THE UNIVERSITY OF TEXAS
MD Anderson
Cancer Center
Making Cancer History®

In-Vivo Dosimetry for External Beam Radiation Therapy and Brachytherapy

Sam Beddar, Ph.D., FCCPM, FAAPM
Professor & Chief of Research

Department of Radiation Physics
The University of Texas MD Anderson Cancer Center

Is there a need for *In Vivo* Dosimetry ?

LESSONS FROM RECENT ACCIDENTS IN RADIATION THERAPY IN FRANCE

Table 1. Recent accidents in radiotherapy in France.

Where	Year/period	Patients involved
Case 1	2003	1
Case 2	2004	1
Case 3	2004	1
Case 4.1	May 2004 – May 2005	24
Case 4.2	2001 – 2006	397
Case 4.3	1987 – 2000	312
Case 5	April 2006–April 2007	145

ability of complications or reduced probability of tumour control).

Is there a need for *In Vivo* Dosimetry ?

HOME PAGE | TODAY'S PAPER | VIDEO | MOST POPULAR | TIMES TOPICS

Log In | Register Now | TimesPeople

The New York Times — U.S.

Search All NYTimes.com

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION | ARTS | STYLE | TRAVEL | JOBS | REAL ESTATE | AUTOS

POLITICS EDUCATION

June 20, 2009

SIGN IN TO E-MAIL | FEEDBACK

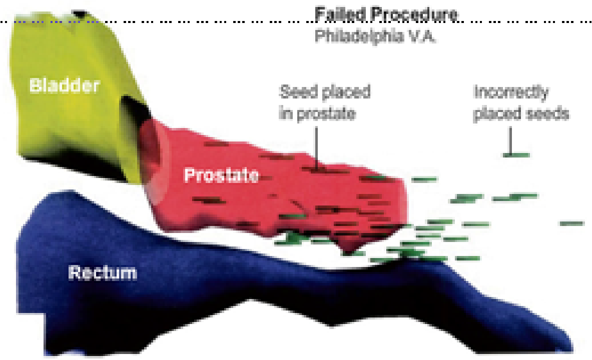
Failed Prostate Procedures at the Philadelphia V.A.

Investigators from the Nuclear Regulatory Commission have found that from 2002 to 2008, a cancer unit at the Philadelphia V.A. botched 92 of 116 brachytherapy procedures. A look at how the procedure is commonly performed.

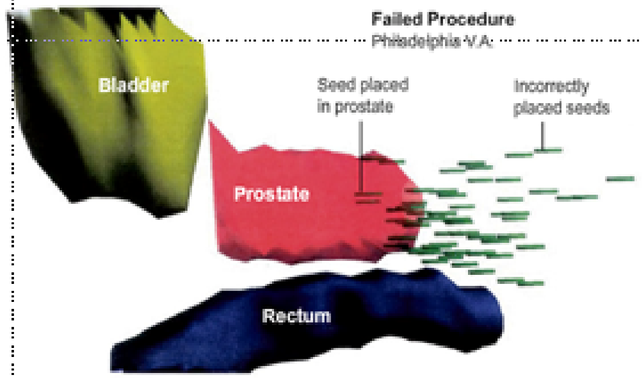
1 2 3 4 5 6 7 8 9 10 NEXT

What went wrong at the Philadelphia V.A.

These computer-generated images, part of a presentation produced by the Nuclear Regulatory Commission, show two specific patients who received the treatment. The images show the major organs, with the surrounding tissue rendered as white. Seeds that are implanted in or near the bladder or rectum can cause undue damage to otherwise healthy organs.



Here some of the radioactive seeds were implanted near the patient's rectum, potentially causing damage to that organ. In addition, the patient's prostate received only 43 gray of the 160 prescribed by the doctor.

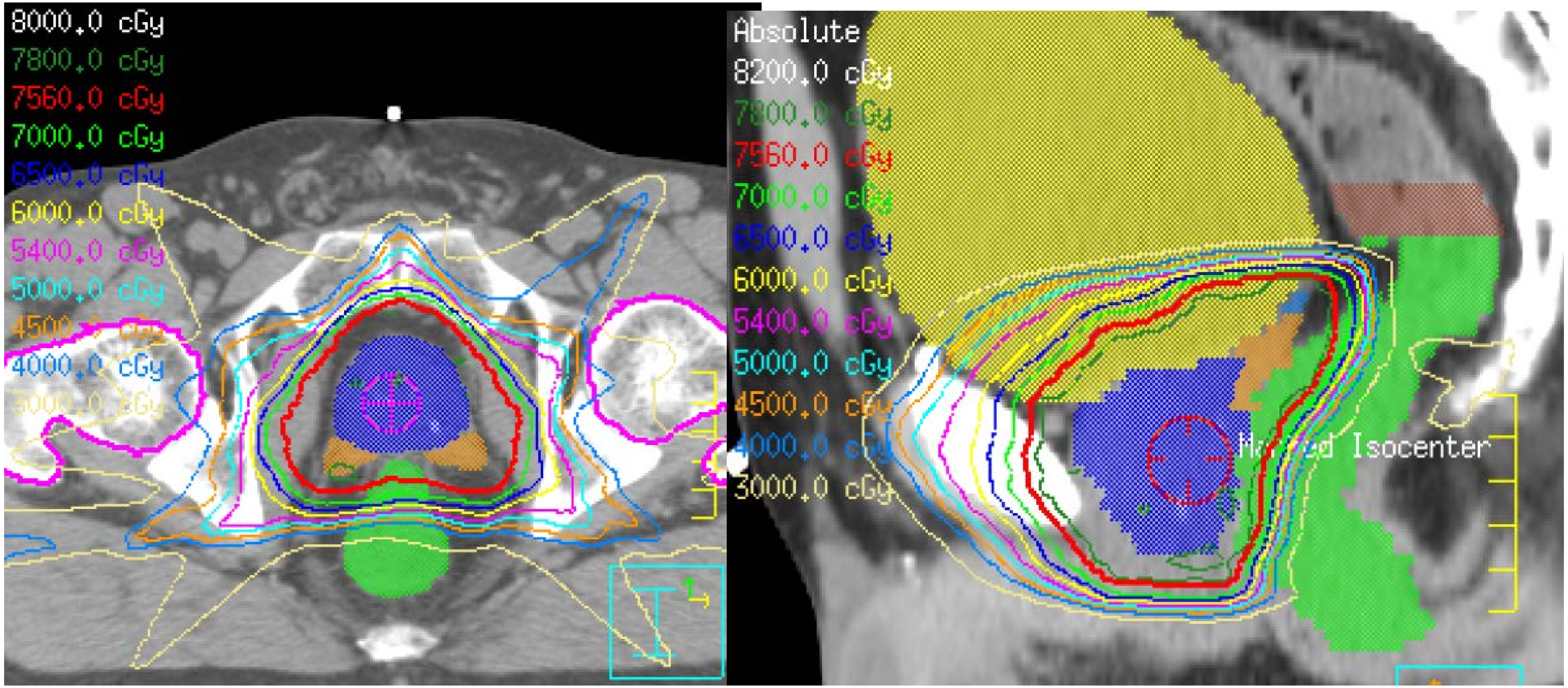


In this case, nearly all of the seeds have been placed outside of the prostate, in the perineum. Of the prescribed dose of 160 gray, the prostate received only 24. This means that the patient's prostate cancer was only minimally treated by the procedure.

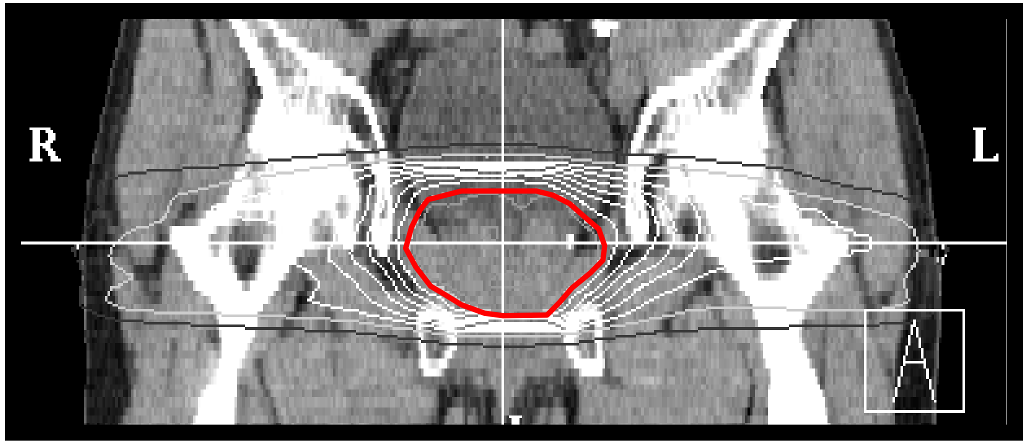
Sources: Dr. Adam P. Dicker and Dr. Yan Yu, Jefferson Medical College of Thomas Jefferson University; The Nuclear Regulatory Commission

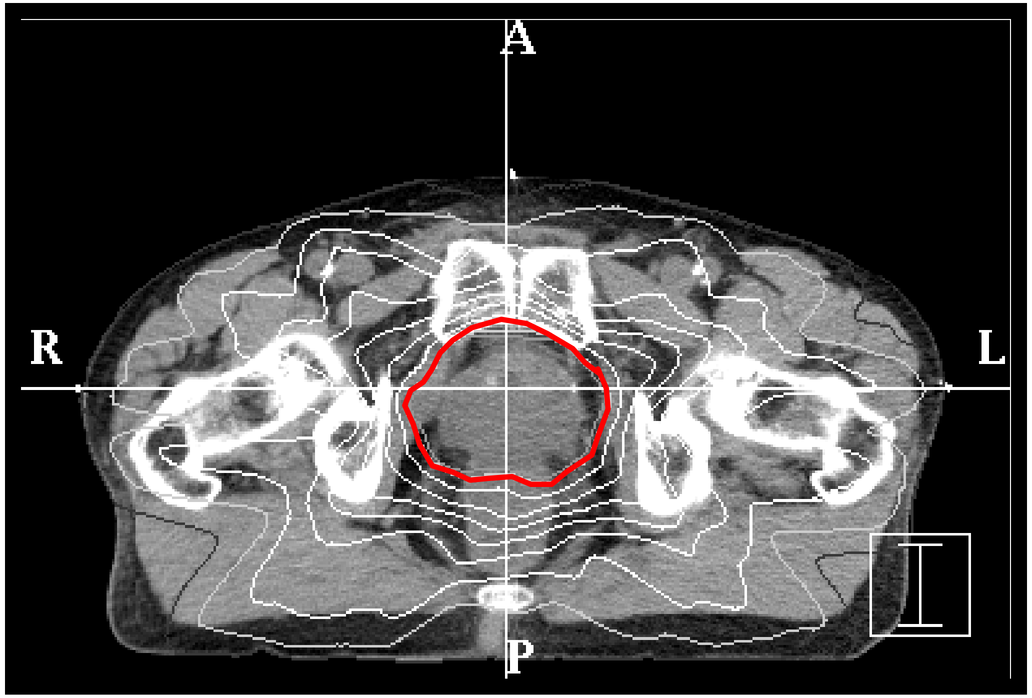
Graham Roberts/The New York Times

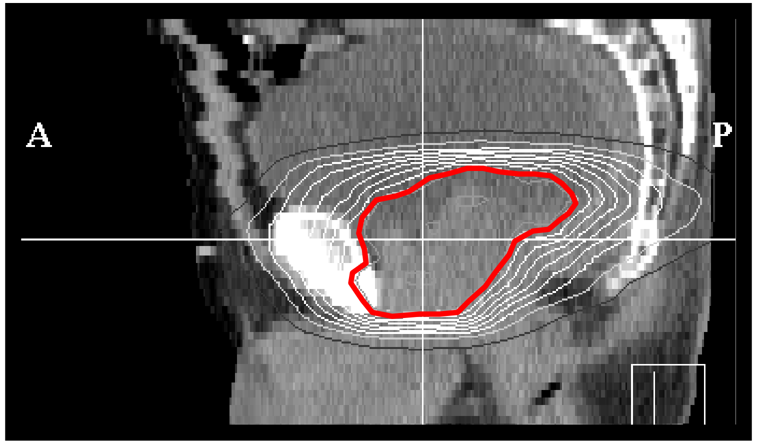
IMRT (8 angles)
Axial and sagittal dose distribution



PROSTATE MOTION results in INTER-fraction errors

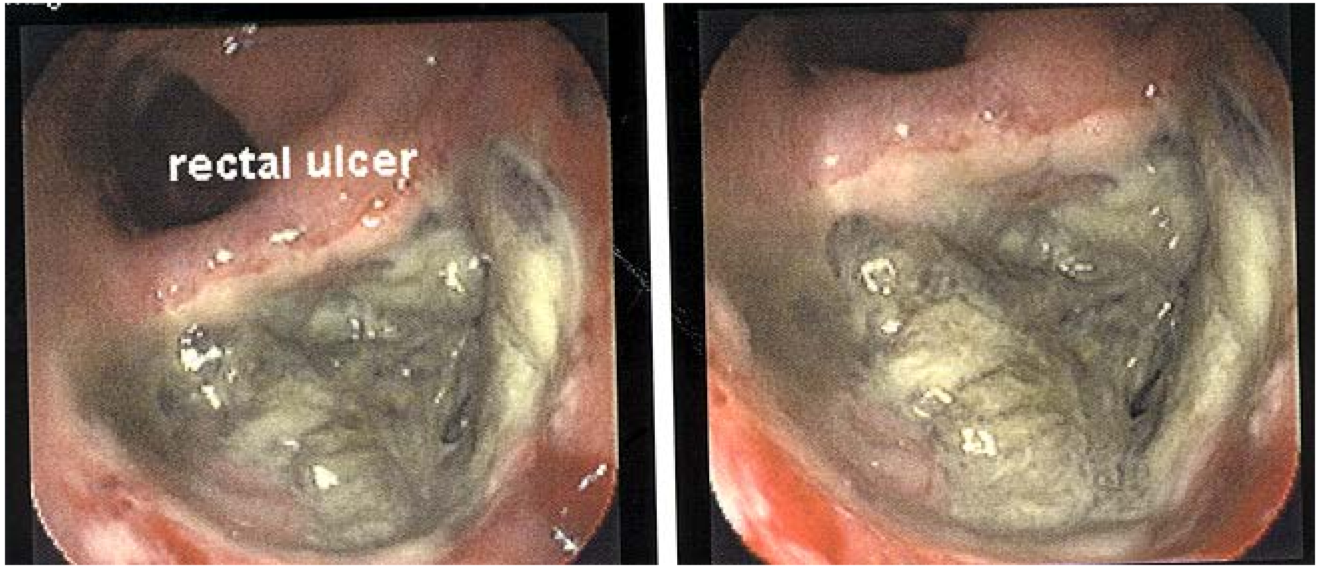






25 treatment CTs acquired during a course of 42 Txs

What we want to avoid

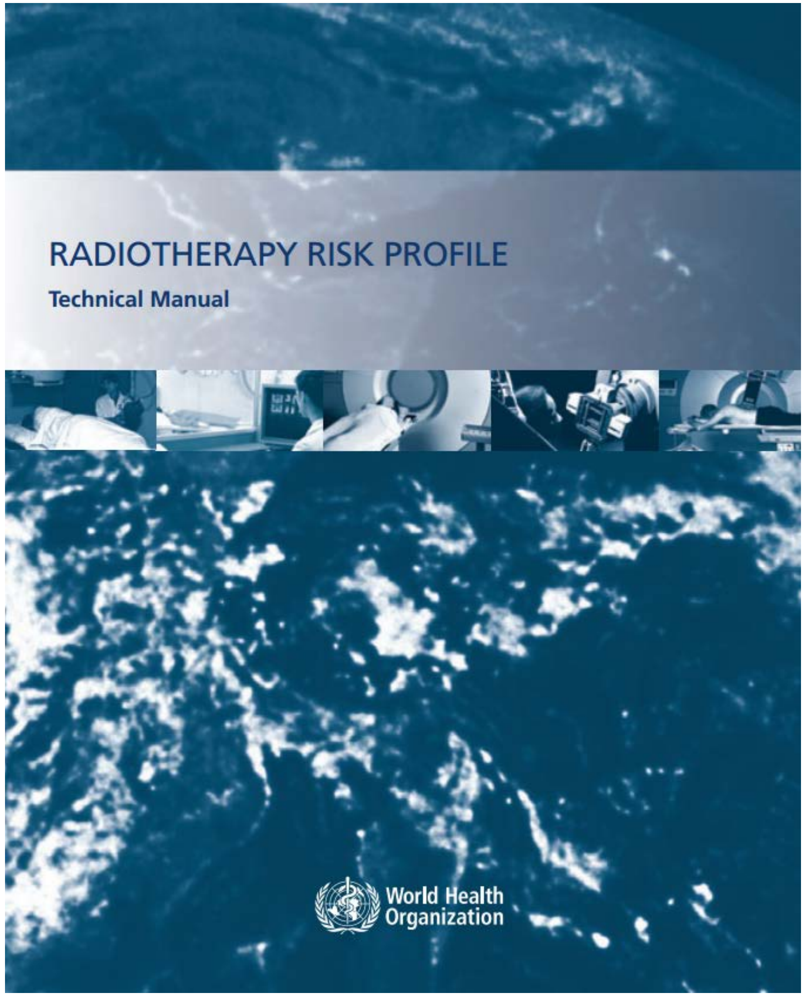


Courtesy of Andrew Lee, M.D.

