Roles of In-Vivo Dose Verification in Radiation Therapy

-- *PHOTON THERAPY* --

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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

of the healthy ti
radiation.

ability of complications or reduced probability of tumour control).

Is there a need for *In Vivo* Dosimetry ?

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POLITICS EDUCATION

June 20, 2009

SIGN IN TO E-MAIL | FEEDBACK

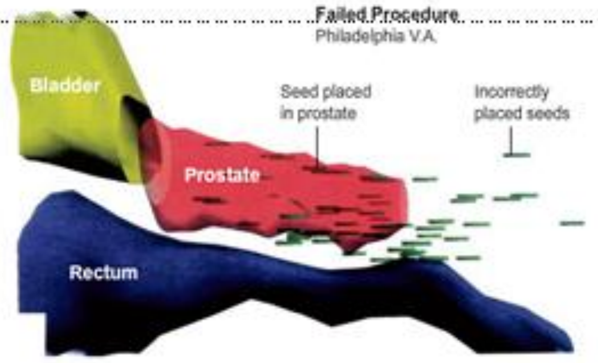
Failed Prostate Procedures at the Philadelphia V.A.

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.

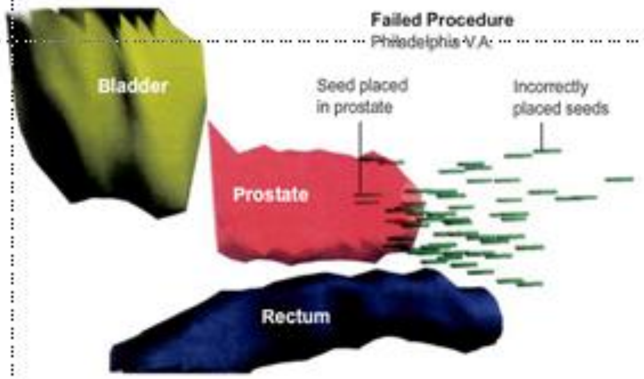
1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | NEXT ▸

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.

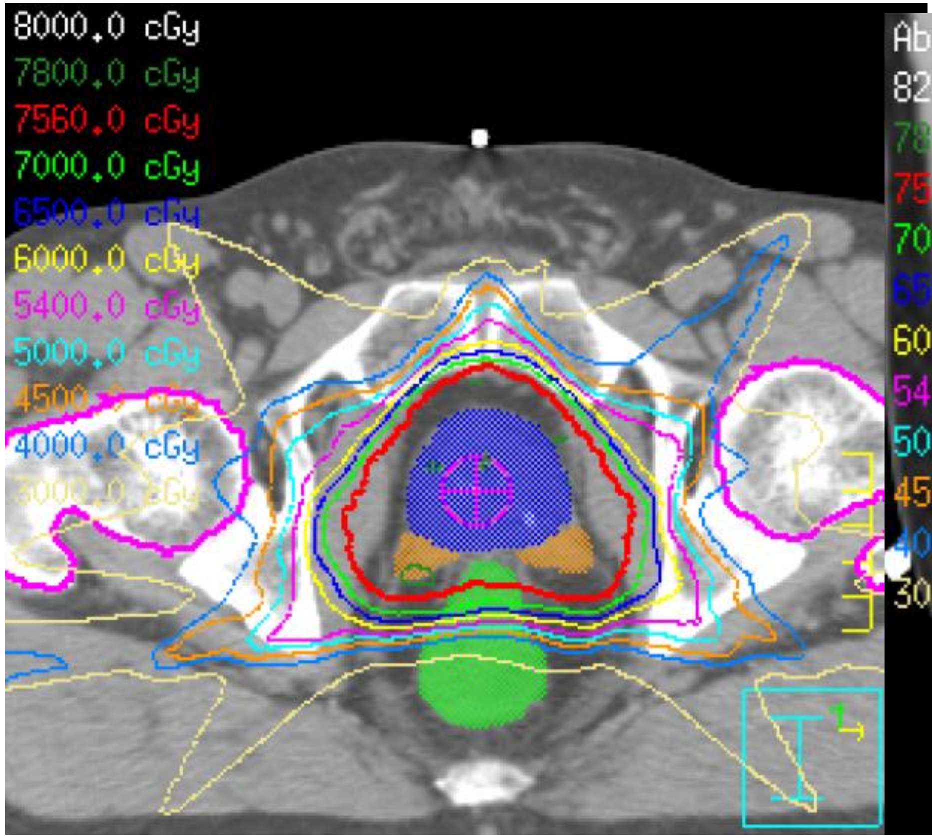


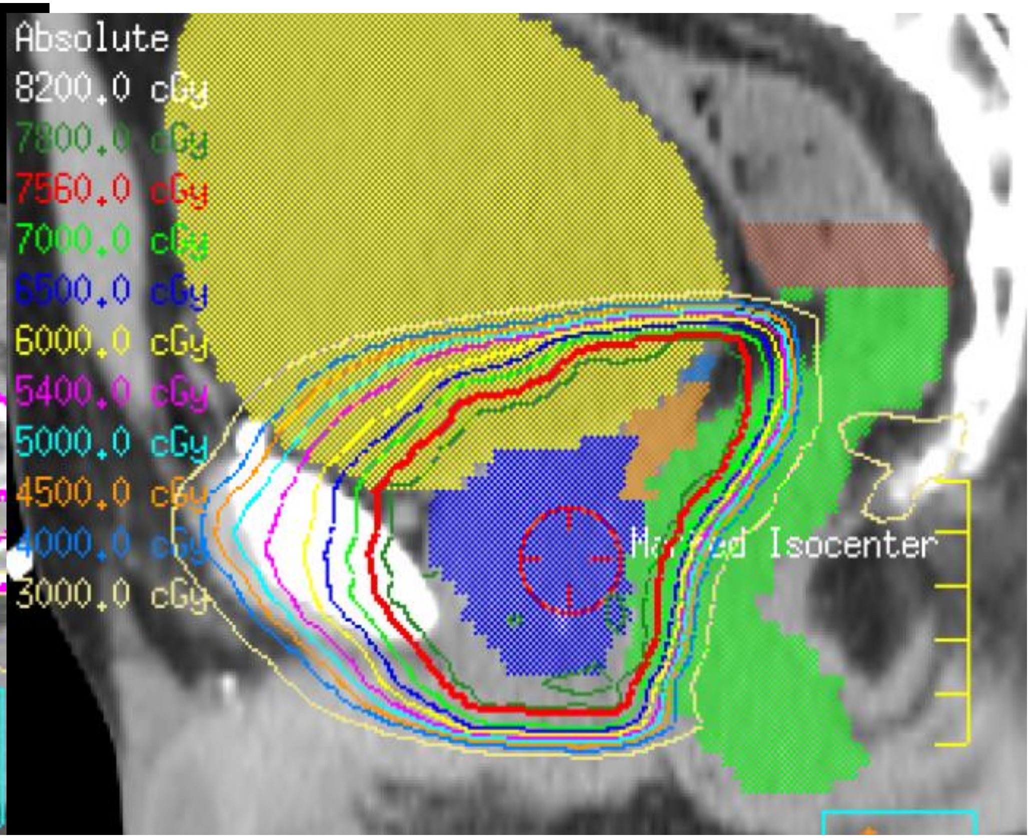
In this case, nearly all of the seeds have been placed outside of the prostate, in the perineum. Of the prescribed dose of 160 gray, the prostate received only 24. This means that the patient's prostate cancer was only minimally treated by the procedure.

