In-vivo dosimetry

Rajat Kudchadker, PhD
Associate Professor
Department of Radiation Physics
Introduction

• What is *in-vivo* dosimetry?
• Why is *in-vivo* dosimetry important?
• Types of detectors
• Characteristics, advantages and disadvantages of detectors
• Clinical examples
**In-vivo dosimetry**

- In Latin “in-vivo” means “within the living”
- *In-vivo* dosimetry (IVD) in radiation therapy means the measurement of radiation dose received by the patient during treatment, as compared to *ex-vivo* which means dose measurements in a phantom
- In external beam radiation therapy a detector or dosimeter is placed in a natural orifice inside a patient or on the patient skin in an area where the dose has to be measured
- The detector response can then be correlated with the dose inside the patient
Rationale for in-vivo dosimetry

• For patient QA it provides an independent verification of the treatment procedure to identify possible errors in:
  - Calculation
  - Patient setup
  - Data transfer

TCP – Tumor Control Probability
NTCP – Normal Tissue Complication Probability
Table 2. Number of deviations observed between measured and prescribed dose larger than 5%, for the studies mentioned in Table 1

<table>
<thead>
<tr>
<th>Ref.</th>
<th>No. patients</th>
<th>No. deviations</th>
<th>Reason for deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(38)</td>
<td>1991</td>
<td>14</td>
<td>Erroneous calculation of the dose for irregular fields</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Erroneous calculation for isocentric instead of SSD treatment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>Drifted output of the treatment unit*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Compensators erroneously placed in tray: gross error*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>SSD set-up incorrect: gross error*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Wedge filter forgotten: gross error*</td>
</tr>
<tr>
<td>(39)</td>
<td>792</td>
<td>1</td>
<td>Difference in density of the patient</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>Errors in calculations, sometimes gross errors</td>
</tr>
<tr>
<td>(40)</td>
<td>7519</td>
<td>3</td>
<td>Data mismatch in prescription*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Incorrect input of data in treatment planning system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>46</td>
<td>Data transcription, miscalculation, neglect of shielding blocks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>Wrong or missing shielding blocks or wedges*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19</td>
<td>Incorrect monitor unit setting*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Mechanical failure of a timer on a cobalt unit*</td>
</tr>
</tbody>
</table>

* Indicates that this error could not have been traced by means of an independent dose calculation program instead of in vivo dosimetry. A gross error is an error larger than 10%.
Importance of implementing in-vivo dosimetry (USA data)
• Radiation Offers New Cures and Ways to Do Harm – January 2010
• As Technology Surges, Radiation Safeguards Lag – January 2010
• When Medical Radiation Goes Awry - January 2010
• Radiation Errors Reported in Missouri – February 2010
• VA is Fined over Errors in Radiation in Philadelphia – March 2010
• Stereotactetic Radiosurgery Overdoses Harm Patients – December 2010
New York State Rad Onc Records

The New York Times

The Radiation Boom
Radiation Therapy Offers New Cures, and Ways to do Harm
By WALT BOGDANICH Published: January 24, 2010

NY State Records 2001-2008

– 621 events, 1,264 causes, 2 notable deaths

- 46% - missed target
- 41% - wrong dose
- 8% - wrong patient

<table>
<thead>
<tr>
<th>#</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>352</td>
<td>Flawed Q/A plan</td>
</tr>
<tr>
<td>252</td>
<td>Human data entry/calculation error</td>
</tr>
<tr>
<td>174</td>
<td>Wrong patient, wrong site</td>
</tr>
<tr>
<td>133</td>
<td>Wedge or collimator misused</td>
</tr>
<tr>
<td>60</td>
<td>Hardware malfunction</td>
</tr>
<tr>
<td>24</td>
<td>Software bug</td>
</tr>
<tr>
<td>19</td>
<td>Erroneous software override</td>
</tr>
</tbody>
</table>
Countries requiring in-vivo dose measurement during treatment

- England (The royal college of Radiologists 2008)
- France (Derreumaux et al. 2008)
- Sweden (Nyholm 2008)
In vivo dosimeters

