Properties of a dosimetric material from an experimental point of view

Guerda Massillon-JL

massillon@fisica.unam.mx

Instituto de Física

Universidad Nacional Autónoma de México, México

Dosimetry

Radiation dosimetry is based on the understanding of the energy deposited into the matter by ionizing radiation and its quantification in terms of absorbed dose

Dosimetry

Absorbed dose: **Energy deposited in matter due to interaction of ionizing radiation per unit of mass**

$$D = \frac{dE}{dm} \text{ (1 J/kg =1 Gy)}$$

Dosimeter: **material with a sensitive volume that provides a response related to the energy deposited**

Objective of Dosimetry

Determination of the correct absorbed dose within a given medium

↓

Accurate and precise knowledge of:

Relation between the energy deposited within a dosimeter’s sensitive volume and its corresponding response

Where radiation dosimetry is needed?

1. Medical applications
2. Space trips
3. Nuclear Reactors
4. Accidental monitoring
5. Biological applications
6. Food conservations

Medical physics dosimetry

Fundamental to evaluate the energy absorbed by human being due to exposition to ionizing radiation during:

1. Treatments
2. Diagnosis
3. Early detection
4. Prevention

Which area of Medical physics, dosimetry is needed?

Treatments

1. Low-energy photon brachytherapy sources
2. Intravascular brachytherapy beta particle sources
3. Use of small fields in radiotherapy techniques:
    a) Stereotactic Radiosurgery
    b) Intensity modulated radiation therapy
    c) New radiotherapy techniques
4. Ion therapy

Which area of Medical physics, dosimetry is needed?

Diagnosis

1 Mammography
2 Computerized Tomography
3 Dental radiography
4 Fluoroscopy
5 General radiography

Medical Radiation Dosimetry

Objectives

Treatments

To deliver the absorbed dose accurately to increase the tumor control and minimize the normal tissue complication probability

The rate of the tumor volume control depends on absorbed dose

Diagnosis

To deliver an amount of dose enough to obtain a high-quality image for a better evaluation by the physician and avoid irreversible damage to the patient

Medical Radiation Dosimetry

Dosimeters that are commonly used

Ionization chambers (1D),
Thermoluminescent (TL) dosimeters (1D)
Optically stimulated (OSL) dosimeters (1D and 2D?)
Diode detectors, semiconductors etc. (1D)
Detector arrays (2D) poor spatial resolution
Radiochromic films (2D) good spatial resolution
Gel dosimetry (3D)

Medical Radiation Dosimetry

What you need to know before using a given dosimeter

For Ionization chambers, diodes and semiconductors

IAEA-TRS-398 (2005), TRS-483 (2017), TRS-457 (2007), AAPM-T51 (1999, 2024), AAPM-TG61 (2001)

For TL and OSL dosimeters:

AAPM-TG-191:Clinical use of luminescent and optically stimulated dosimeters: TLDs and OSLDs

Med. Phys. **47** (2020) e19

For radiochromic films:

Report of AAPM Task Group 235 Radiochromic Film Dosimetry: An Update to TG-55

Med Phys **47** (2020) 5986

9.1 INTRODUCTION

9.1.5 Reference dosimetry with ionization chambers

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS

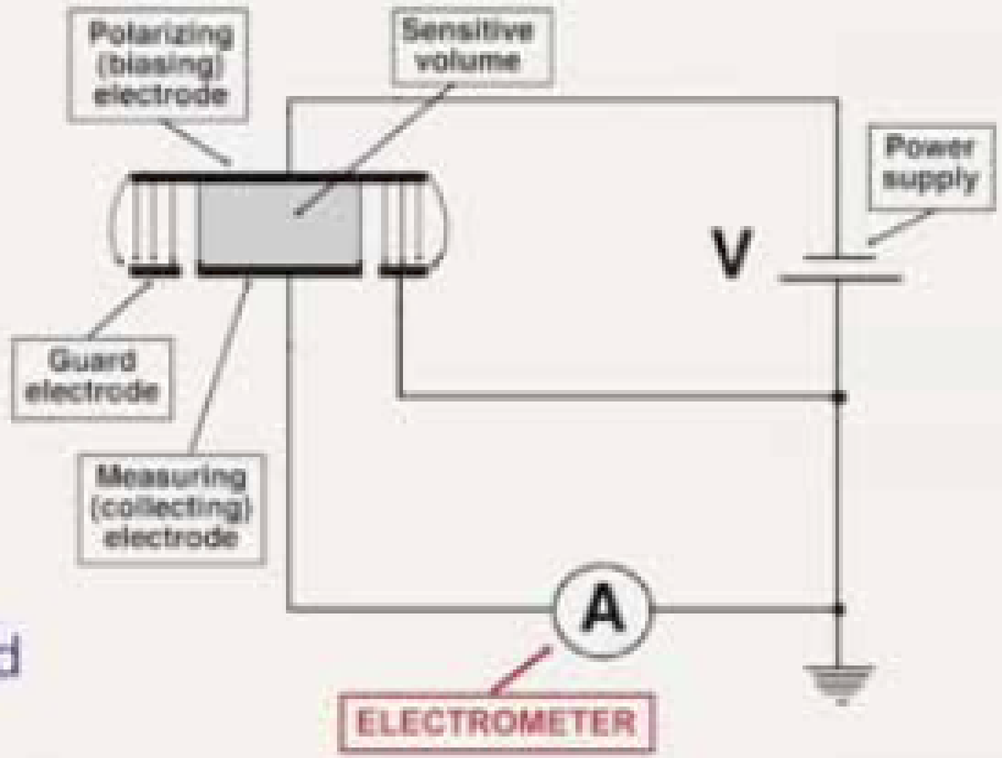
9.2.2 Electrometer and power supply

- ☐ Ionization chamber is essentially a capacitor

  in which leakage current or leakage charge is induced through the action of a radiation beam.

- ☐ Charge or current induced in the chamber

  are very small and are measured by a very sensitive charge or current measuring device called an electrometer.



9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS

9.2.1 Ionization chambers

- ☐ Air is usually used as the sensitive gas in an ionization chamber.
- ☐ Some of the electrons released in the chamber wall enter the chamber sensitive volume and ionize the air through Coulomb interactions with the air molecules producing low energy electrons and positive ions.

9.3 CHAMBER SIGNAL CORRECTIONS FOR INFLUENCE QUANTITIES

- ☐ For each ionization chamber, reference conditions are described by a set of influence quantities for which a chamber calibration coefficient is valid without any further corrections.
  - Influence quantities are defined as quantities that are not the subject of a measurement but yet influence the value of the quantity that is being measured.
  - If the chamber is used under conditions that differ from the reference conditions, then the measured signal must be corrected for influence quantities.

9.3 CHAMBER SIGNAL CORRECTIONS FOR INFLUENCE QUANTITIES

☐ Examples of influence quantities in ionization chamber dosimetry measurements are:

- Ambient air temperature
- Ambient air pressure
- Ambient air humidity
- Applied chamber voltage
- Applied chamber polarity
- Chamber leakage currents
- Chamber stem effects

Medical Radiation Dosimetry

Thermoluminescent dosimeters.

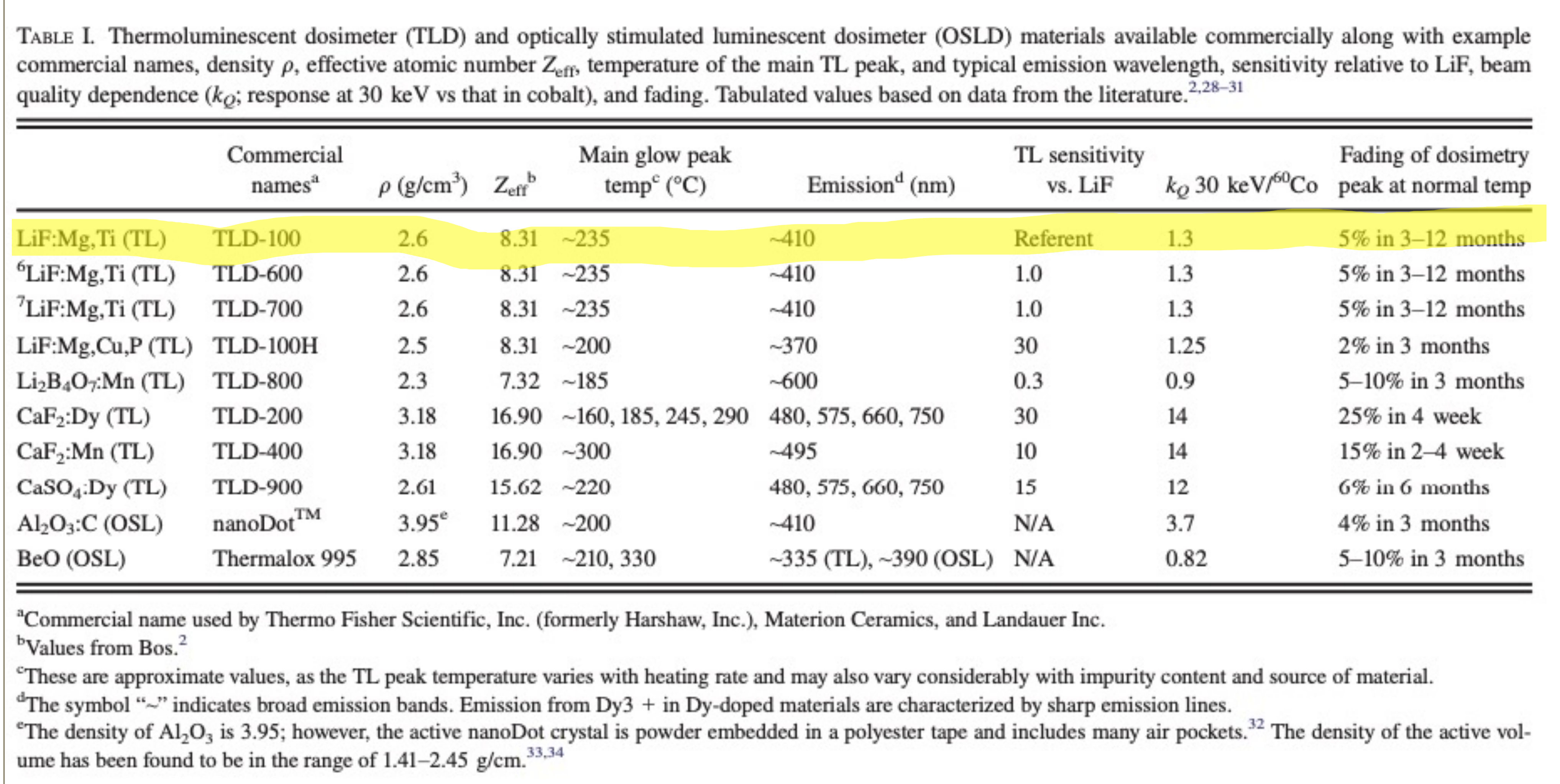


Table I. Thermoluminescent dosimeter (TLD) and optically stimulated luminescent dosimeter (OSLD) materials available commercially along with example commercial names, density ρ, effective atomic number Z_{eff}, temperature of the main TL peak, and typical emission wavelength, sensitivity relative to LiF, beam quality dependence (k_Q; response at 30 keV vs that in cobalt), and fading. Tabulated values based on data from the literature.[2,28–31]

	Commercial names[a]	ρ (g/cm^3)	Z_{eff}[b]	Main glow peak temp[c] (°C)	Emission[d] (nm)	TL sensitivity vs. LiF	k_Q 30 keV/^{60}Co	Fading of dosimetry peak at normal temp
LiF:Mg,Ti (TL)	TLD-100	2.6	8.31	~235	~410	Referent	1.3	5% in 3–12 months
^{6}LiF:Mg,Ti (TL)	TLD-600	2.6	8.31	~235	~410	1.0	1.3	5% in 3–12 months
^{7}LiF:Mg,Ti (TL)	TLD-700	2.6	8.31	~235	~410	1.0	1.3	5% in 3–12 months
LiF:Mg,Cu,P (TL)	TLD-100H	2.5	8.31	~200	~370	30	1.25	2% in 3 months
$Li_2B_4O_7$:Mn (TL)	TLD-800	2.3	7.32	~185	~600	0.3	0.9	5–10% in 3 months
CaF_2:Dy (TL)	TLD-200	3.18	16.90	~160, 185, 245, 290	480, 575, 660, 750	30	14	25% in 4 week
CaF_2:Mn (TL)	TLD-400	3.18	16.90	~300	~495	10	14	15% in 2–4 week
$CaSO_4$:Dy (TL)	TLD-900	2.61	15.62	~220	480, 575, 660, 750	15	12	6% in 6 months
Al_2O_3:C (OSL)	nanoDot™	3.95[e]	11.28	~200	~410	N/A	3.7	4% in 3 months
BeO (OSL)	Thermalox 995	2.85	7.21	~210, 330	~335 (TL), ~390 (OSL)	N/A	0.82	5–10% in 3 months

[a] Commercial name used by Thermo Fisher Scientific, Inc. (formerly Harshaw, Inc.), Materion Ceramics, and Landauer Inc.

[b] Values from Bos.[2]

[c] These are approximate values, as the TL peak temperature varies with heating rate and may also vary considerably with impurity content and source of material.

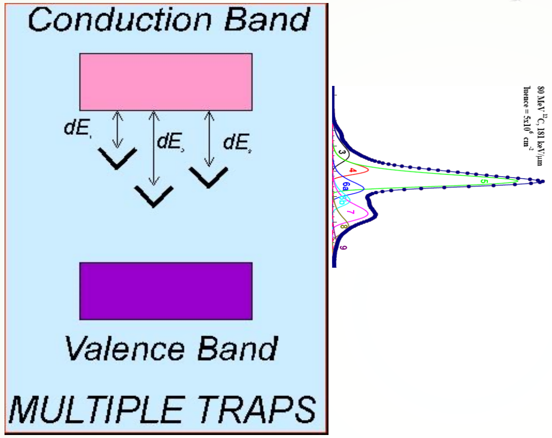
[d] The symbol "~" indicates broad emission bands. Emission from Dy3 + in Dy-doped materials are characterized by sharp emission lines.