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

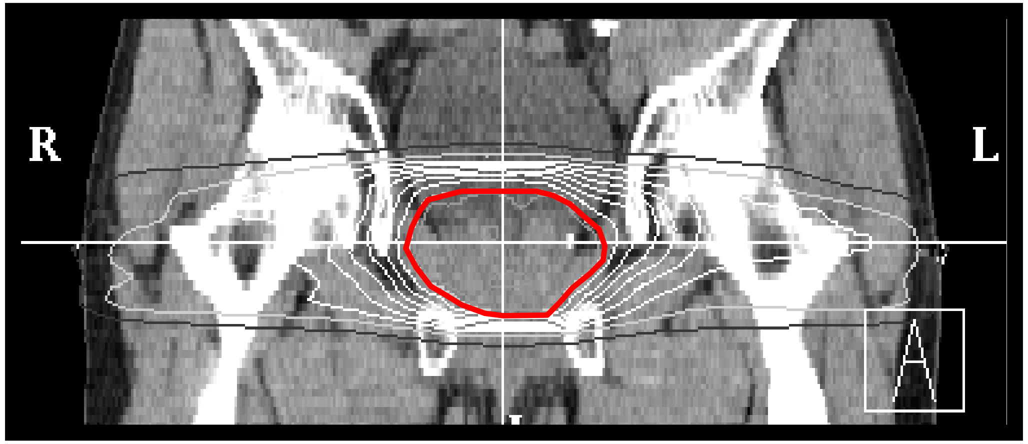
Graham Roberts/The New York Times

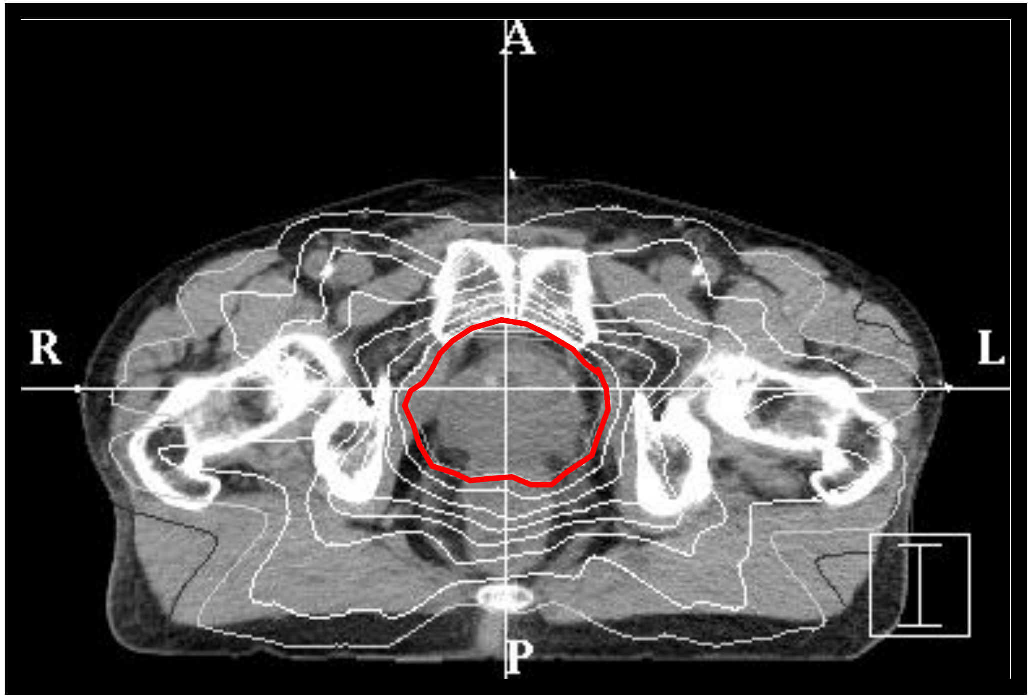
IMRT (8 angles)
Axial and sagittal dose distribution