Table 1. Summary of characteristics of detectors used for external beam in vivo dosimetry, given as the dependence of the detector sensitivity on a specific parameter.\textsuperscript{a,b}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Diode</th>
<th>MOSFET</th>
<th>TLD</th>
<th>OSLD</th>
<th>Radiographic</th>
<th>Radiographic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Accumulated dose</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Dose rate</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Energy</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>SSD</td>
<td>+,\textsuperscript{a}</td>
<td>+,\textsuperscript{a}</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Field size</td>
<td>+,\textsuperscript{a}</td>
<td>+,\textsuperscript{a}</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Linearity</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Reproducibility (1SD)</td>
<td>0(\textsuperscript{&lt;1%})</td>
<td>(+\textsuperscript{&lt;2%})</td>
<td>(+\textsuperscript{&lt;2%})</td>
<td>(+\textsuperscript{&lt;2%})</td>
<td>(+\textsuperscript{&lt;2%})</td>
<td>(+\textsuperscript{&lt;3%})\textsuperscript{a}</td>
</tr>
<tr>
<td>Orientation</td>
<td>+,\textsuperscript{a}</td>
<td>+,\textsuperscript{a}</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Temperature</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Readout delay</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Intervening with patient</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Correction factors</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Estimated dose uncertainty (1SD)\textsuperscript{b}</td>
<td>1.5%–3%\textsuperscript{a}</td>
<td>2%–5%\textsuperscript{a}</td>
<td>2%–3%\textsuperscript{a}</td>
<td>2%–3%\textsuperscript{a}</td>
<td>3%\textsuperscript{d}</td>
<td>3%\textsuperscript{e}</td>
</tr>
</tbody>
</table>

Main advantages

- Good reproducibility, immediate readout
- Immediate reading, minor fading
- No cables, reusable after annealing, few corrections
- No cables, readout 10 min postirradiation, reusable after optical bleaching
- 2D dose distribution, resolution, reseau, permanent record, various shapes, light insensitive
- Cost, specific scanning equipment, strict readout protocol
- 2D and 3D dose distribution, resolution, immediate readout, permanent record
- Cost, limited availability of commercial software

Main disadvantages

- Cumbersome calibration, many corrections, cable
- Limited lifetime, high cost
- Labor intensive, specific TLD equipment
- Short lifetime, dependence on accumulated dose, specific OSLD equipment
- Light sensitive, processing equipment and maintenance, specific scanning equipment
- Cost, specific scanning equipment, strict readout protocol

Note: 0—no concern; +—minor concern; ++—serious concern.
\textsuperscript{a}Information for some of the entries was taken from IAEA Human Health Report No. 8 (Ref. 10).
\textsuperscript{b}Because the experience with plastic scintillator detectors and RPL glass dosimeters for IVD during EBRT is still limited, these detector types are not included in the table.
\textsuperscript{c}Assumes calibrations at a particular energy.
\textsuperscript{d}Varies depending on the build-up encapsulation.
\textsuperscript{e}Assumes following a strict readout protocol.
\textsuperscript{f}Orientation plays a role at readout.
\textsuperscript{g}Not of concern for dual MOSFETs that correct for temperature differences.
\textsuperscript{h}Relative to calibrated ionization chamber dose measurements.
\textsuperscript{i}Lower values are applicable for dosimeters that are regularly calibrated and have well-known correction factors.
\textsuperscript{j}Assumes a well-maintained processor.

(Mijnheer et al, Med Phys 40 (2013))
Dose Measurements

Entrance dose:
- Output, SSD
- Wedge, curvature

Exit dose:
- Thickness, density

Point detector
2D detector array
Patient curvature
In-vivo Dosimetry Dose Characteristics

Diagram showing dose characteristics with labels:
- D_{entrance}
- D_{target}
- D_{surface}
- D_{exit}
- midline
- full backscatter
- depth of specification
- 0.05 cm
- d_{max}
- s
- r
- d_{max}
Dosimeter Characteristics

• Accuracy & Precision
• Stability
• Linearity of response
• Directional dependence
• Beam-quality dependence
• Absolute vs. relative
• Size
• Immediacy of results
• Stem and cable effects
• Cost and convenience
• Reusability
• No cables
• Non-destructive readout

High accuracy
Low precision

Low accuracy
High precision
Dosimeter Calibration

• Under *reference conditions*:

\[ N_D = \frac{D_{cal}}{R_{cal}} \]

\[ D = R N_D \sum C_i \]

*R*: dosimeter reading

*N_D*: calibration factor

*C_i*: correction factors
Correction Factors

• Dosimeter reading may depend on:
  ➢ Temperature
  ➢ Accumulated dose
  ➢ Dose rate
  ➢ Beam energy
  ➢ Angle of incident radiation
  ➢ ...

