In-vivo Dosimetry

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In vivo dosimetry is the methodology of choice in verifying whether a correct dose is actually being delivered to the patient, and is as such a crucial tool in quality assurance of the treatment of the individual patient.
Systematic errors in dose delivery for an individual patient may arise due to the influence of
- patient contours
- patient mobility
- inhomogeneities
- internal organ motion

Moreover, errors can be introduced by:
- transferring treatment data from the treatment planning system or simulator
- the treatment machine settings and calibration
- positioning the patient and beam modifiers
The ultimate check of the actual dose delivered to an individual patient can only be performed at the patient level, by means of *in vivo* dosimetry. Several national and international organizations (AAPM, ICRU and NACP) recommend that *in vivo* dose measurements should be made. The purpose of this is to detect errors in individual treatment sessions due to equipment mal-functioning and human mistakes. This approach serves to detect unexplained, non-statistical fluctuations in dose delivery.
SYSTEM AND MEASUREMENT
CONFIGURATION
System & measurement configuration

- Radiation detectors
  - Thermoluminescent dosimeters (TLD)
  - Semiconductors (diodes)
  - ....

- Dose registration system
  - Electrometers for diodes
  - TLD readers
  - ....

- Measurement and action protocol
  - Action levels
  - How to correct
System & measurement configuration

Measurement of the entrance and exit dose, $D_{ent}$ and $D_{exit}$, provide information about whether:

- Calculated out-put dose is correct according to pts. anatomy
- Target volume will receive the intended dose
System & measurement configuration

Based on the measurements of the entrance and exit dose, $D_{\text{ent.}}$ and $D_{\text{exit}}$, actual mid plane or target dose can be found.
System & measurement configuration

- Entrance dose measurements, on axis, will verify correct output and correct SSD.

- Entrance dose measurements, off axis, will verify appropriate use of wedge according to anatomy.
System & measurement configuration

Exit dose measurements, on axis, will verify whether calculated monitor units are correct according to thickness and tissue density.
System & measurement configuration

Combined exit and entrance measurement can provide information about mid plan dose
System & measurement configuration

In vivo measurements

Dose registration and automatic comparison with expected values

Action suggested and taken according to predefined protocol
DETECTORS

- Semiconductors (diodes)
- Thermoluminescent dosimeters (TLD)
- Electronic portal device (EPID)
- Electron paramagnetic dosimetry
Diodes

The diodes in use for *in vivo* dosimetry are silicon detectors.

The base material can be n- or p-type silicon.

The dependence of the diode response on accumulated dose, dose rate, and temperature is related to several crystal characteristics, for example, the doping level.

P-type diodes resist radiation much better than n-type detectors; the decrease in sensitivity with irradiation is much smaller for p-type than for n-type diodes.
Diodes

- Illustration of a diode detector circuit. Radiation produces electrons and 'holes'.
- These are attracted to the positive and negative side.
- A current in the circuit is thus induced.
Diodes

- *In vivo* dosimetry semiconductor detectors consist of a diode surrounded by a build-up cap.
- Hemispherical build-up cap is equivalent in attenuation and build-up to 2 cm water and can be used with full build-up for dose measurements in high energy x-ray beams up to 8 MV.
- Surface dose will be increased to at least 90% of maximum dose.
- Dose at larger depths will be reduced by at least 5%.
- Cylindrical build-up cap, the beam attenuation on the central beam axis is up to 4%, 8%, and 13% for a 4 MV, 6 MV, and 15 MV x-ray beam, respectively.
Diodes

Main advantages of diodes are:

– a high sensitivity to radiation, small size, good mechanical stability
– The sensitivity per unit volume of a diode is about 18,000 times higher than for an air-filled ionization chamber.
– absence of external voltage, and immediate availability of the measured dose.
– On-line dose verification allow dose adaptation during the treatment session
## Diodes

The following table is a guide to select the appropriate detector:

<table>
<thead>
<tr>
<th>Entrance dose, few corrections</th>
<th>photons</th>
<th>Electrons</th>
<th>Cobalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDP-10&lt;sup&gt;g&lt;/sup&gt; (4-8 MV)</td>
<td>EDP-5&lt;sup&gt;g&lt;/sup&gt;</td>
<td>EDP-2&lt;sup&gt;g&lt;/sup&gt;</td>
<td>EDP-5&lt;sup&gt;g&lt;/sup&gt; (1.25 MeV)</td>
</tr>
<tr>
<td>EDP-15&lt;sup&gt;g&lt;/sup&gt; (6-12 MV)</td>
<td>EDP-2&lt;sup&gt;g&lt;/sup&gt;</td>
<td>EDP-5&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>EDP-20&lt;sup&gt;g&lt;/sup&gt; (10-20 MV)</td>
<td>EDP-2&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDP-HL&lt;sup&gt;g&lt;/sup&gt; (16-25 MV)</td>
<td>EDP-2&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total body irradiation</td>
<td>EDD-5&lt;sup&gt;g&lt;/sup&gt;</td>
<td>EDD-2&lt;sup&gt;g&lt;/sup&gt;</td>
<td>EDD-2&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>Exit dose</td>
<td>EDD-2&lt;sup&gt;g&lt;/sup&gt;</td>
<td>-</td>
<td>EDD-2&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>Risk organ monitoring,</td>
<td>EDD-5&lt;sup&gt;g&lt;/sup&gt;</td>
<td>EDD-5&lt;sup&gt;g&lt;/sup&gt;</td>
<td>EDD-5&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>measurements outside the field</td>
<td>IDF-1&lt;sup&gt;g&lt;/sup&gt; (e.g. rectum)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Intracavitary (Teletherapy)</td>
<td>IDF-1&lt;sup&gt;g&lt;/sup&gt; (e.g. rectum)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Brachytherapy</td>
<td>IDF-3&lt;sup&gt;g&lt;/sup&gt; (e.g. rectum)</td>
<td>IDF-5&lt;sup&gt;g&lt;/sup&gt; (e.g. rectum)</td>
<td>IDF-thin (e.g. bladder)</td>
</tr>
</tbody>
</table>

(1) High energy, low perturbation; can be used up to 25 MV.

(2) When using spoiler (build-up), otherwise same recommendations as entrance dose, low corrections.

Diodes

Example of detector design;

a) spherical
b) droplet
Diodes

Dose response relationship for a given detector;

- a linear response is preferable.
- otherwise correction factors have to be introduced.
Variation in response as function of collimator size for different energies and build up cap
Diodes

Sensitivity of the diode decreases with accumulated dose:

- Pre-irradiation reduces the change in response
- Regularly calibration is demanded
Diodes

Response of the detector is dependent on the temperature.

Detector temperature after taping onto the patient.
Diodes

A unique calibration factor for both exit and entrance measurements is insufficient, as the response have been shown to differ.

\[ F_{\text{exit}} = \frac{D_{\text{exit}}}{R_{\text{sc,exit}}} \]

\[ F_{\text{entrance}} = \frac{D_{\text{entrance}}}{R_{\text{sc,entrance}}} \]
Diodes

Entrance and exit dose correction factor, $C_{\text{field size}}$, as a function of the side of a square field, for an 8-MV and 18-MV photon beam.

$$D_{\text{diode}} = R_{\text{diodo}} \cdot N_D \cdot i \cdot C_i$$

Diodes

Entrance and exit dose correction factor, $C_{SSD}$, as a function of the SSD for an 8-MV and 18-MV photon beam.

$$D_{\text{diode}} = R_{\text{diode}} \cdot N_D \cdot i C_i$$

Diodes

Entrance and exit dose correction factor, $C_{\text{thickness}}$, as a function of the phantom thickness for an 8-MV and 18-MV photon beam.

\[ D_{\text{diode}} = R_{\text{diode}} \cdot N_D \cdot iC_i \]

TLD

TLDs have been in use for *in vivo* dosimetry for a very long time. They are based on the principle that imperfect crystals can absorb and store the energy of ionizing radiation.

Free electrons and holes are formed. The electrons may be trapped at defects in the crystalline structure.

When heated to a temperature which is typical for the detector material, electrons return to the conduction band and then may recombine with a hole, while emitting energy in the form of electromagnetic radiation.
Free electrons and holes are formed and trapped at defects in the crystalline structure. When heated the electrons return to the conduction band while emitting energy.
This radiation, mainly in the visible wavelength region, is detected by a photomultiplier and correlated to the absorbed dose received by the material.

After annealing, the TLD can be used again.
TLD

Schematic illustration of a TLD reader
TL materials used for *in vivo* dosimetry are: lithium fluoride (LiF), lithium borate (Li$_2$B$_4$O$_7$), and calcium sulphate (CaSO$_4$).

TL detectors can either be powders or solid dosimeters, in the form of rods, chips, or pellets.

Their small dependence on dose rate, temperature, and energy in the therapeutic range, and their wide applicable dose range make TLDs suitable for *in vivo* dosimetry purposes.