In Vivo Dosimetry

2008 WHO Report summarized widely reported radiation therapy incidents.

- 3125 Major Incidents (1976-2007)
- 4616 Near Misses (1992-2007)



In vivo dosimetry in external beam radiotherapy

Ben Mijnheer[a)]
Department of Radiation Oncology, The Netherlands Cancer Institute-Antoni van Leeuwenhoek Hospital, Amsterdam 1066 CX, The Netherlands

Sam Beddar
Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, Texas 77030

Joanna Izewska
Division of Human Health, International Atomic Energy Agency, Vienna 1400, Austria

Chester Reft
Department of Radiation and Cellular Oncology, University of Chicago Medical Center, Chicago, Illinois 60637

(Received 30 November 2012; revised 15 May 2013; accepted for publication 22 May 2013; published 25 June 2013)

In vivo dosimetry (IVD) is in use in external beam radiotherapy (EBRT) to detect major errors, to assess clinically relevant differences between planned and delivered dose, to record dose received by individual patients, and to fulfill legal requirements. After discussing briefly the main characteristics of the most commonly applied IVD systems, the clinical experience of IVD during EBRT will be summarized. Advancement of the traditional aspects of *in vivo* dosimetry as well as the development of currently available and newly emerging noninterventional technologies are required for large-scale implementation of IVD in EBRT. These new technologies include the development of electronic portal imaging devices for 2D and 3D patient dosimetry during advanced treatment techniques, such as IMRT and VMAT, and the use of IVD in proton and ion radiotherapy by measuring the decay of radiation-induced radionuclides. In the final analysis, we will show in this Vision 20/20 paper that in addition to regulatory compliance and reimbursement issues, the rationale for *in vivo* measurements is to provide an accurate and independent verification of the overall treatment procedure. It will enable the identification of potential errors in dose calculation, data transfer, dose delivery, patient setup, and changes in patient anatomy. It is the authors' opinion that all treatments with curative intent should be verified through *in vivo* dose measurements in combination with pretreatment checks.

[http://dx.doi.org/10.1118/1.4811216]

Key words: *in vivo* dosimetry, external beam radiotherapy, detector characteristics, patient safety, dose verification

In vivo dosimetry in brachytherapy

Kari Tanderup[a)]
Department of Oncology, Aarhus University Hospital, Aarhus 8000, Denmark and Department of Clinical Medicine, Aarhus University, Aarhus 8000, Denmark

Sam Beddar
Department of Radiation Oncology, The University of Texas MD Anderson Cancer Center, Houston, Texas 77030

Claus E. Andersen and Gustavo Kertzscher
Center of Nuclear Technologies, Technical University of Denmark, Roskilde 4000, Denmark

Joanna E. Cygler
Department of Physics, The Ottawa Hospital Cancer Centre, Ottawa, Ontario K1H 8L6, Canada

(Received 15 January 2013; revised 12 April 2013; accepted for publication 16 April 2013; published 25 June 2013)

In vivo dosimetry (IVD) has been used in brachytherapy (BT) for decades with a number of different detectors and measurement technologies. However, IVD in BT has been subject to certain difficulties and complexities, in particular due to challenges of the high-gradient BT dose distribution and the large range of dose and dose rate. Due to these challenges, the sensitivity and specificity toward error detection has been limited, and IVD has mainly been restricted to detection of gross errors. Given these factors, routine use of IVD is currently limited in many departments. Although the impact of potential errors may be detrimental since treatments are typically administered in large fractions and with high-gradient-dose-distributions, BT is usually delivered without independent verification of the treatment delivery. This Vision 20/20 paper encourages improvements within BT safety by developments of IVD into an effective method of independent treatment verification. [http://dx.doi.org/10.1118/1.4810943]

Key words: *in vivo* dosimetry, brachytherapy, treatment errors, quality assurance

Treatment errors

- All radiotherapy modalities are subject to errors
- However, ***brachytherapy involves many manual procedures and mechanical equipment that are susceptible to mistakes/errors***

IAEA Safety Report Series 17. Vienna, Austria: IAEA. IAEA Safety Reports Series (2000).

P.O. Lopez, P. Andreo, J.-M. Cosset, A. Dutreix, T. Landberg, ICRP Publications 86, Annals of the ICRP. New York, NY: Pergamon (2000).

L. P. Ashton, J.-M. Cosset, V. Levin, A. Martinez, S. Nag, ICRP Publications 97, Annals of the ICRP. New York, NY: Pergamon (2004).

Reported treatment errors:

source calibration, afterloader source positioning, afterloader dwell time, afterloader malfunction, incorrect treatment plan, applicator movement, reconstruction/fusion errors, applicator length, source indexer-length, source step size, interchanged guide tubes, failure of retraction system, dislodged applicator, etc.

What are the challenges?

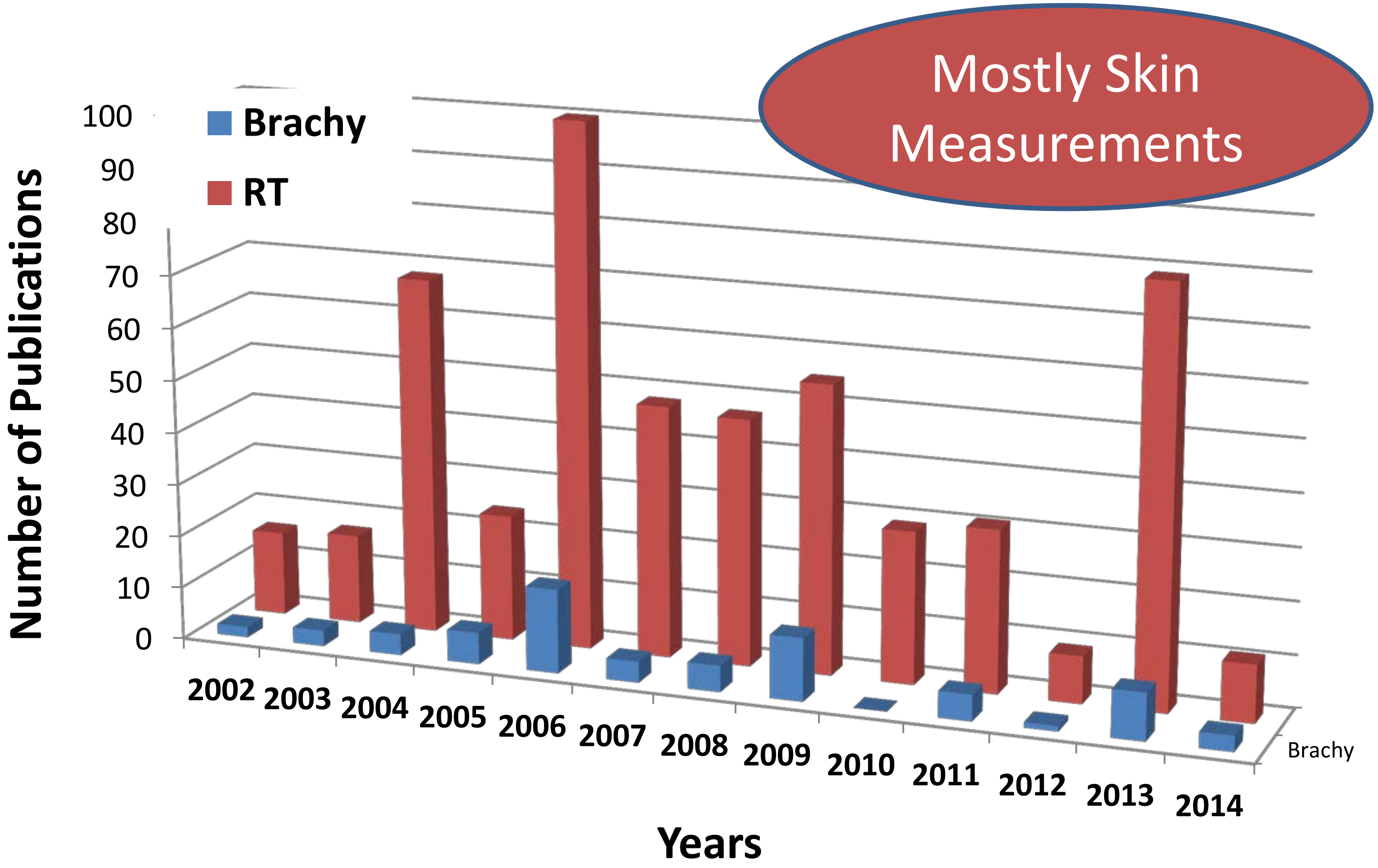
- The energy response of the detectors available at hand.
- The need for precise detector positioning, especially in high-dose gradient regions.
- The large range of doses and dose rates encountered in external beam radiation therapy EBRT or brachytherapy.

Therefore

- IVD is mostly used for legal purposes or reimbursement issues
- or to prevent (rare) major incidents in treatment delivery and used with action levels above 10 - 20 % depending on the site

However, we need to move forward and change the role of IVD by taking it to a higher level.

IVD more common for EBRT than Brachy



Source: PubMed, March 31st 2014: "in vivo dosimetry" AND "<Modality>" AND "<Year>"

Current Status of EBRT vs. BT

Quality item	Current status EBRT	Current status BT	Aims for the future
Patient specific QA	- Pre-treatment plan verification tools such as DRRs and EPID prediction (clinical routine) - Pre-treatment fluence and/or dose measurements (clinical routine)	**Manual pre-treatment checks**	- On-board 3D verification of implanted catheter - Off-line computational verification of treatment plans
On-board patient imaging	- 2D kV x-ray (clinical routine) - 3D CBCT (clinical routine) - CT on rails (clinical routine) - 3D MRI (under clinical testing) - On board fast replanning	**Not available in clinical routine**	- On-board 3D US, x-ray and MRI - On board fast re-planning
Real-time dose verification	- EPID: real-time fluence and 3D dose reconstruction (under clinical testing) - MRI linac: real-time imaging and tracking (under development)	**Not available in clinical routine**	- Real-time verification with in vivo dosimetry - On-line computational verification techniques

State of the Art Detectors

A *quick* highlight of detectors that have been used for IVD…

With special focus for Brachytherapy

State of the Art Detectors: TLDs

- LiF rods are the most commonly used for brachytherapy.
- Prostate, urethral and rectal dose measurements in HDR prostate implants[1,2,3,4]
- Skin dose measurement for HDR breast implants[5]

1- I.A. Brezovich, J. Duan, P. N. Pareek, J. Fiveash, and M. Ezekiel. ***In vivo* urethral dose measurements: A method to verify high dose rate prostate treatments**. Med Phys 27, 2297–2301 (2000);

2 – G. Anagnostopoulos *et al.*, ***In vivo* thermoluminescence dosimetry dose verification of transperineal 192Ir high-dose-rate brachytherapy using CT based planning for the treatment of prostate cancer**. Int J Radiat Oncol Biol Phys 57, 1183–91 (2003);

3 – R. Das, W. Toye, T. Kron, S. Williams, and G. Duchesne. **Thermoluminescence dosimetry for *in vivo* verification of high dose rate brachytherapy for prostate cancer.** Australas Phys Eng Sci Med 30, 178–184 (2007);

4 – W. Toye, R. Das, T. Kron, R. Franich, P. Johnston, and G. Duchesne. **An *in vivo* investigative protocol for HDR prostate brachytherapy using urethral and rectal thermoluminescence dosimetry.** Radiother. Oncol. 91, 243–248 (2009);

5 – J. A. Raffi *et al.* **Determination of exit skin dose for ^{192}Ir intracavitary accelerated partial breast irradiation with thermoluminescent dosimeters** Med. Phys. 37, 2693–2702 (2010).

State of the Art Detectors: TLDs



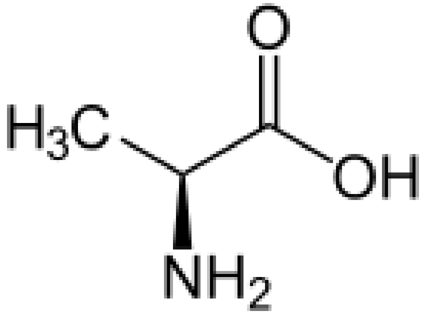
Advantages

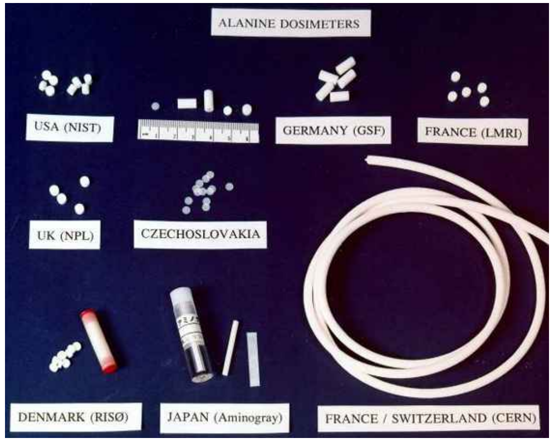
- Different shapes & materials
- No angular dependence
- Not attached to any wire/cable
- Well studied

Disadvantages

- Require special preparation (annealing, individual calibration, careful handling, fading correction)
- Read-out process post-irradiation
- **Not for online dosimetry**

State of the Art Detectors: Alanine



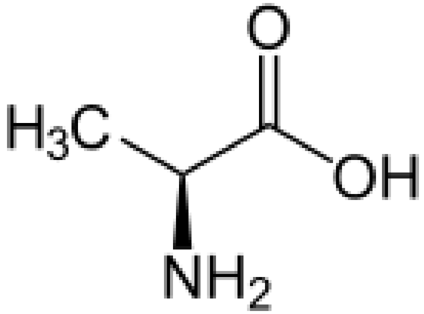


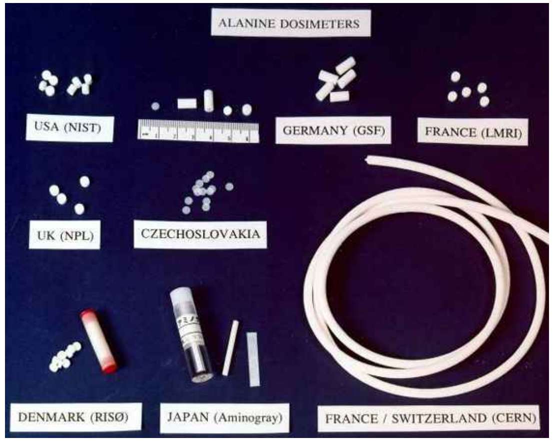
- Chemical detector
- Requires electron paramagnetic resonance (EPR) for read-out.
- Few reports on IVD during gynecological treatments[1,2]

1 – B. Ciesielski, K. Schultka, A. Kobierska, R. Nowak, and Z. Peimel-Stuglik. ***In vivo* alanine/EPR dosimetry in daily clinical practice: A feasibility study.** Int. J. Radiat. Oncol., Biol., Phys. 56, 899–905 (2003).
2 - Schultka, B. Ciesielski, K. Serkies, T. Sawicki, Z. Tarnawska, and J. Jassem. **EPR/alanine dosimetry in LDR brachytherapy: A feasibility study.** Radiat. Prot. Dosim. 120, 171–175 (2006).

