Chapter XII: Chemical dosimeters

Chemical dosimeters

- Introduction
- Fricke dosimeter
- Polymer gel dosimeter
- Alanine dosimeter
- Radiochromic film

Principle of chemical dosimeters

- In a chemical dosimeter → the dose is determined from a measurable modification of the chemical state of the considered medium (gas, liquid or solid)
- Any well-characterized chemical reaction may serve as the basis for a chemical dosimeter

Fricke dosimeter: Composition

- The standard Fricke dosimeter is a solution composed of ferrous sulfate ($FeSO_4$ → Fe as Fe^{2+}) and of sulfuric acid (H_2SO_4) in water or in a gel (→ Fricke dosimetry is thus assimilated in this case to gel dosimetry)

- Organic contaminants can significantly affect performance → high purity is necessary

- NaCl is sometimes added to reduce or eliminate any sensitivity to organic impurities → NaCl has no effect on the dosimetric reaction except at high dose → in this case, to be avoided

Dosimetric principle

- The detector is based on the reaction ferrous sulfate → ferric sulfate ($Fe_2(SO_4)_3$) i.e. → Fe^{2+} → Fe^{3+}
- The ionizing radiations induce this reaction either by direct absorption (rare) either via the free radicals produced in water → H* and OH* (frequent in water because water is the dominating medium → radiations especially interact with water)
- Chemical reactions →

HO_2^*: hydridodioxygen
OH*: hydroxyl
H_2O_2: hydrogen peroxide

1ère étape

$$H^* + O_2 \rightarrow HO_2^*$$
$$HO_2^* + Fe^{2+} \rightarrow HO_2^- + Fe^{3+}$$
$$HO_2^- + H^+ \rightarrow H_2O_2$$

2ème étape

$$OH^* + Fe^{2+} \rightarrow Fe^{3+} + OH^-$$
$$OH^- + H^+ \rightarrow H_2O$$

because acid medium

3ème étape

$$H_2O_2 + 2Fe^{2+} \rightarrow 2Fe^{3+} + 2OH^-$$
$$OH^- + H^+ \rightarrow H_2O$$

Measurement of the production of Fe^{3+}

The measurement may be done by

- Chemical titration
- Nuclear magnetic resonance (measurement of the paramagnetic properties)
- Optical absorption → most often used because good sensitivity, only requires small samples and easy to implement (Fe^{3+} → blue color)

Optical absorption

- Principle of optical absorption → measurement of ΔM: the variation of molar concentration (mol/l) of Fe^{3+} before and after the irradiation
- We consider the ratio between the light intensity transmitted through the irradiated sample (I) and another one which was not irradiated (I_0) →

$$\frac{I}{I_0} = 10^{-\Delta(OD)}$$

  with $\Delta(OD)$ the modification of optical density
- And we have with the Beer-Lambert expression →

$$\Delta(OD) = \epsilon l \Delta M$$

  with ϵ: the molar absorption (or extinction) coefficient (ϵ = 2187 l/mol at 25 °C for Fe^{3+}), l: the size of the sample (≈ 1cm)