[e] The density of Al_2O_3 is 3.95; however, the active nanoDot crystal is powder embedded in a polyester tape and includes many air pockets.[32] The density of the active volume has been found to be in the range of 1.41–2.45 g/cm.[33,34]

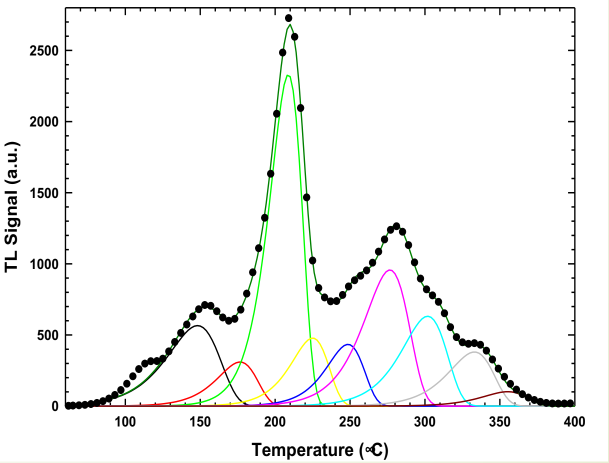
TG-191

TLDs and OSLDs?

- ❖ Irradiation
- ❖ Readout
- ❖ Quantification
  - ➢ emited light
  - ➢ The glow curve is interpreted in terms of defect states