• Accuracy may be reduced if dependence is not corrected
1D Dosimeters

- Ion chambers
- Diodes
- MOSFET’s
- TLD’s
- OSLD’s
- Plastic Scintillation detectors
Small-volume Ion-chambers

• Advantages
  ➢ Stability
  ➢ Linear dose response
  ➢ Small directional dependence
  ➢ Traceable calibration

• Disadvantages
  ➢ Volume averaging
  ➢ Energy response dependence if central electrode is made up of high Z material
  ➢ Stem effect
  ➢ Bias voltage needed for operation
Ionization Chamber *In-Vivo* Dosimetry

**Wertz et al., IJROBP, 67 288-295 (2007)**
Diode Detectors

• **N-type diode** is formed by doping “acceptor” (3 valance electrons element) into **N-type semiconductor**

• **P-type diode** is formed by doping “donor” (5 valance electrons element) into **P-type semiconductor**

• Diode detector is made by P-N junction principle
How do diodes measure dose?

Incident ionizing radiation

Electron-hole pairs

The minority carriers (electrons on the p-side and holes on the n-side) diffuse toward the opposite side

Measured by the electrometer

AAPM TG-62
Diode Detectors - No Bias Voltage

• The typical width of the “depletion region” is less than several \( \mu \text{m} \)

• “built-in potential” is less than 1 volt, the electric field across the \textit{pn junction} is very high (greater than \( 10^3 \) V/cm)

• The high electric field across the \textit{pn junction} makes charge collection possible for the diode without external bias
Diode Detectors as *In-vivo* Detectors

- **Advantages**
  - Flat design for easy placement
  - Small size (0.8 x 0.8 mm)
  - No bias
  - Cylindrical design for isotropic response
  - High radiation sensitivity (32 nC/Gy)
  - Accurate and stable
  - Quick response (1 – 10 µs)
  - Mechanical stability
Diode Detectors as *In-vivo* Detectors

- Disadvantages
  - Over-responsive to low-energy photons
  - Some energy dependence
  - Dose-rate dependence
  - Angular dependence for non-normal incidence
  - Change in sensitivity over time due to radiation damage
  - Temperature dependence
  - Requires electrical connection during irradiation
Energy and Dose Rate Dependence

Saini AS and Shu TC Med Phys, 2004, 20007
Diodes Temperature Sensitivity

Temperature dependence

Detector temperature after placing on patient

Saini AS and Shu TC Med Phys, 2002
Diode In-Vivo Dosimetry

ACCURATE IN VIVO DOSIMETRY OF A RANDOMIZED TRIAL OF PROSTATE CANCER IRRADIATION

Gert J. Meijer, M.Sc., André W. H. Minken, Ph.D., Karel M. van Ingen, B.Sc., Bob Smulders, B.Sc., Hans Uiterwaal, and Ben J. Munneer, Ph.D.

Measured Dose/Prescribed Dose

Action level: 2.5%

- measured dose
- dose after correction

\[\bar{r} = 1.008\]
\[\sigma = 1.2\%\]
$\Delta V_T$ is a function of absorbed dose.
The function is linear when MOSFET operates in biased mode during irradiation.
Absorbed dose linearity region increases with increased bias voltage.

