al2O3:C luminescence dosimetry system for online in vivo dose verification during 192Ir brachytherapy, Med Phys, 36 (3), 708-718, 2009

Component	RL (%)	OSL (%)
Basic reproducibility	1.3	1.3
Energy response	2	2
Angular dependence	2	2
Stem effect	6	0
Instrument temperature	1	1
Crystal temperature	1	1
Fiber-cable transmission	1	1
Readout uncertainty	7.0	3.6
Calibration (at 11.2 mm)	3.7	3.7
Combined standard uncertainty	8	5

Impact of positional uncertainties of dosimeter (single source position)



"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**

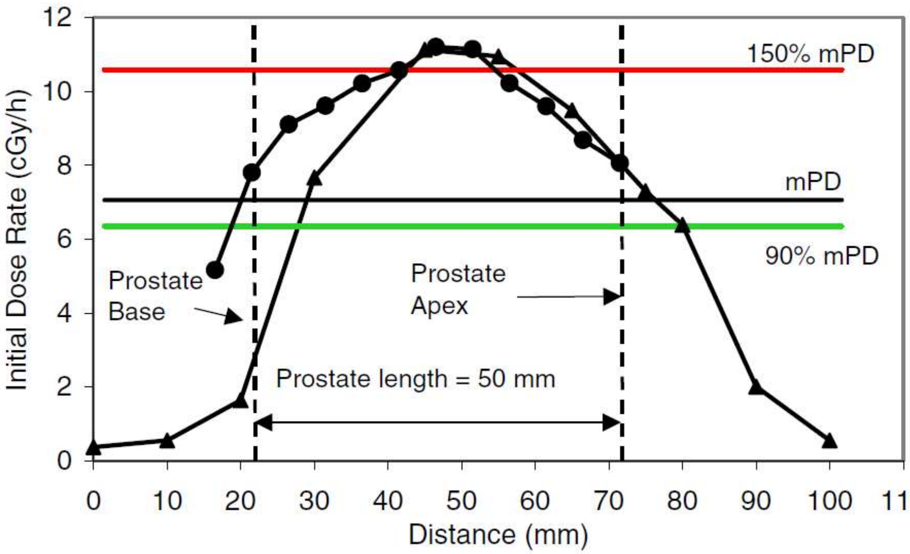


Fig. 5. Initial pre-plan (●) and measured post-implant (▲) dose rates inside the urethra.

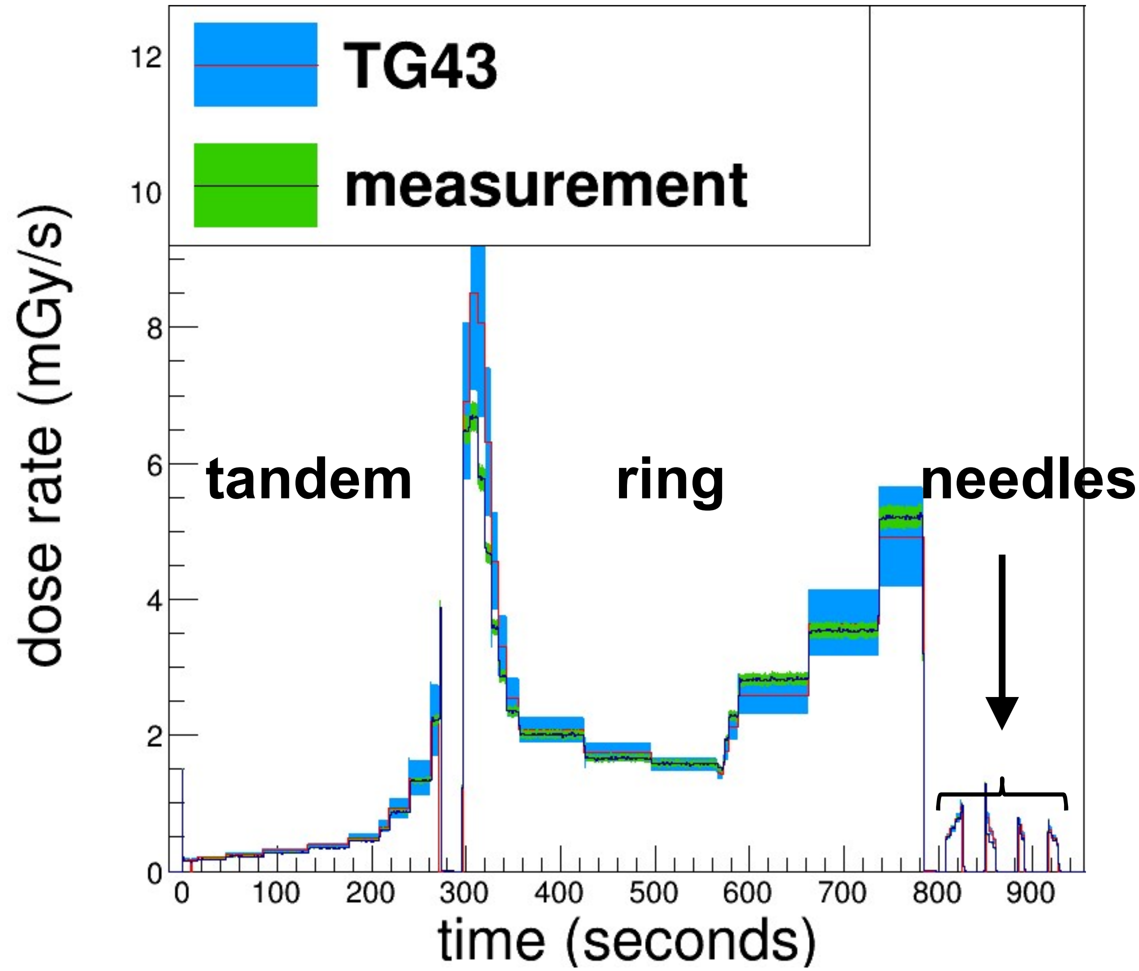
Cygler et al, Radiother Oncol, 80, 2006, 296-301