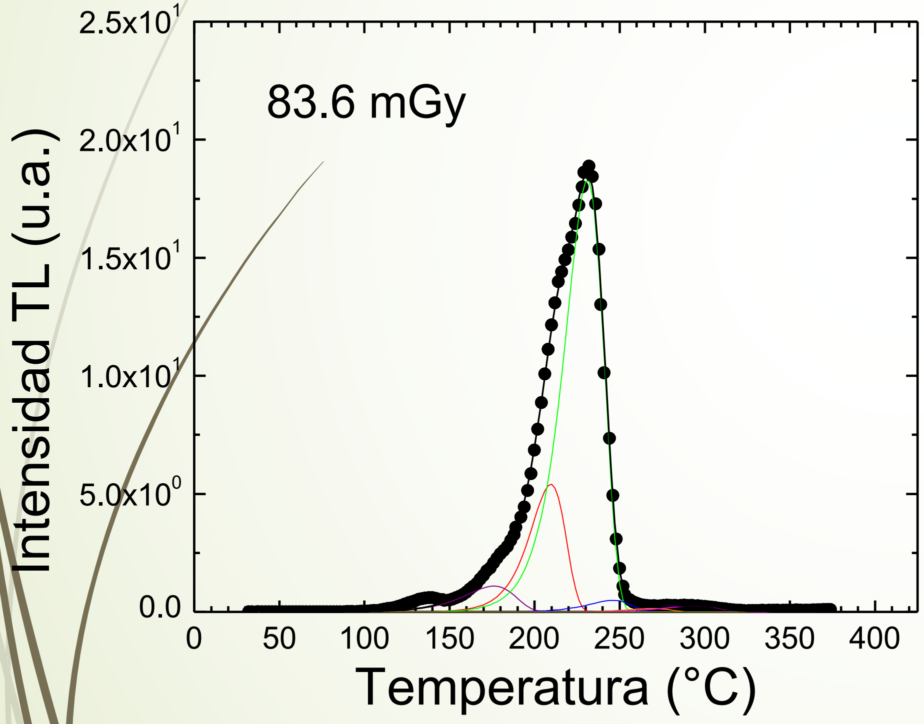


LiF:Ti,Mg

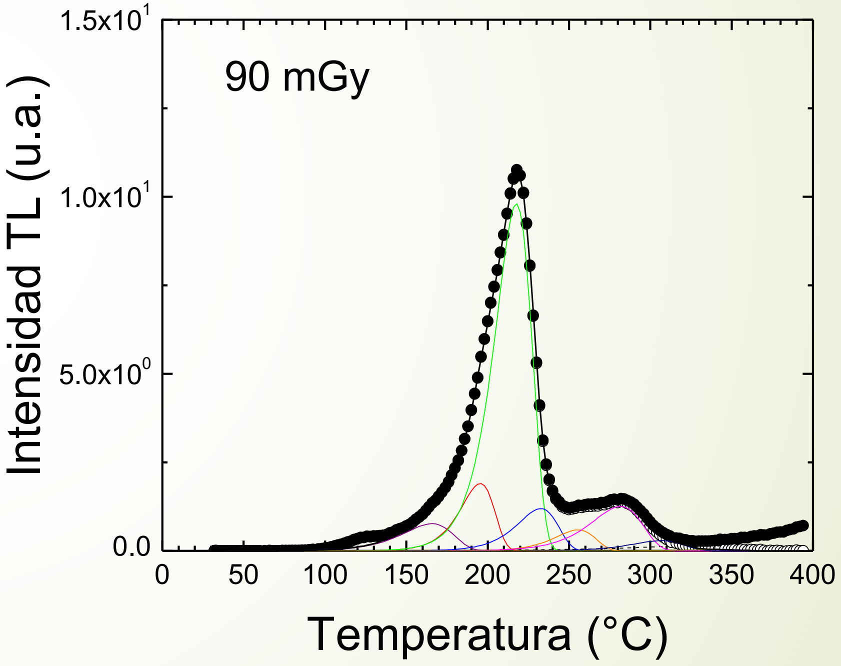


The shape of the TL glow curve depend on the radiation quality

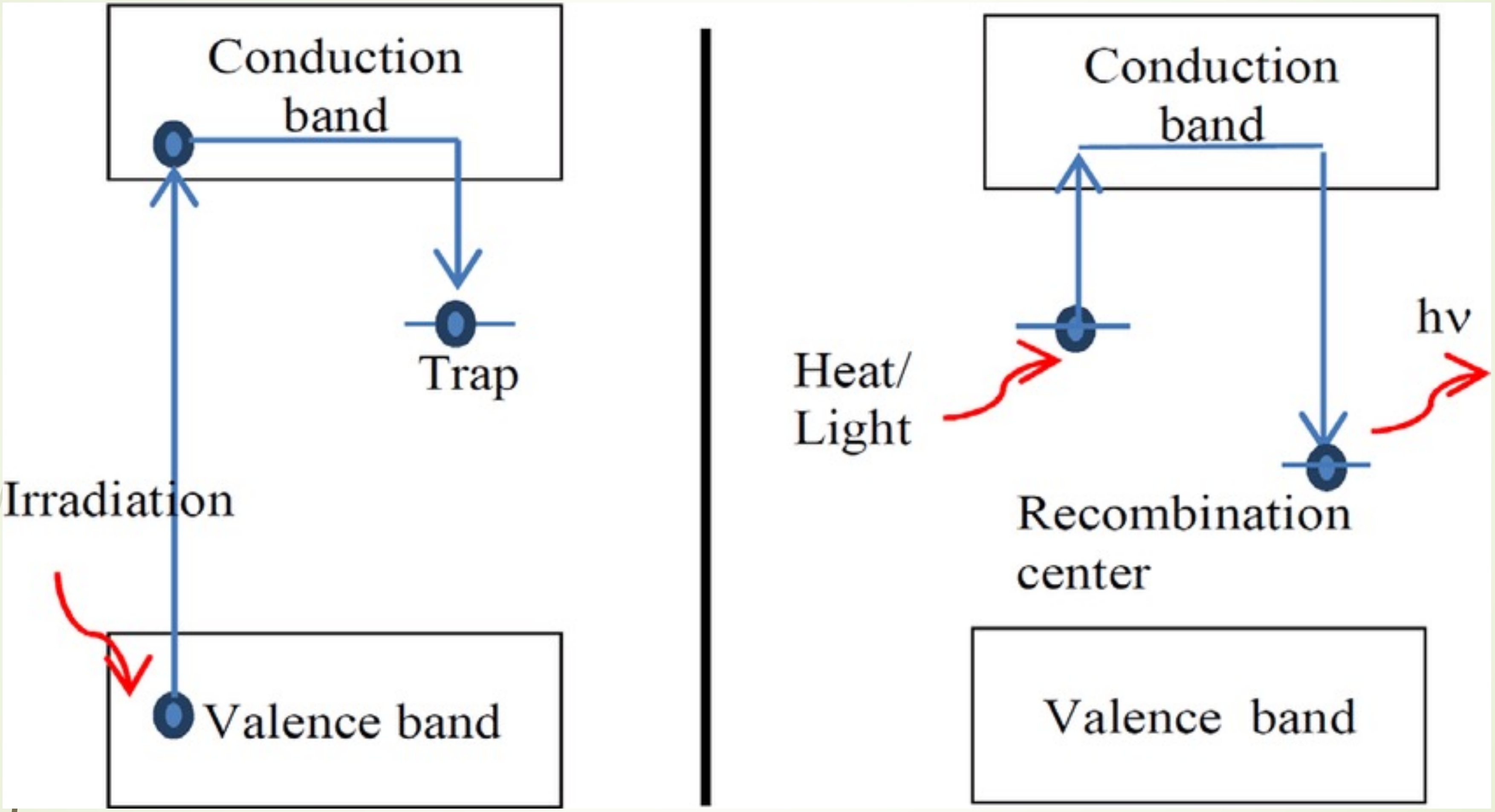
Gamma rays



Ions



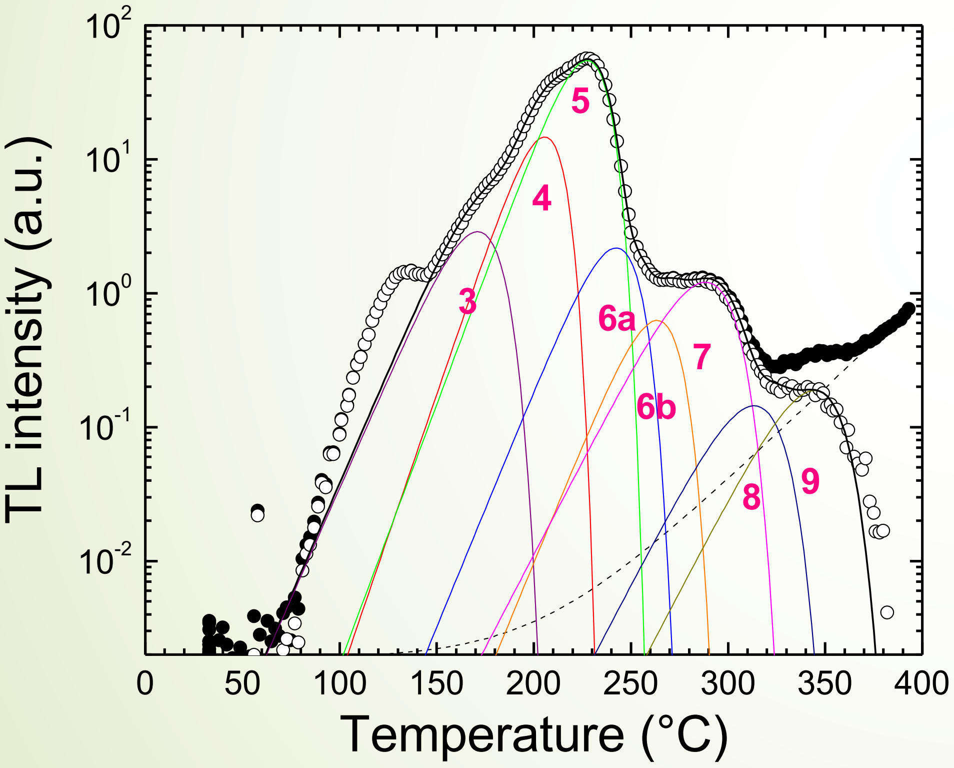
TL and OSL processes

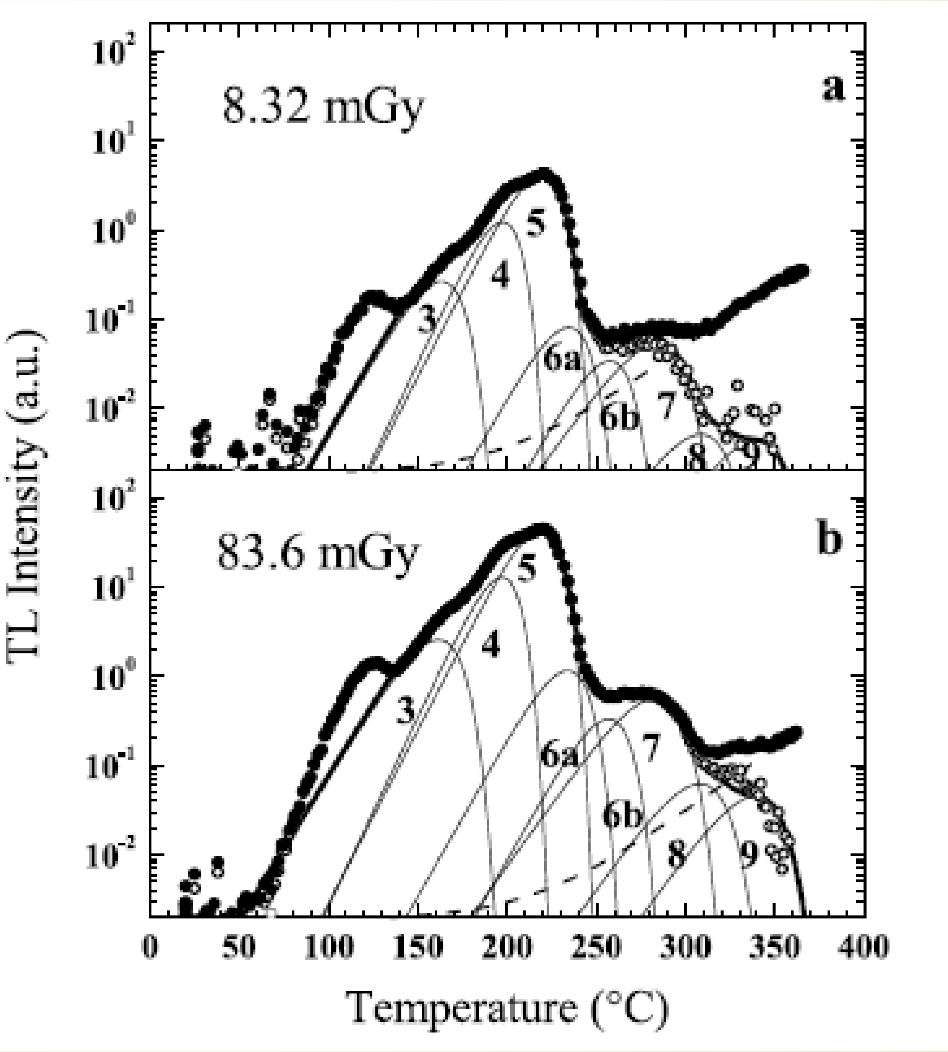


TL glow curve of TLD-100 after exposure to ions and gamma rays

Massillon-JL et al, J. Phys. D: App. Phys 39 (2006) 262-268

G Massillon-JL, PhD Thesis UNAM 2006





The TL response is linear, supralinear and sub-linear

Massillon-JL et al. J. Phys. D: Appl. Phys. **39** (2006) 262–268

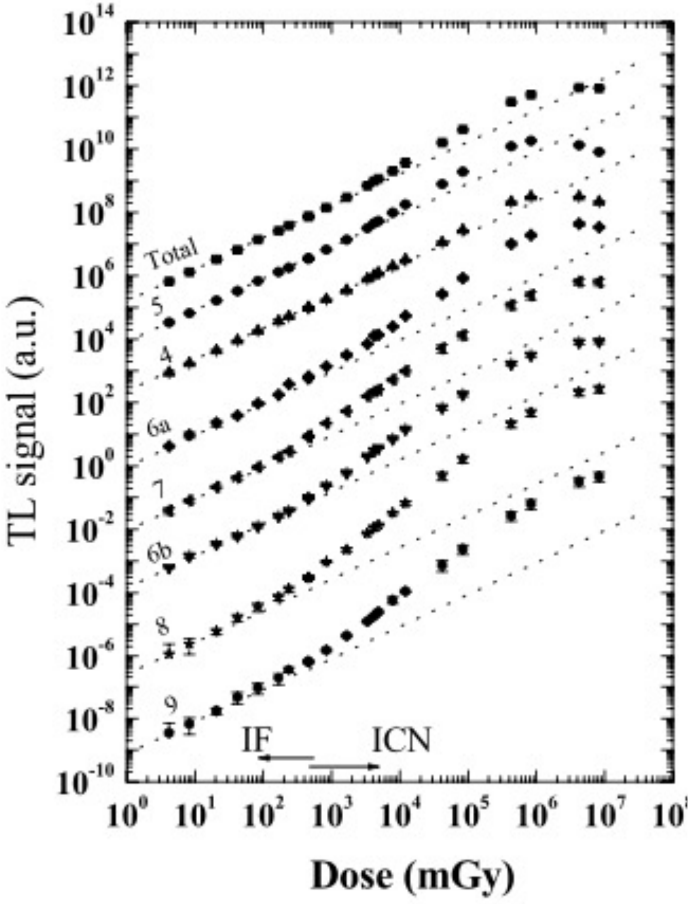


Figure 3. TL signal as a function of dose for the total signal peaks 4–9. The dashed lines correspond to a linear response. Individual data sets have been normalized for clarity in the d Arrows at the bottom show the use of different ^{60}Co sources. bars are explained in the text.

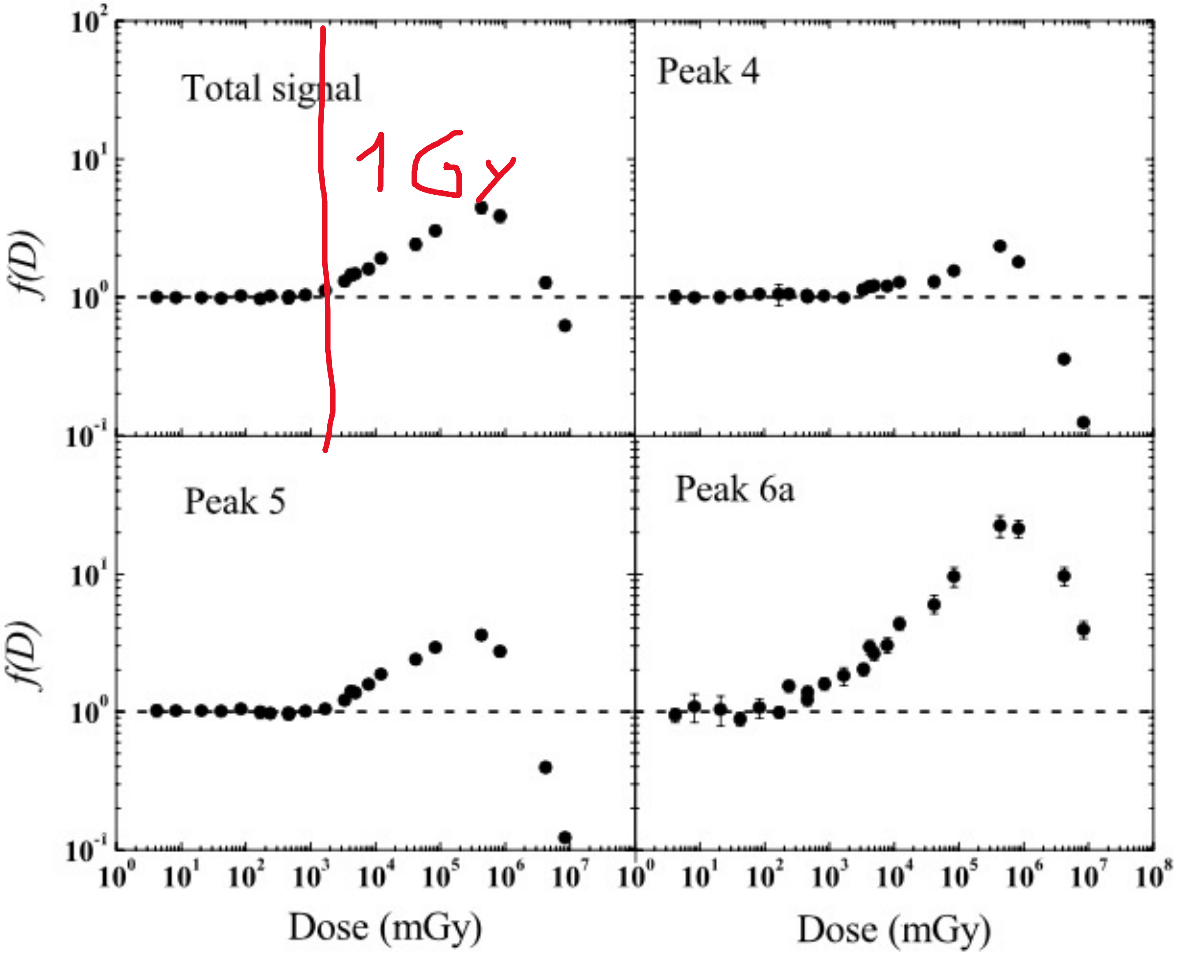
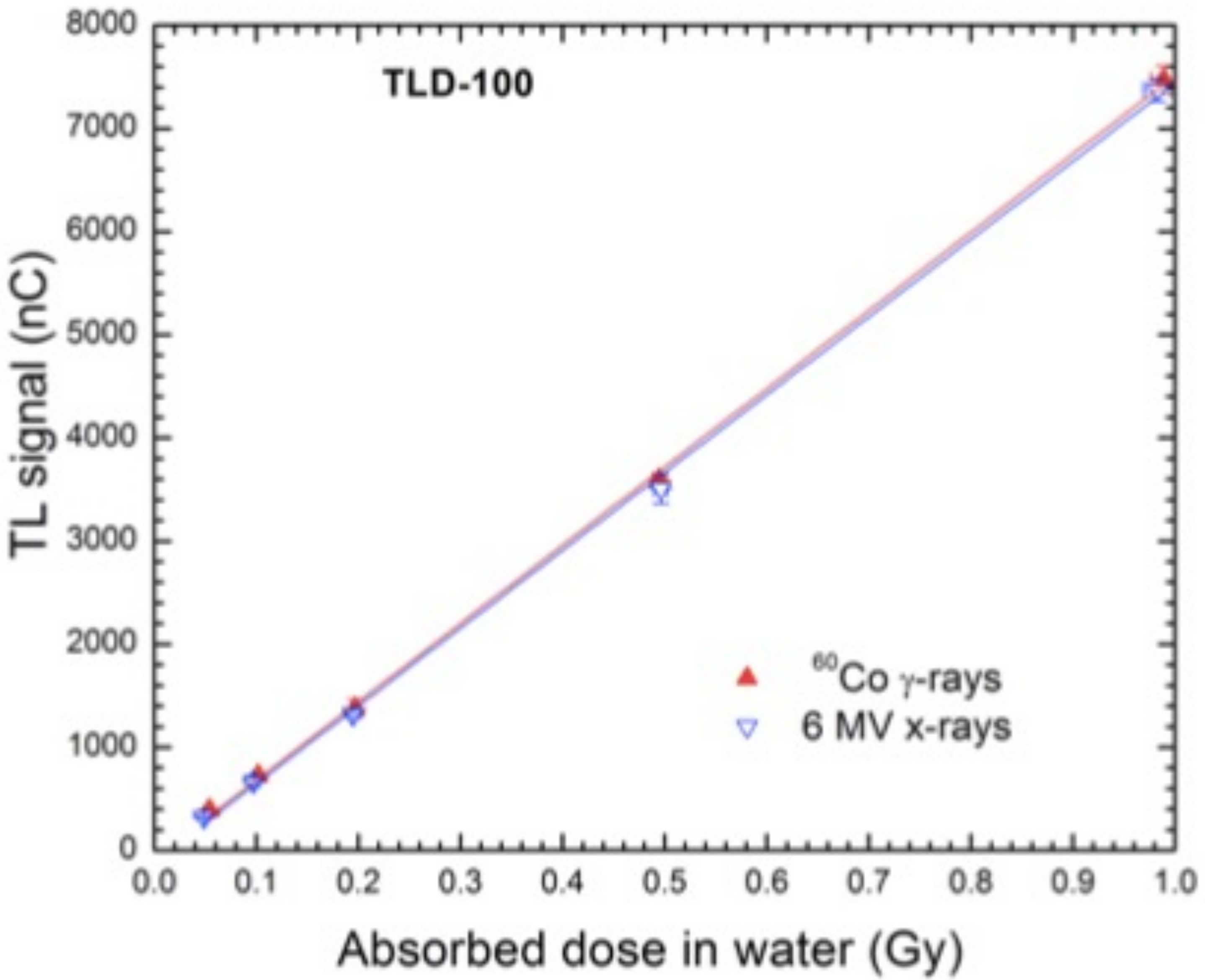


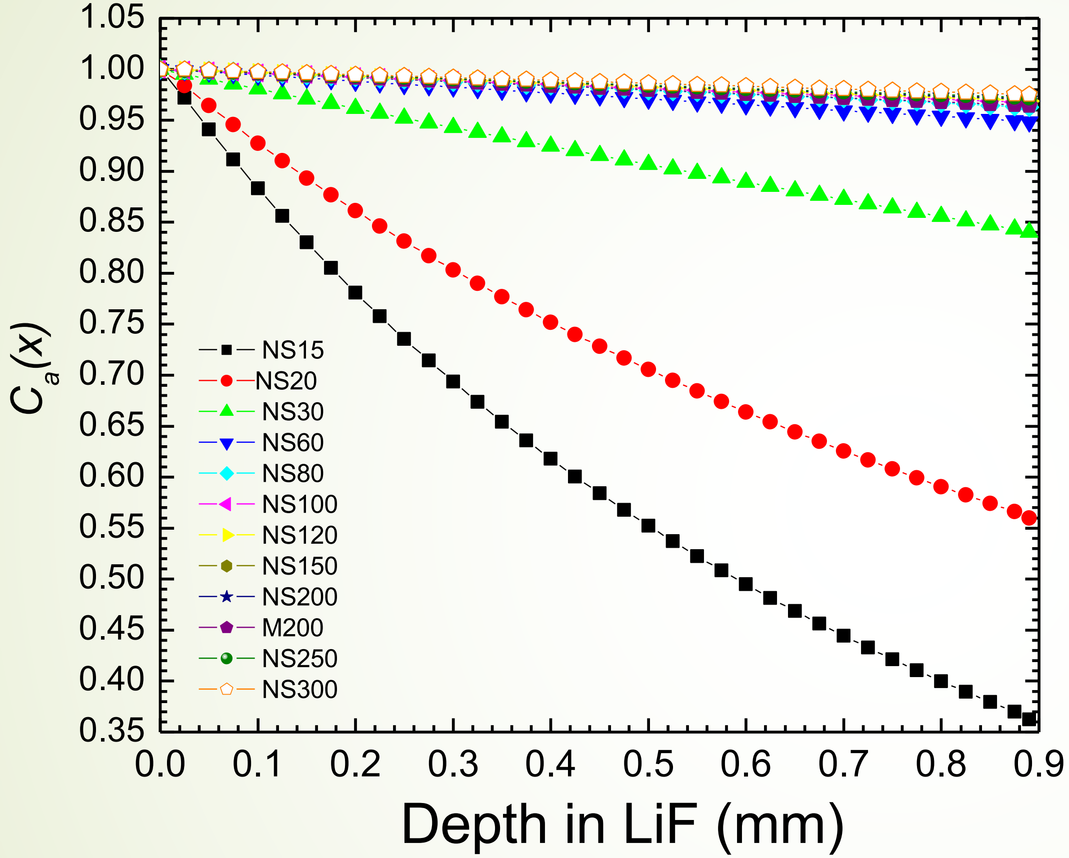
Figure 4. Dose-response function $f(D)$ for the total signal and for peaks 4–6a.