Dose ↔ Optical absorption

- By definition →

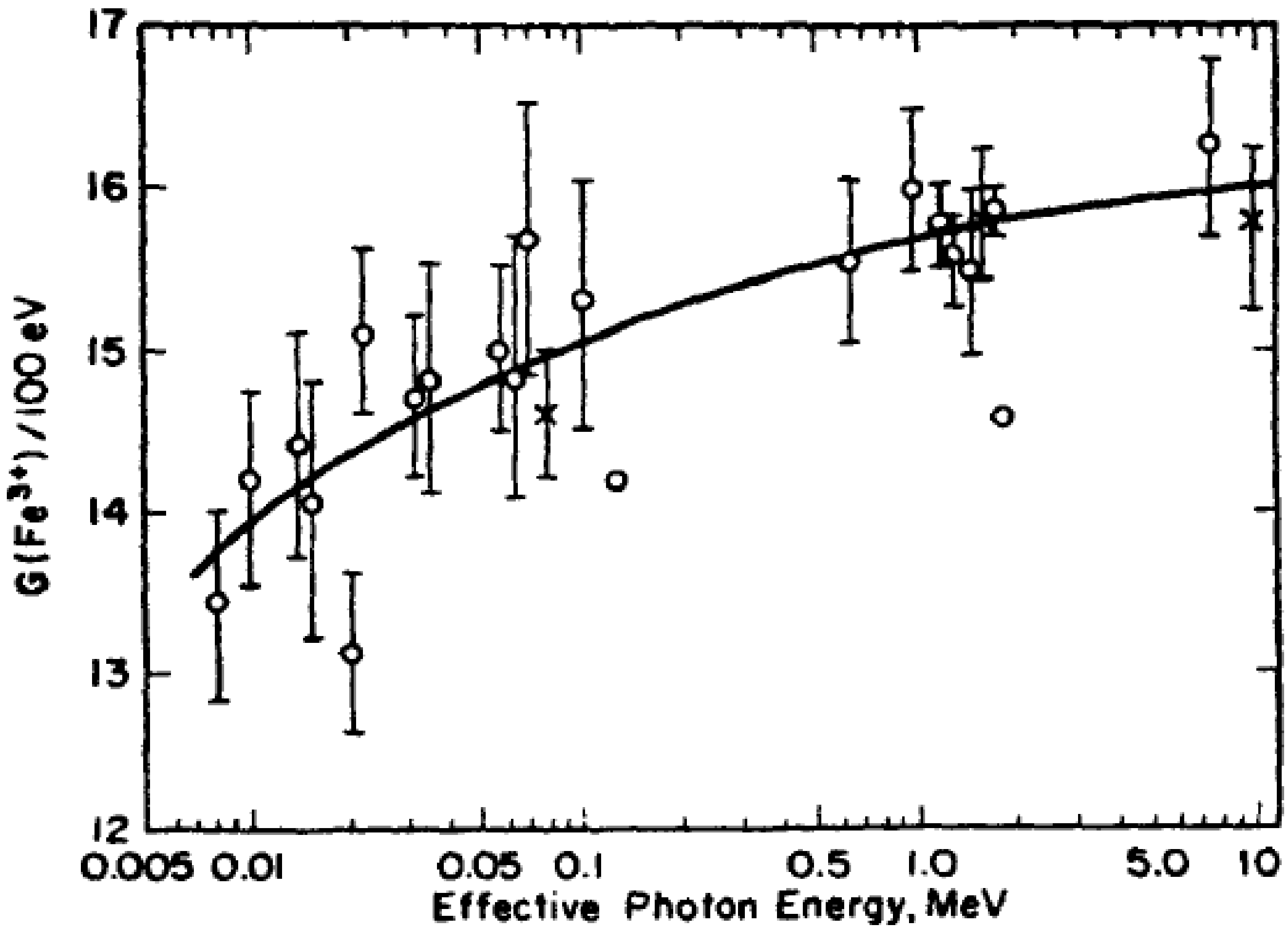
$$\overline{D} = \frac{\Delta M}{\rho G(Fe^{3+})}$$

with ρ, the « density » of the solution (in kg/l) and $G(Fe^{3+})$ (in mol/J), the chemical yield of Fe^{3+} (i.e. the quantity of Fe^{3+} produced per unit of incident energy → depends on the type and on the energy of the incident particles) → for ^{60}Co-γ → $G(Fe^{3+}) = 1.607 \times 10^{-6}$ mol/j