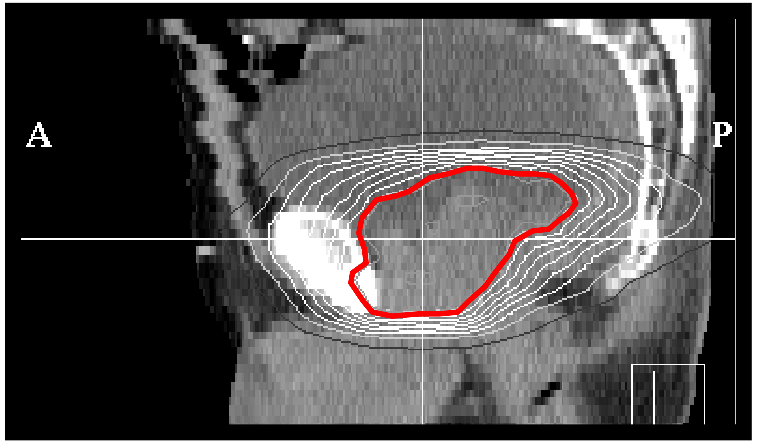




PROSTATE MOTION results in INTER-fraction errors

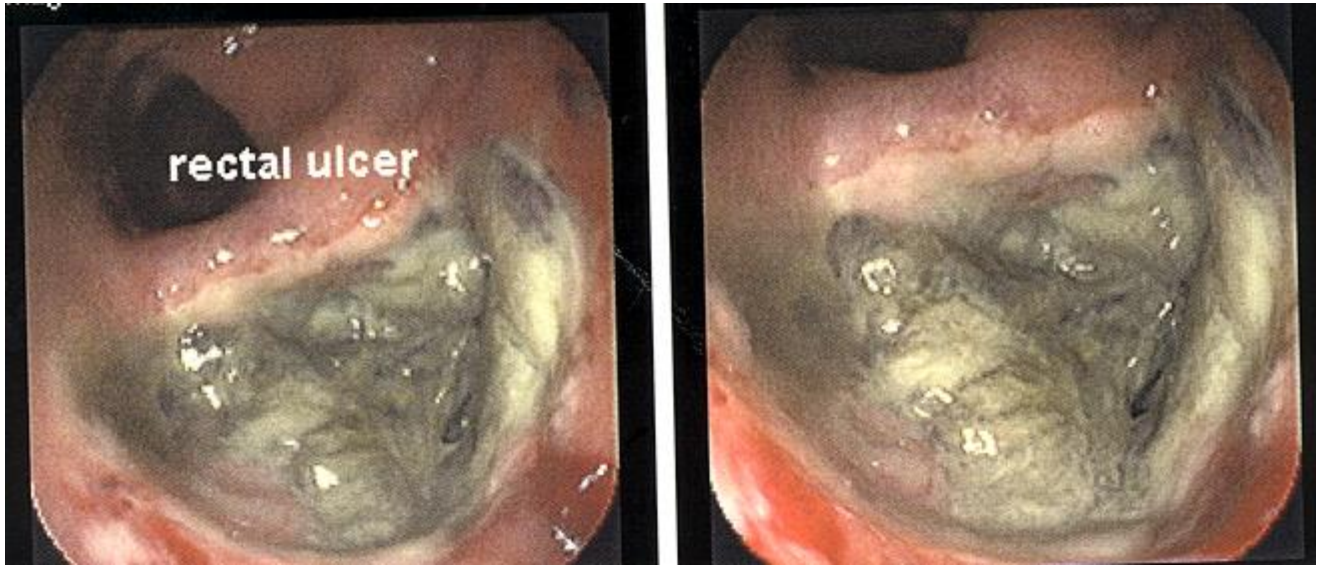






25 treatment CTs acquired during a course of 42 Txs

What we want to avoid

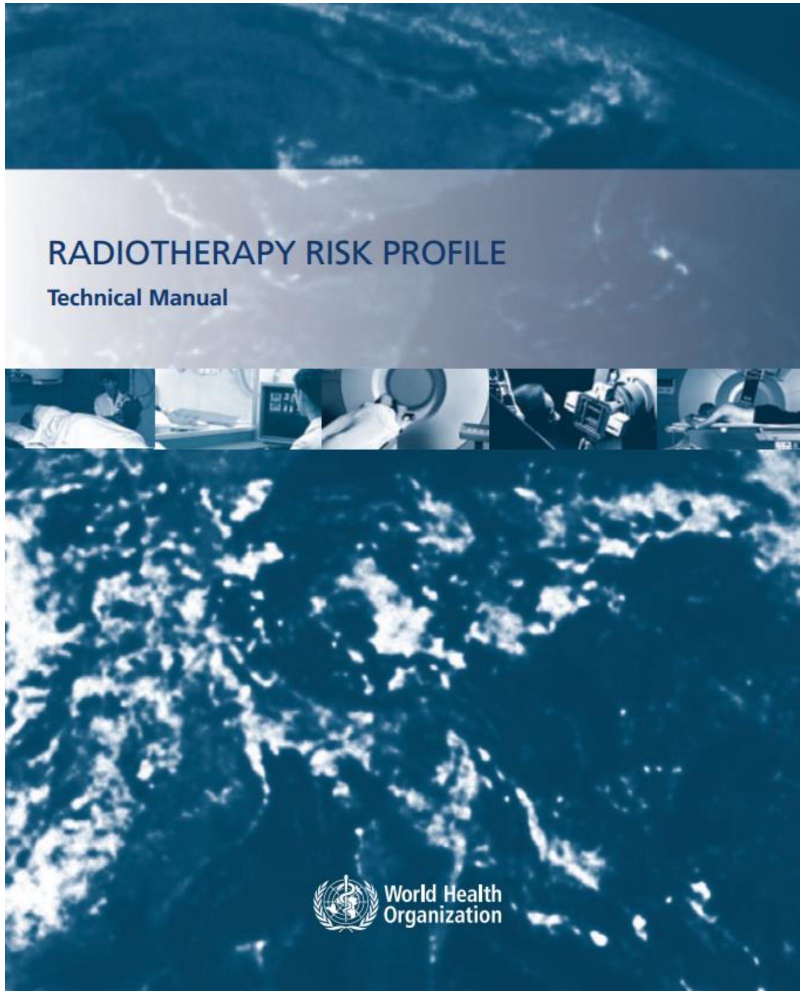


Courtesy of Andrew Lee, M.D.

In Vivo Dosimetry

2008 WHO Report summarized widely reported radiation therapy incidents.

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



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.

State of the Art Detectors

A *quick* highlight of current detectors.

State of the Art Detectors: TLDs

- Skin dose measurement for EBRT and HDR breast implants
- Monitoring implanted devices: Implantable pulse generators or cardioverter defibrillators
- LiF rods are the most commonly used for brachytherapy
- Prostate, urethral and rectal dose measurements in HDR prostate implants

State of the Art Detectors: TLDs

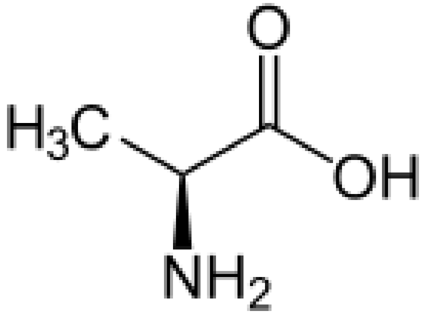
Advantages

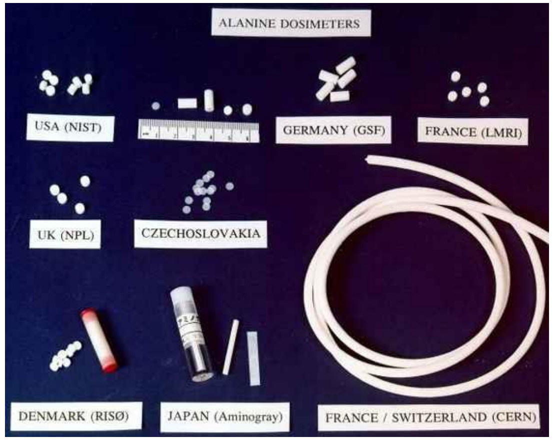
- Different shapes & materials
- No angular dependence
- Not attached to any wire/cable
- Well studied

Disadvantages

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

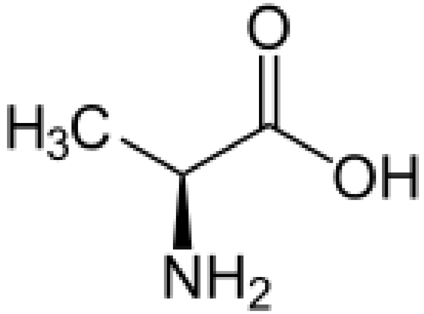
State of the Art Detectors: Alanine

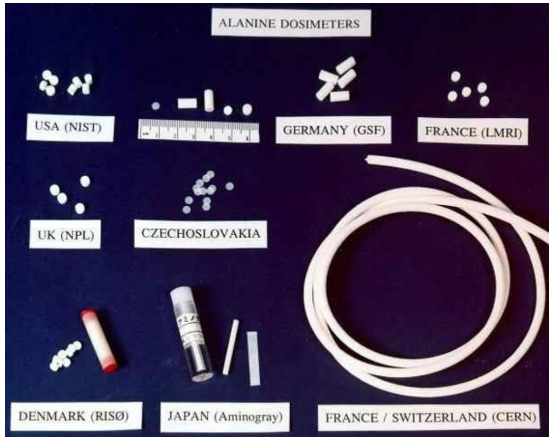




- Chemical detector
- Requires electron paramagnetic resonance (EPR) for read-out
- Few reports on IVD during gynecological treatments

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**

***EPR**: Electron Paramagnetic Resonance*

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 and bladder dosimeters
- Overall uncertainty in phantom of 7-10%