***EPR**: Electron Paramagnetic Resonance*

State of the Art Detectors: Alanine





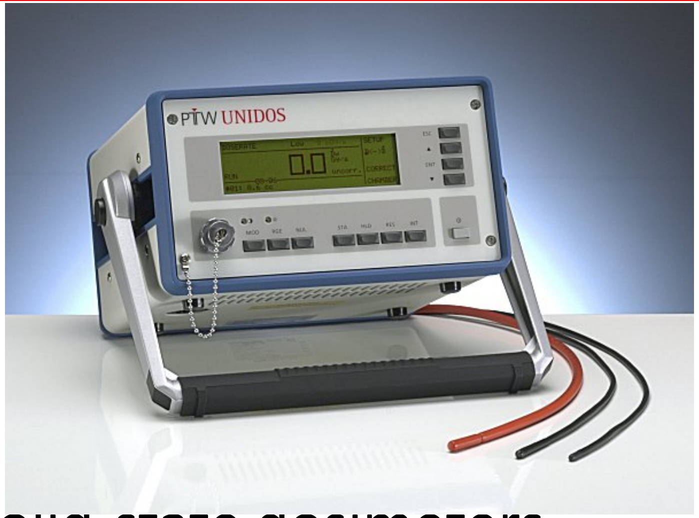
Advantages

- Almost independent of energy
- Not attached to any wire/cable
- Non-destructive read-out

Disadvantages

- Expensive EPR equipment and not easily available in clinic
- Tedious read-out process
- Insensitive to doses < 2 Gy
- **Not for online dosimetry**

State of the Art Detectors: Diodes



- Silicon-based solid-state dosimeters
- Mostly used for EBRT for different purposes (i.e. right wedges, etc…)
- 5-diode arrays used as rectal[1] and bladder[2] dosimeters
- Overall uncertainty in phantom of 7-10%

1 – C. Waldhäusl, A. Wambersie, R. Potter, and D. Georg. ***In-vivo* dosimetry for gynaecological brachytherapy: Physical and clinical considerations.** Radiother. Oncol. 77, 310–317 (2005).
2 – E.L. Seymour, S. J. Downes, G. B. Fogarty, M. A. Izard, and P. Metcalfe. ***In vivo* real-time dosimetric verification in high dose rate prostate brachytherapy**. Med Phys 38, 4785–4794 ,(2011).

State of the Art Detectors: Diodes

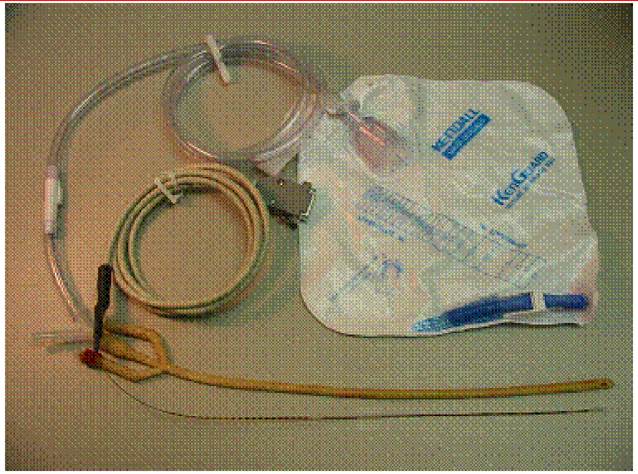
Advantages

- Immediate read-out
- High sensitivity
- Good mechanical stability
- Fairly small size
- Available in arrays

Disadvantages

- **Angular dependence**
- **Energy dependence**
- Temperature dependence
- Changes in sensitivity with radiation

State of the Art Detectors: MOSFETs



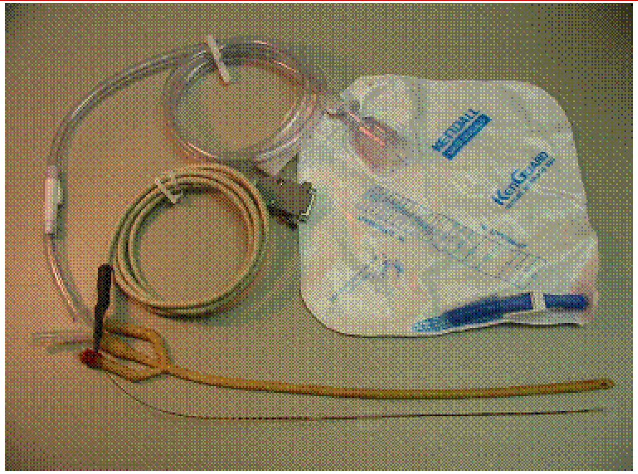
- Metal-oxide-semiconductor field-effect transistor (MOSFET) based on silicon
- Used for monitoring urethral dose in seeds implant[1,2,3]
- Uncertainty of 8%[2]

1 – J.E. Cygler, A. Saoudi, G. Perry, C. Morash, and C. E. Andersen **Feasibility study of using MOSFET detectors for *in vivo* dosimetry during permanent low dose- rate prostate implants** Radiother. Oncol. **80,** 296–301 (2006).

2 – E. J. Bloemen-van Gurp *et al.* ***In vivo* dosimetry using a linear MOSFET array dosimeter to determine the urethra dose in 125I permanent prostate implants** Int. J. Radiat. Oncol., Biol., Phys. 73, 314–321 (2009);

3 – A. Cherpak, J. Cygler, and G. Perry. **Real-time measurement of urethral dose and position using a RADPOS array during permanent seed implantation for prostate brachytherapy** Med. Phys. **38**, 3577 (2011).

State of the Art Detectors: MOSFETs



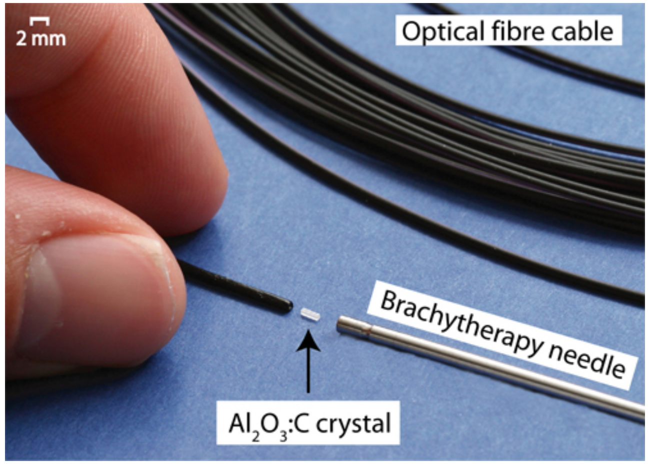
Advantages

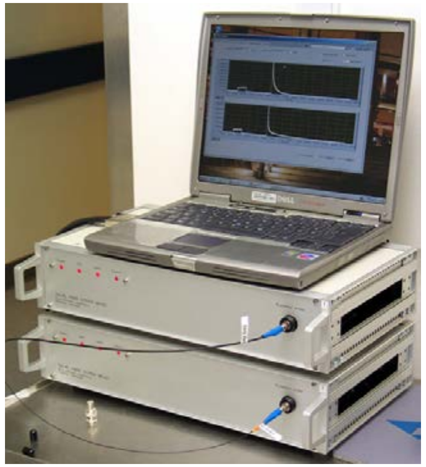
- Small size (can be inserted in catheters)
- Available in arrays
- ~ No angular dependence

Disadvantages

- Not water-equivalent
- **Limited life-time**
- Temperature dependence
- Response degrades with accumulated exposure

State of the Art Detectors: RL/OSLDs

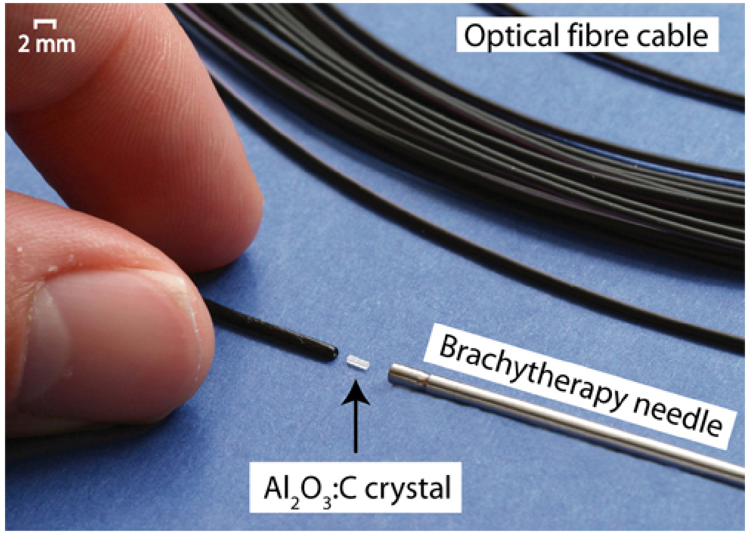


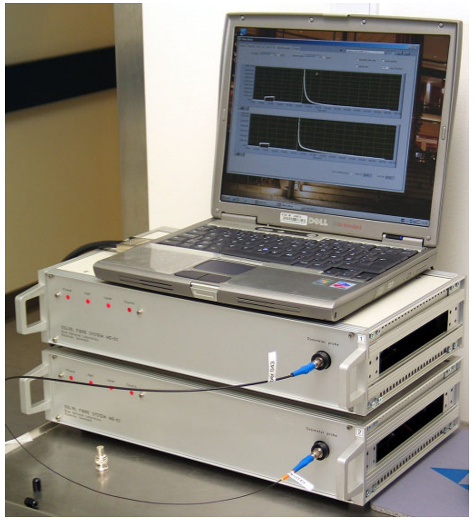


- Generally composed of Al_2O_3:C
- OSLD: Optically stimulated luminescence dosimeter / RL: Radoluminescence
- Prevention and identification of dose delivery errors in cervix, gynecological and prostate HDR and PDR brachytherapy[1,2]
- Potential to detect interchanged guide tube errors and source mispositioning[2]
- Uncertainty of 5% (OSL) and 8% (RL)

1 – C. E. Andersen, S. K. Nielsen, J. C. Lindegaard, and K. Tanderup. **Time resolved *in vivo* luminescence dosimetry for online error detection in pulsed dose-rate brachytherapy.** Med. Phys. **36**, 5033–5043 (2009).
2 – G. Kertzscher, C. E. Andersen, F. A. Siebert, S. K. Nielsen, J. C. Lindegaard, and K. Tanderup. **Identifying afterloading PDR and HDR brachytherapy errors using real-time fiber-coupled Al2O3:C dosimetry and a novel statistical error decision criterion** Radiother. Oncol. 100, 456–462 (2011).

State of the Art Detectors: RL/OSLDs





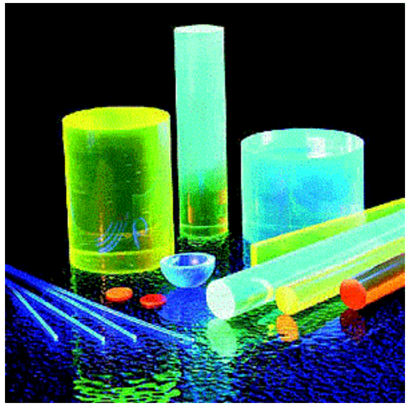
Advantages

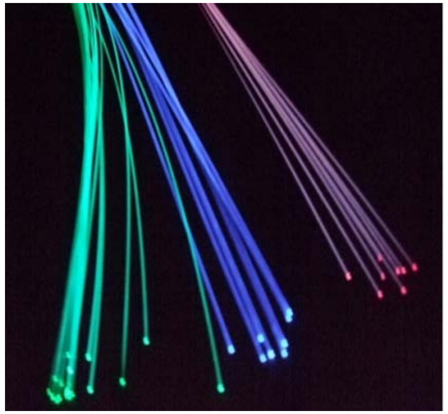
- Small size
- RL feedback in real-time
- Passive/active detector
- Good reproducibility (1.3%)

Disadvantages

- **Not water-equivalent**
- **Stem effect (Cerenkov)**
- Small temperature dependence

State of the Art Detectors: PSDs





- PSD: Plastic scintillation detector made of polystyrene, PVT or PMMA
- Coupled to an optical fiber, the stem effect has to be subtracted for HDR[1]
- Phantom studies showed excellent dose measurement accuracy[2-3]
- *In vivo* dose measurement in urethra reported with a maximum difference to expected dose of 9%[4]

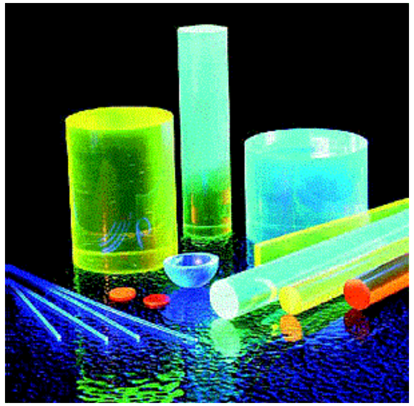
1 – F. Therriault-Proulx, S. Beddar, T.M. Briere, L. Archambault, and L. Beaulieu. **Removing the stem effect when performing Ir-192 HDR brachytherapy in vivo dosimetry using plastic scintillation detectors: a relevant and necessary step.** Med Phys 38, 2176-93, 2011

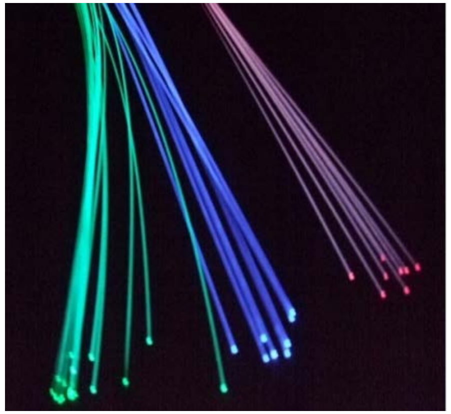
2 - J. Lambert, D. R. McKenzie, S. Law, J. Elsey, and N. Suchowerska. **A plastic scintillation dosimeter for high dose rate brachytherapy.** Phys. Med. Biol. 51, 5505–5516 (2006).

3 - F. Therriault-Proulx, T. M. Briere, F. Mourtada, S. Aubin, S. Beddar, and L. Beaulieu. **A phantom study of an *in vivo* dosimetry system using plastic scintillation detectors for real-time verification of ^{192}Ir HDR brachytherapy.** Med. Phys. 38, 2542–2551 (2011).