For medical applications the TLD-100 should be used at absorbed dose less than or equal to 1 Gy

Massillon-JL et al. PlosOne 2013



TLDs as “gold standards” for low-energy brachytherapy dosimetry



Rapid decrease of the absorbed dose with increasing dosimeter depth

⇓

Correction due to attenuation must be applied

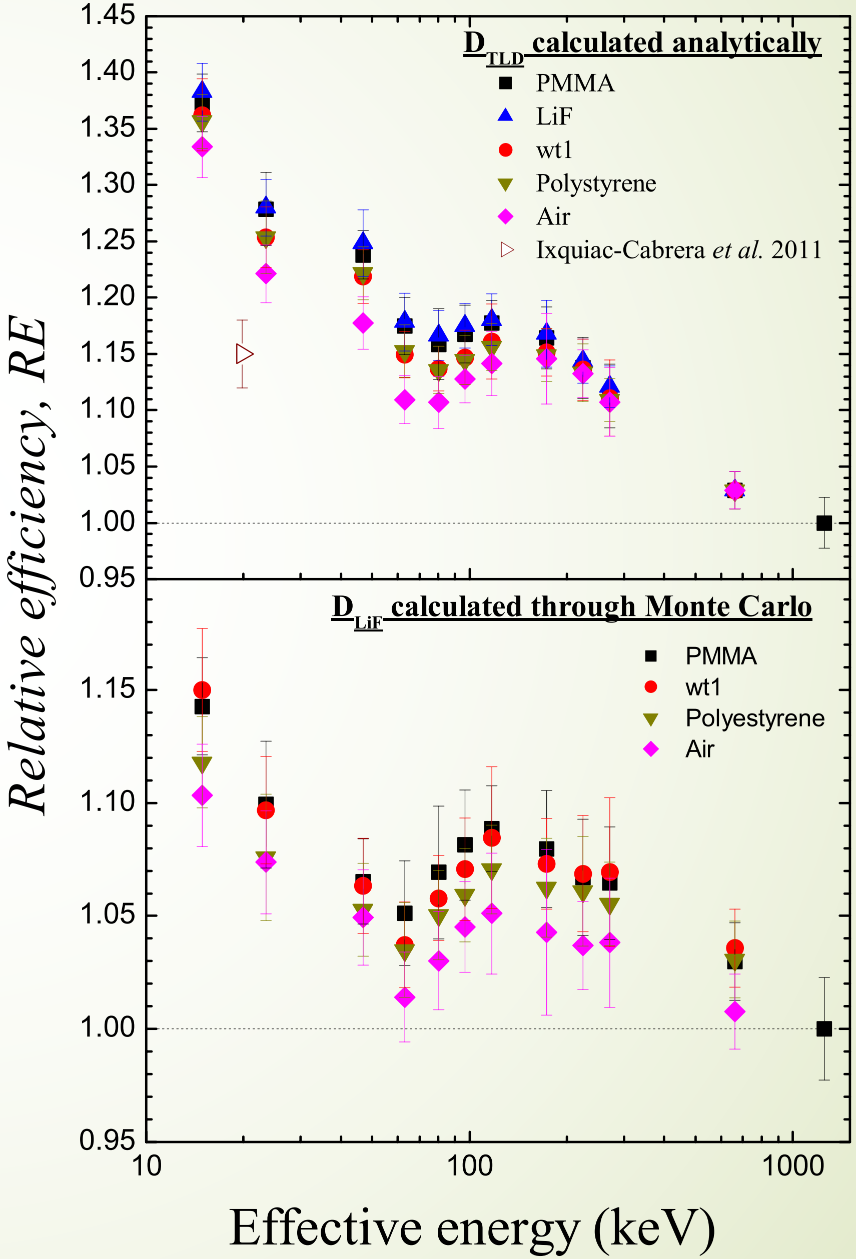
$$f_a = \frac{\int_{x=0}^{x_{max}} C_a(x)\,dx}{\int_{x=0}^{x_{max}} dx} = \frac{1}{x_{max}} \frac{\int_{x=0}^{x_{max}} \int_{E=0}^{Emax} \Phi(E) \left(\frac{\mu_{en}(E)}{\rho}\right)_{LiF} exp\left[-\left(\frac{\mu(E)}{\rho}\right)_{LiF} \rho x\right] EdEdx}{\int_{E=0}^{Emax} \Phi(E) \left(\frac{\mu_{en}(E)}{\rho}\right)_{LiF} EdE},$$

Massillon-JL *et al. Phys. Med. Biol.* **59** (2014) 4149

Relative efficiency depends on phantom material and how the dose is calculated

$$R = \frac{\dfrac{TLR_Q}{K_{air,Q}}}{\dfrac{TLR_{Q0}}{K_{air,Q0}}} \qquad RE = \frac{\dfrac{TLR_Q}{D_{TLD,Q}}}{\dfrac{TLR_{Q_0}}{D_{TLD,Q_0}}}$$

$$R_{MC} = \frac{\dfrac{D_{LiF,Q}}{K_{air,Q}}}{\dfrac{D_{LiF,Q_0}}{K_{air,Q_0}}} \qquad RE_{MC} = \frac{R}{R_{MC}} = \frac{\dfrac{TLR_Q}{D_{LiF,Q}}}{\dfrac{TLR_{Q_0}}{D_{LiF,Q_0}}}$$



Difference up to 20%

Massillon-JL *et al. Phys. Med. Biol.* **59** (2014) 4149

Radiochromic films

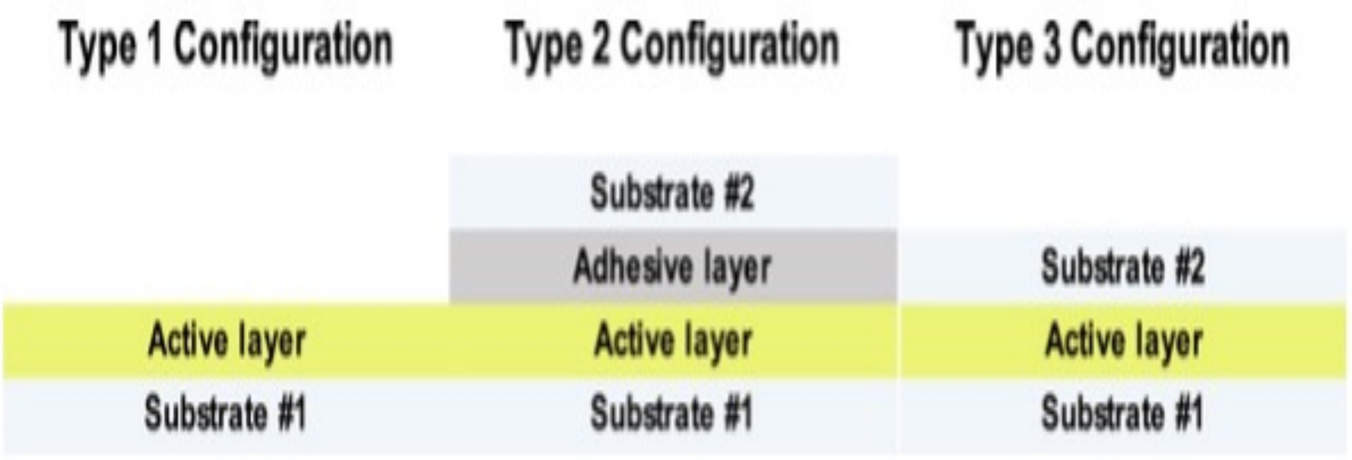


Fig. 1. Schematic diagrams (not to scale) of three types of RCF layer configurations. [Color figure can be viewed at wileyonlinelibrary.com]

TG-235

Radiochromic films

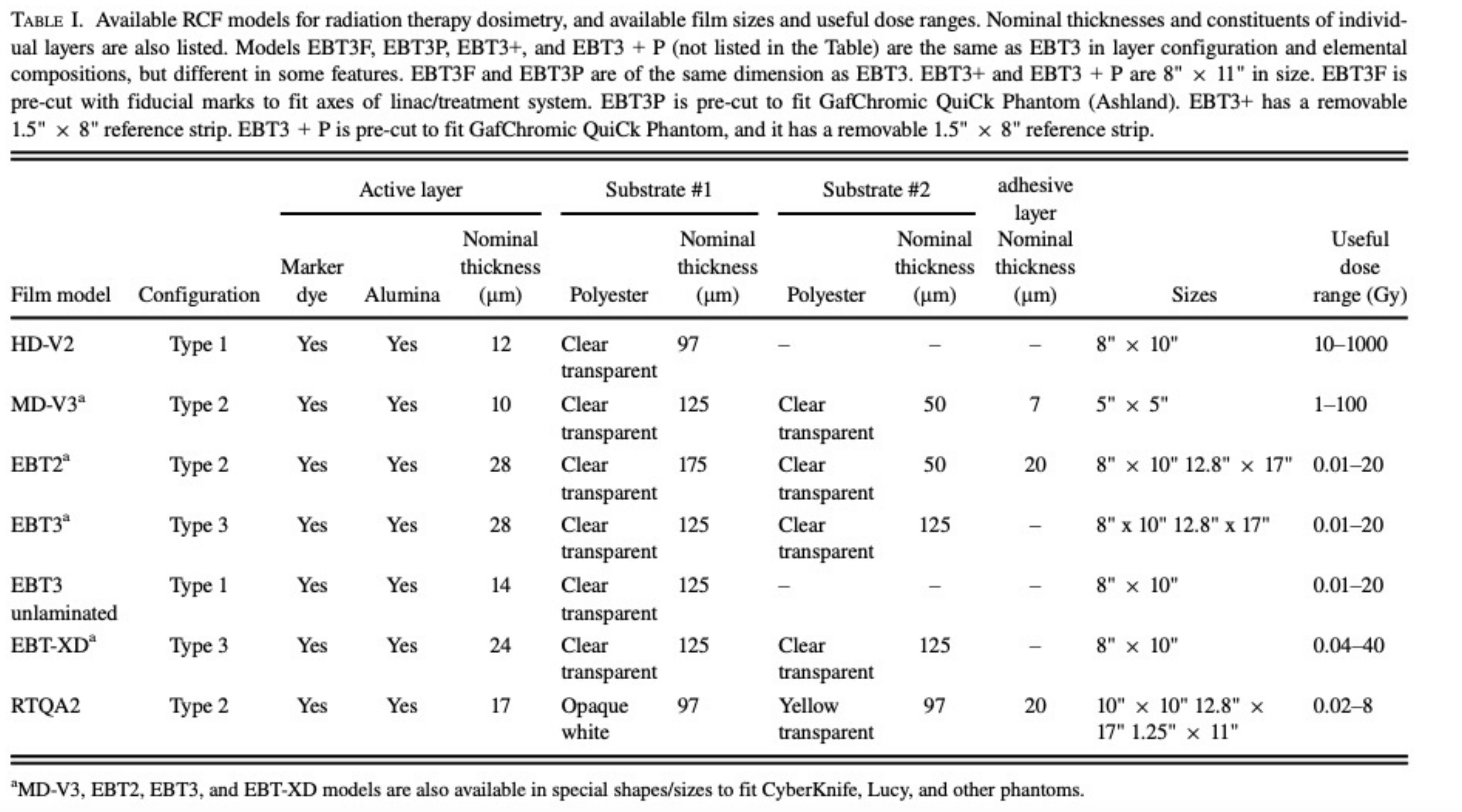


TABLE I. Available RCF models for radiation therapy dosimetry, and available film sizes and useful dose ranges. Nominal thicknesses and constituents of individual layers are also listed. Models EBT3F, EBT3P, EBT3+, and EBT3 + P (not listed in the Table) are the same as EBT3 in layer configuration and elemental compositions, but different in some features. EBT3F and EBT3P are of the same dimension as EBT3. EBT3+ and EBT3 + P are 8" × 11" in size. EBT3F is pre-cut with fiducial marks to fit axes of linac/treatment system. EBT3P is pre-cut to fit GafChromic QuiCk Phantom (Ashland). EBT3+ has a removable 1.5" × 8" reference strip. EBT3 + P is pre-cut to fit GafChromic QuiCk Phantom, and it has a removable 1.5" × 8" reference strip.

		Active layer			Substrate #1		Substrate #2		adhesive layer		
Film model	Configuration	Marker dye	Alumina	Nominal thickness (µm)	Polyester	Nominal thickness (µm)	Polyester	Nominal thickness (µm)	Nominal thickness (µm)	Sizes	Useful dose range (Gy)
HD-V2	Type 1	Yes	Yes	12	Clear transparent	97	–	–	–	8" × 10"	10–1000
MD-V3[a]	Type 2	Yes	Yes	10	Clear transparent	125	Clear transparent	50	7	5" × 5"	1–100
EBT2[a]	Type 2	Yes	Yes	28	Clear transparent	175	Clear transparent	50	20	8" × 10" 12.8" × 17"	0.01–20
EBT3[a]	Type 3	Yes	Yes	28	Clear transparent	125	Clear transparent	125	–	8" x 10" 12.8" x 17"	0.01–20
EBT3 unlaminated	Type 1	Yes	Yes	14	Clear transparent	125	–	–	–	8" × 10"	0.01–20
EBT-XD[a]	Type 3	Yes	Yes	24	Clear transparent	125	Clear transparent	125	–	8" × 10"	0.04–40
RTQA2	Type 2	Yes	Yes	17	Opaque white	97	Yellow transparent	97	20	10" × 10" 12.8" × 17" 1.25" × 11"	0.02–8

[a] MD-V3, EBT2, EBT3, and EBT-XD models are also available in special shapes/sizes to fit CyberKnife, Lucy, and other phantoms.

TG-235

Radiochromic films

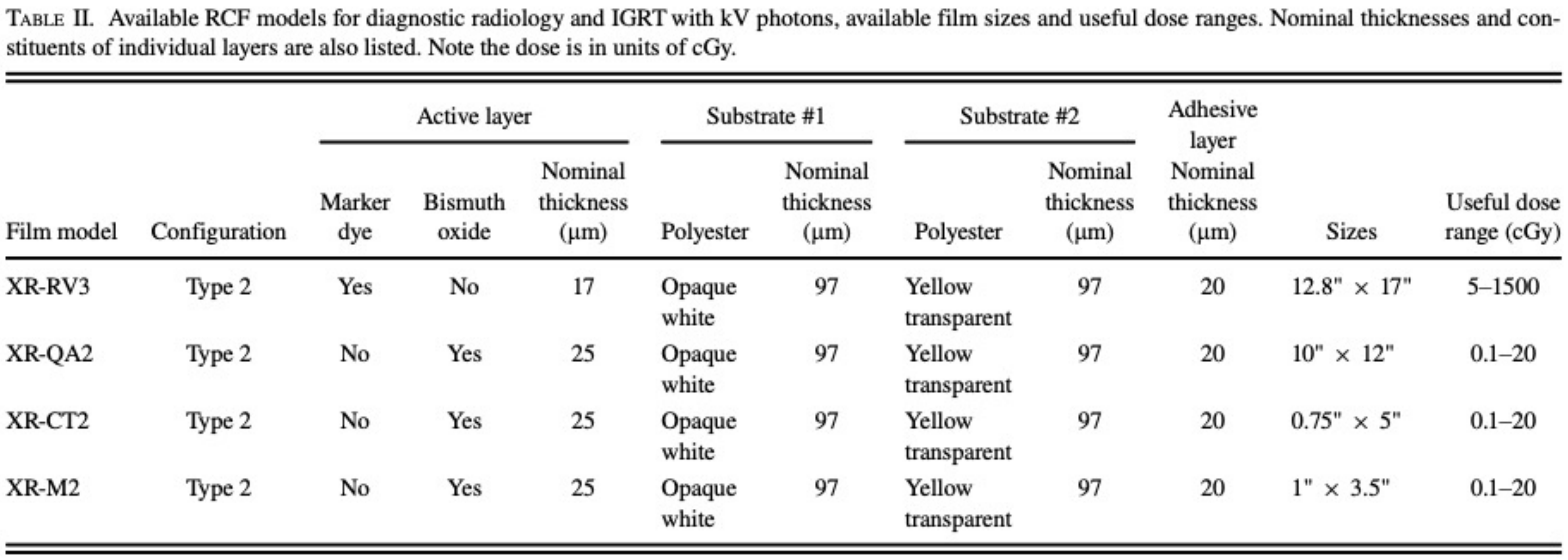


TABLE II. Available RCF models for diagnostic radiology and IGRT with kV photons, available film sizes and useful dose ranges. Nominal thicknesses and constituents of individual layers are also listed. Note the dose is in units of cGy.