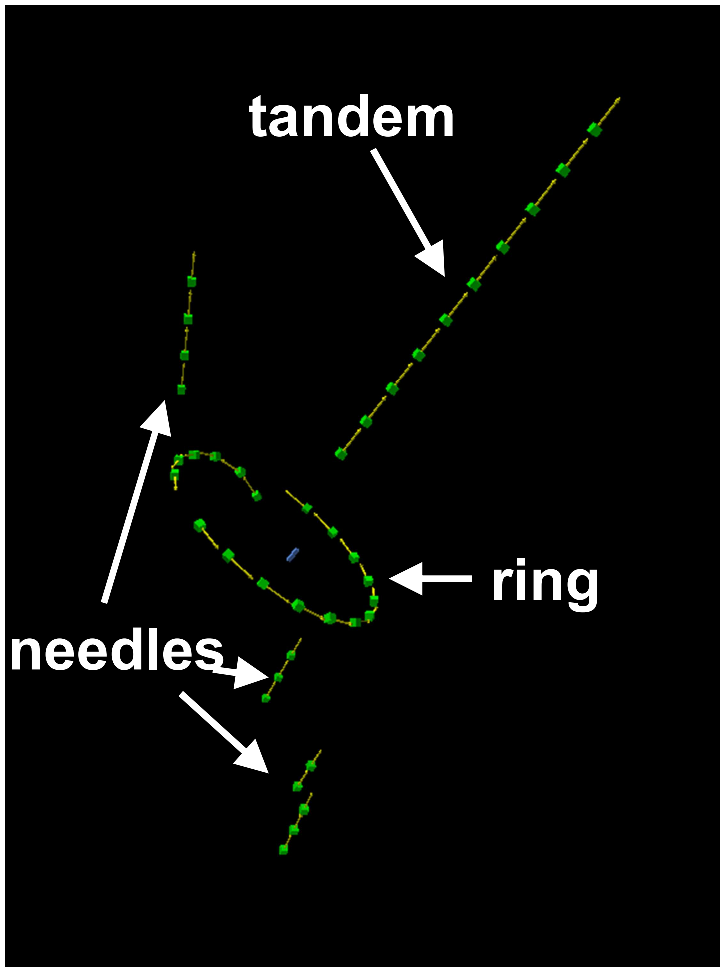
Rethink *in vivo* dosimetry: From organ point dose measurement to overall treatment verification

- **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?