Soubra et al, Med. Phys. 21, 1994
MOSFET’s

• Advantages
  ➢ Very small size
  ➢ Linear dose response
  ➢ Small directional dependence
  ➢ Immediate readout
  ➢ Waterproof
  ➢ Dual MOSFET dual bias eliminates most correction factors

• Disadvantages
  ➢ Not tissue equivalent
  ➢ Some energy dependence
  ➢ Limited lifetime (~100 Gy)
  ➢ Change in sensitivity over time due to radiation damage
  ➢ Energy, temperature, dose rate, field size, directional dependence
Urethral dose using MOSFET detectors during prostate brachytherapy

Cherpak et al, Brachytherapy 13 169-177 (2014)
Thermoluminescence Dosimetry (TLD)

- In the form of rods (cylinders) or chips, contains Lithium fluoride (LiF)- has an effective atomic # Z (8.4) similar to tissue (7.2)
- X-ray exposure raises electrons that normally reside in a lower energy state, the valence band of the crystal, to the conduction band, a region in which the electrons have a higher energy state.
- The electrons drop back toward the valence band as they de-excite; however, they are often caught in traps between the two bands. The electrons may stay here for a long time.
- Heating the crystal empties the traps by pushing out the electrons (thermoluminescence). The final de-excitation of the electrons emits visible light. The total amount of emitted light (TL) is related to the original radiation dose absorbed by the crystal.
- TLD come in various forms – chips, powder, discs, rods, etc.
TLD Process - Electron Trapping

Ionizing Radiation

Energy Band Gap = 10 eV

Visible Light

Electron Migration
Conduction Band

Trap

Hole Migration
Valence Band

$E_a$

$\alpha, \beta, \gamma$ radiation

thermal or optical release

light emission
### TLD Reader Construction

- **Power Supply**
- **PMT**
- **DC Amp**
- **Heated Cup**
- **TL material**

**To High Voltage**

**To ground**

**Recorder or meter**

**Glow Curve**

- **Filter**

**Hows**

- I
- II
- III
- IV and V
- VI

**Power Supply**
As the TLD material is heated light is emitted as a series of “glow-peaks” A) CaSO$_4$:Mn ;B) LiF:Mg,Ti ;C) CaF$_2$ ;and D) CaF$_2$:Mn. As the temperature rises above 200°C “black body” radiation increases.
TLD Detectors as In-Vivo Detectors

- Advantages:
  - Small crystals
  - Passive dosimeter - no cables required
  - Wide dosimetric range (μGy to 100s of Gy)
  - Can be reused
  - Density tissue equivalent (LiF)
  - TLD has a higher sensitivity over a wide photon energy range
  - Dose rate independence (0 – 1000 cGy/s)
  - Angular independence
  - Readout convenience
  - Economical
  - Accuracy and precision
TLD Detectors as In-Vivo Detectors

- Dis-advantages:
  - Higher cost than film
  - Does not keep a permanent record of exposure like film
  - Delayed readout and time consuming process
  - Many different materials (LiF:Mg,Ti, CaF$_2$, CaSO$_4$, BeO, Al$_2$O$_3$)
  - Non linear dose response
  - Some energy dependence
  - Lack of uniformity
  - Fading
  - Light sensitivity
  - Reader instability
Dose Response

- Linear region: Up to 1 Gy for "LiF"
- Superlinear region
- Saturation dose ~ 1000 Gy for "LiF"
Energy Response

Relative response
**TLD Dose Calculation**

\[ D = (R-B) \times C \times k_E \times k_F \times k_D \]

- \( R \) – TLD reader output signal
- \( B \) – Background signal
- \( C \) – TLD system calibration factor
- \( k_E \) – energy correction factor
- \( k_D \) – dose response correction factor
- \( k_F \) – correction factor for fading
TLD Calibration Procedure

• Photon energies between 50 – 110 kV
• Individual calibration for each radiation machine
• Calibration for entrance dose v.s. calibrated ion-chamber

Determination of calibration factor according to the procedure for each TLD used
TLD Calibration Procedure

(a) PMMA Slabs
(b) Ionization chamber
(c) X ray couch

TLDs
X ray tube
TLDs
PMMA Slabs

Slots
TLD dosimetry

- Place TLD on the surface of skin and apply tape
- Document orientation
- Treat patient (one fraction)
- Irradiate standards
- Read TLD
- Compare TLD to TPS

- We do not expect excellent agreement
  - TLD are on skin (not truly device dose)
  - There may be some tissue in between
Total Skin Electron Irradiation
Patient QA Using TLD