State of the Art Detectors: Diodes

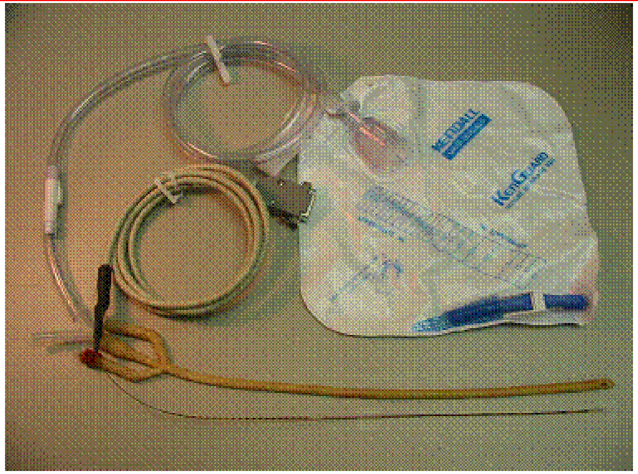
Advantages

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

Disadvantages

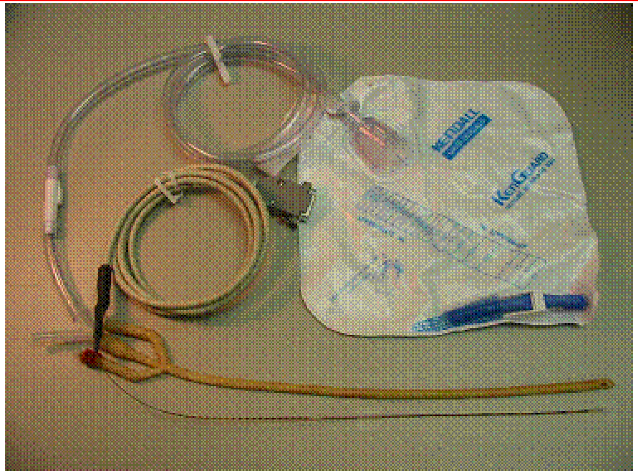
- **Angular dependence**
- **Energy dependence**
- Temperature dependence
- Changes in sensitivity with radiation

State of the Art Detectors: MOSFETs



- Metal-oxide-semiconductor field-effect transistor (MOSFET) based on silicon
- Mostly used for monitoring urethral dose in seeds implant
- Uncertainty of 8%

State of the Art Detectors: MOSFETs



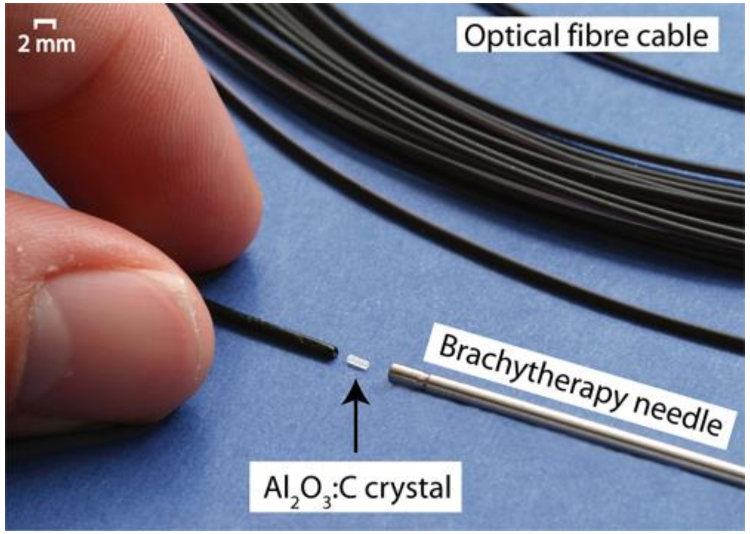
Advantages

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

Disadvantages

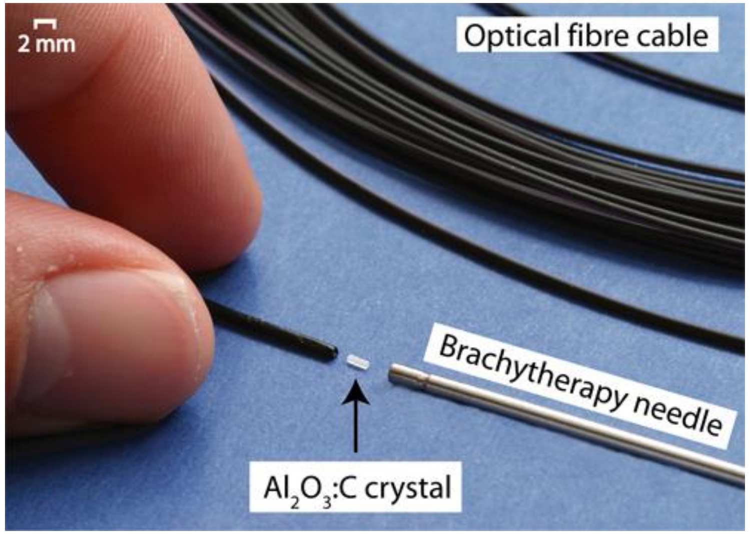
- Not water-equivalent
- **Limited life-time**
- Temperature dependence
- Response degrades with accumulated exposure

State of the Art Detectors: RL/OSLDs



- Generally composed of Al_2O_3:C
- RL: Radoluminescence
- *Previously used also as RL/OSLD: Optically stimulated luminescence dosimeter*
- Prevention and identification of dose delivery errors in cervix, gynecological and prostate HDR and PDR brachytherapy
- Potential to detect interchanged guide tube errors and source mispositioning

State of the Art Detectors: RL/OSLDs



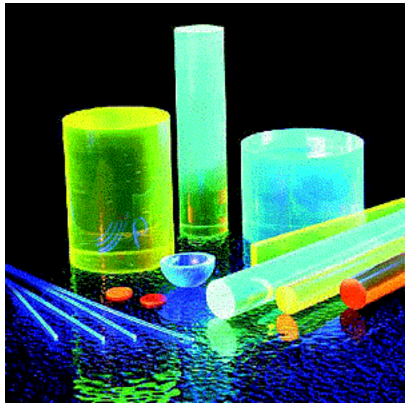
Advantages

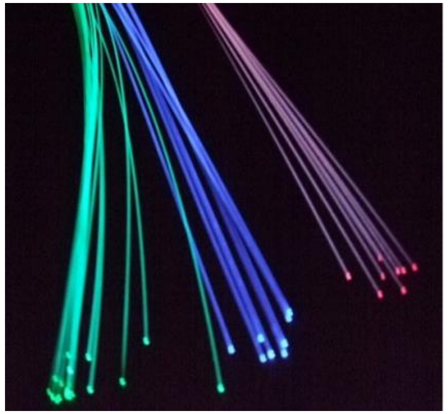
- Small size
- RL feedback in real-time
- Passive/active detector
- Good reproducibility (1.3%)