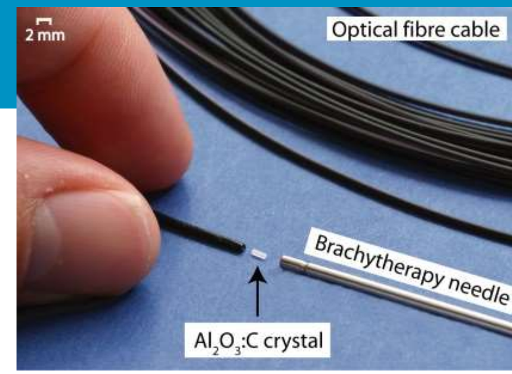




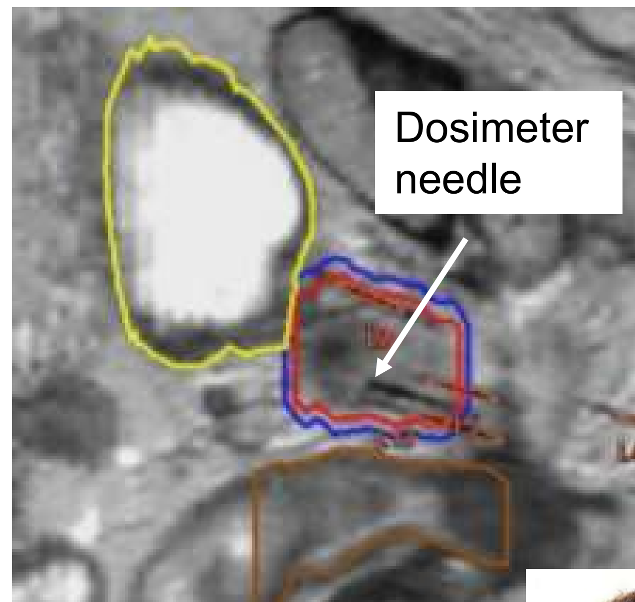
Foot print of source progression!!

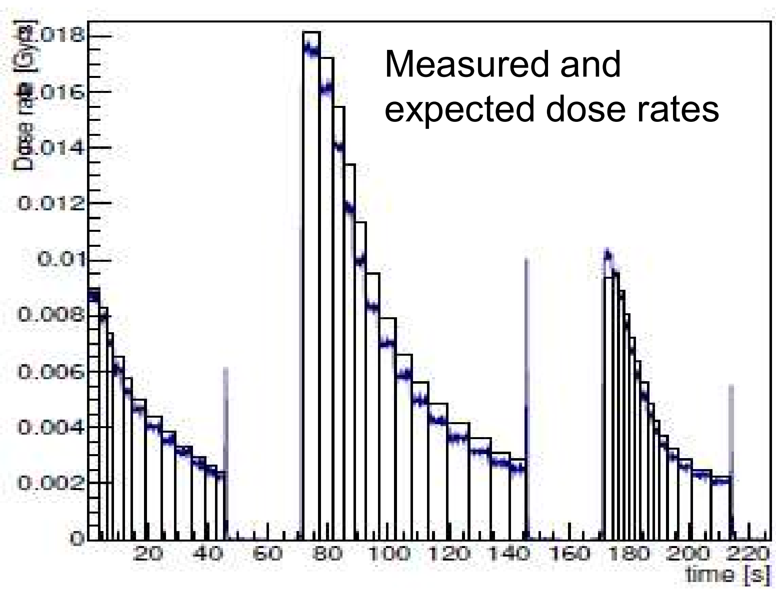
Courtesy Gustavo Kertzscher

Dose rate → geometry



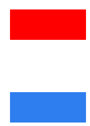
- **Prostate HDR brachytherapy**
- **Real-time in vivo dosimetry**
- **Al2O3 luminescent dosimeter placed in additional needle**





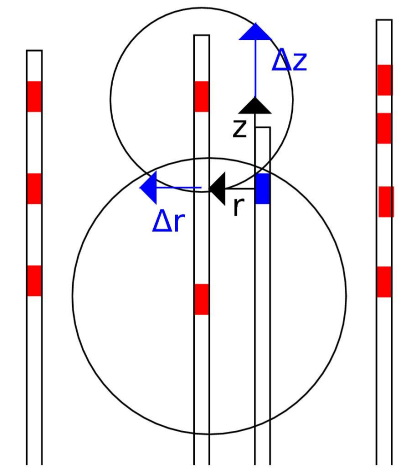
Jacob Johansen et al,
Aarhus University Hospital, 2017