• TLD’s taped to various anatomical sites and irradiated for one full cycle (12 beams)
  ➢ Accuracy and uniformity of delivered dose
  ➢ Patient positioning consistency
  ➢ Where are the dose deficits and need for boost

• Reference TLD’s:
  ➢ Regular 9 MeV at 100 cm SSD, 10x10 cm², 2.0 cm depth in Acrylic
# TLD Placement and Results

<table>
<thead>
<tr>
<th>TLD #</th>
<th>Location</th>
<th>% of 200 cGy</th>
<th>TLD #</th>
<th>Location</th>
<th>% of 200 cGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Scalp (top rear)</td>
<td>109%</td>
<td>8</td>
<td>Inner Thigh, LT</td>
<td>75%</td>
</tr>
<tr>
<td>2</td>
<td>Upper thorax</td>
<td>97%</td>
<td>9</td>
<td>Breast Fold, RT</td>
<td>98%</td>
</tr>
<tr>
<td>3</td>
<td>Rt Groin</td>
<td>82%</td>
<td>10</td>
<td>Breast Fold, LT</td>
<td>97%</td>
</tr>
<tr>
<td>4</td>
<td>Lt Groin</td>
<td>91%</td>
<td>11</td>
<td>Umbilicus</td>
<td>99%</td>
</tr>
<tr>
<td>5</td>
<td>Buttock, RT</td>
<td>72%</td>
<td>12</td>
<td>Lower Abdomen, Rt</td>
<td>93%</td>
</tr>
<tr>
<td>6</td>
<td>Buttock, LT</td>
<td>54%</td>
<td>13</td>
<td>Lower Abdomen, Mid</td>
<td>100%</td>
</tr>
<tr>
<td>7</td>
<td>Inner Thigh, RT</td>
<td>92%</td>
<td>14</td>
<td>Lower Abdomen, Lt</td>
<td>98%</td>
</tr>
</tbody>
</table>
Patient TLD Variation and Rando Phantom Validation

TSEB: TLD results (68 patients) (Error bars: 1 Std Dev)

% Prescribed Dose

TLD Site

Patient TLD
Rando TLD
OSL Dosimetry (Al$_2$O$_3$::C)

- Aluminum oxide crystal is melted, doped with carbon and re-crystalized. Dopants and oxygen vacancies determine the radiation sensitive properties of the crystal.
- Environmentally stable for heat moisture and chemical exposures
- Processed by exposing to green laser light and detecting the intensity of the emitted blue light
- Luminescence is proportional to the exposure
- Can be processed multiple times as only a portion of the signal is depleted when processed.
- High sensitivity and wide range, from 10 $\mu$Sv to 100 Sv.
OSL Detectors as In-Vivo Detectors

• Advantages:
  - Linear response to dose
  - Dose rate independence
  - Energy and angular independence
  - Particle type (photons and electrons) independence
  - Good spatial resolution
  - Easier readout procedure
  - Detector readout can be repeated
  - Optical bleaching easier than thermal annealing to remove dose
**OSL Detectors as In-Vivo Detectors**

- Disadvantages:
  - A very small temperature dependence
  - Radiation damage lowers light yield
  - Encapsulated in light tight plastic housing
  - Optical bleaching cannot clear all the radiation effects resulting in increased background signal
  - Sensitivity changes with accumulated dose (>20 Gy)
Plastic Scintillation Detectors

- Radiation will excite atoms or molecules of the scintillating medium
- The decay of these excited states will produce photons in the visible part of the spectrum
- These photons are guided by a photodetector and then get converted into an electric signal
- Light output is directly proportional to excitation energy
- There are two types of scintillators:
  - Inorganic (NaI, NaI (Tl), CsI, CsI (Tl), CsF, etc.)
    - Advantages for stopping radiation; disadvantage for dosimetry
  - Organic (plastics, etc.)
    - Lower density, atomic number, nearly tissue equivalent; advantage for dosimetry
Scintillation Process

Charged Particle Interactions (keV to MeV) → Energy Absorption → Energy Deposition → Ionization - Excitation → Light Emission (a few eV)
Plastic Scintillation Detectors