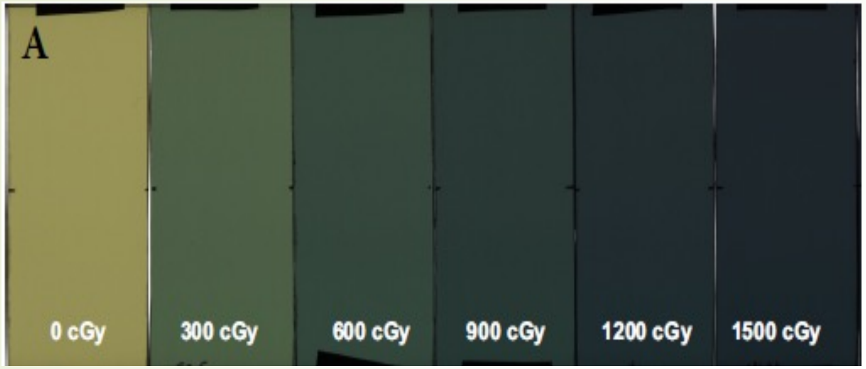
		Active layer			Substrate #1		Substrate #2		Adhesive layer		
Film model	Configuration	Marker dye	Bismuth oxide	Nominal thickness (μm)	Polyester	Nominal thickness (μm)	Polyester	Nominal thickness (μm)	Nominal thickness (μm)	Sizes	Useful dose range (cGy)
XR-RV3	Type 2	Yes	No	17	Opaque white	97	Yellow transparent	97	20	12.8" × 17"	5–1500
XR-QA2	Type 2	No	Yes	25	Opaque white	97	Yellow transparent	97	20	10" × 12"	0.1–20
XR-CT2	Type 2	No	Yes	25	Opaque white	97	Yellow transparent	97	20	0.75" × 5"	0.1–20
XR-M2	Type 2	No	Yes	25	Opaque white	97	Yellow transparent	97	20	1" × 3.5"	0.1–20

TG-235

Characteristics of radiochromic films

- **LOW UNCERTAINTIES? NO**
- **High spatial resolution? Yes**
- **Dose rate independent? Yes**
- **Energy dependent? Yes and NO**
- **Tissue equivalent? Yes and NO**

Radiochomic film /document scanner



$$\mathrm{netOD} = \log_{10}\left(\frac{I_{\mathrm{unexp}} - I_{\mathrm{opf}}}{I_{\mathrm{exp}} - I_{\mathrm{opf}}}\right), \qquad (2)$$

$$\sigma_{\mathrm{netOD}} = \frac{1}{\ln(10)}\sqrt{\frac{\sigma^2_{I_{\mathrm{unexp}}} + \sigma^2_{I_{\mathrm{opf}}}}{(I_{\mathrm{unexp}} - I_{\mathrm{opf}})^2} + \frac{\sigma^2_{I_{\mathrm{exp}}} + \sigma^2_{I_{\mathrm{opf}}}}{(I_{\mathrm{exp}} - I_{\mathrm{opf}})^2}} \qquad (3)$$

Biomed. Phys. Eng. Express 2 (2016) 045005

How to reduce uncertainties?

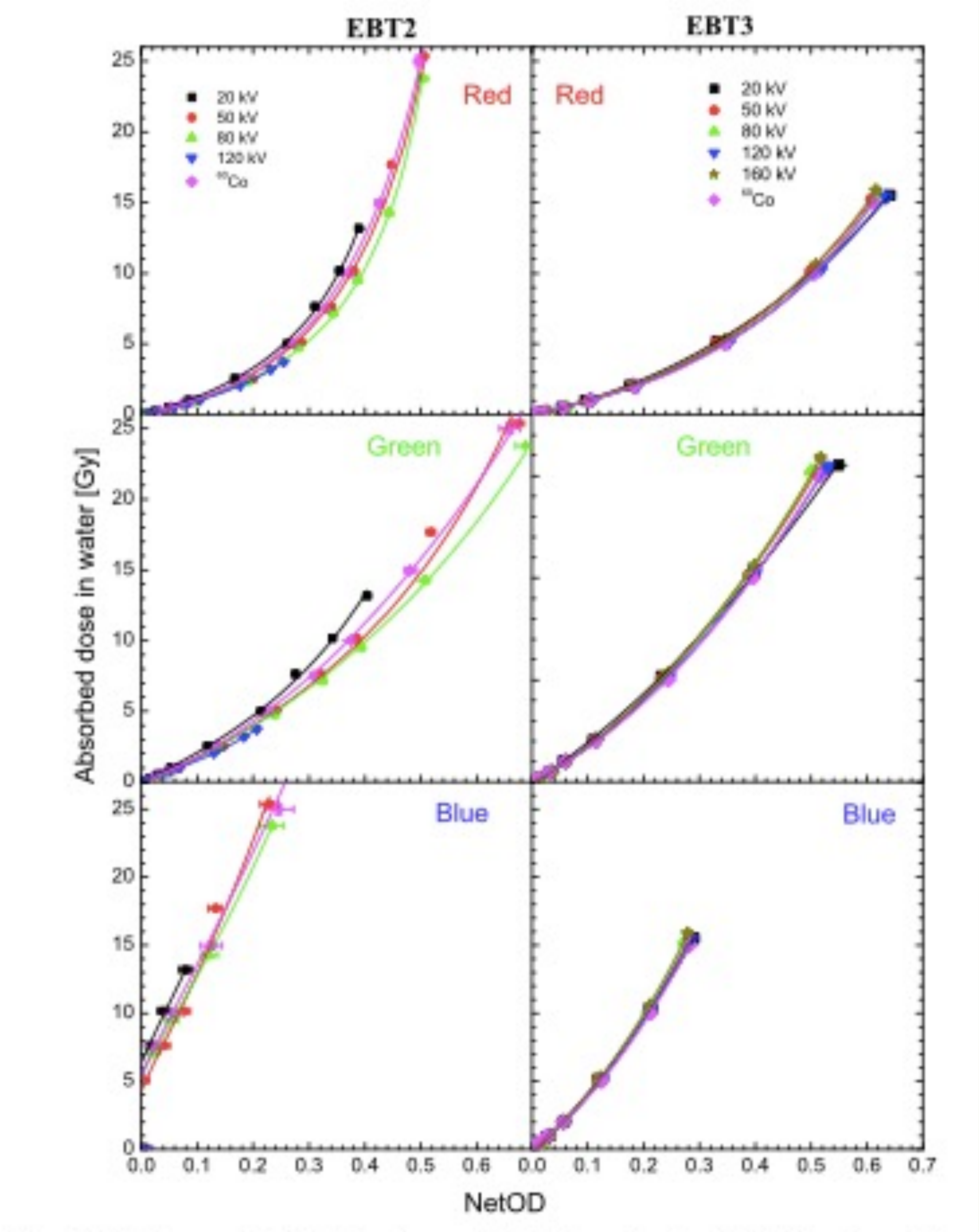


Figure 3. Absorbed dose versus NetOD for all energy beams studied and the three colour channels for both films. The symbols represent the data and the lines are fitted function.

Radiochomic film /document scanner

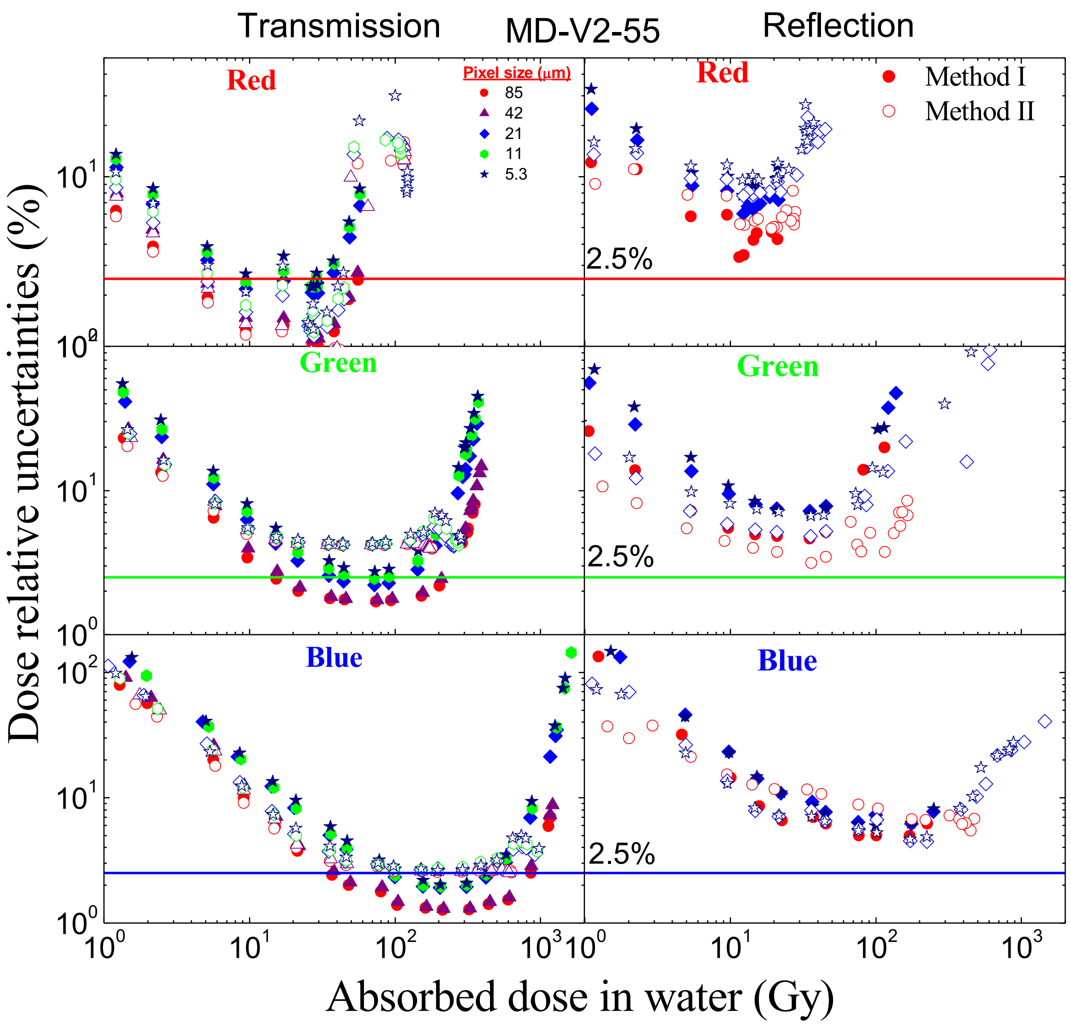
$$D_{\text{fit}}\,(\text{Gy}) = a + b\,(\text{netOD}) + c\,(\text{netOD})^2 + d\,(\text{netOD})^3,$$

$$\sigma^2_{D_{\text{fit}}} = \left(\frac{\partial}{\partial a}D_{\text{fit}}\right)^2\sigma_a^2 + \left(\frac{\partial}{\partial b}D_{\text{fit}}\right)^2\sigma_b^2 + \left(\frac{\partial}{\partial c}D_{\text{fit}}\right)^2\sigma_c^2 + \left(\frac{\partial}{\partial d}D_{\text{fit}}\right)^2\sigma_d^2 + \left(\frac{\partial}{\partial \text{netOD}}D_{\text{fit}}\right)^2\sigma^2_{\text{netOD}}.$$

Biomed. Phys. Eng. Express 2 (2016) 045005

How to reduce uncertainties?

Radiochomic film/document scanner



The uncertainties depend on the spatial resolution

Massillon-JL *and* Zúñiga-Meneses, Phys. Med. Biol. **55** 2010

How to reduce uncertainties?

Radiochomic film/document scanner: EBT2

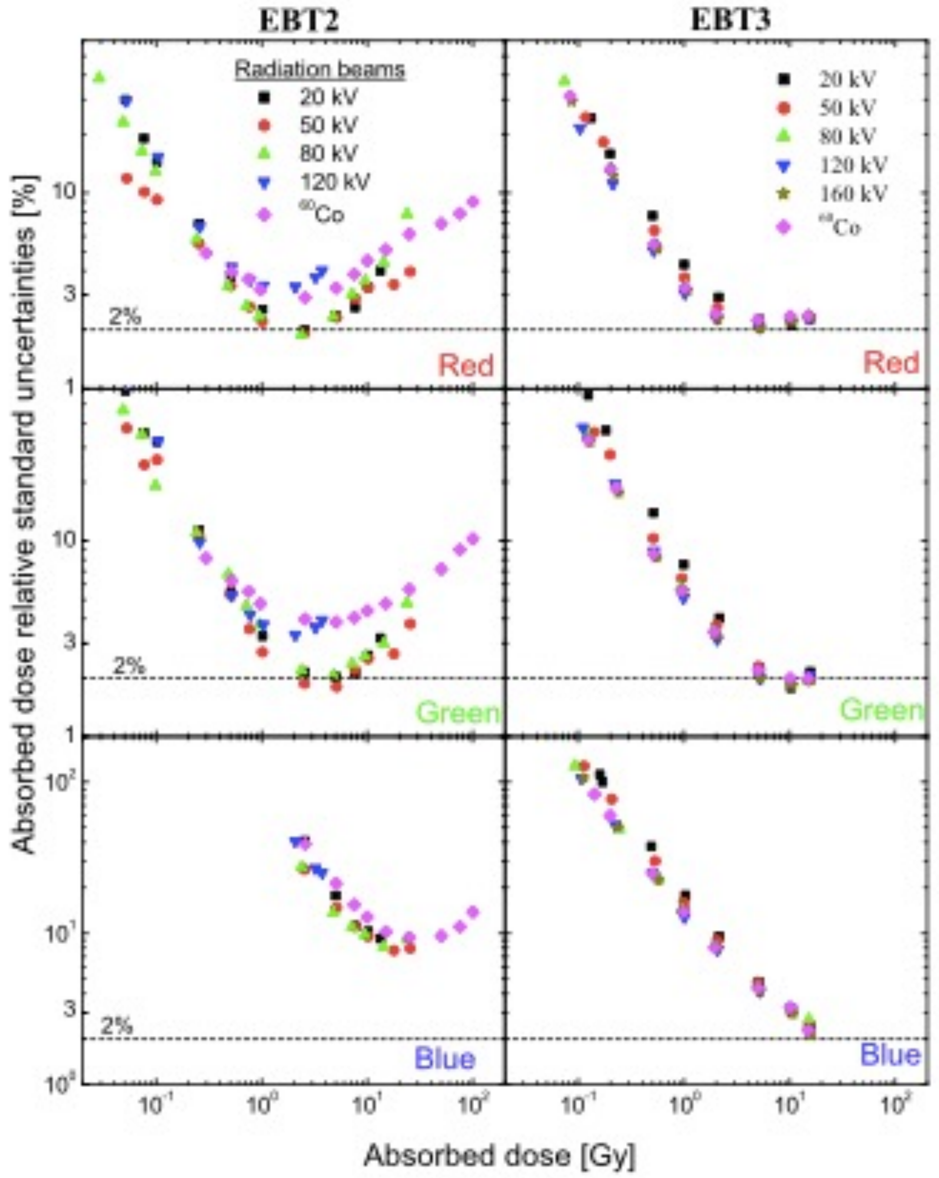


Figure 4. Relative combined standard uncertainty on the absorbed dose for the three colour channels.