Disadvantages

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

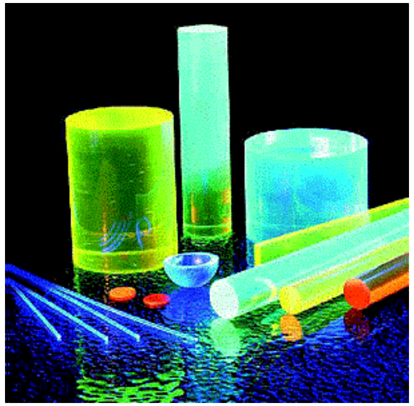
State of the Art Detectors: PSDs

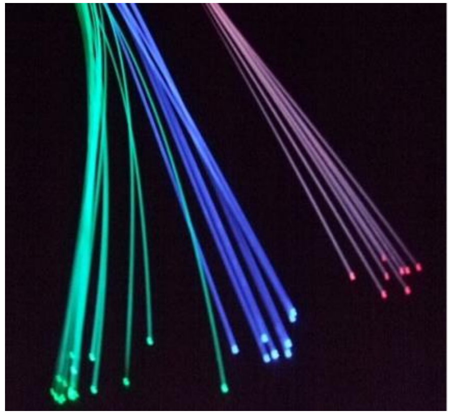




- PSD: Plastic scintillation detector made of polystyrene, PVT or PMMA
- Coupled to an optical fiber, the stem effect has to be subtracted
- Phantom studies showed excellent dose measurement accuracy

State of the Art Detectors: PSDs





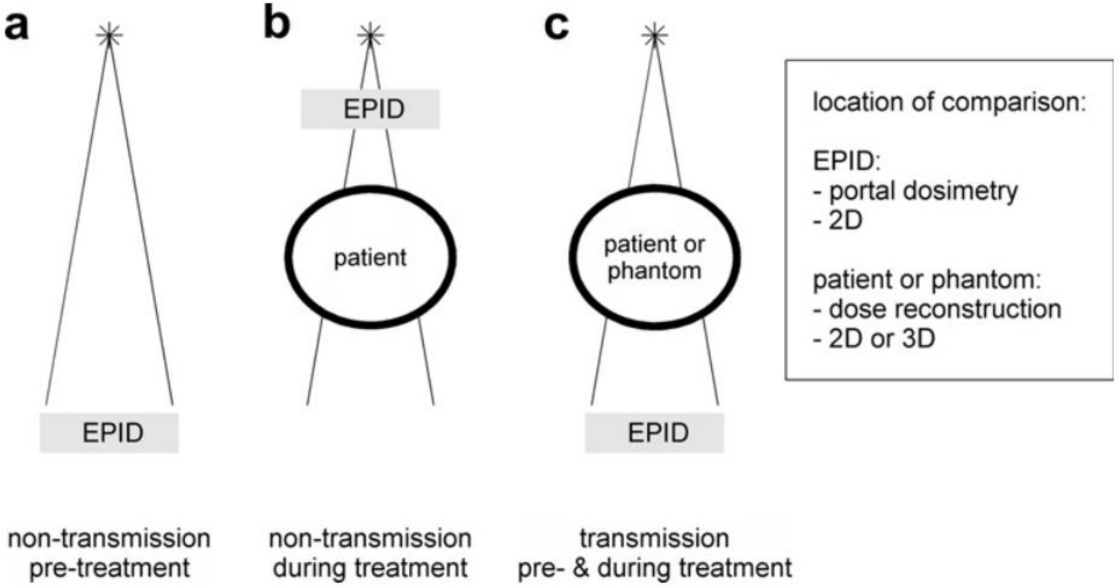
Advantages

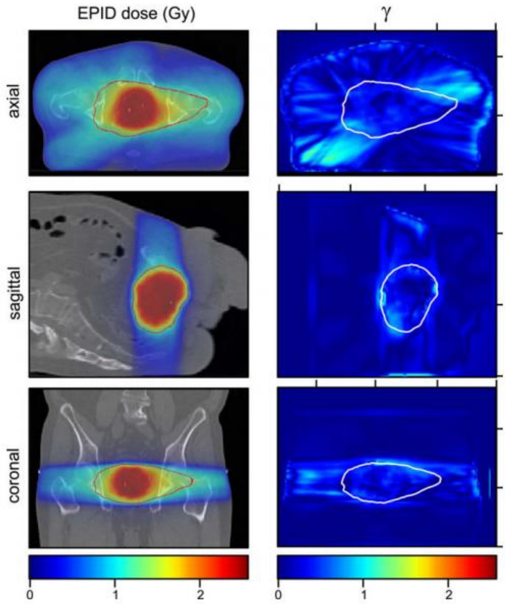
- Linearity to dose/dose-rate
- Small size
- Energy independence
- Water-equivalence
- No angular dependence
- Real-time dosimetry
- New commercial detectors are emerging

Disadvantages

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

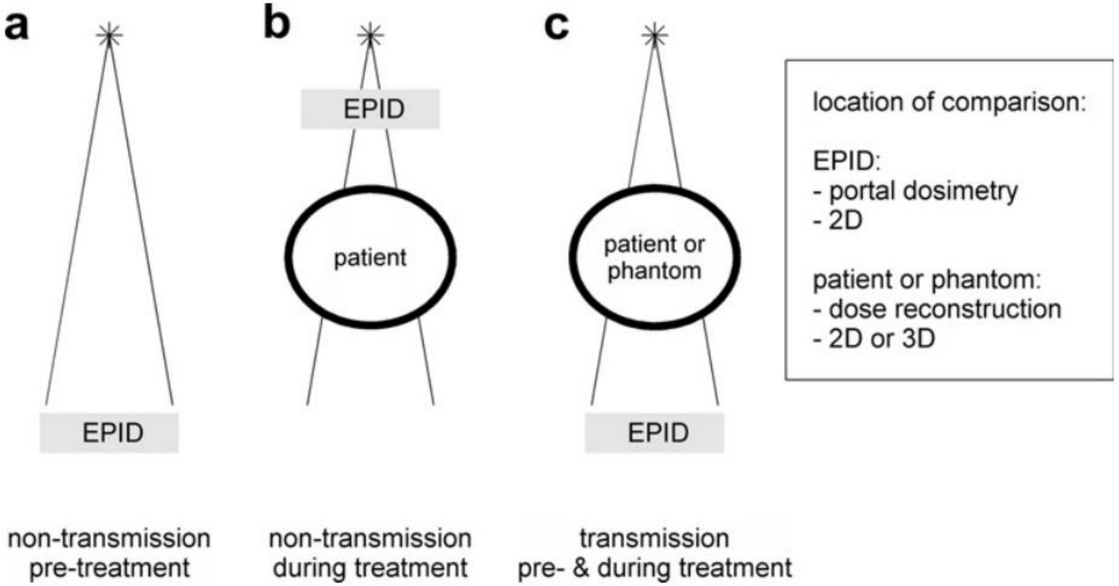
State of the Art Detectors: EPIDs

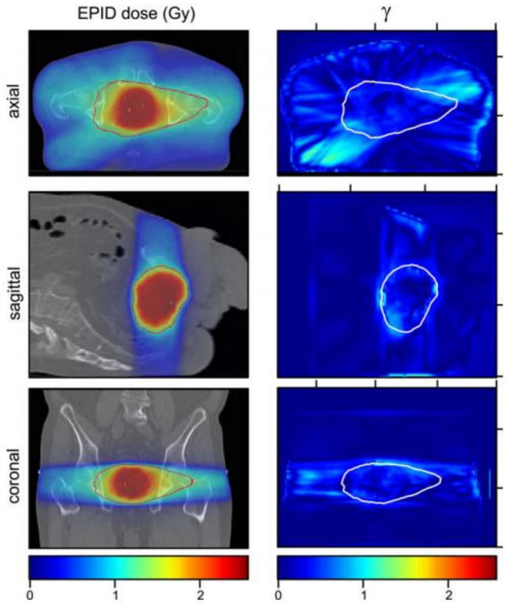




- EPIDs: Electronic portal imaging devices – flat panel detector commonly based on amorphous silicon photodiode technology
- Developed for acquiring megavoltage portal images during treatments, mainly for determining setup errors
- Back-projection models have been used to reconstruct 3D dose distributions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

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
  - Line detectors, planar detection, volumetric (???)

