Principles of dosimetry –
The ionization chamber

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Ionometry

- Ionometry: the measurement of the number of ionizations in substance
- The number of ionizations are used as a measure of the radiation dose
- Air filled ionizing chamber (*thimble*):
Ionometry 2)

- High voltage between central and outer electrode
- Air ionized, electrons emitted from the atoms
- The electrons moves to the positive electrode
- Current induced
- An electrometer then count the number of total charges \( Q \) (of one type of charged \(+/-\))
- \( Q \) is proportional with the dose to the air volume
Exposure

- *The exposure, $X$: the number of charges $Q$ (ether positive or negative) which is produced in the gas with mass $m$ as a result of the radiation:*

  $$X = \frac{dQ}{dm}$$

- The number of charges produced in the gas must be proportional with the dose; $X \propto D_{\text{air}}$

- The value connecting $X$ and $D_{\text{air}}$ is the mean energy expended in a gas per ion pair formed $\overline{W}$
The mean energy per ion pair, $\overline{W}$

• Definition of $\overline{W}$:
  
  — Charged particles with kinetic energy $T_0$ is stopped inside the gas:

  ![Diagram of charged particles]

  — Energy deposit per ion pair detected:
    $W = NT_0$ (the bremsstrahlung of electrons ought to be corrected for)

  — Mean energy per charge:
    $\overline{W} = \frac{NT_0}{eQ}$
Dose to air, $D_{\text{air}}$

- Air has $\overline{W}/e = 33.97 \text{ J/C}$

- Then the dose to air becomes:

$$D_{\text{air}} = \frac{N T_0}{m} = \frac{Q}{m} \left( \frac{W}{e} \right)_{\text{air}} = X \left( \frac{W}{e} \right)_{\text{air}}$$

- Thereby: when measuring the number of charges produced per unit of mass air, the $D_{\text{air}}$ can be determined – independent of the type and energy of the ionizing radiation ($\overline{W}/e$ is close to constant for all electrons and photon energies)
Dose to air, \( D_{\text{air}} \)

- When CPE is present inside the ionizing chamber, will the dose as a result of the photon exposure be given by:
  \[
  D_{\text{air}}^{\text{CPE}} = K_{c,\text{air}} = \Psi \left( \frac{\mu_{\text{en}}}{\rho} \right)_{\text{air}} = X \left( \frac{\overline{W}}{e} \right)_{\text{air}}
  \]

- The exposure can thereby be expressed by:
  \[
  X = \Psi \left( \frac{\mu_{\text{en}}}{\rho} \right)_{\text{air}} \left( \frac{\overline{W}}{e} \right)_{\text{air}}^{-1}
  \]

- If the primary field is charged particles, Bragg-Gray theory is used:
  \[
  X = \Phi \left( \frac{dT}{\rho dx} \right)_{\text{air}} \left( \frac{\overline{W}}{e} \right)_{\text{air}}^{-1}
  \]
Exposure, example 1)

- An electrometer and an air filled ionizing chamber (volume = 0.65 cm$^3$) measure the number of charges $Q = 50 \text{nC}$ in 2 minutes – the radiation source is 100 keV monoenergetic photons (CPE assumed)

- Exposure:

$$X = \frac{Q}{m \rho V} = \frac{50 \times 10^{-9} \text{C}}{1.2 \times 10^{-3} \text{g/cm}^3 \times 0.65 \text{cm}^3} = 0.064 \text{ C/kg}$$

- What is the energy fluence of the photon field?

$$\Psi = X \left( \frac{\mu_{en}}{\rho} \right)_{air} \left( \frac{W}{e} \right)_{air} \left( \frac{\mu}{\rho} \right)_{en \text{ from table}}$$

$$= 0.064 \text{ C/kg} \times \frac{1}{0.0234 \text{ cm}^2/\text{g}} \times 33.97 \text{ J/C} = 0.093 \text{ J/cm}^2$$
Exposure, example 2)

- What is the dose to air and what is dose rate?
  \[ D_{\text{air}} = X \left( \frac{\overline{W}}{e} \right)_{\text{air}} = 0.064 \text{ C/kg} \times 33.97 \text{ J/C} = 2.2 \text{ J/kg} = 2.2 \text{ Gy} \]
  \[ \dot{D}_{\text{air}} = \frac{\Delta D_{\text{air}}}{\Delta t} = \frac{2.2 \text{ Gy}}{2 \text{ min}} = 1.1 \text{ Gy/min} = 18.3 \text{ mGy/s} \]

- If the ionizing chamber is placed in water what is the dose to water?
  \[ \frac{D_{\text{water}}}{D_{\text{air}}} = \left( \frac{\mu_{\text{en}}}{\rho} \right)_{\text{water}} = \frac{0.0256}{0.0234} = 1.094 \]
  \[ D_{\text{water}} = 1.094 \times D_{\text{air}} = 1.094 \times 2.2 \text{ Gy} = 2.4 \text{ Gy} \]
Exposure, example 3)

- If the same exposure is produced by 100 MeV protons, what is the energy fluence of that field?