The uncertainties depend on energy photons

Biomed. Phys. Eng. Express 2 (2016) 045005

Energy dependency

Radiochomic film/document scanner

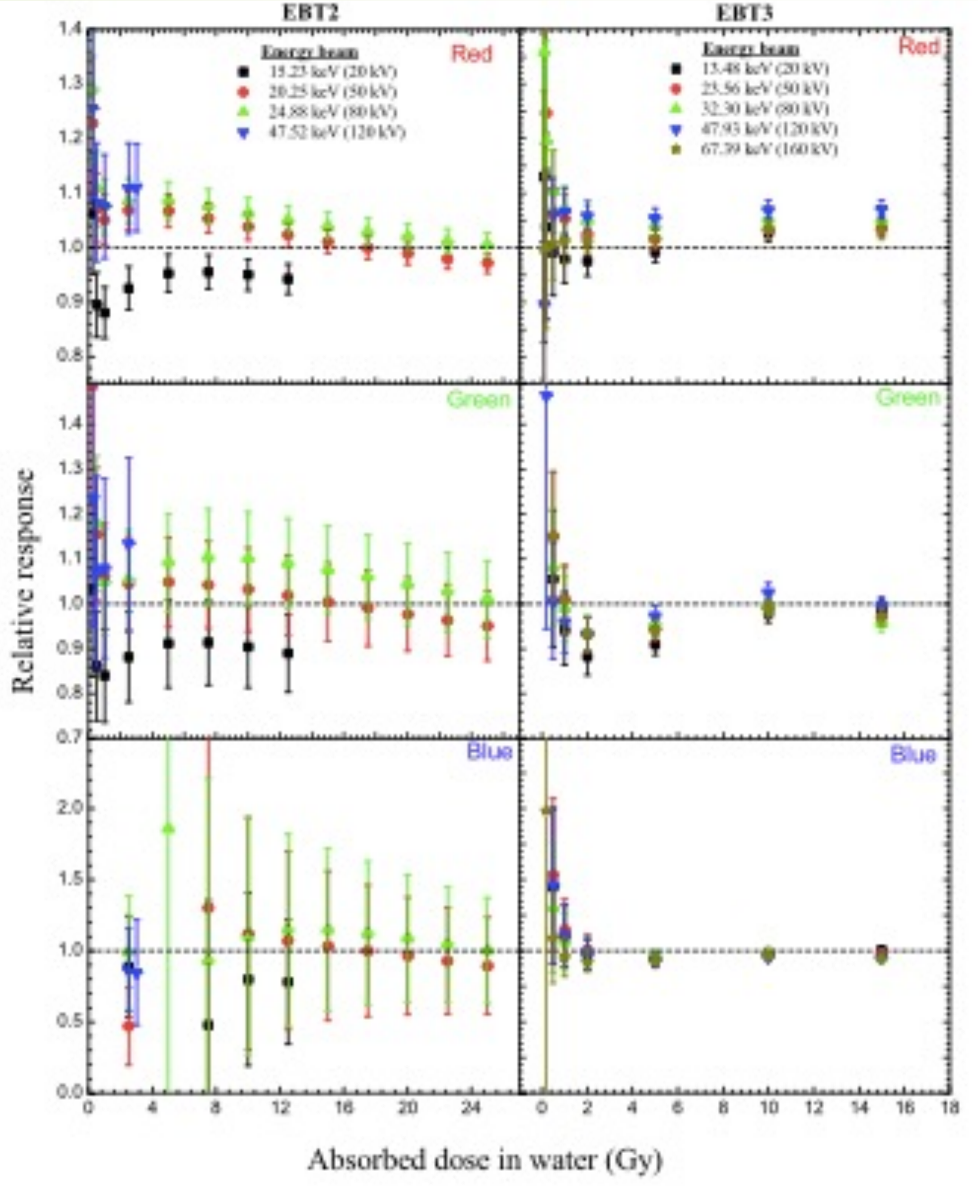


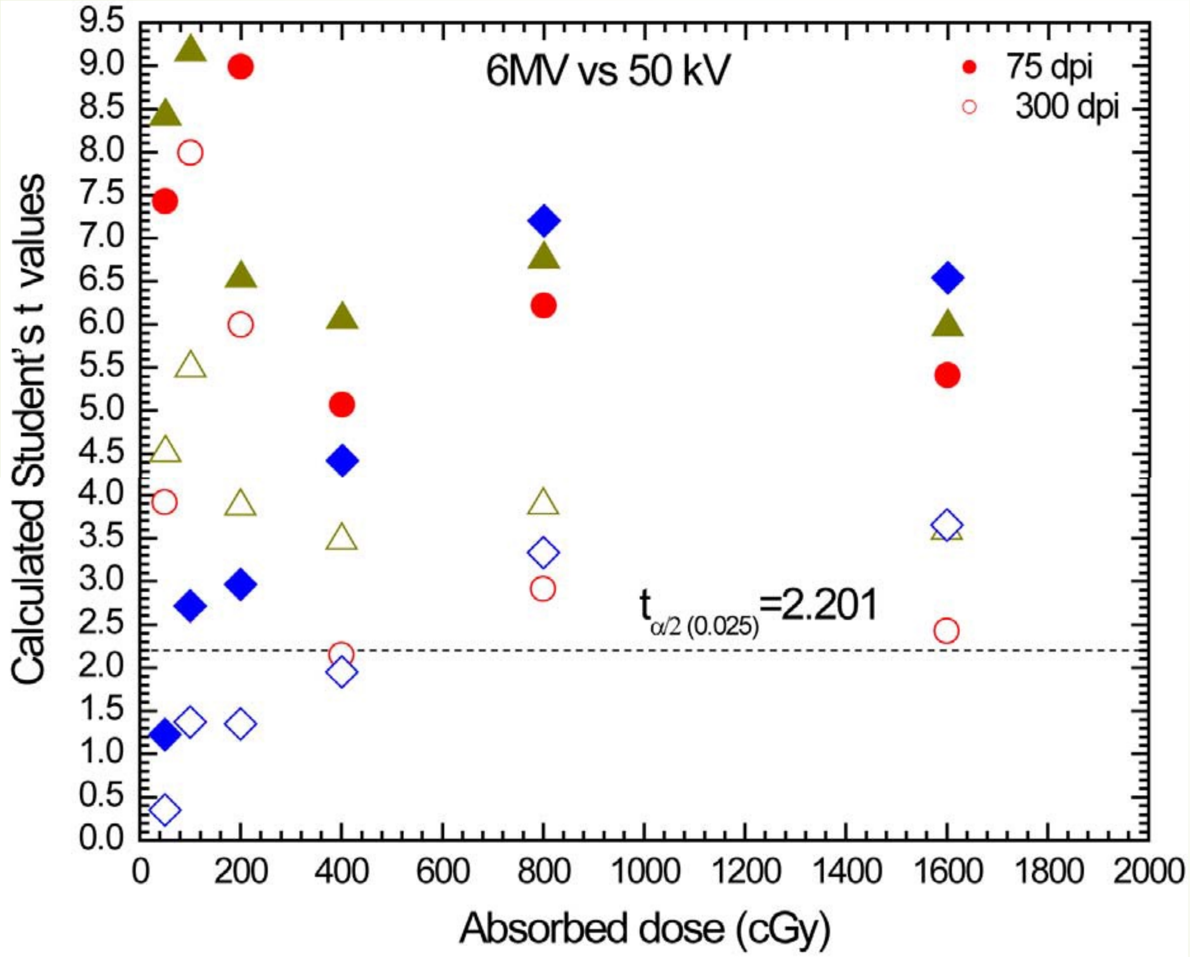
Figure 5. Relative response versus absorbed dose for all x-ray beams and colour channels.

The degree of energy dependence is a function of spatial resolution, color channel and <u>absorbed dose</u>

Biomed. Phys. Eng. Express 2 (2016) 045005

How to reduce uncertainties?

Radiochomic film/document scanner: EBT3



The degree of energy dependence is a function of spatial resolution, color channel and absorbed dose?

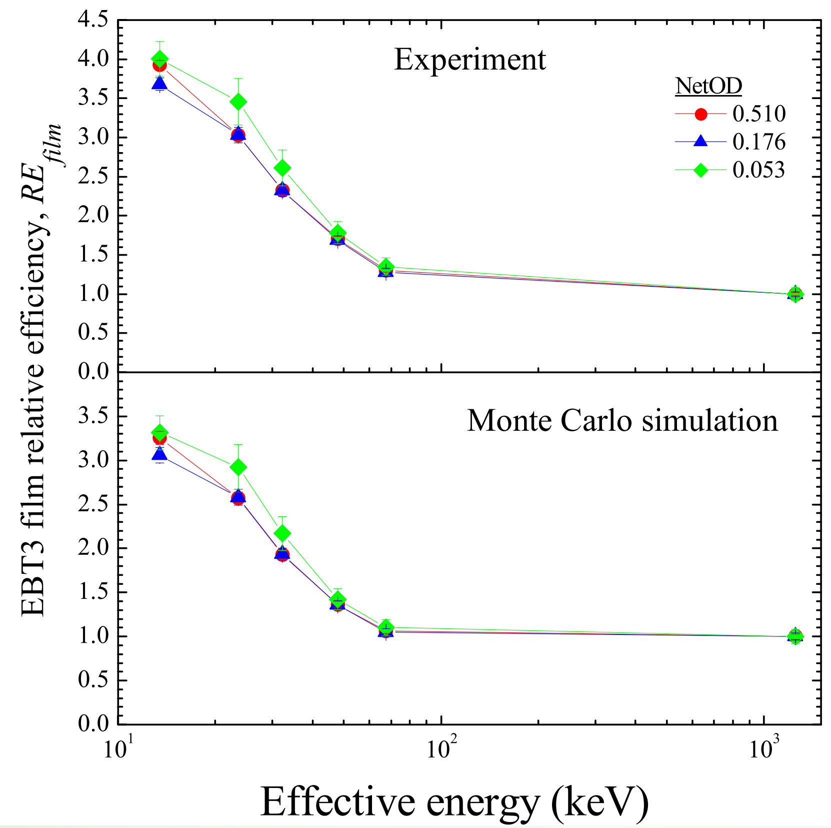
Massillon-JL *et al.* IJMPCERO 2012

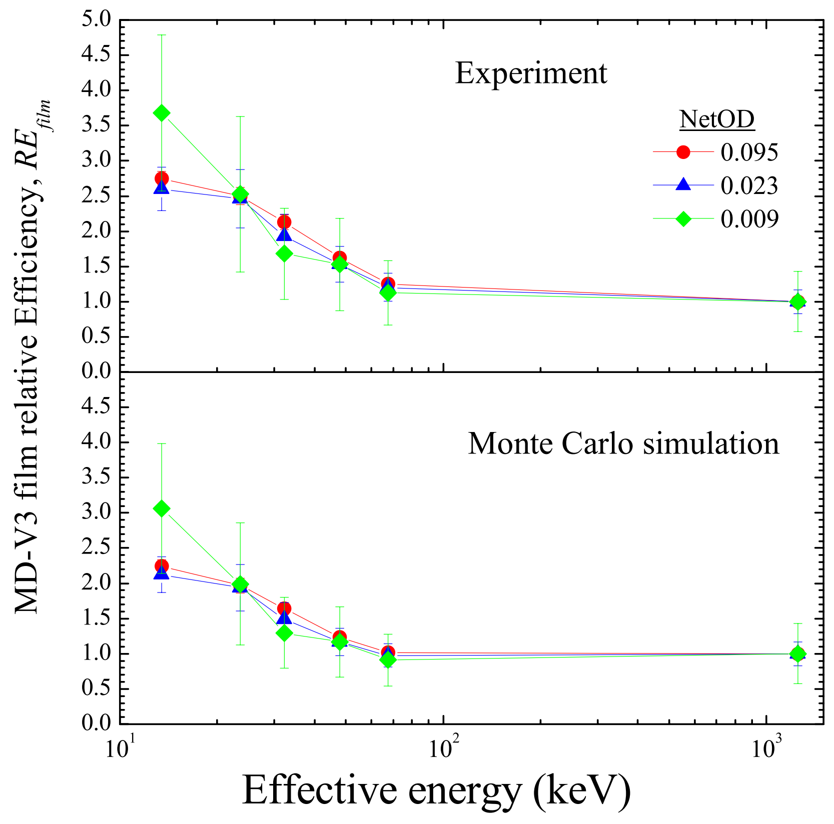
Relative efficiency of radiochromic films