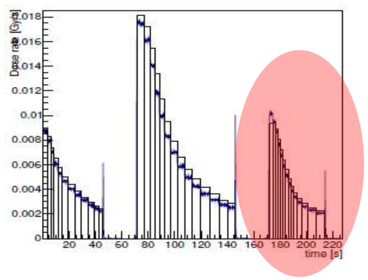
Dose rate → geometry



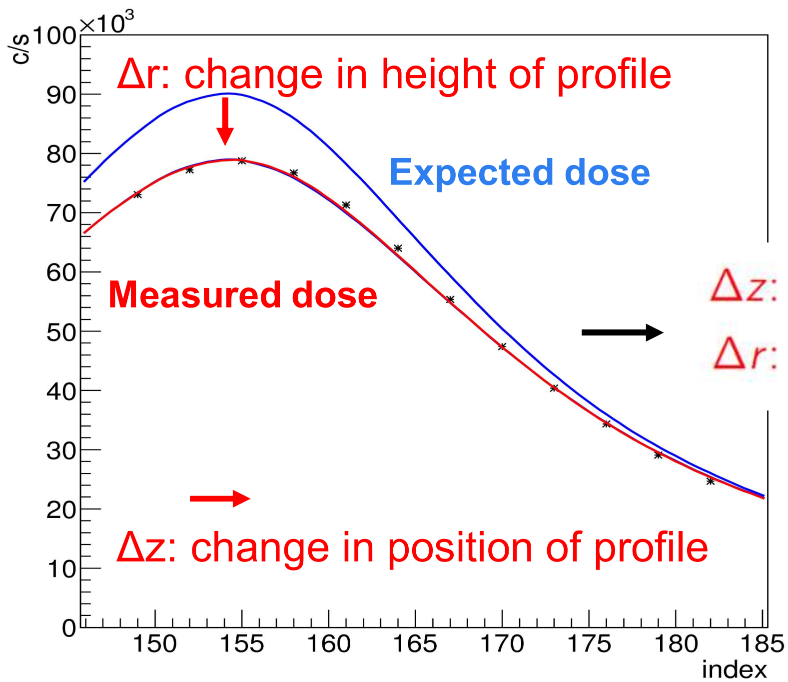
Source position

Detector



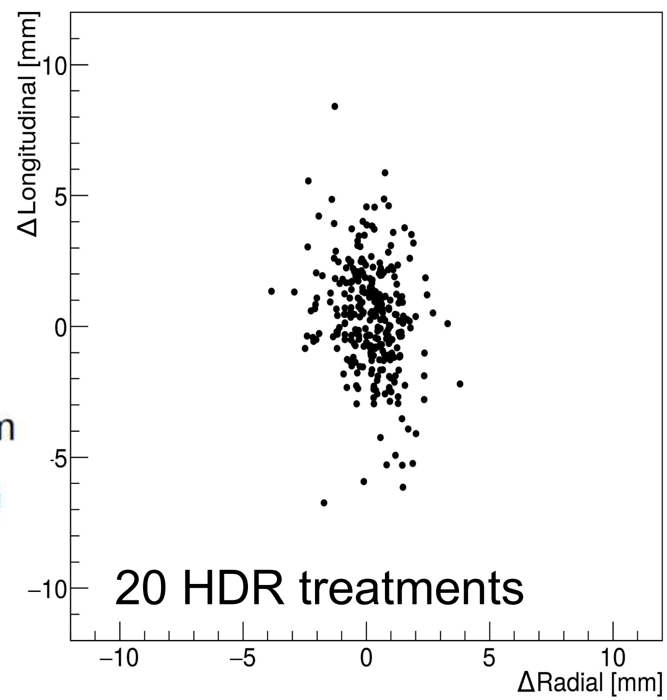


Dose rate profile of
a single needle



Δz: -0.25mm

Δr: 1.31mm



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?