4 - N. Suchowerska, M. Jackson, J. Lambert, Y. B. Yin, G. Hruby, and D. R. McKenzie,. **Clinical trials of a urethral dose measurement system in brachytherapy using scintillation detectors.** Int. J. Radiat. Oncol., Biol., Phys. 506, 609–615 (2011).

State of the Art Detectors: PSDs





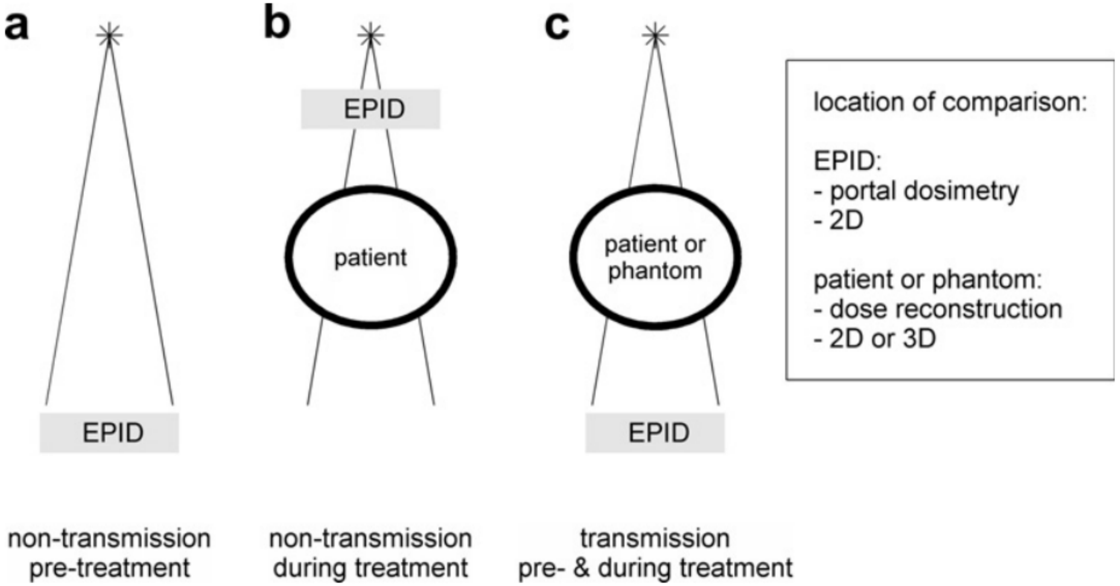
Advantages

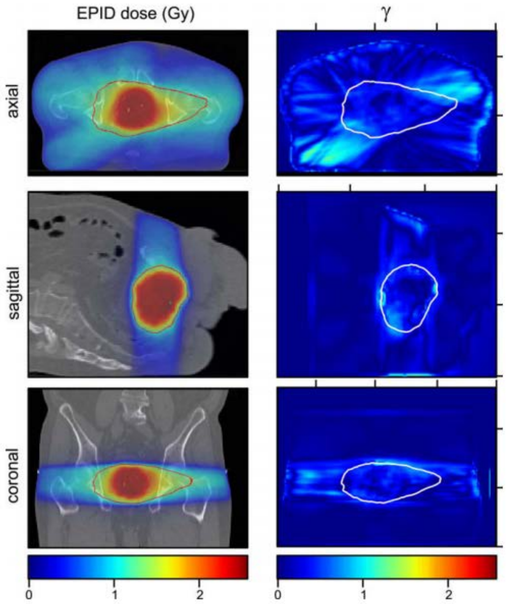
- Linearity to dose/dose-rate
- Small size
- Energy independence
- Water-equivalence
- No angular dependence
- Real-time dosimetry
- New commercial detectors are emerging

Disadvantages

- **Stem effect (Cerenkov)**
- Small temperature dependence

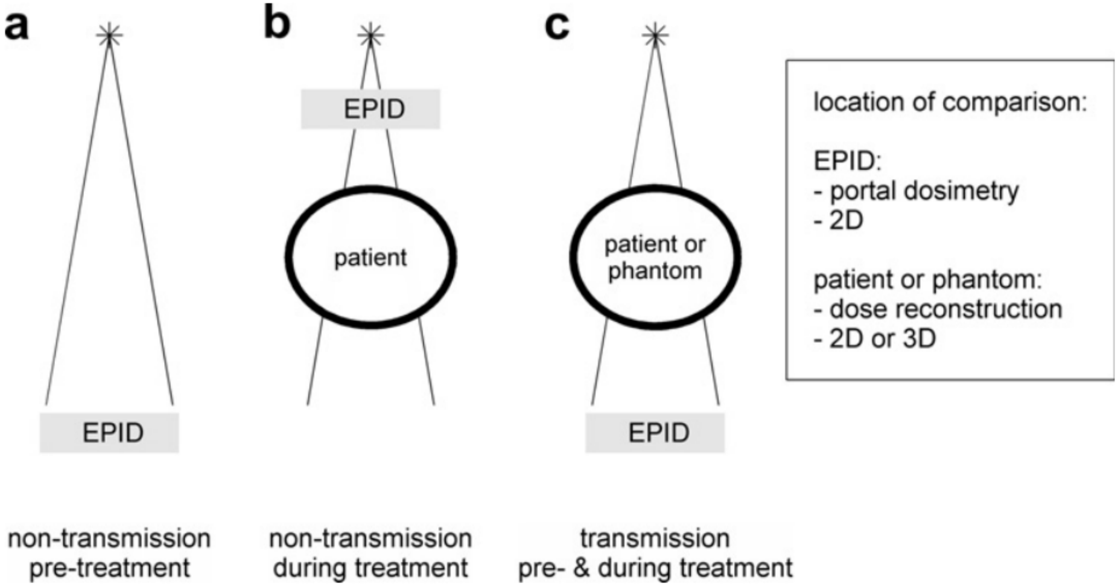
State of the Art Detectors: EPIDs

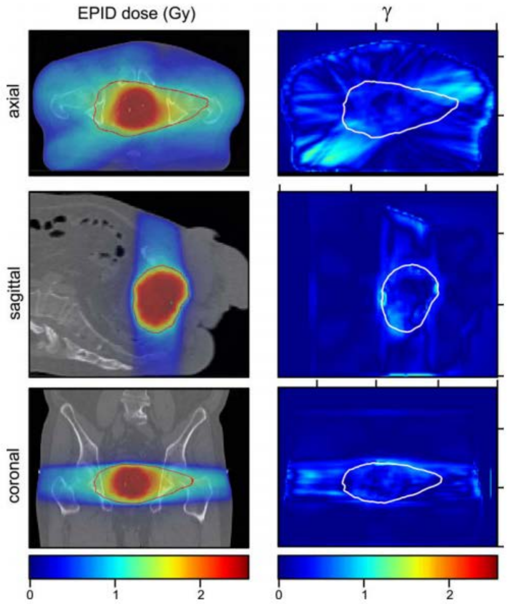




- EPIDs: Electronic portal imaging devices – flat panel detector commonly based on amorphous silicon photodiode technology
- Developed for acquiring megavoltage portal images during treatments, mainly for determining setup errors
- Back-projection models have been used to reconstruct 3D dose distributions in patients during IMRT and VMAT

State of the Art Detectors: EPIDs





Advantages

- Real-time 2D and 3D dose information
- Non-invasive in vivo dosimetry
- Good reproducibility (< 1%)

Disadvantages

- Many correction factors (Mijnheer, *et al* 2013)
- Over-sensitive to low-E photons (response dependence on off-axis beam-hardening effects, patient/phantom thickness in beam)
- Ghosting (non-linearity with dose)

Requirements of IVD

- Minimal to no need for energy response corrections
- Tissue or water-equivalent materials – *would be nice to have*
- High spatial resolution and precise positioning to account for the high dose gradients regions.
  - High dose gradients magnify the effect of positional uncertainty on dosimetric uncertainty.
- High dynamic range to account for varied doses and dose rates.
- Real-time monitoring of the dose delivery – Detectors
- On line monitoring of the dose delivery – Visual Screen

Real-time verification during brachytherapy

Desired Properties

- Large light yield
  - Large dynamic range
  - High signal-to-noise ratio → use low-cost photodiodes
  - Stem background negligible (Cerenkov & fluorescence in PMMA)
- Longer emission wavelengths
  - Good compatibility with solid state photodetectors
  - Less overlap with stem background
- Stable scintillation during constant irradiation (insignificant bleaching effects)
- Negligible afterglow
- Timing properties not stringent – 1 ms is fine

New “kids” on the block…

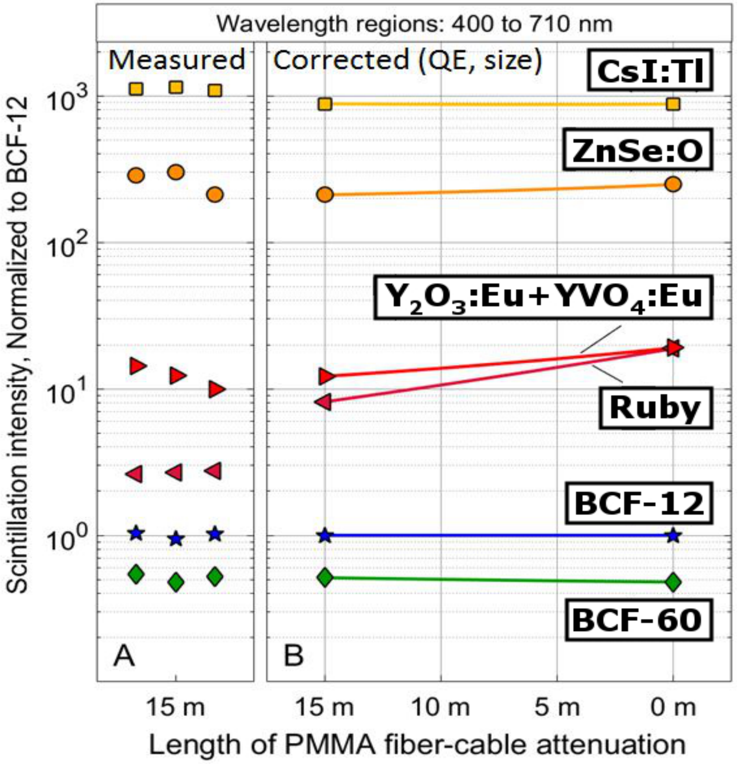
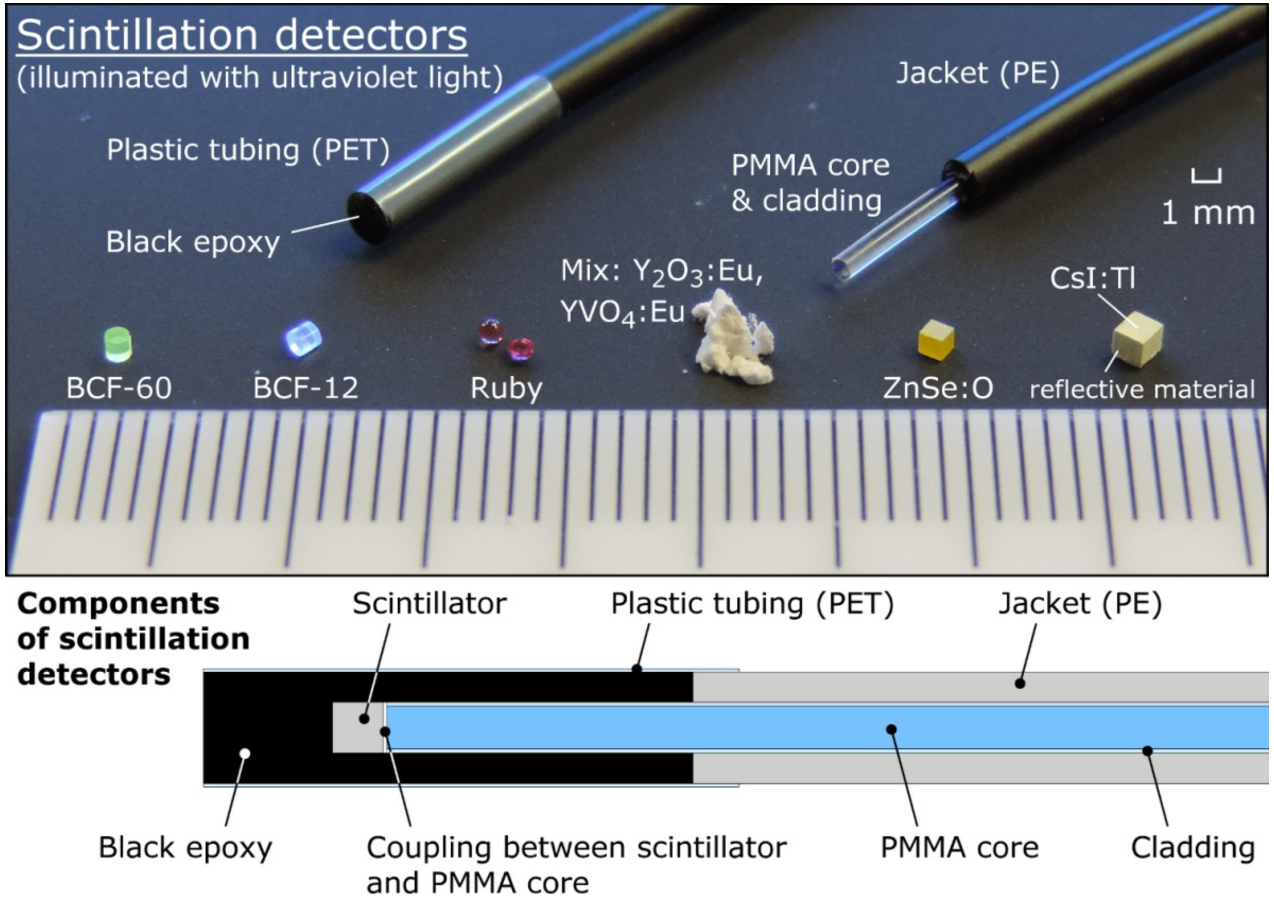
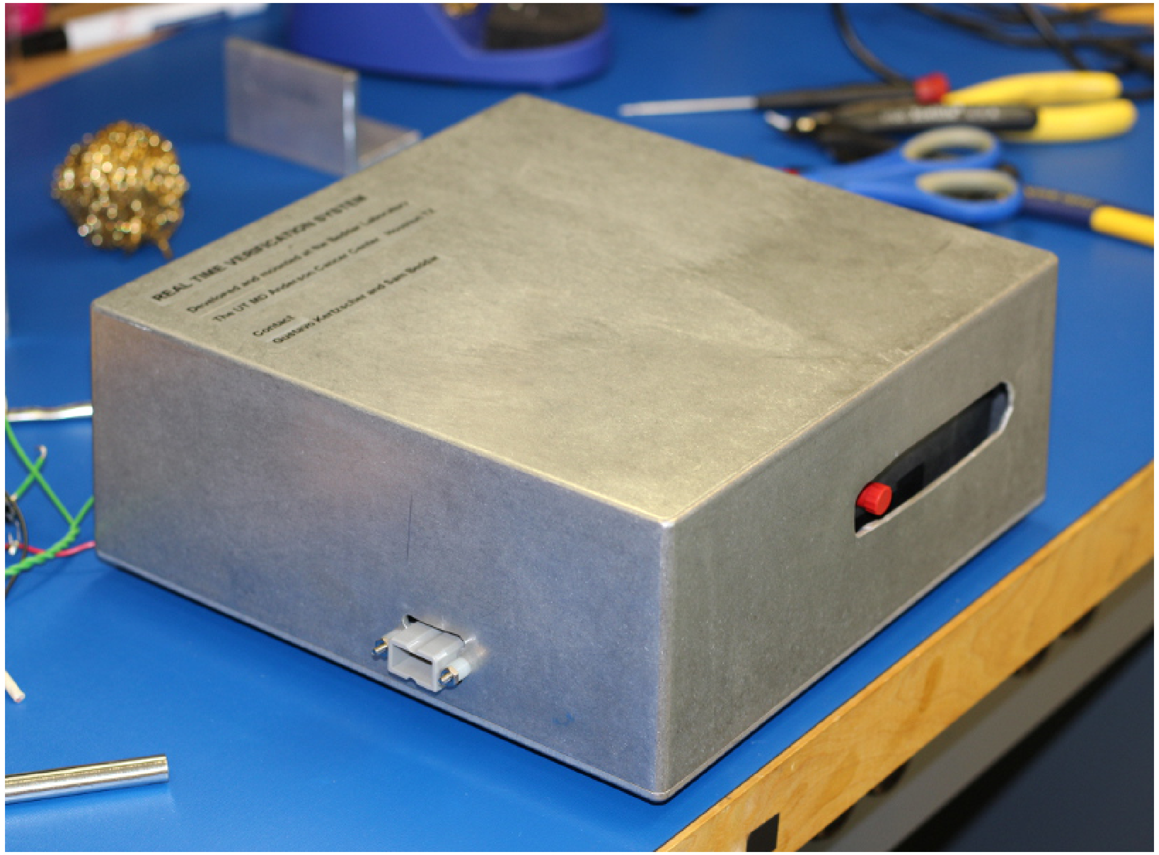