EBT3

$$RE_{film} = \frac{D_{Film,Q_0}(netOD)}{D_{Film,Q}(netOD)},$$

MD-V3



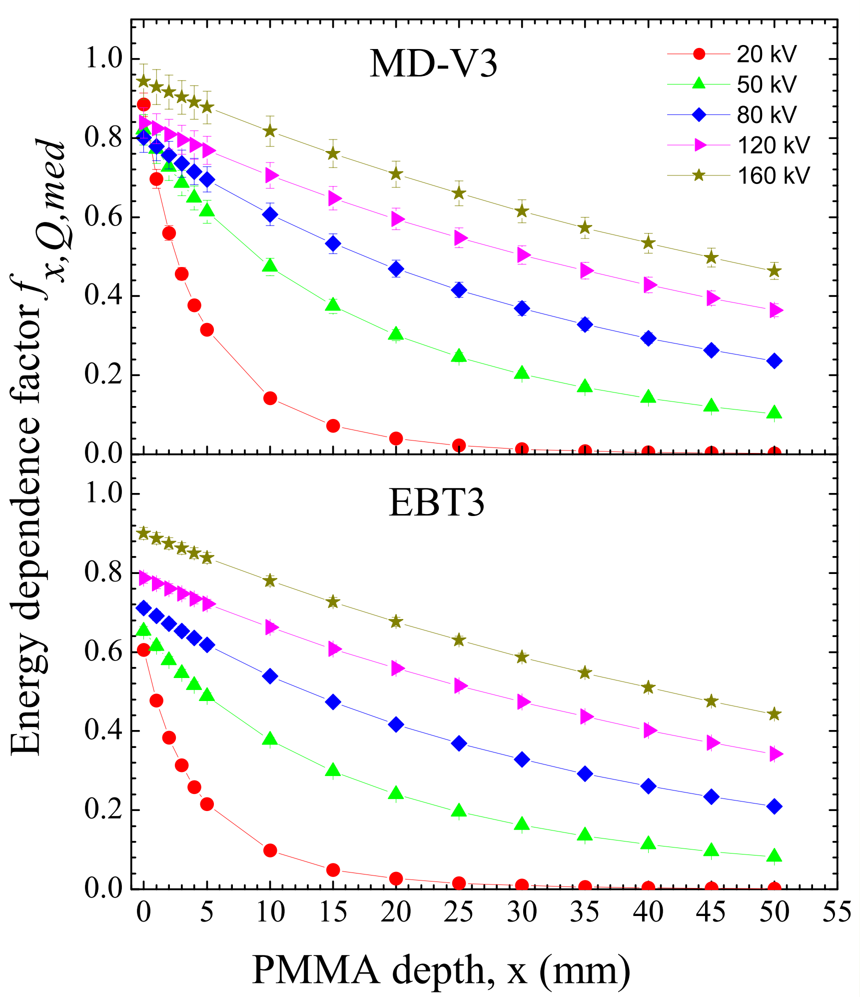


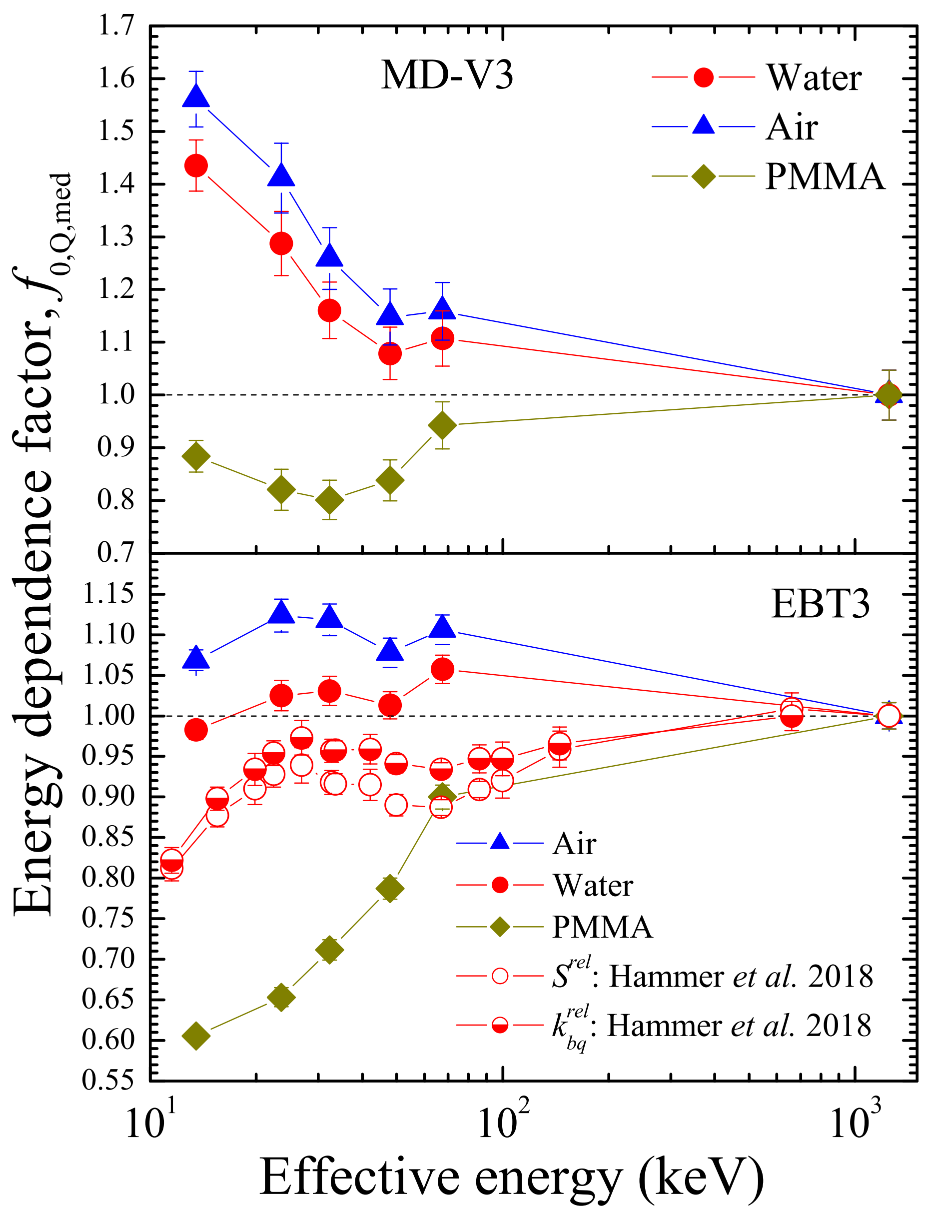
About 3 to 4 times absorbed dose from ^{60}Co are needed to produce the same response from mammography x-rays

Massillon-JL *et al.* *Physica Medica* **61** (2019) 8–17

Energy dependence factor: Independent of absorbed dose

$$f_{0,Q,med} = \frac{1}{RE_{film}} \cdot \frac{\left[\left(\frac{\overline{\mu_{en}}}{\rho}\right)^{med}_{film}\right]_{Q}}{\left[\left(\frac{\overline{\mu_{en}}}{\rho}\right)^{med}_{film}\right]_{Q_0}},$$





Massillon-JL *et al.* *Physica Medica* **61** (2019) 8–17

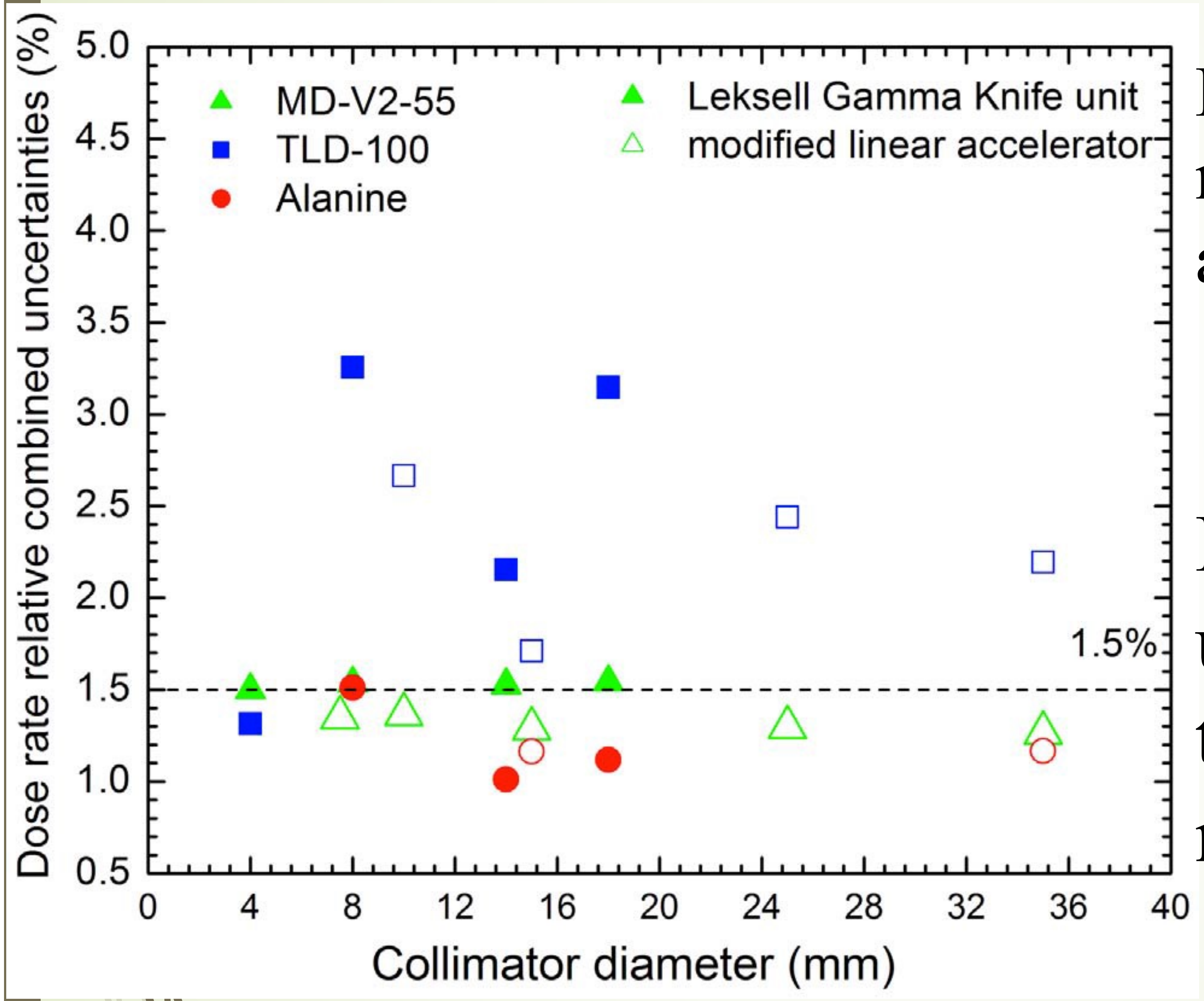
Reference absorbed dose to water rate computed in the Leksell Gamma Knife® unit

Massillon-JL et al. PlosOne 2013

		Collimator diameters (mm)			
		4	8	14	18
Dosimeter	Size	(mGy s^{-1})	(mGy s^{-1})	(mGy s^{-1})	(mGy s^{-1})
MD-V2-55	~240[a]	20.18 ± 0.30	22.23 ± 0.34	22.92 ± 0.35	23.31 ± 0.36
TLD-100	3.1×3.1×0.89[b]	19.34 ± 0.27	21.86 ± 0.72	22.28 ± 0.52	23.06 ± 0.73
Alanine	4.9[c] x 3.0[d]		21.09 ± 0.32	21.47 ± 0.24	21.89 ± 0.22
CD		18.94	20.83	21.48	21.82

Massillon-JL et al. PlosOne 2013

TLDs and film vs CD



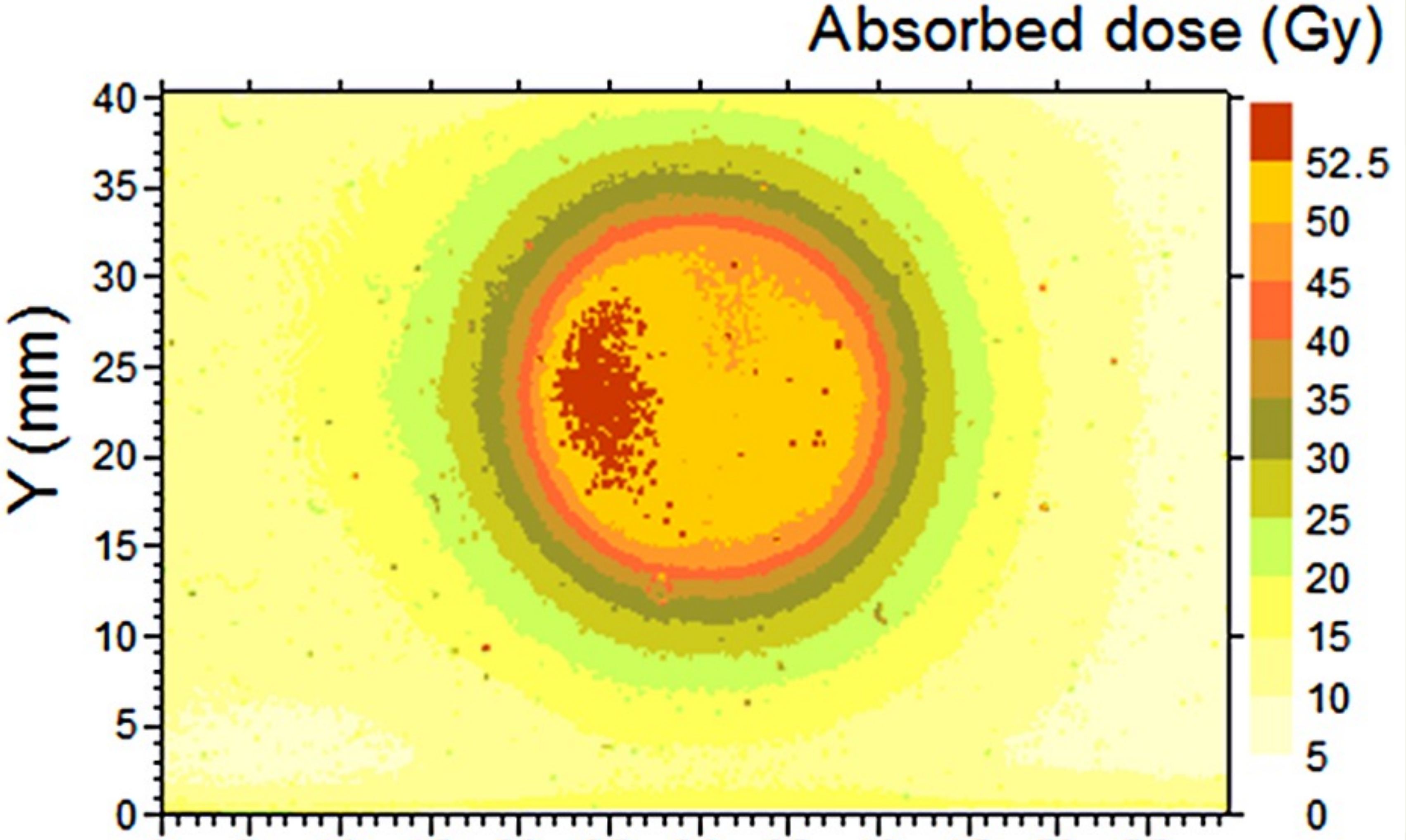
Knowing the minimum limit of absorbed dose