In vivo dosimetry in external beam radiotherapy

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(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

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(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. © *2013 American Association of Physicists in Medicine*. [http://dx.doi.org/10.1118/1.4810943]

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

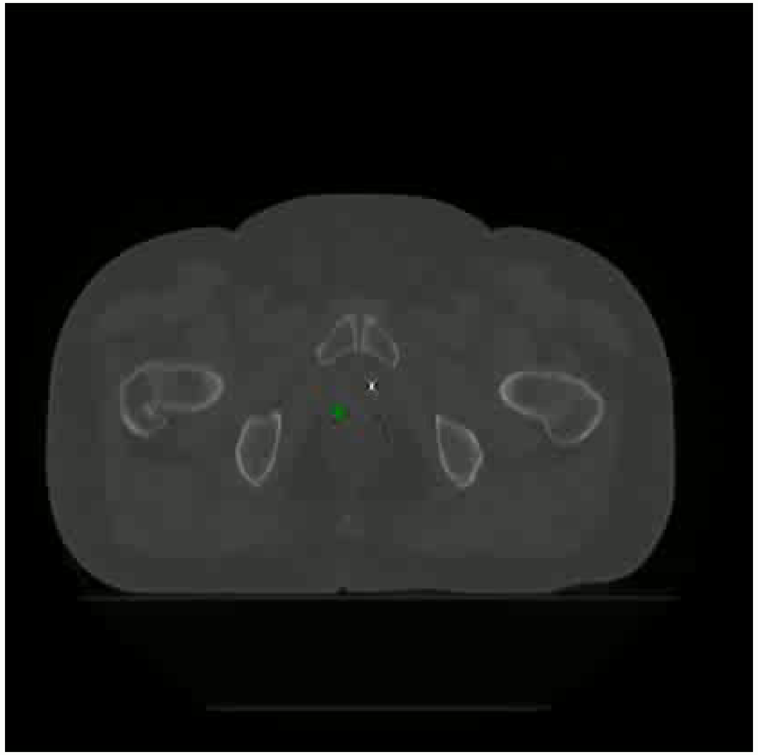
Real-time IVD systems with a future in EBRT or BT

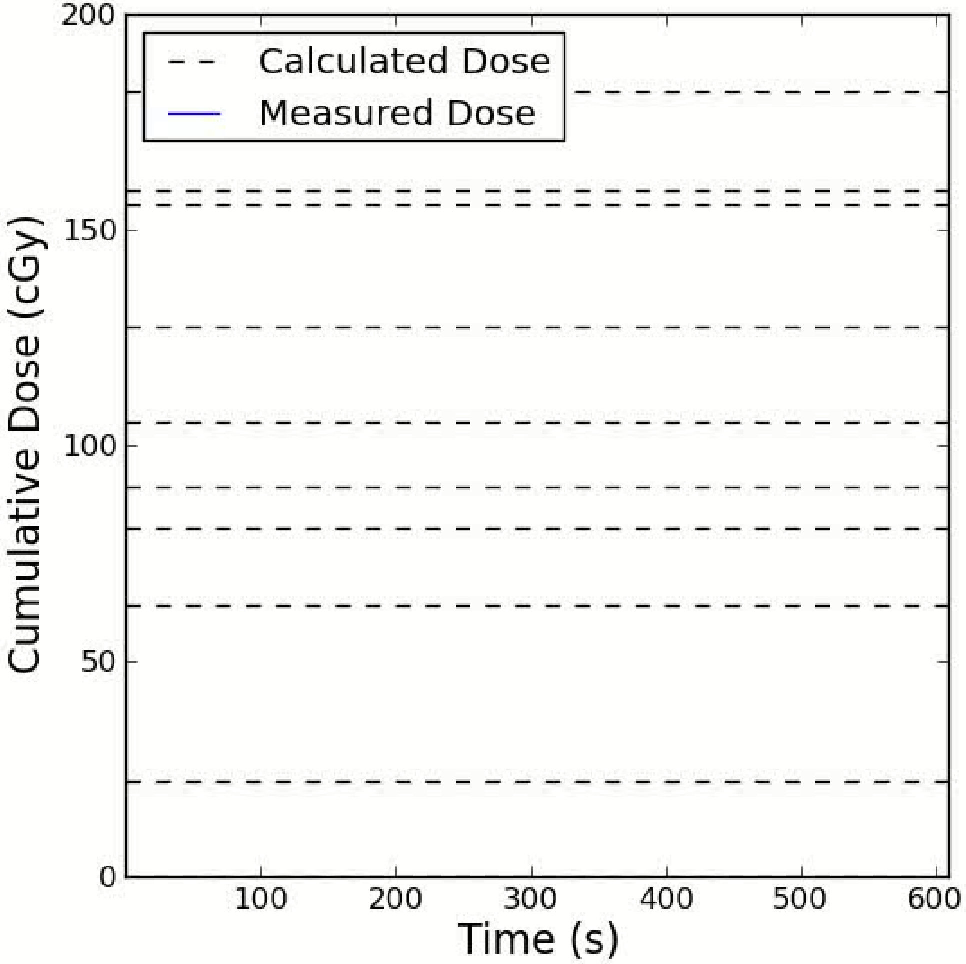
The items are rated according to good/adequate (+) and inconvenient (-)

Properties	MOSFET	RL	PSD	EPID
Size/positional resolution	+	+	+	+
Sensitivity to dose	+	+	+	+
Energy dependence	-	-	+	-
Angular/off-axis dependence	+	+	+	-
Online dosimetry	+	+	+	+
Main advantages	▪ Small size ▪ Commercial system at reasonable prize	▪ Small size ▪ High sensitivity	▪ Small size ▪ No angular dependence ▪ No energy dependence	▪ 2D and 3D dose distributions ▪ Permanent record
Main disadvantages	▪ Limited life ▪ Energy dependence	▪ Stem effect ▪ Needs frequent calibration ▪ Not commercially available	▪ Stem effect	▪ Cost ▪ Limited availability of commercial software

Adapted from Vision 20/20 by Kari Tanderup *et al., Med Phys, 2013, and Mijnher et al., Med Phys, 2013*