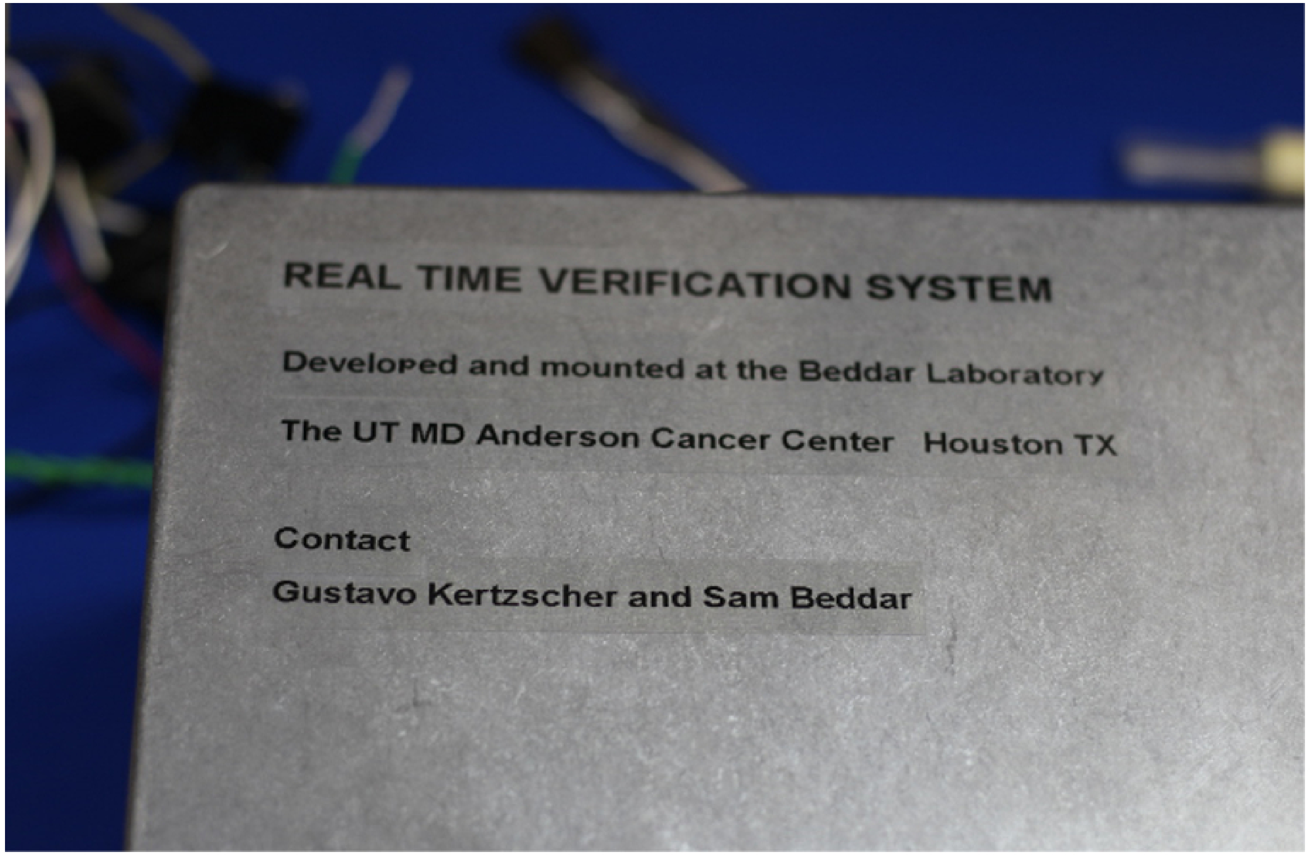
Figure 1. Measured scintillaiton intensities of the inorganic scintillation detectors with respect to BCF-12 based detectors (A) and scintillation intensities for fiber-optic cable lenghts between 0 and 15 m (B).



From… PSDs …to… ISDs

The MDACC in vivo dosimetry & verification system





From... PSDs ...to... ISDs

The MDACC in vivo dosimetry & verification system

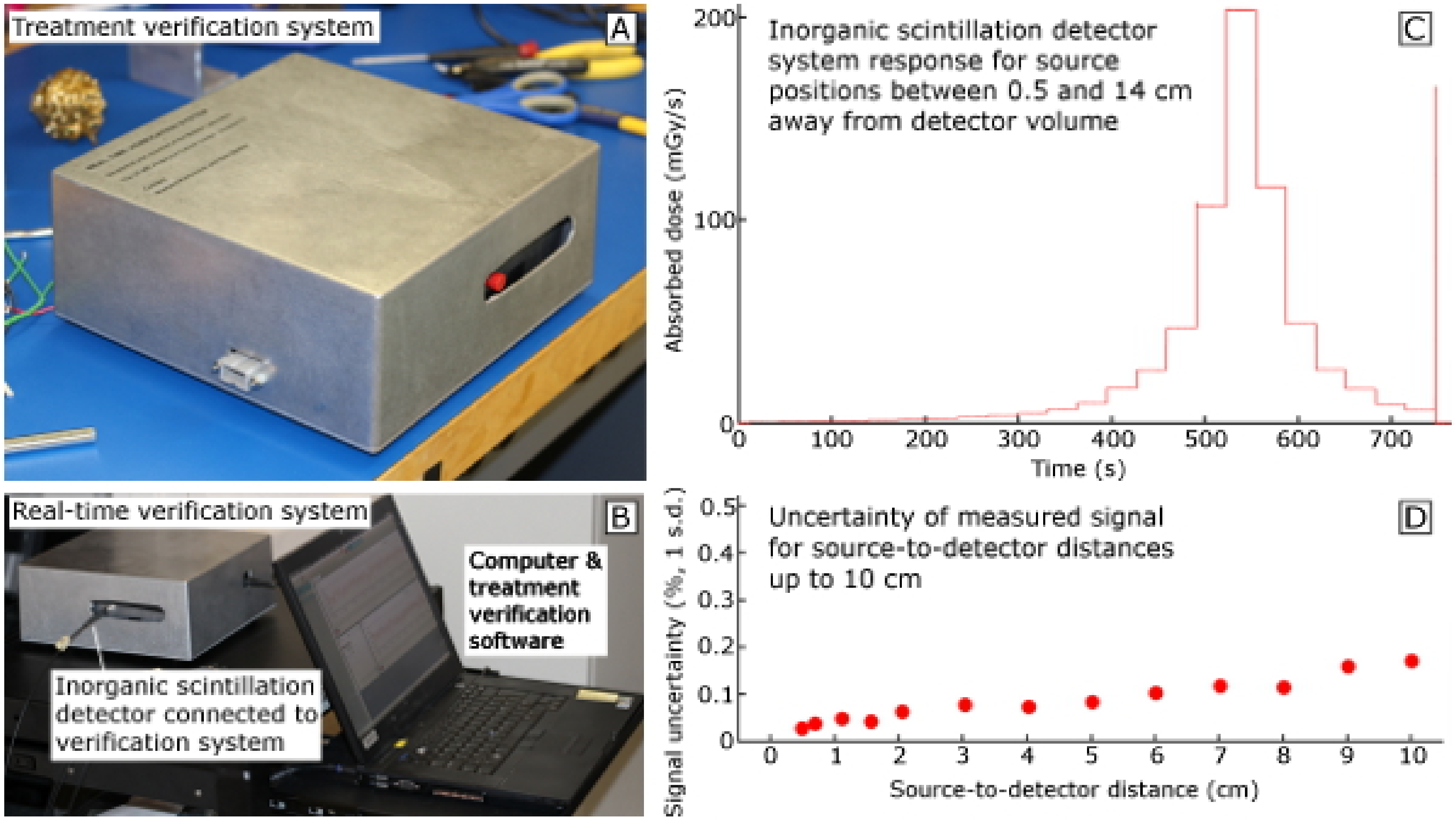


Figure 2. A. Enclosure with instrumentation for new real-time treatment verification system. **B.** Real-time treatment verification system and operating software. **C.** Time-resolved dose rates measured at 20 s^{-1} sample rate with treatment verification system and inorganic scintillation detector. **D.** Measurement uncertainty of 1-second signal accumulation.

Additional Requirements of IVD

- It's not enough for a detector to be just suitable for a specific application: EBRT, Brachytherapy or Protons. We need to push IVD to the next level by focusing on detector systems that would also have these additional properties as well.

✓ Real time feedback
  – Catch errors as they occur and minimize adverse outcomes.

✓ Well integrated with the clinical workflow
  – Too much extra work for therapists or the physicists will discourage adoption.

✓ Invisible to the patient as much as possible

➢ Dose monitoring at multiple locations… Next Phase
  – Line detectors, planar detection, volumetric (???)

Real-time verification during brachytherapy

K. Tanderup, S. Beddar, C. E. Ander herapy”,
Med. Phys. 40(7), 070902 (15 pp.)

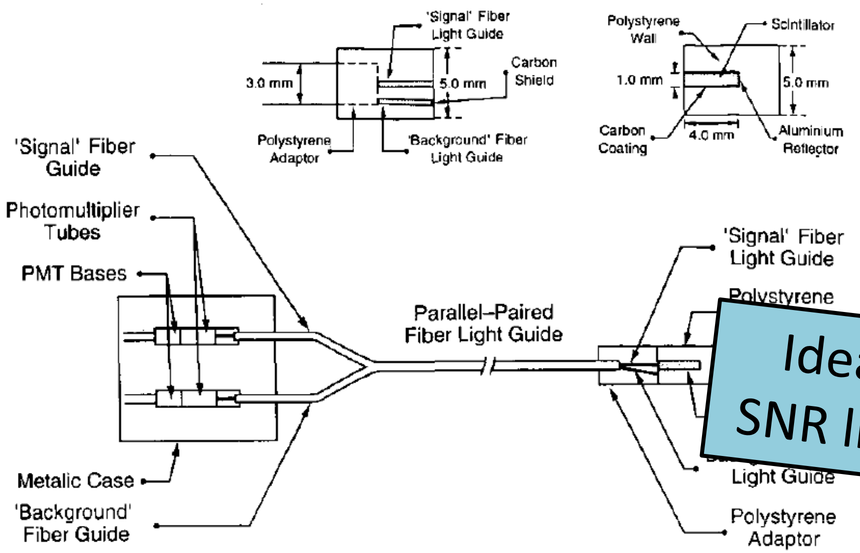
Real-time measurement technology

TABLE III. Characteristics of detectors and dosimetry systems of importance for precise routine IVD in brachytherapy. The items are rated according to: advantageous (++), good (+), and inconvenient (−).

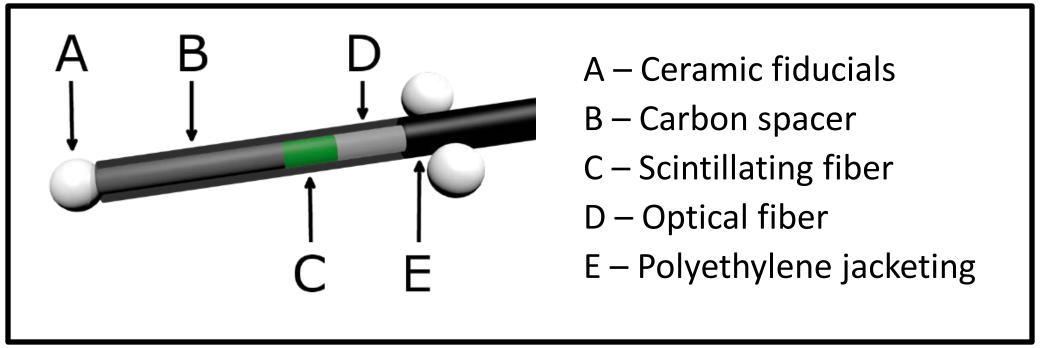
	TLD	Diode	MOSFET	Alanine	RL	PSD	ISD
Size	+	+/−	+/++	−	++	++	++
Sensitivity	+	++	+	−	++	+/++	++
Energy dependence	+	−	−	+	−	++	-
Angular dependence	++	−	+	+	++	++	++
Dynamic range	++	++	+	−	++	++	+/++
Calibration procedures, QA, stability, robustness, size of system, ease of operation	+	++	++	−	−/+	+/++	-/+
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 pendence, ergy pendence
Main disadvantages	Tedious procedures for calibration and readout, not online dosimetry	Ang dep		expensive readout equipment not available in clinics			

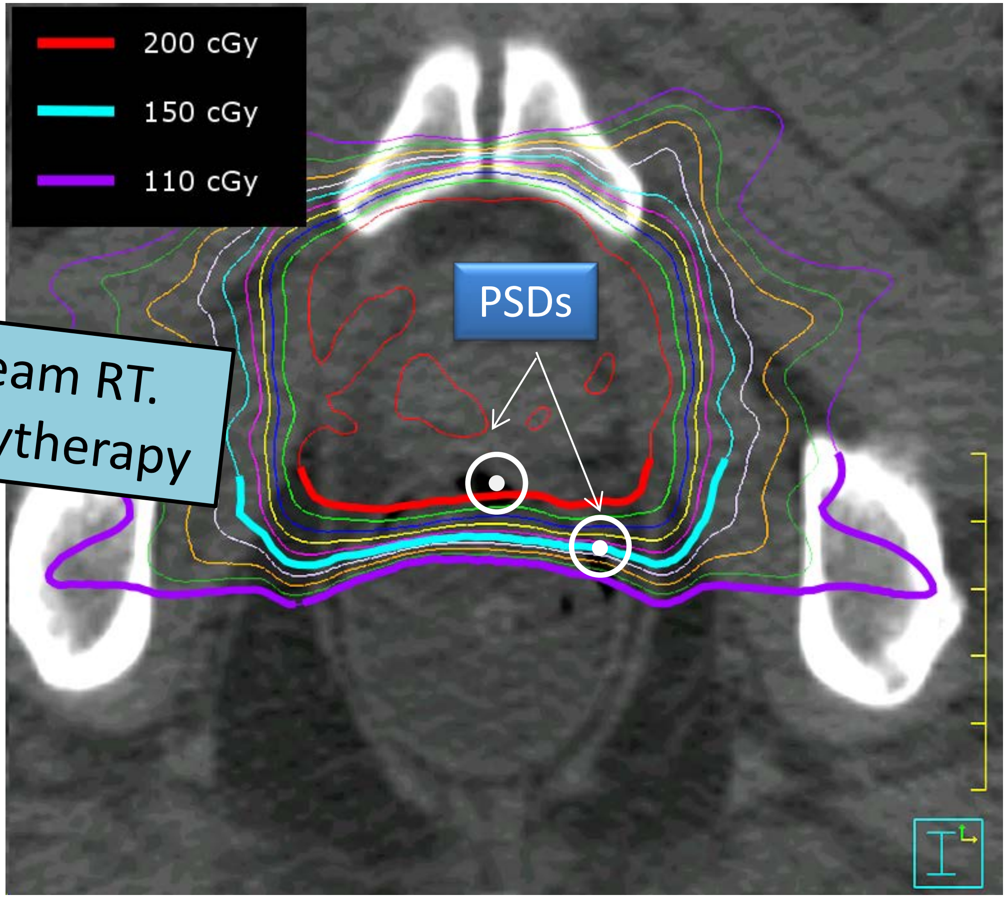
Prompt detection of treatment errors
Can fit inside BT needles (except diodes)
Wide dynamic range