Passive dosimeters

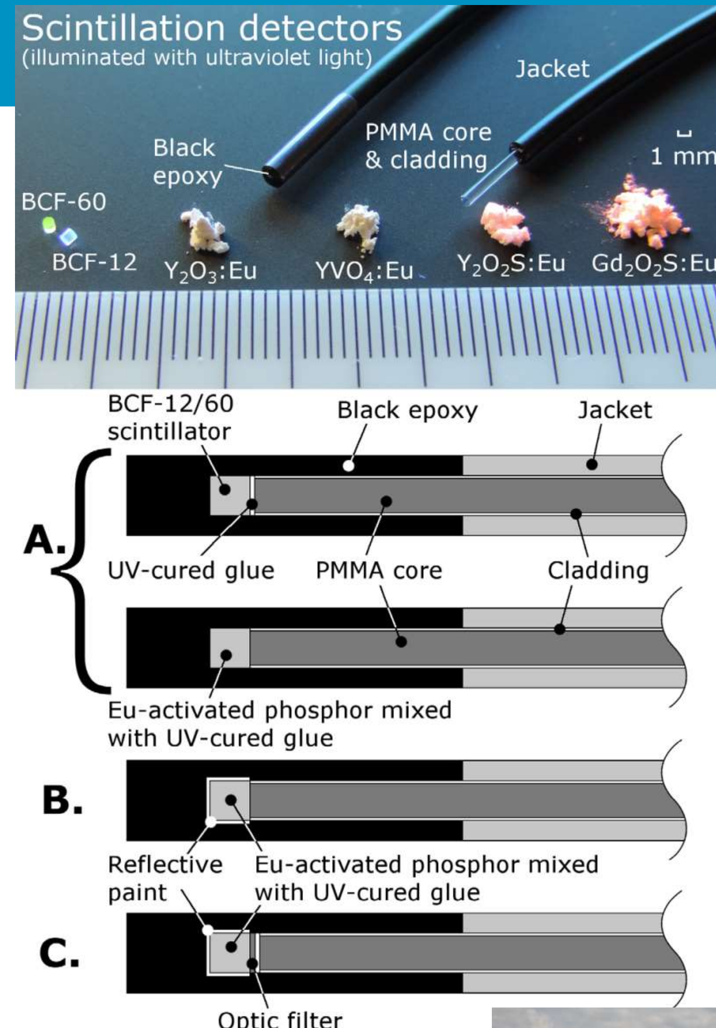
TABLE III. Characteristics of detectors [covered] IVD in brachytherapy. The items are rated according to: advantageous (++), good (+), and inconvenient (−).

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

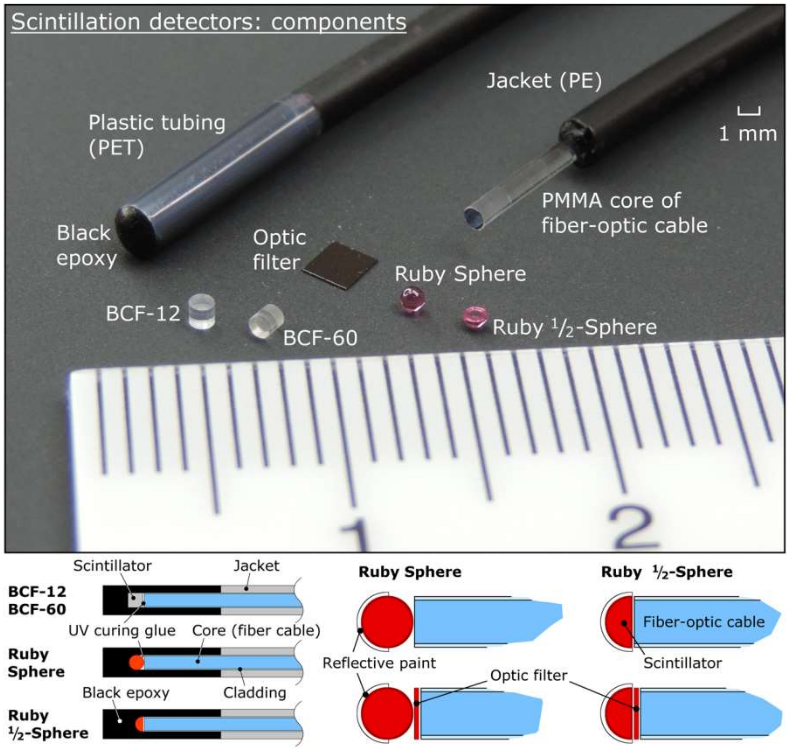
K. Tanderup, S. Beddar, C. E. Andersen, G. Kertzscher, J. E. Cygler, **"*In vivo* dosimetry in brachytherapy"**, Med. Phys. 40(7), 070902 (15 pp.) (2013).

Novel developments inorganic scintillators: Large light yield

Eu-activated phosphors



Ruby-based



G. Kertzscher, S. Beddar, **“Inorganic scintillation detectors based on Eu-activated phosphors for 192Ir brachytherapy”**, Phys. Med. Biol. 62 (2017) 5046–5075

G. Kertzscher, S. Beddar, **“Ruby-based inorganic scintillation detectors for 192Ir brachytherapy”**, Phys. Med. Biol. 61 (2016) 7744–7764

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

In vivo dosimetry may enable us to see!