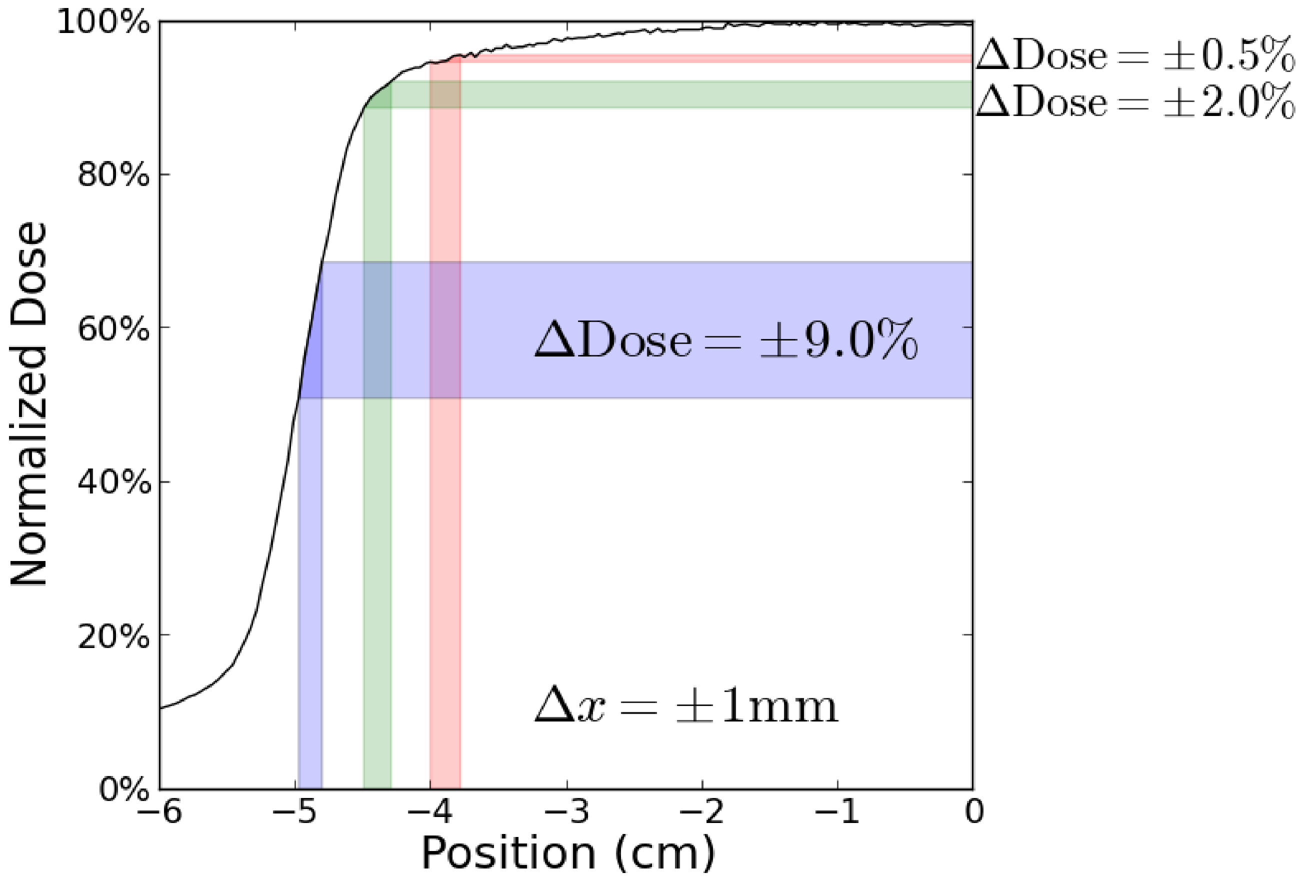
Real-time Accuracy



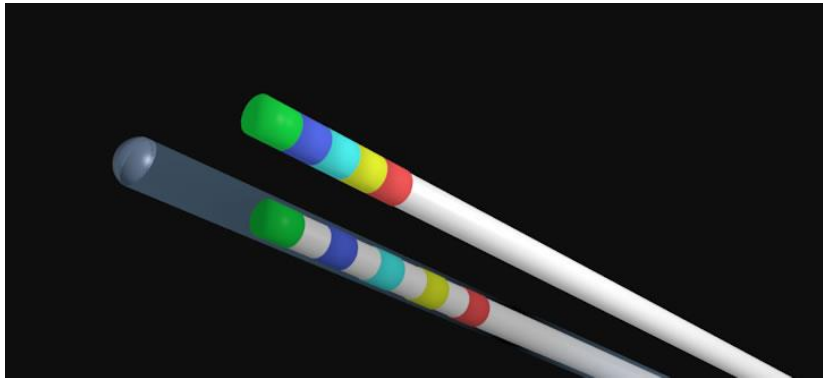


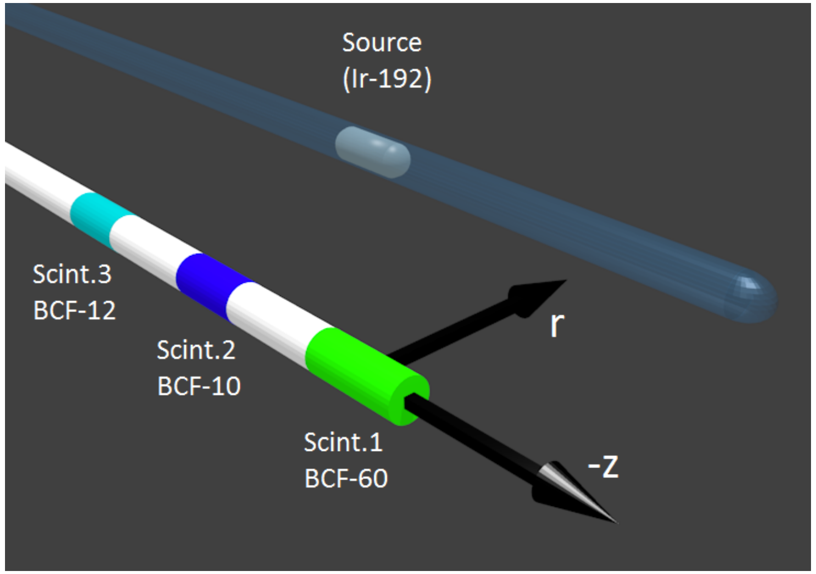
Limitation due to high dose gradients

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



New Detector Technology

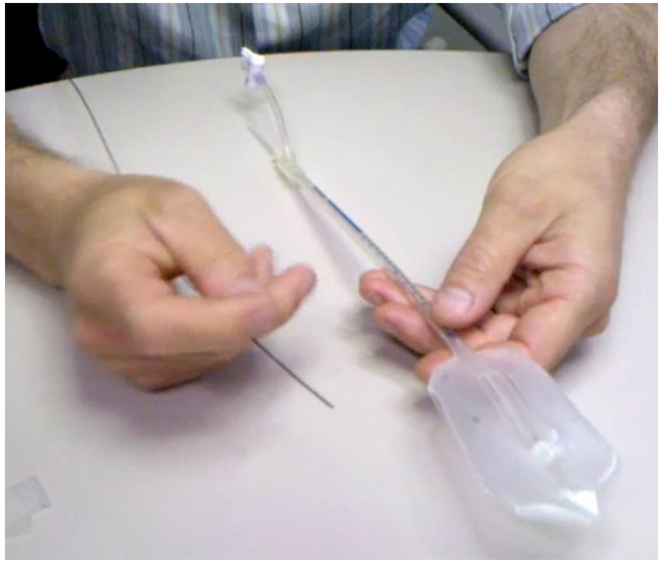


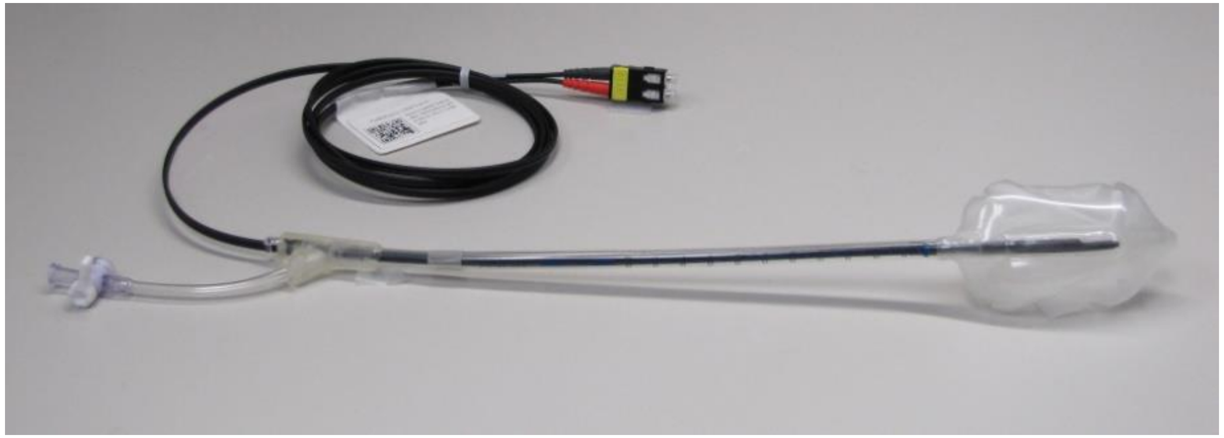


- Multi-point Plastic Scintillation Detector (mPSD)
- Measures dose at multiple points simulteneously with one optical fiber.
- Can track source position during HDR/PDR BT.
- Real time capability.
- Small enough to fit in catheters.

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)

Application Specific PSDs





OARtrac System

EPID systems

Implementation of An Efficient Workflow for the Analysis of Alerts Observed During Large Scale EPID-Based 3D in Vivo Dosimetry

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B Mijnheer

Presentations

SU-K-205-10 (Sunday, July 30, 2017) 4:00 PM - 6:00 PM Room: 205

Purpose: In our institution, more than 5000 RT treatments per year are verified using EPID-based 3D in vivo dosimetry. With our current set of tolerance levels, deviations are detected in about 30% of the treatments. The purpose of this study is to investigate the usefulness of a newly developed workflow to analyze the alerted treatments.

Methods: In the new workflow, in vivo reports are automatically created almost immediately after treatment delivery. If no deviation is detected, the treatment is automatically approved. In case of an alert, the new framework links extra sources of information (e.g., cone-beam CT and trends per patient) and imposes treatment-site specific checks to help medical physicists to explain the