Real-time verification during BT – similar to EBRT



Ideal for external beam RT.
SNR limited for brachytherapy

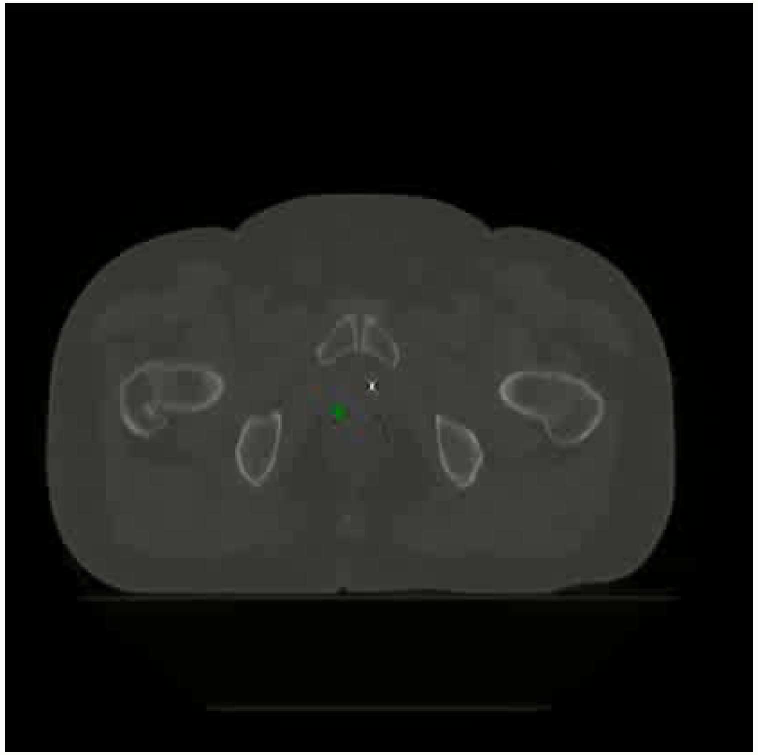


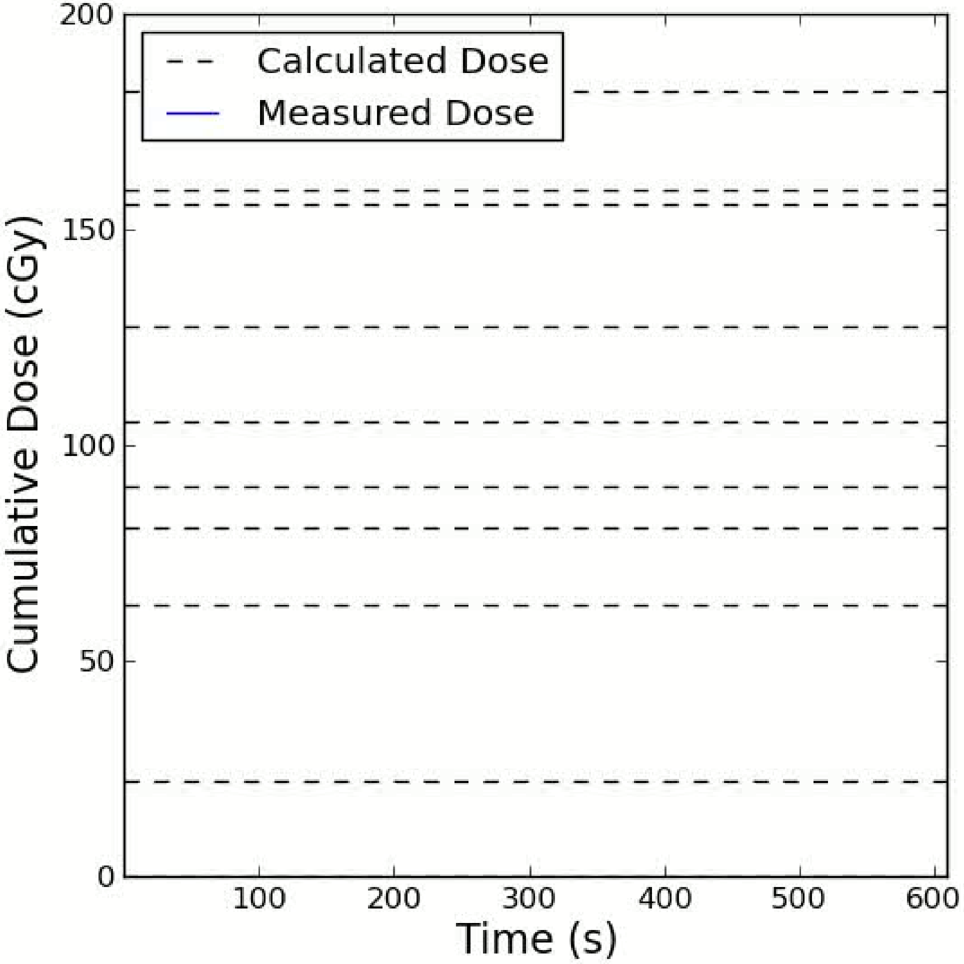


Beddar AS, Mackie TR, Attix FH. ***Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical consideration***. Phys Med Biol 37(10):1883-900, 1992

Wootton L, Kudchadker R, Lee A, Beddar S. ***Real-time in vivo rectal wall dosimetry using plastic scintillation detectors for patients with prostate cancer***. Phys Med Biol 59(3):647-60, 2014

Real-time verification with required "Accuracy"

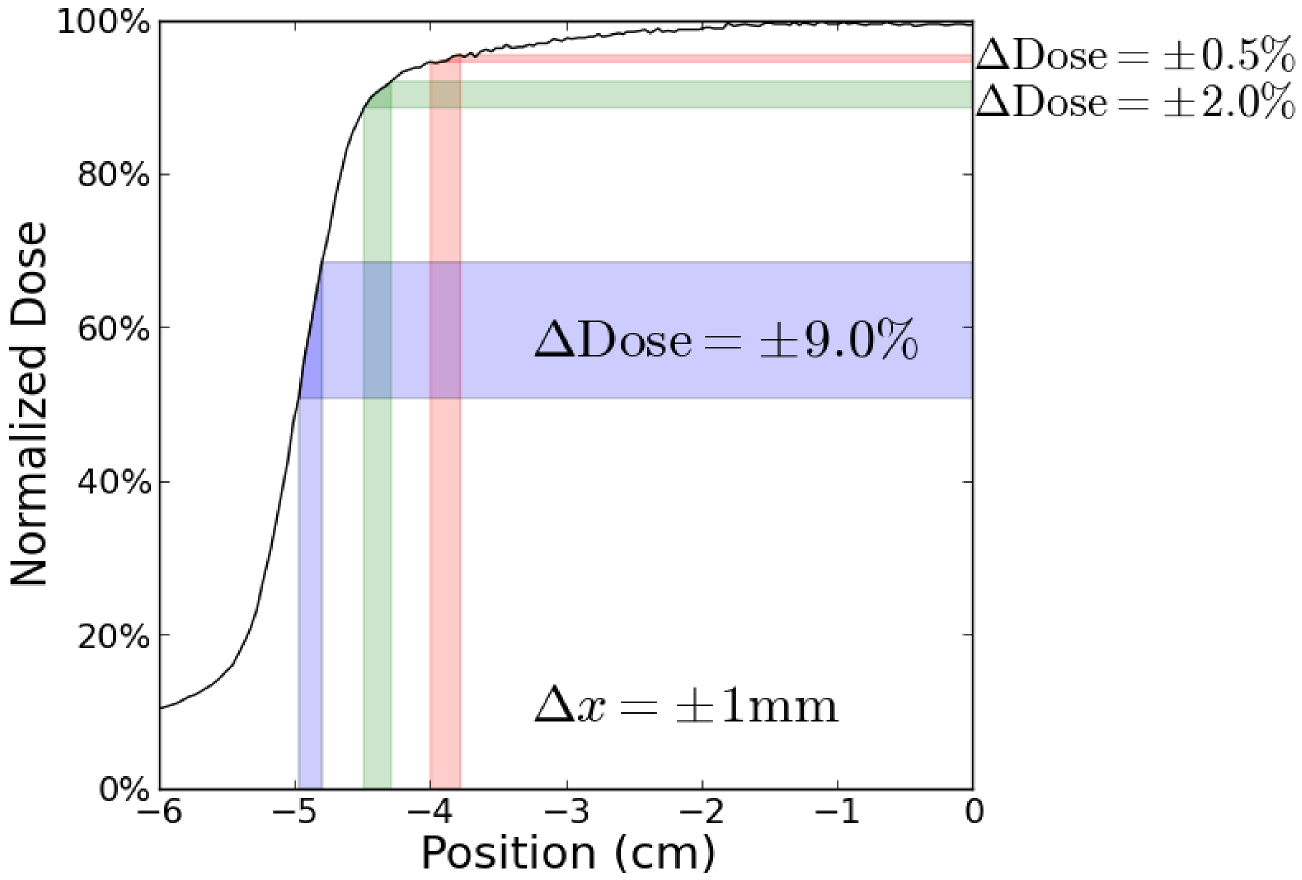




Produced by Landon Wootton

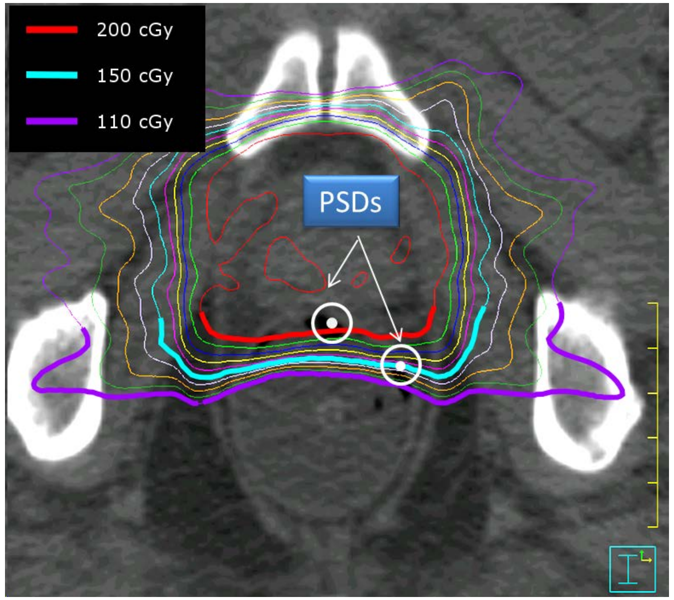
Limitation due to high dose gradients

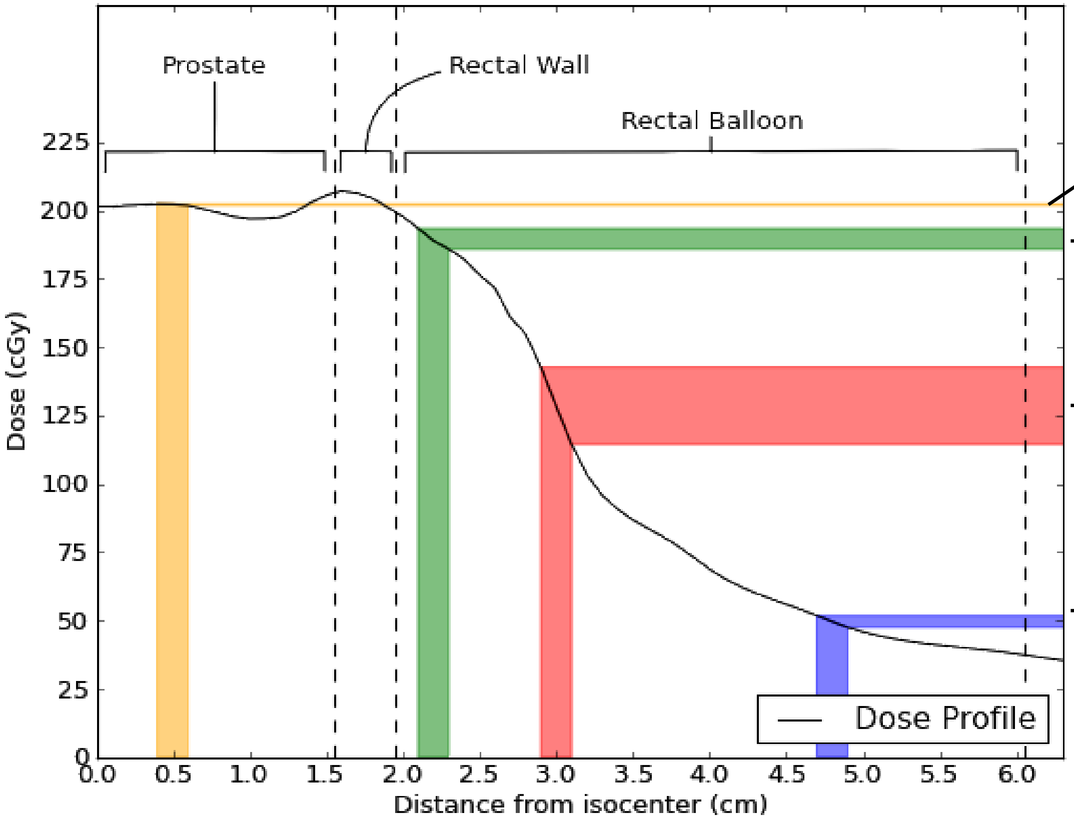
The effect of positional uncertainty on dosimetric uncertainty depends highly on the dose gradient.