- Bragg-Gray theory is used:

\[
D_{\text{air}} = \Phi \left( \frac{dT}{\rho dx} \right)_{\text{air}} = X \left( \frac{W}{e} \right)_{\text{air}} \quad (\overline{W}/e \text{ assumed to be } 33.97 \text{ J/C})
\]

- The proton energy is ~unchanged over the air cavity:

\[
\Rightarrow \Psi = \Phi T_0 \quad \Rightarrow \quad \frac{\Psi}{T_0} = X \left( \frac{W}{e} \right)_{\text{air}} \left( \frac{dT}{\rho dx} \right)_{\text{air}}^{-1}
\]

\[
\Rightarrow \Psi = XT_0 \left( \frac{W}{e} \right)_{\text{air}} \left( \frac{dT}{\rho dx} \right)_{\text{air}}^{-1}
\]

\[
= \frac{0.064 \text{ C/kg} \times 100 \text{ MeV} \times 33.97 \text{ J/C}}{6.43 \text{ MeV cm}^2 / g} = 0.034 \text{ J/cm}^2
\]
Exposure, example 4)

- Dose to air:
  \[ D_{\text{air}} = X \left( \frac{W}{e} \right)_{\text{air}} = 0.064 \text{ C/kg} \times 33.97 \text{ J/C} = 2.2 \text{ Gy} \]

(has to be the same as of photon, because it gave the same exposure)

- Dose to water:
  \[ \frac{D_{\text{water}}}{D_{\text{air}}} = \left( \frac{dT}{\rho dx} \right)_{\text{water}} = \frac{7.29}{6.34} = 1.13 \]

  \[ \Rightarrow D_{\text{water}} = 1.13 \times D_{\text{air}} = 1.13 \times 2.2 \text{ Gy} = 2.5 \text{ Gy} \]

- The equal exposure of air by photons or protons give the equal doses to air but not to water!
Ionizing chamber, use 1)

- The problem with the ionizing chamber is among other difficulties to precisely decide the size of the air volume – increase the uncertainty in dose.
- In practice is the chamber calibrated in a point of the radiation field where the dose is known – done at a primary standard laboratory (PSDL).

A certain dose gives a measured value $M$. 

$\gamma$, e$^-$, …
Ionizing chamber, use 2)

- A certain dose to water $D_{\text{water}}$ gives a measured value $M$. Then:
  $$D_{\text{water}} \propto M \iff D_{\text{water}} = M \cdot N_{D,\text{water}}$$

- The calibration factor of the chamber is then:
  $$N_{D,\text{water}} = \frac{D_{\text{water}}}{M}$$

- The dose is then established from the (measured) calibration factor – do not have to use $W/e$, $\mu_{\text{en}}/\rho$ or $dT/\rho dx$
• But: the calibration factor is (weakly) dependent of radiation type and energy.

• Usually the calibration takes place in a well known radiation field as that of $^{60}$Co $\gamma$-rays (mean energy 1.25 MeV)

• The corrections in the calibration factor, $k_Q$, is then introduced for other radiation qualities ($radiation qualities, Q$)

• The dose is then given by:

$$D_{water,Q} = M_Q \cdot N_{D,water} \cdot k_Q$$
Ionizing chamber, use 4)

- $k_Q$ is named the energy correction factor; shown below in the case of high energy photons:

![Graph showing the relationship between $k_Q$ and Photon Beam Quality Q (TPR_{20,10}).](image)

- $k_Q$ values are shown as a function of Photon Beam Quality Q, with error bars indicating variability.

- The x-axis represents Photon Beam Quality Q (TPR_{20,10}) with values 1, 3.5, and 6.

- The y-axis shows $k_Q$ values ranging from 0.95 to 1.01.

- The graph includes a line of best fit and data points, indicating the approximate mean photon energy, MeV.
Other methods 1)

• The method and theory explained is basically the same also in other measuring methods – the measurable unit $M$ is transferred into dose by a calibration factor.

• Example: *EPR dosimetry*. To calibrate are dosimeters radiated in a known radiation field ($^{60}$Co-$\gamma$) to a known dose. The EPR-intensity of the dosimeters ($M$) is then proportional with the dose. The calibration factor of the dosimeters will then be determined as described above. $k_Q$ must then be found if other *radiation qualities* if these are to be used.
Other methods 2)

- Calorimetric: measure the temperature in detector – very good method in absolute dosimetry:

\[
\Delta \text{Temp} = \frac{\varepsilon (1-\delta)}{hm} = \frac{D(1-\delta)}{h}
\]

\[\Rightarrow D = \frac{h \Delta \text{temp}}{(1-\delta)}\]

\(\delta\): thermal defect

\(h\): heat capacity
Other methods 3)

- Semiconductor dosimetry: current induced by the radiation over the depletion layer. Current proportional with the dose rate.