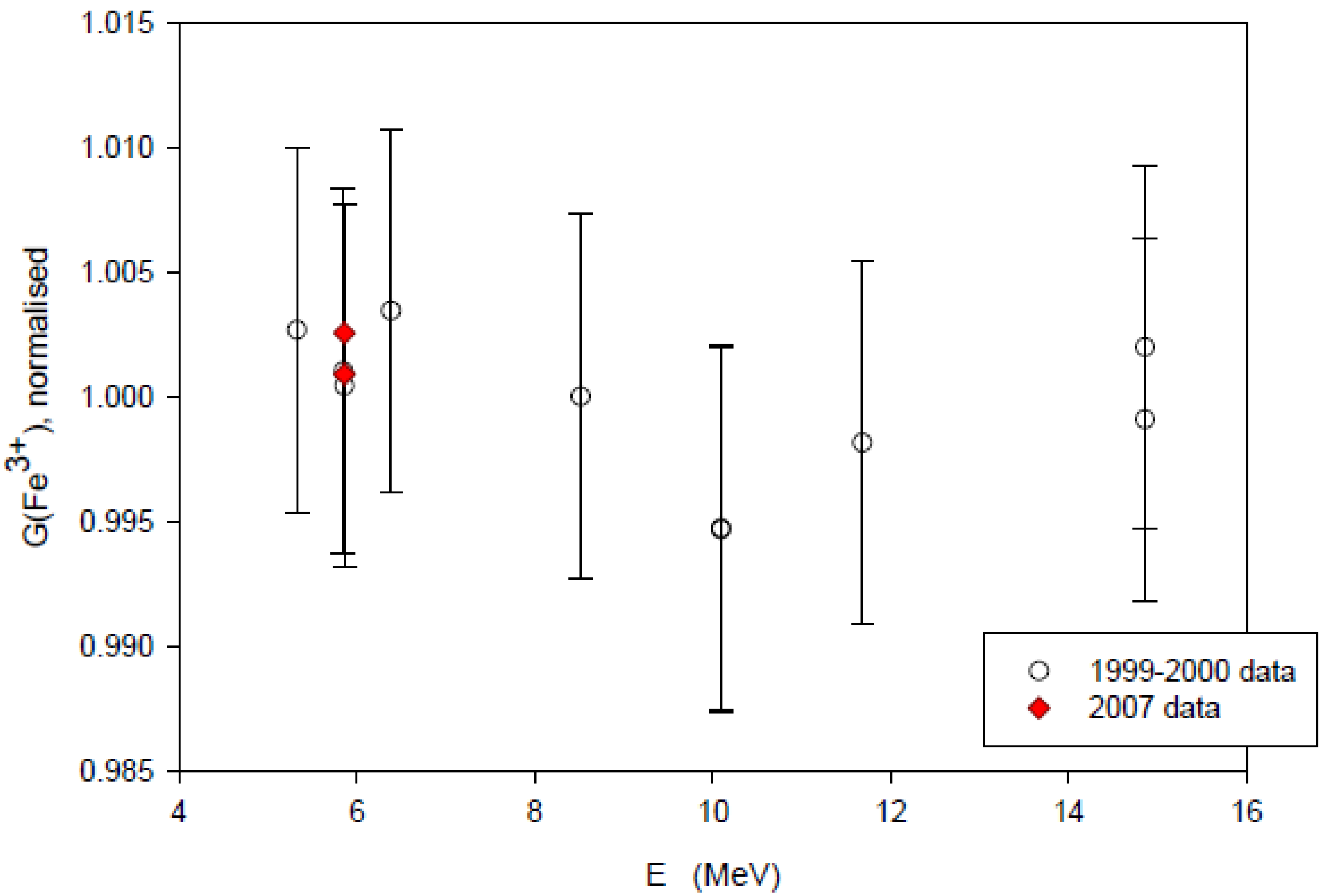
- We obtain thus →

$$\overline{D} = \frac{\Delta(OD)}{\epsilon l \rho G(Fe^{3+})} \quad \Rightarrow \quad \overline{D} = 278\Delta(OD) \quad \mathrm{Gy}$$

Chemical yield as a function of E for γ-rays



Chemical yield as a function of E for e^-



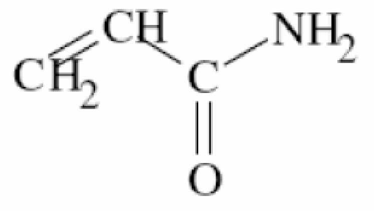
Applications of Fricke dosimeters

- Dose response linear between ≈ 4 Gy and 4000 Gy
- Z and μ_{en}/ρ close to values of water → tissue-equivalent
- Variable shape and volume
- Absolute dosimeter
- Little stable in time → major defect
- Use and readout are complex → major defect
- High lower dose limit → major defect
- Large dependence on E and on particle type → major defect

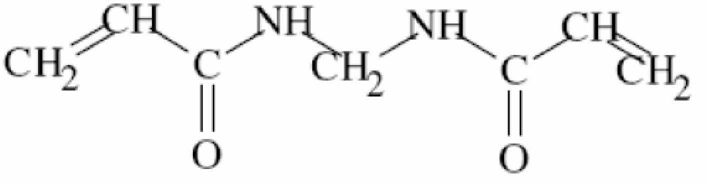
→ **Gradual disappearance**

Polymer gel dosimeter

- In a polymer gel → monomers dispersed into a matrix → example: acrylamide (C_3H_5NO) dispersed into gelatin



- Exposed to irradiation → the monomers follow a polymerization reaction (polyacrylamide)→ polymerized gel in 3D



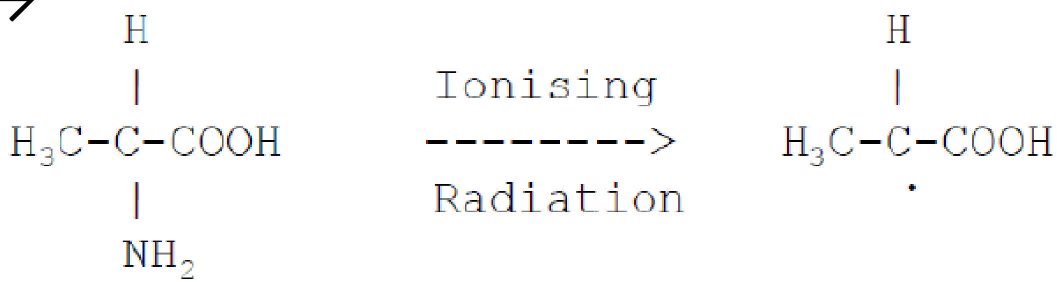
- The degree of polymerization depends on the dose
- The dose can be evaluated by RMN, tomodensitometry (scanner-X), optical tomography (IR), …