Limitation due to high dose gradients: Prostate patient

Uncertainty in expected dose for a detector with a positional uncertainty of ± 1 mm





Uncertainty in Expected Dose

Δ D = ± 0.2%

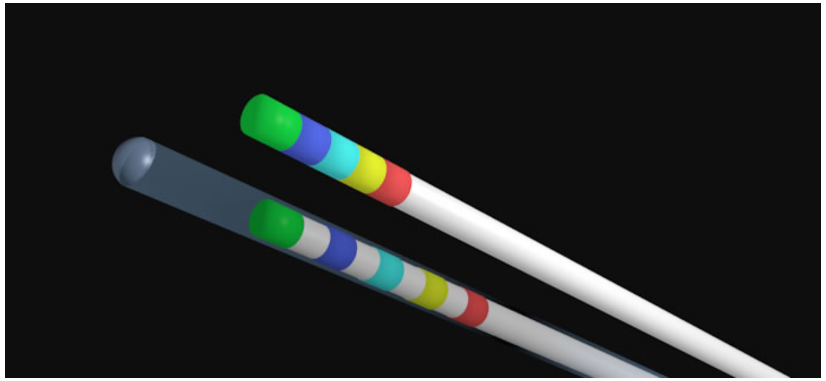
Δ D = ± 2%

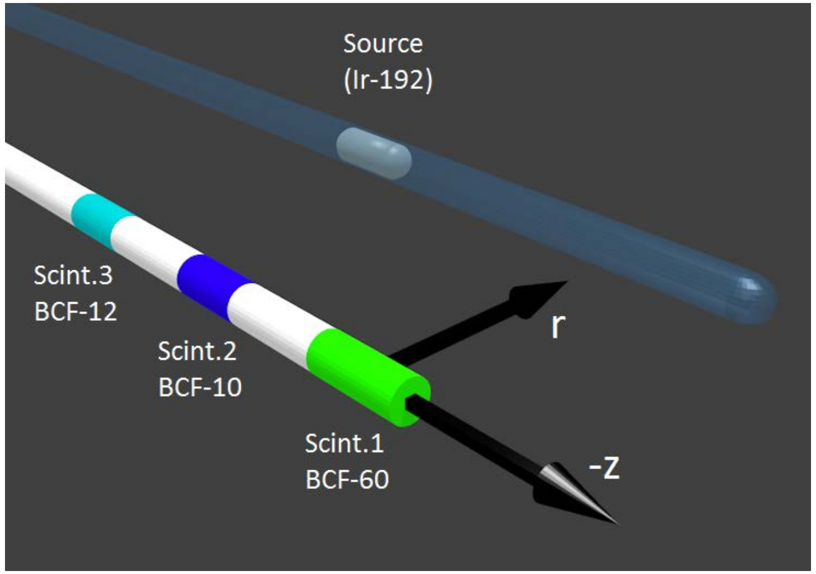
Δ D = ± 11%

Δ D = ± 4%

Patient dose profile taken from isocenter to posterior rectum.

New Detector Technology



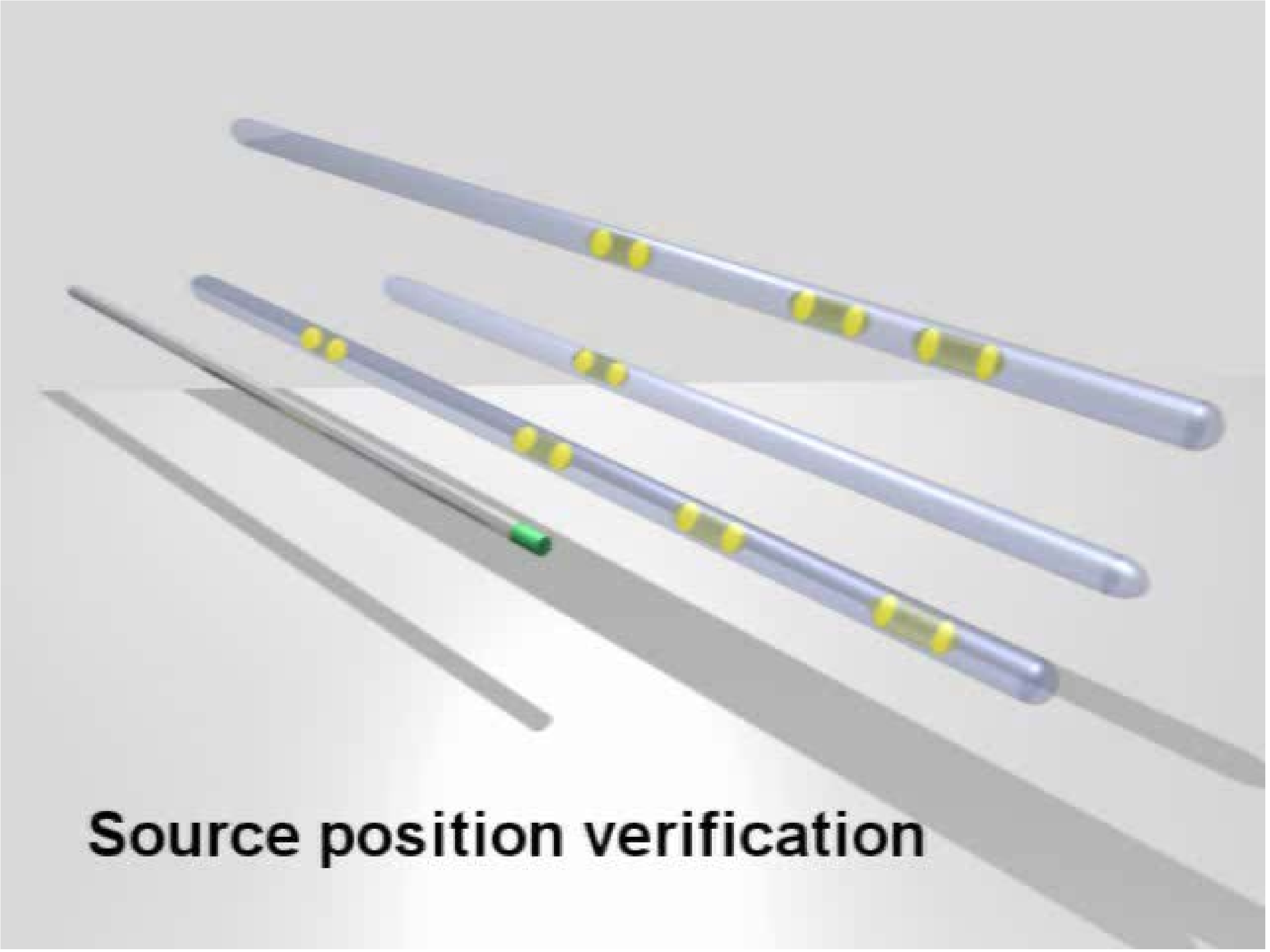


- Multi-point Plastic Scintillation Detector (mPSD)
- Measures dose at multiple points simulteneously with one optical fiber.
- Can track source position during HDR/PDR BT.
- Real time capability.
- Small enough to fit in catheters.

Therriault-Proulx F, Archambault L, Beaulieu L, Beddar S. **Development of a novel multi-point plastic scintillation detector with a single optical transmission line for radiation dose measurement.** Phys. Med. Biol. **57** 7147-7159 (2012)

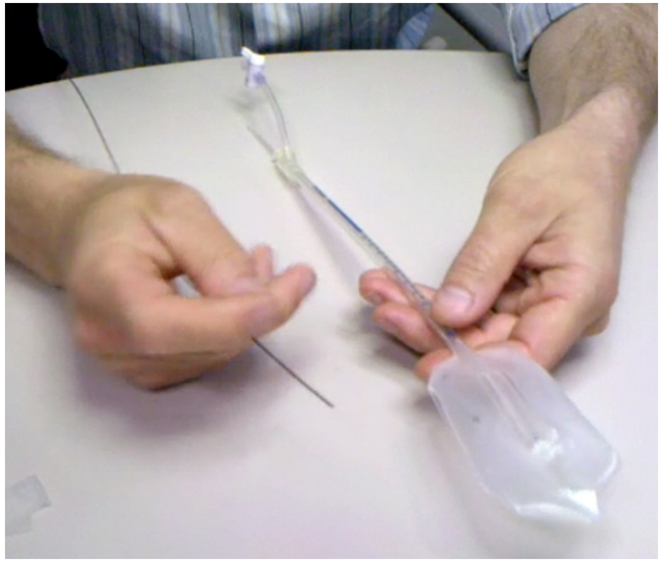
One approach for treatment verification in BT

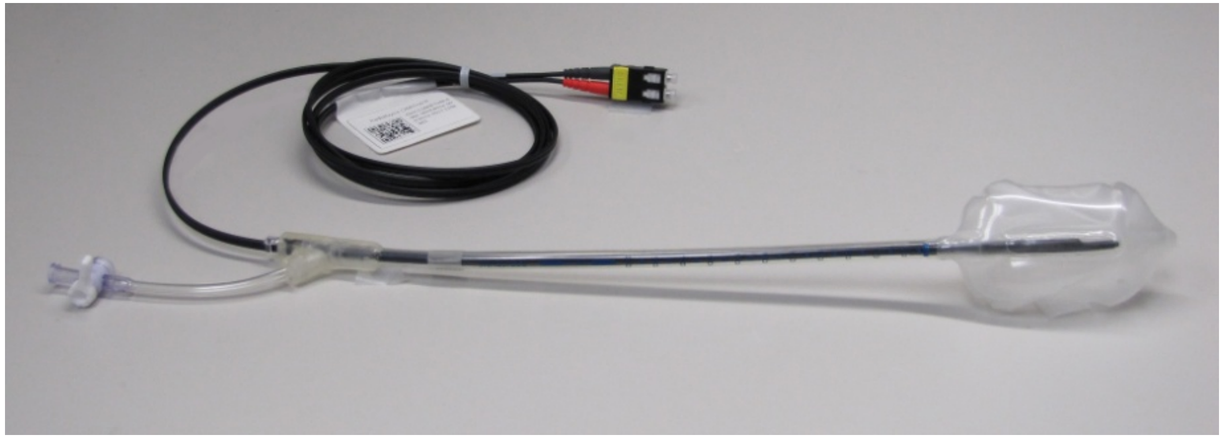
- Verification in **real time**
- **Prompt** error detection
- Identification of:
  - **Systematic** errors caused by delivery systems (i.e. HDR unit)
  - **Random** errors caused by human interventions (i.e. switching transfer tube connections, wrong applicator, etc.)



Produced by Francois Therriault-Proulx

Application specific PSDs or ISDs

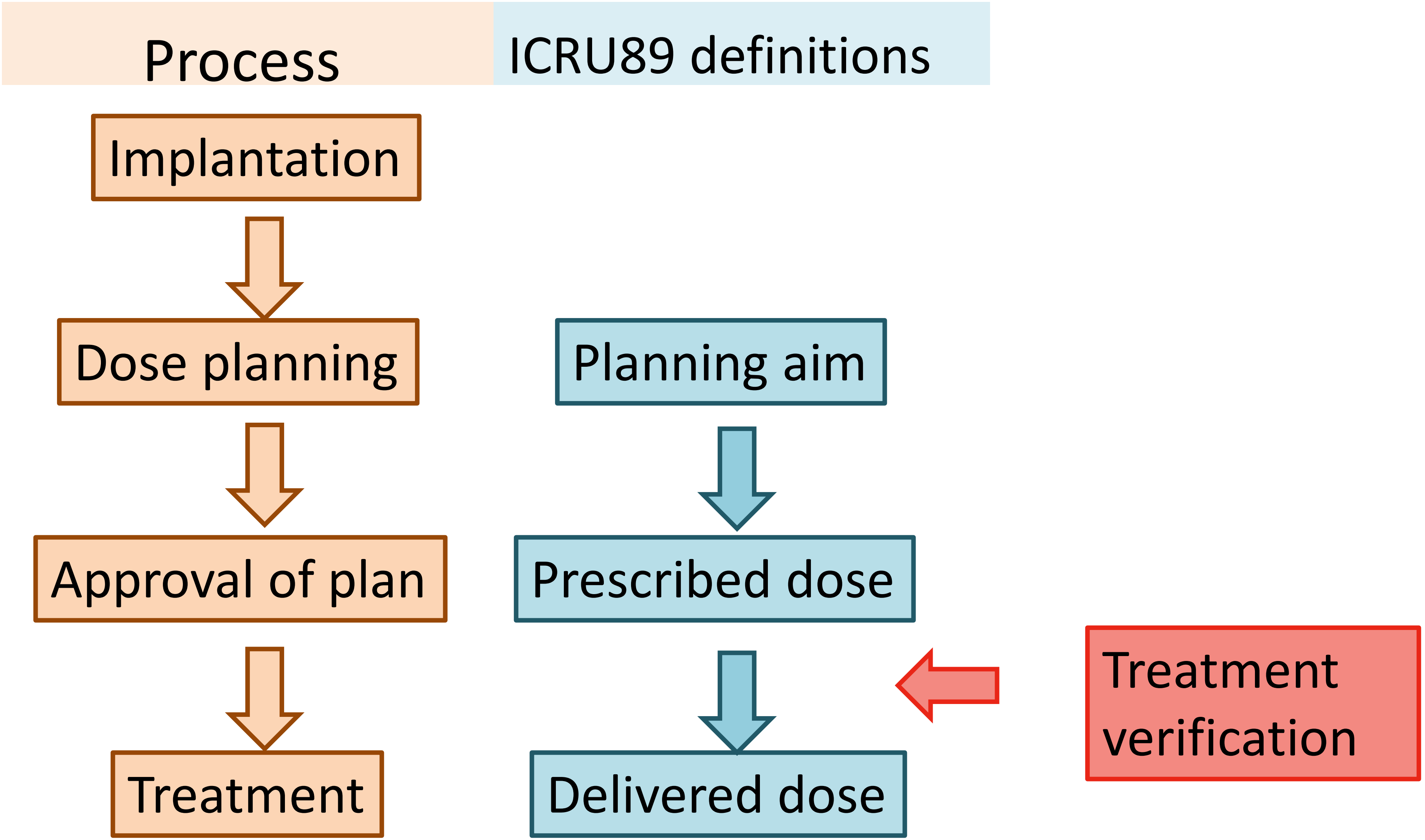




OARtrac System

BRACHYTHERAPY

Planning, prescription and delivery



Which errors happen during BT?
U.S. Nuclear Regulatory Commission reports: 2005-2013

QUALITY ITEM	# Errors	DETECTABILITY	
Nu	)	IVD	IMAGING
So		✓	
Aft		✓	
Aft		✓	
Pa			✓
Co		✓	
Int	1	(✓)	✓
Ap	4	✓	✓
Ap	5	✓	
So		✓	
Int		✓	
Recording of dose		✓	
Other (e.g. defective catheter)	7	?	?