• Advantages:
  ➢ Linear response to dose
  ➢ Dose rate independence
  ➢ Energy independence
  ➢ Spatial resolution
  ➢ Water equivalence

• Disadvantages
  ➢ Cerenkov emission
Plastic Scintillation Detectors

Wootton et al, PMB 59 647-660 (2014)
2-D Detectors

• Film
  - Radiographic
  - Radiochromic

• EPID

• Diode and ion chamber arrays
Radiographic Film

Fig. 1. Gurney and Mott model of latent image (Ref. 29). AgBr remains in ionic form ($\text{Ag}^+\text{Br}^-$) in the crystal of the grain. Radiation produces ionization of $\text{Br}^-$ to $\text{Br}^+e^-$. These electrons make the speck negatively charged. The $\text{Ag}^+$ migrate to neutralize the speck and forms a lump of Ag (aggregate) on the speck.
Film Processing

- Developer (Metol) - Converts all Ag+ atoms to Ag. The latent image Ag+ are developed much more rapidly
- Stop Bath (Dilute acetic acid) - Stops all reaction and further development
- Fixer (Sodium Thiosulphate) – It dissolves all undeveloped grains
- Washing
- Drying
Film Dosimeter Calibration Curve

![Film Dosimeter Calibration Curve](image)

- **Total Density**
- **log Relative Exposure**

- **Shoulder**
- **Toe**
- **Base plus fog density**
Radiographic Film

• Advantages
  ➢ High spatial resolution
  ➢ Relatively inexpensive

• Disadvantages
  ➢ Light sensitive
  ➢ Oversensitive to low-energy photons
  ➢ Dependence on film batch, processor conditions, digitizer
  ➢ Need to measure response curve for each measurement session
Radiochromic Film

- Nearly tissue equivalent
- No processor required
- Film sensitivity comparable to EDR2
- No laser densitometers
  - Polarization artifacts
- Flatbed scanner
  - Rotation
  - Scanner uniformity
  - Scanner temperature
- Hydroscopic emulsion
- Pixel to pixel variation greater than other detectors
Older Radiochromic Films

- Colorless before irradiation
- Monomer crystals dispersed in gelatin binder
- Deposited on polyester film base
- Ionizing radiation causes polymerization reaction - polymer has blue color
- Diacetylene -> Polydiacetylene
Newer Gafchromic Films

- **HS** = “High Sensitivity”
  - 1 to 50 Gy
  - Atomic Composition:
    - 57% C, 9% H, 18% O, 16% N

- **EBT** = “External Beam Therapy”
  - 0.01 to 8 Gy
  - Introduced in 2004
  - Different active material from older types (proprietary?)
  - Atomic composition:
    - 42.3% C, 39.7% H, 16.2% O, 1.1% N, 0.3% Li, 0.3% Cl
  - $Z_{\text{eff}} = 6.98$

Devic et al., Med Phys 32, 2005, pg. 2245
Fuss et al., PMB, 2007, pg. 4211
Radiochromic Film

• Advantages
   High spatial resolution
   Does not require processing
   Not sensitive to indoor light
   Nearly tissue-equivalent
   Decreased sensitivity to low-energy photons

• Disadvantages
   Low OD at clinical doses
   Susceptible to scanner artifacts and temperature
Radiochromic Film

- QA for Stereotactic treatment using EBT2
- High spatial resolution, but scanning process limits the resolution by 0.1 mm

T. Kron et al., Radiation Measurements 46 (2011) 1920-1923
EPIID Dosimetry

• Active matrix flat panel imagers (AMFPIs)
• Portal “dosimetry”
• Often a fluence or response verification
• Based on transmission measurements
• Conversion of transmission measurements to dose via EPIID calibration
• Attenuation and scatter within the EPIID need to be accounted for in correction factors

Jean Moran AAPM 2009
EPIID Dosimetry

- back-project primary dose
- determine patient attenuation
- add patient scatter

- correct patient scatter to EPIID

- pixel sensitivity matrix
- pixel-to-dose conversion
- correction for scatter in EPIID