Advantages and disadvantages of gels

- Easily commercially available and cheap
- Due to the large proportion of water in gel → water-equivalent → little corrections needed for the energy response
- Possible 3D measurements
- Perfectly adapted for measurements showing large spatial variations of dose → application in stereotaxic radio-surgery
- Access to a RMN, scanner machine is necessary → not so obvious
- Little sensitive → applications in radiotherapy

Alanine dosimetry

- The irradiation of the alanine amino acid produces stable alkyl free radicals →



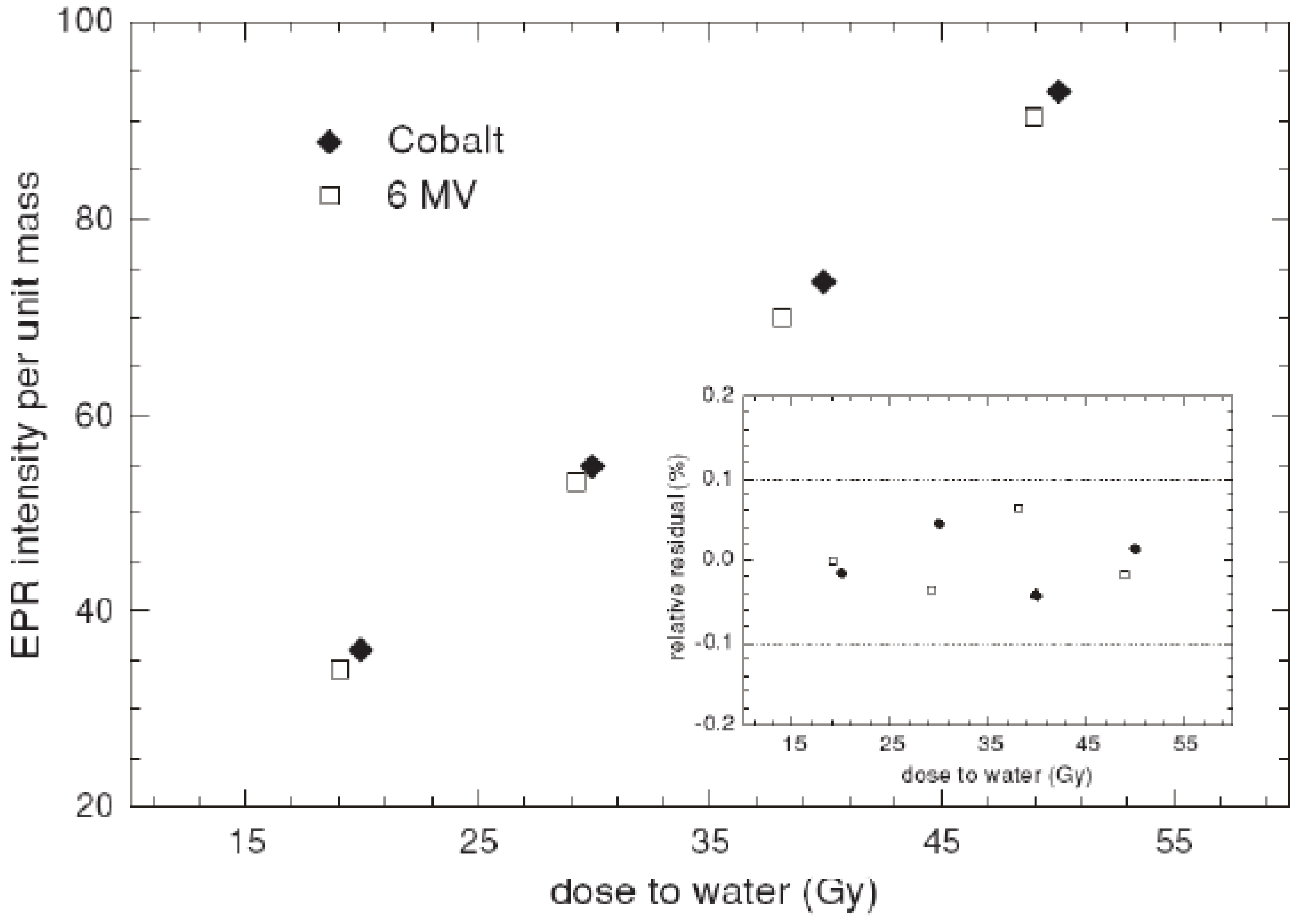
- Concentration of free radicals $\propto$ absorbed dose and measured by electron paramagnetic resonance or EPR (technique similar to RMN but the spins of the e^- are excited instead of the spins of the atomic nuclei)