TLDs are small with a good spatial resolution.
TLD

Dose response relationship:

- a linear response is preferable.
- is used outside the linear region, correction factors must be applied.
The response is dependent on energy to a certain extent, but varies between different TL materials.
TLD

- TLDs have the main advantage over diodes that they do not have to be connected to an electrometer with a cable, and that they are easy to transport.
- The dose information can be stored over a long period of time, TLDs are suitable detectors for mailing, which implies they can be used for inter-comparison of dose values delivered in different institutions, such as in a multi-centre trial.
- They can also be tissue or bone equivalent.
- Disadvantages are that they cannot be used for on-line *in vivo* dosimetry.
### Table III.2: Values of the different correction factors to be applied in clinical conditions for diodes and radiothermoluminescent dosimeters.

<table>
<thead>
<tr>
<th>Correction factors (Parameter)</th>
<th>Value for diodes (conditions)</th>
<th>Value for TLD (conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_D$ (dose)</td>
<td>1</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td></td>
<td>(in linear region of dose/response curve)</td>
<td></td>
</tr>
<tr>
<td>$C_{DR}$ (dose rate)</td>
<td>$&gt; 1$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(in supralinear region)</td>
<td>(calibration per dose rate range: entrance, exit, TBI)</td>
</tr>
<tr>
<td>$C_T$ (temperature)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(in usual conditions provided $SVWT &lt; 0.6%$ per °C)</td>
<td>(TBI)</td>
</tr>
<tr>
<td>$C_E$ (energy)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(separate calibration per beam)</td>
<td>(calibration detectors irradiated with same radiation quality as patient detectors)</td>
</tr>
<tr>
<td>$C_D$ (direction)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(close to field centre)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>($\neq 1$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(tangential field or non-central position)</td>
<td></td>
</tr>
</tbody>
</table>
EPID dosimetry

EPID can determine transmission dose in the entire irradiation field, and from these measurements, the exit or midline dose in a plane might be obtained.

Using this information, the dose homogeneity in the e.g. target volume can be assessed.

EPID dosimetry

Exit dose rate measurements under inhomogeneous phantom

Relative dose distributions in the mid-plane of a lung cancer patient irradiated with an anterior-posterior field at the Netherlands Cancer Institute, Amsterdam, The Netherlands. (a) Calculated with the 3D treatment planning system; and (b) measured with an EPID behind the patient and converted to patient dose values.

EPR

- Radiation induced radiocal proportional to absorbed dose
- The amount of radicals can be determined from electron paramagnetic resonance spectroscopy
- The intensity of the spectrum can be converted to dose
The relative response EPR and TL dosimeters for 4, 6, 10 and 15 MV X-rays, as evaluated at different dose levels

Clinical example

Patient with an EDP-20 diode with extra build-up cap.

The diode is slightly shifted with respect to the central beam axis, to avoid shielding by the entrance diode, which is shifted in the opposite direction.

The electronic portal imaging device (EPID) on the right is used to verify the correct diode position.

Clinical example

*In vivo* dosimetry results of 225 prostate patients. The open circles correspond to the IVD results after correction.

Clinical example

Entrance dose measurements: overall results.

650 entrance dose measurements for lung, H&N, breast and pelvic irradiation.

Scanditronix, EDE type, detectors covered with a hemi-spherical perspex build-up cap with a water-equivalent thickness of 5 mm.

Dosimeters were connected to a Scanditronix DPD 10-channel electrometer

Clinical example

<table>
<thead>
<tr>
<th></th>
<th>Lung, mediastinum</th>
<th>Brain, head and neck</th>
<th>Pelvis (anterior/posterior)</th>
<th>Pelvis (left/right)</th>
<th>Breast</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>112</td>
<td>98</td>
<td>97</td>
<td>53</td>
<td>156</td>
</tr>
<tr>
<td>$\bar{X}$</td>
<td>-0.8</td>
<td>-1.6</td>
<td>0.2</td>
<td>0.43</td>
<td>-2.5</td>
</tr>
<tr>
<td>SD</td>
<td>2.1</td>
<td>1.9</td>
<td>2.3</td>
<td>3.2</td>
<td>3.6</td>
</tr>
<tr>
<td>$D&gt;5%$</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>37</td>
</tr>
</tbody>
</table>

$N$, number of measurements; $\bar{X}$, mean deviation; SD, standard deviation; $D>5\%$, number of deviation >5%.