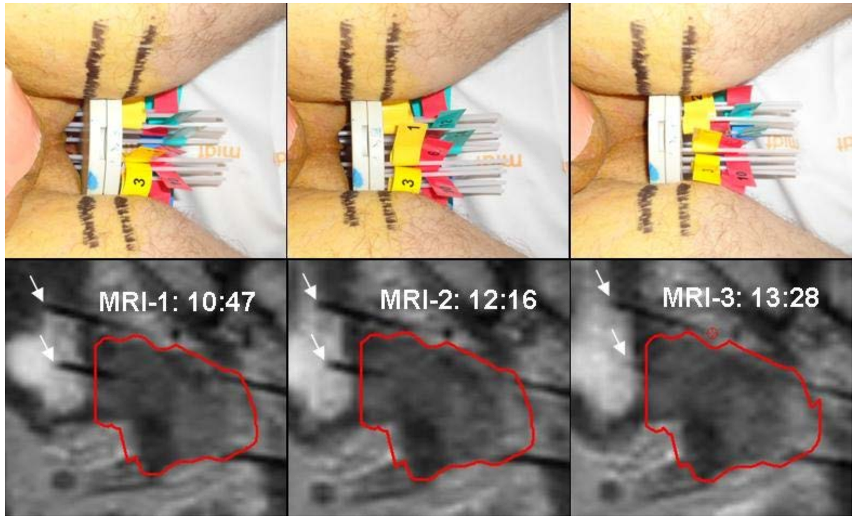
<u>Examples – most (in principle) detectable:</u>

- 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

Dosimetric and geometrical treatment verification

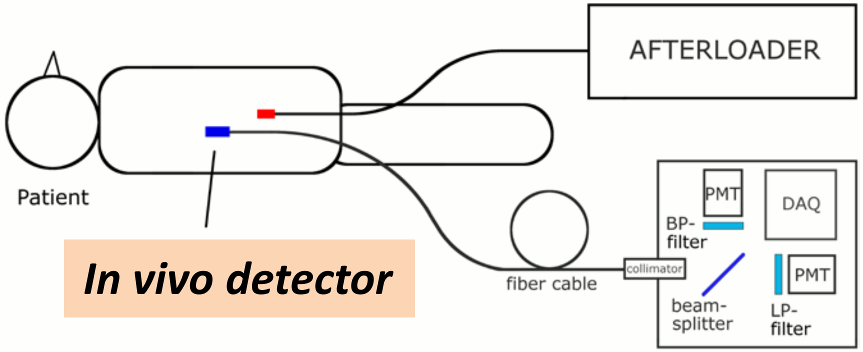
Geometric verification:

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

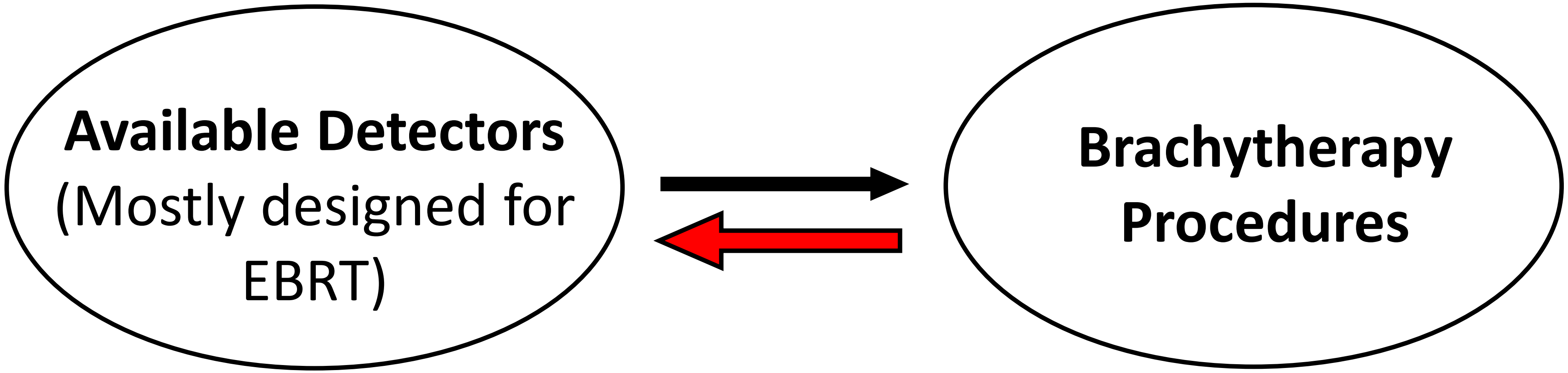


Dosimetric verification:

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



IVD Program Development



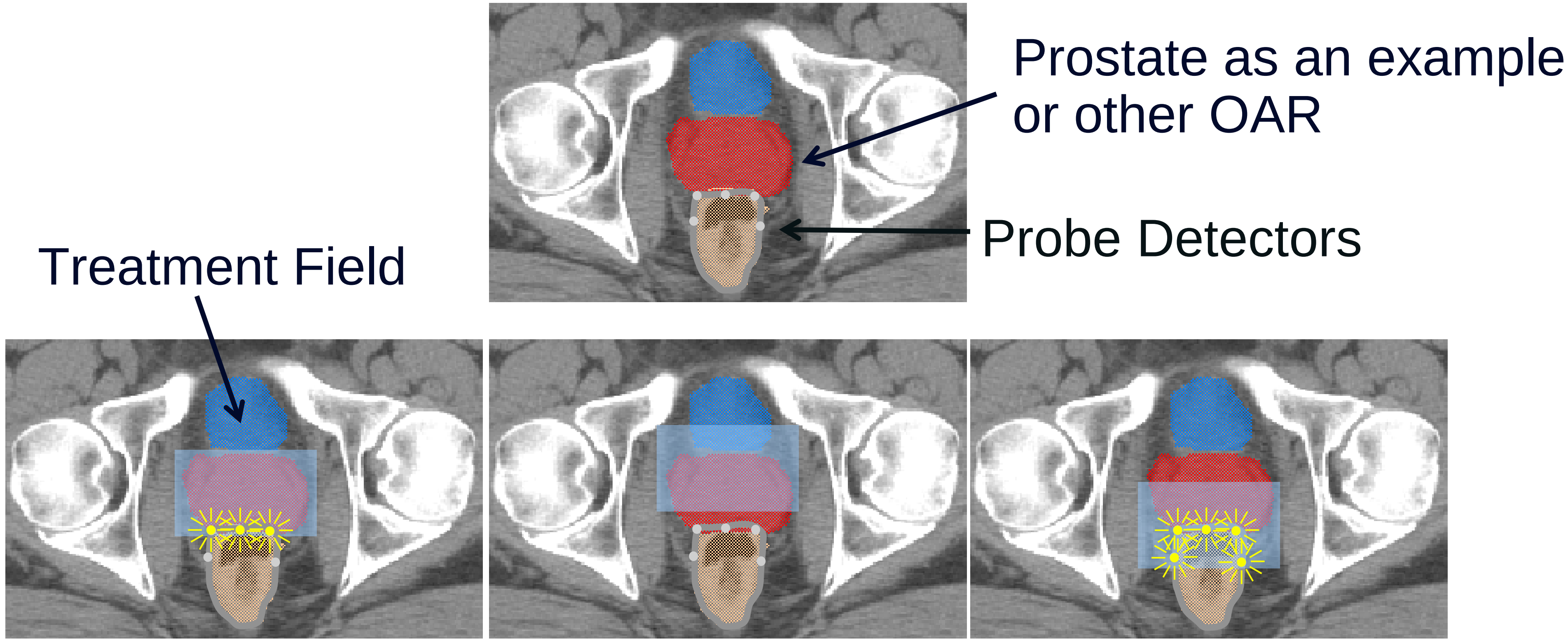
- Currently we apply available detector "as-is" to brachytherapy to perform IVD.
- Instead, the specific requirements of brachytherapy applications should drive detector development.

    HDR? LDR? Prostate Implant? Cervical Cancer?

    What applicators can we use in conjunction with detectors?

- Our goal should be focused on developing IVD systems wholly integrated with the treatment modality and disease site.

Future Direction



Warning system – critical structure in high dose region

⇒ Intervention: Beam off

… More reasons to …

Phantom Results

Comparison between institution's plan and delivered dose.

Phantom	H&N	Liver insert	Lung	Prostate	Spine
Irradiations	1880	143	950	556	308
Pass	1595 (85%)	105 (73%)	784 (82%)	474 (85%)	237 (77%)
Fail	285	38	166	82	71
Criteria	7%/4mm	7%/4mm	5%/5mm	7%/4mm	5%/3mm

IROC™ IMAGING AND RADIATION ONCOLOGY CORE

Global Leaders in Clinical Trial Quality Assurance

Courtesy of David Followill

Conclusion

- In vivo dosimetry is needed:

PERGAMON

ICRP Publication 86

Annals of the ICRP

Prevention of accidental exposures to patients undergoing radiation therapy

ICRP Publication 86
Approved by the Commission in October 2000

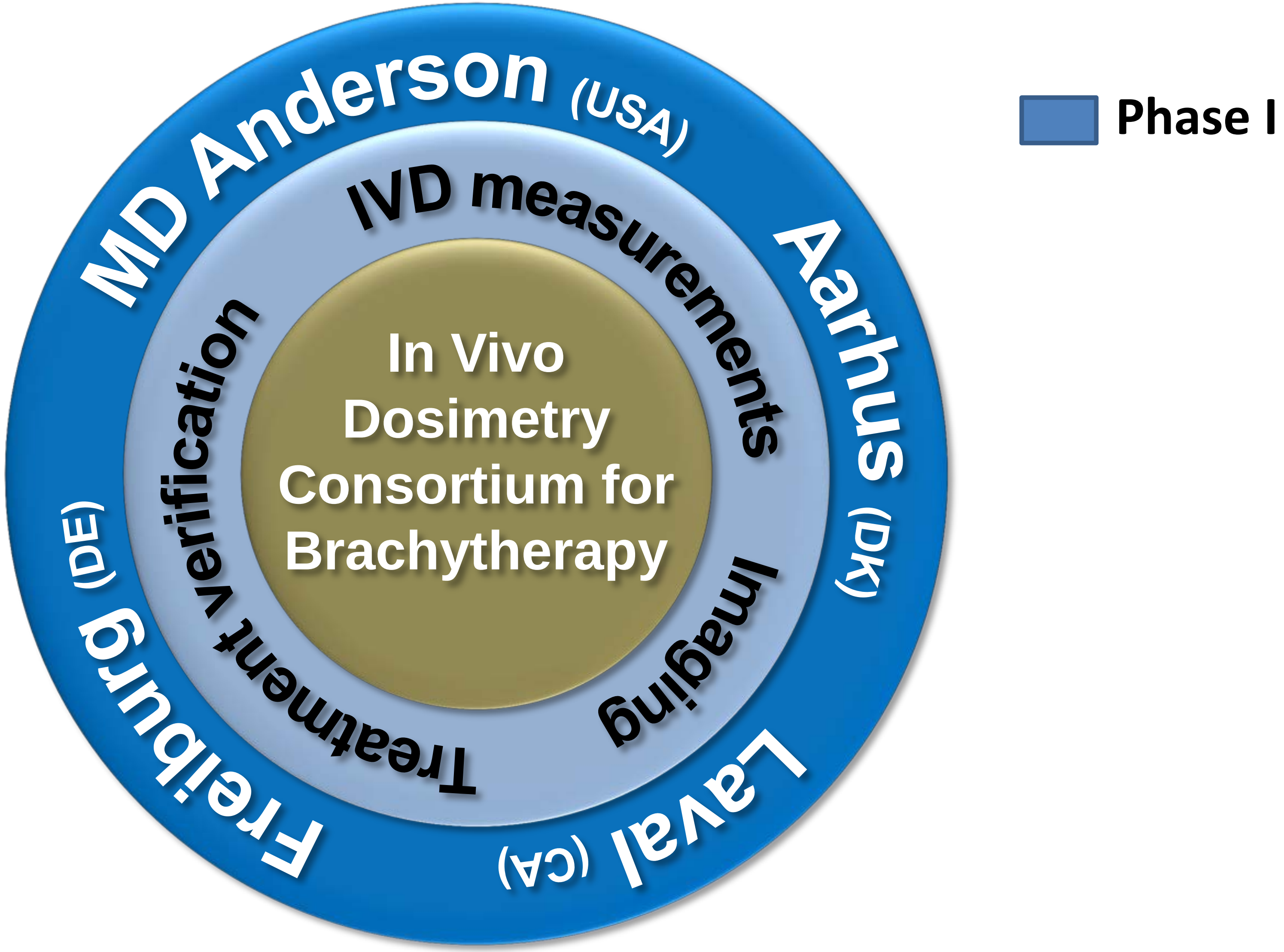
5.7.3. In-vivo dose measurements

(143) Many of the accidents described in this publication could have been avoided if in-vivo measurements had been performed on a selected group of patients. In-vivo measurements (Leunens et al., 1990; Garavaglia et al., 1993; Van Dam and Marinello, 1994) are an effective way of verifying the quality of the entire radiotherapy treatment procedure. The additional cost of in-vivo dosimetry does not require a considerable increase in funding even in a small hospital (Kesteloot et al., 1993). It is an especially valuable investment, but to be effective, it requires careful preparation in terms of equipment, staff training and quality assurance.

(144) Diodes and thermoluminescent dosimeters can be used for in-vivo measurements. It is important to realise that when the detector used for in-vivo dosimetry has been calibrated in the same treatment unit where patients are treated, the results from in-vivo measurements will be correlated with the calibration of the machine and, therefore, will not be able to show a potential error in the calibration of the machine. A correct calibration of the dosimeter is thus an essential necessity.

- Developments of in vivo dosimetry technology must target
  - Real-time feedback and algorithms that identifies error types and facilitate decision making
  - Compatibility with workflow (e.g. straightforward calibration)
  - Software that facilitates straightforward operation of technology

In Vivo Dosimetry Consortium for BT



Conclusion

The role of In Vivo Dosimetry
SHOULD
no longer be ignored

Question 1

Detectors that are capable to provide real-time in vivo dosimetry data include:

- a. MOSFETS, PSDs, OSLDs, TLDs and diodes
- b. MOSFETS, PSDs, EPIDs and radiochromic films
- c. MOSFETS, PSDs, EPIDS and diodes
- d. OSLDs, PSDs, EPIDS and RPLDs
- e. c) and d)

Question 1

Detectors that are capable to provide real-time in vivo dosimetry data include:

- a. MOSFETS, PSDs, OSLDs, TLDs and diodes
- b. MOSFETS, PSDs, EPIDs and radiochromic films
- c. **MOSFETS, PSDs, EPIDS and diodes**
- d. OSLDs, PSDs, EPIDS and RPLDs
- e. c) and d)

Answer: (c)

Reference: Mijnheer B, Beddar S, Izewska J, Reft C. Vision 20/20 Article: In vivo dosimetry in external beam radiotherapy. Med Phys 40(7):070903 (19 pages), 7/2013.

Question 2

The detectors that are advantageous with regards to energy dependence are:

- a. PSDs, MOSFETS, TLDs and diodes
- b. TLDS, MOSFETs and Alanine
- c. PSDs, OSLDs, diodes
- d. PSDs, TLDs and Alanine

Question 2

The detectors that are advantageous with regards to energy dependence are:

- a. PSDs, MOSFETS, TLDs and diodes
- b. TLDS, MOSFETs and Alanine
- c. PSDs, OSLDs, diodes
- d. **PSDs, TLDs and Alanine**

Answer: (d)

Reference: Tanderup K, Beddar S, Andersen CE, Kertzscher G, Cygler JE. Vision 20/20 Article: In Vivo Dosimetry in Brachytherapy. Med Phys 40(7):070902 (15 pages), 7/2013.

Question 3

The effect of the positional uncertainty for an in vivo dosimeter depend highly on their location within the irradiation field and are more important when:

- a. The detector is placed on the surface
- b. The detector is placed within the center of the treated volume
- c. The detector is located in the vicinity of the penumbra
- d. The detector is located in the high dose gradient of the dose distribution
- e. c) and d)

Question 3

The effect of the positional uncertainty for an in vivo dosimeter depend highly on their location within the irradiation field and are more important when:

- a. The detector is placed on the surface
- b. The detector is placed within the center of the treated volume
- c. The detector is located in the vicinity of the penumbra
- d. The detector is located in the high dose gradient of the dose distribution
- e. **c) and d**)

Answer: (e)

Reference: Wootton L, Kudchadker R, Lee A, Beddar S Real-time in vivo rectal wall dosimetry using plastic scintillation detectors for patients with prostate cancer. Phys Med Biol 59 (3) :647-60, 2014.

Question 4

Brachytherapy in vivo dosimetry uncertainties are normally most influenced by:

a) Energy dependence of the detector

b) Temperature dependence of the detector

c) Calibration uncertainties

d) Uncertainty of detector position

Question 4

Brachytherapy in vivo dosimetry uncertainties are normally most influenced by:

a) Energy dependence of the detector
b) Temperature dependence of the detector
c) Calibration uncertainties
d) Uncertainty of detector position

Answer: (d)

Reference: Tanderup K, Beddar S, Andersen CE, Kertzscher G, Cygler JE. Vision 20/20 Article: In Vivo Dosimetry in Brachytherapy. Med Phys 40(7):070902 (15 pages), 7/2013.

Question 5

Which of the following is the most frequent source of errors in brachytherapy:

a) Human errors during treatment planning and patient set-up

b) Afterloader malfunction

c) Failures in treatment planning commissioning

Question 5

Which of the following is the most frequent source of errors in brachytherapy:

a) Human errors during treatment planning and patient set-up

b) Afterloader malfunction

c) Failures in treatment planning commissioning

Answer: (a)

Reference: Reports by the United States Nuclear Regulatory Commission (http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0090/)