Mijnheer R, PMB 444, 2013
EPID Dosimetry

• Advantages:
  ➢ Mounted to linear accelerator – known geometry with respect to the beam
    ❖ Detector sag must be accounted for at different gantry angles
    ❖ Positioning reproducibility important
  ➢ Real time digital evaluation
  ➢ Finer resolution than array detectors

• Challenges:
  ➢ Conversion of image response to “dose” is complex
  ➢ Ghosting, lag
  ➢ Cannot be placed in a solid water stack
**EPID Dosimetry**

### EPID DOSIMETRY REPORT

**Patient name:** xxx  
**Treatment site:** OESOPHAGUS  
**Medical Record No:** xxx  
**Plan UPI:** xxx

**Analysis, Gamma:** 10/08/2012 11:59:11, 3.0%, 3.0 mm  
**Plan Name, Trial:** Oes, 41.4Gy  
**Linac, Cal, Th:** A5, A5F, ROI

<table>
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<tr>
<th>Field</th>
<th>OEO.0.6.180</th>
<th>OEO.0.5.105</th>
<th>OEO.0.4.50</th>
<th>OEO.0.3.10</th>
<th>OEO.0.2.330</th>
<th>OEO.0.1.215</th>
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<tr>
<td>G, C, T, E</td>
<td>180,0,0,10</td>
<td>105,350,0,10</td>
<td>50,0,0,10</td>
<td>10,0,0,10</td>
<td>330,5,0,10</td>
<td>215,0,0,10</td>
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</tbody>
</table>

<table>
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<tr>
<th>Im(s), R, C</th>
<th>001,2,2,0,0, epid</th>
<th>002,2,2,0,0, epid</th>
<th>003,2,2,3,7, epid</th>
<th>004,2,2,2,4, epid</th>
<th>005,2,2,2,7, epid</th>
<th>006,2,2,0,0, epid</th>
</tr>
</thead>
</table>

| mean γ | 0.46 | 0.55 | 0.37 | 0.33 | 0.45 | 0.53 |
| γ 1% | 2.76 | 3.12 | 1.31 | 1.10 | 1.39 | 1.89 |
| % γ ≤ 1 | 90.3 | 89.4 | 95.1 | 98.5 | 90.8 | 82.9 |
| Plan | 22.5 | 34.8 | 29.3 | 30.0 | 31.8 | 25.8 |
| Epid | 22.0 | 36.4 | 29.3 | 29.5 | 33.8 | 25.8 |

| Nr. Fields | Plan: 6  
|------------|-----------|
| Epid: 6  
| Isoc (cGy): | 174.2  
| 176.9 (1.6%) |

Mijnheer R, PMB 444, 2013
Detector arrays

- SunNuclear IC PROFILER
- IBA MatriXX
- PTW OCTAVIUS Detector 1000 srs
  - Very small detector size (2.3 mm x 2.3 mm x 0.5 mm) with high spatial resolution (2.5 mm)
- Dose magnifying glass
  - 0.2 mm spatial resolution

Wong et al, Medical Physics 37, 427 (2010)
3-D detectors

• Sun Nuclear Arc Check
  ➢ Pseudo-3-D geometry
• PRESAGE
  ➢ MRI & optical CT
• DEFGELs
  ➢ Deformable gels

Yeo et al., Medical Physics 39, 2203 (2012)
Dose Guided Radiotherapy

Backprojection of filtered dose image into patient image

prescribed isodose
→ OK

target

→ correction
Dose Guided Radiotherapy

Correction
Action Level

• Relative dose difference:

\[ r = 1 - \frac{D_{\text{measured}}}{D_{\text{prescribed}}} \]

• At what dose difference level should the treatment be revised? 1% ? 2.5 % ? 5 %?

• Depends on:
  - dosimetric accuracy and precision
  - non-systematic errors
  - physician discretion
  - ...

Conclusions

• In vivo dosimetry directly monitors the radiation dose delivered to a patient during radiation therapy avoiding a misadministration.

• It allows comparison of prescribed and delivered doses and thus provides a level of radiotherapy quality assurance that supplements port films or cone beam CT and Monitor Unit double checks.

• In vivo dosimetry is an effective tool for quality assurance in external beam radiation therapy.