Alanine for dosimrtry

Pastilles of alanine

Machine of EPR

Dose response



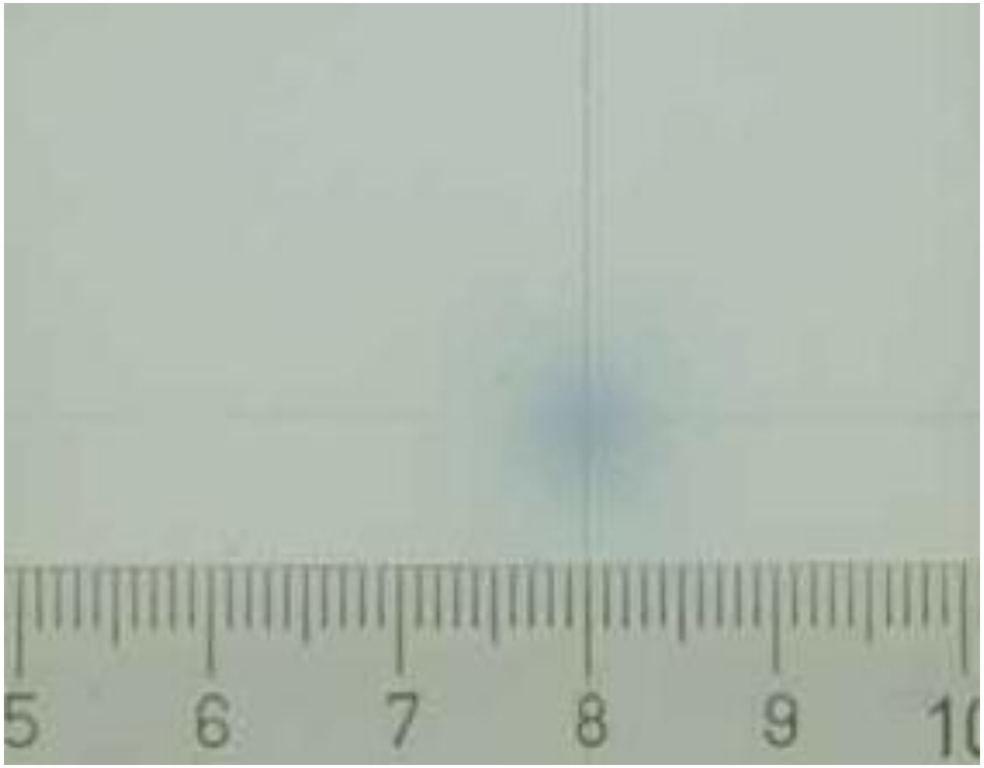
Advantages and disadvantages

- Relatively tissue-equivalent
- Good linearity with the dose
- Small volume
- High lower dose limit → applications in radiotherapy
- Large range of dose measurement → 0.5 – 100 kGy
- Need an EPR machine → little available → major defect

Radiochromic film

- Radiochromic films are translucent films showing a blue color after irradiation
- After the irradiation, the diacetylene crystals (monomers) constituting the film are polymerized giving the blue color of the irradiated film
- Reaction → diacetylene monomers ($H{-}C{\equiv}C{-}C{\equiv}C{-}H$) → acetylene polymer ($H{-}C{\equiv}C{-}H$) with a carbene (carbon atom with 2 non-bounded e^-) linked to the end of each polymer chain
- Analyze by densitometry

Example of result with a radiochromic film



Positioning test for a Gamma Knife

Characteristics of the radiochromic films (1)

- High lower dose limit ($\sim$ Gy) → applications in radiotherapy
- No development → no quality control needed
- Films without « grain » → very good spatial resolution
- Perfectly adapted for measurements showing large spatial variations of dose
- Dose response linear between $\sim$ Gy and a few kGy

Characteristics of the radiochromic films (2)

- Little sensitive to sun light
- Can be cut in any requested shape
- Not very different from tissue-equivalent
- Possible storage
- Small sensitivity → important defect

Could potentially play an increasing role for dosimetry in radiotherapy