reason of the deviation. In cases where the clinical relevance of a deviation is still in doubt, the workflow prompts the scheduling of extra actions such as EPID or ion chamber based 3D phantom dosimetry. Radiation oncologists and therapists can be consulted at various levels during this workflow.

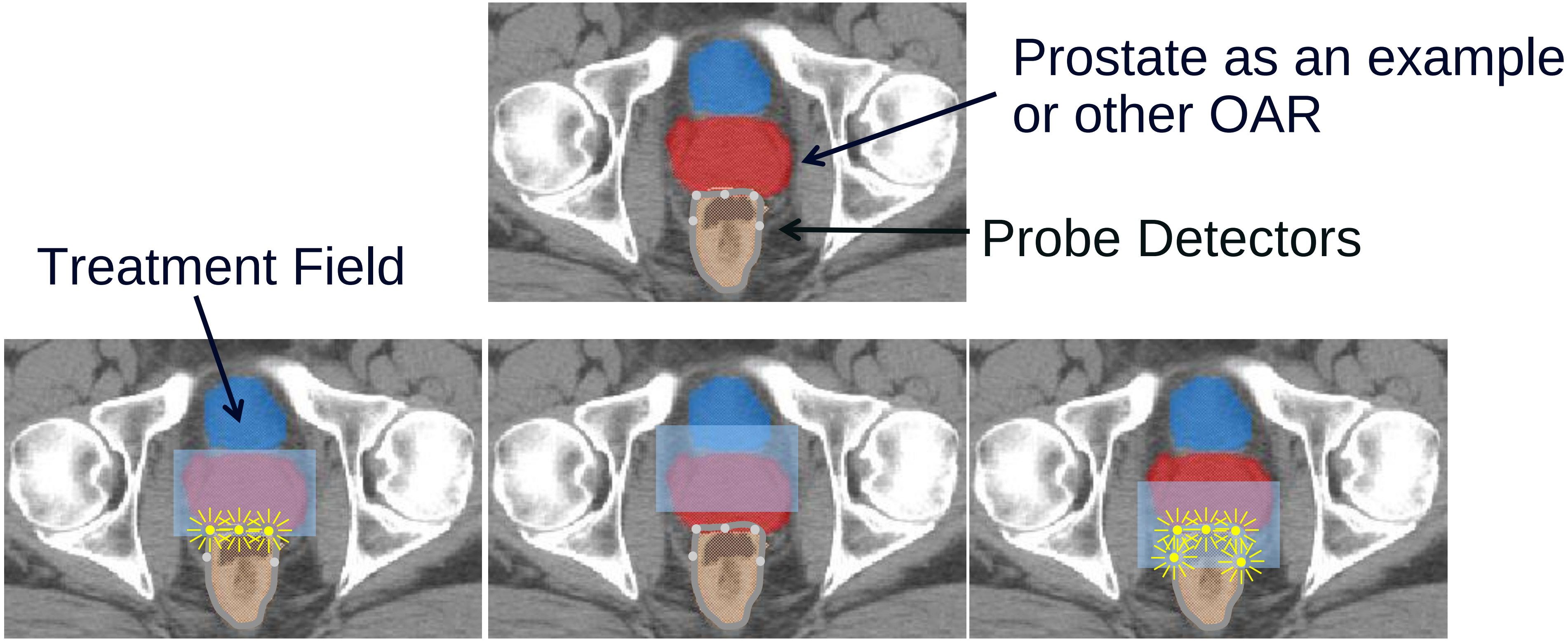
Results: In 2016 about 20 alerts had to be analyzed daily by a medical physicist requiring one to two hours. From these alerted deviations, 83% could immediately be explained following the protocol of the workspace, while 13% and 4% of the alerted cases were approved after an EPID or ion chamber based phantom check, respectively. The extra time for these phantom measurements amounts to about 30 min per day. The plan was adapted in 0.8% of the alerts.

Conclusion: The automated workflow ensures the timely inspection of each palliative and curative RT treatment at a minimal amount of inspection work. Furthermore, the structured alert handling approach facilitates consistent decision making and is an excellent tool to check the overall clinical process.

Add this talk to **vcal** | **ical** | Contact Email: **b.mijnheer@nki.nl**

- Analysis of alerts during routine in vivo dosimetry with EPIDs
- In vivo reports created post-treatment delivery
- 20 alerts/day were analyzed
- 83% of deviations explained immediately after treatment
- 13% explained with EPID based phantom check
- 4% explained with ion chamber based phantom check

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

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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

Conclusion

The role of In Vivo Dosimetry
SHOULD
no longer be ignored