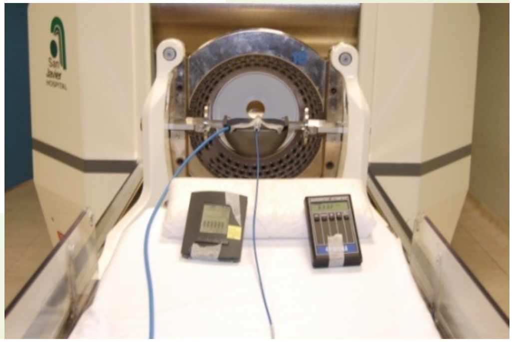
↓

Decreasing uncertainties in the absorbed dose measurements

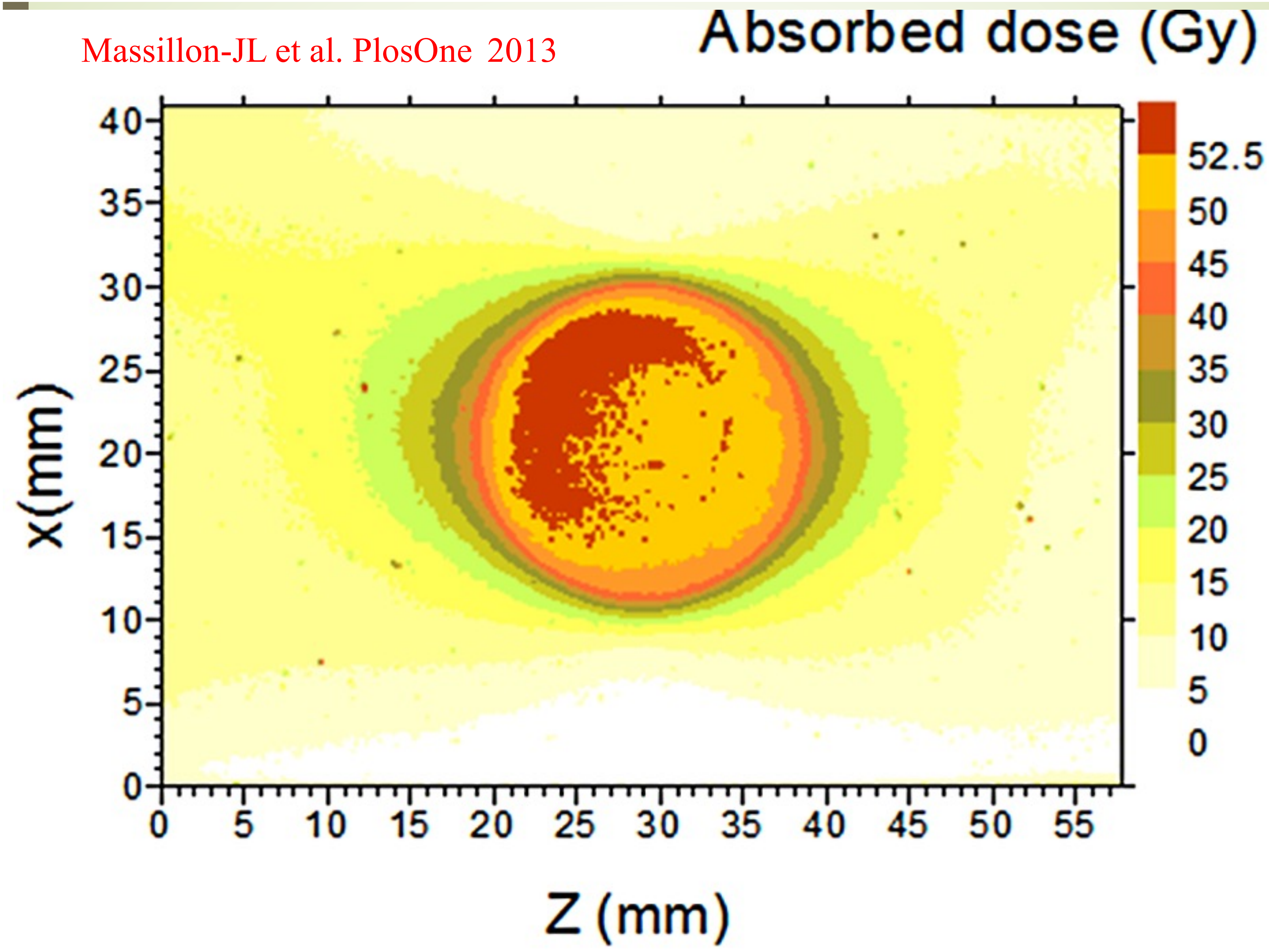
Massillon-JL et al. PlosOne 2013

Massillon-JL et al. PlosOne 2013

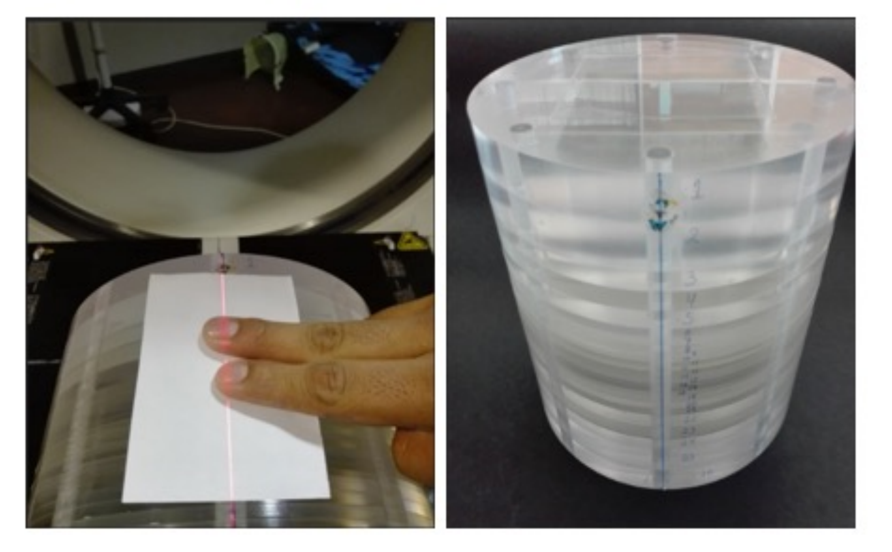




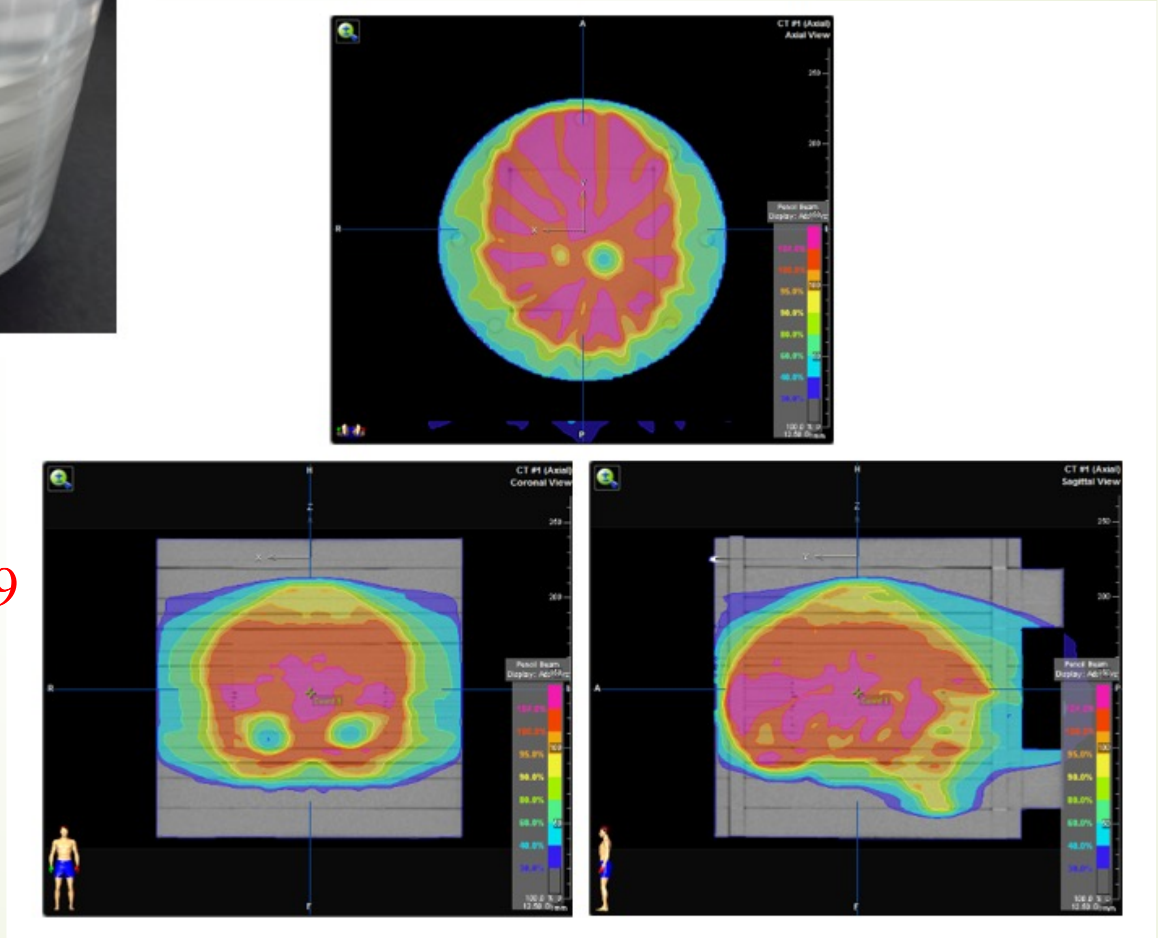
Massillon-JL et al. PlosOne 2013



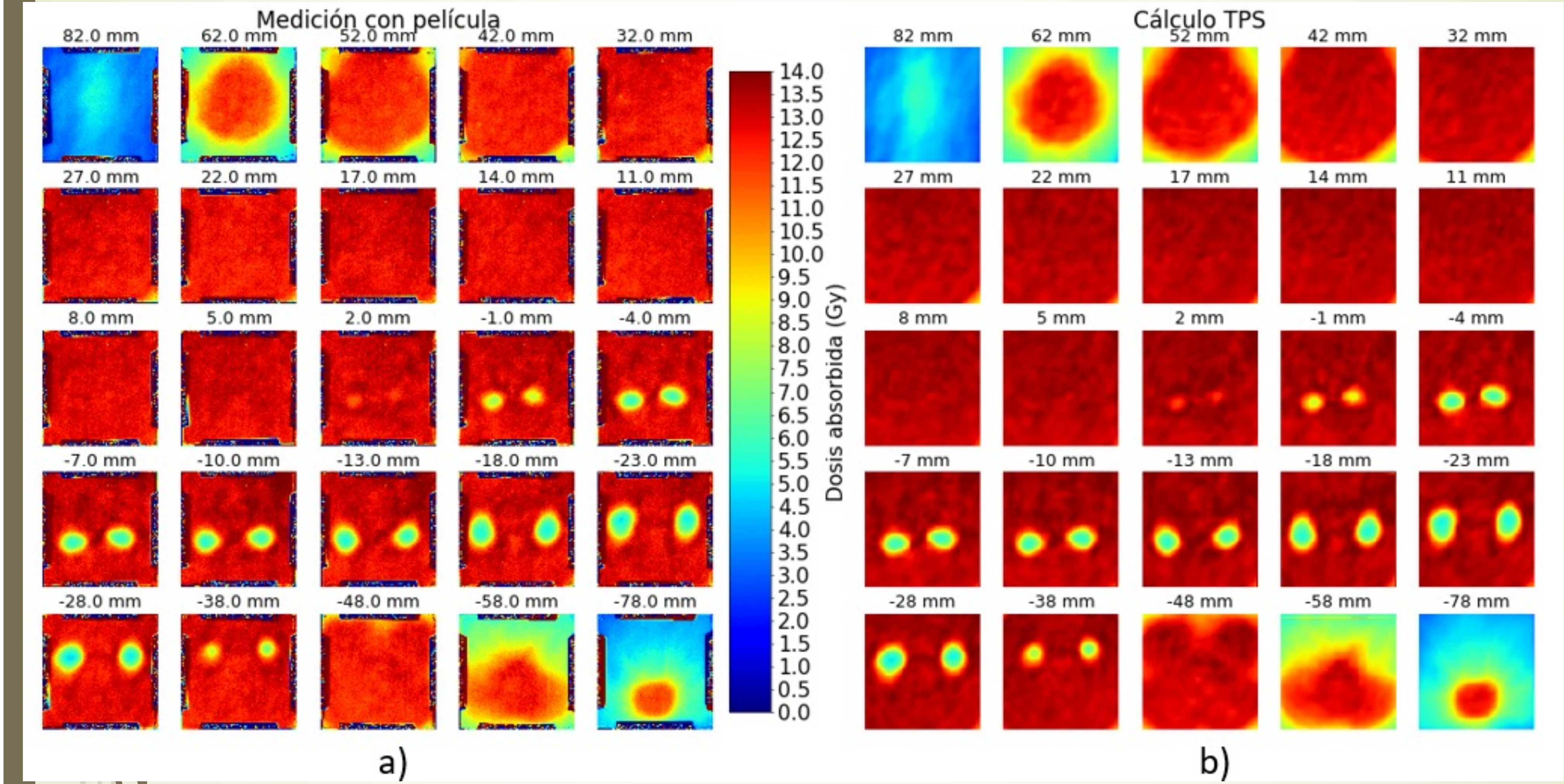
3D dose measurements with radiochromic films



Luis Olivares M.Sc. UNAM 2019

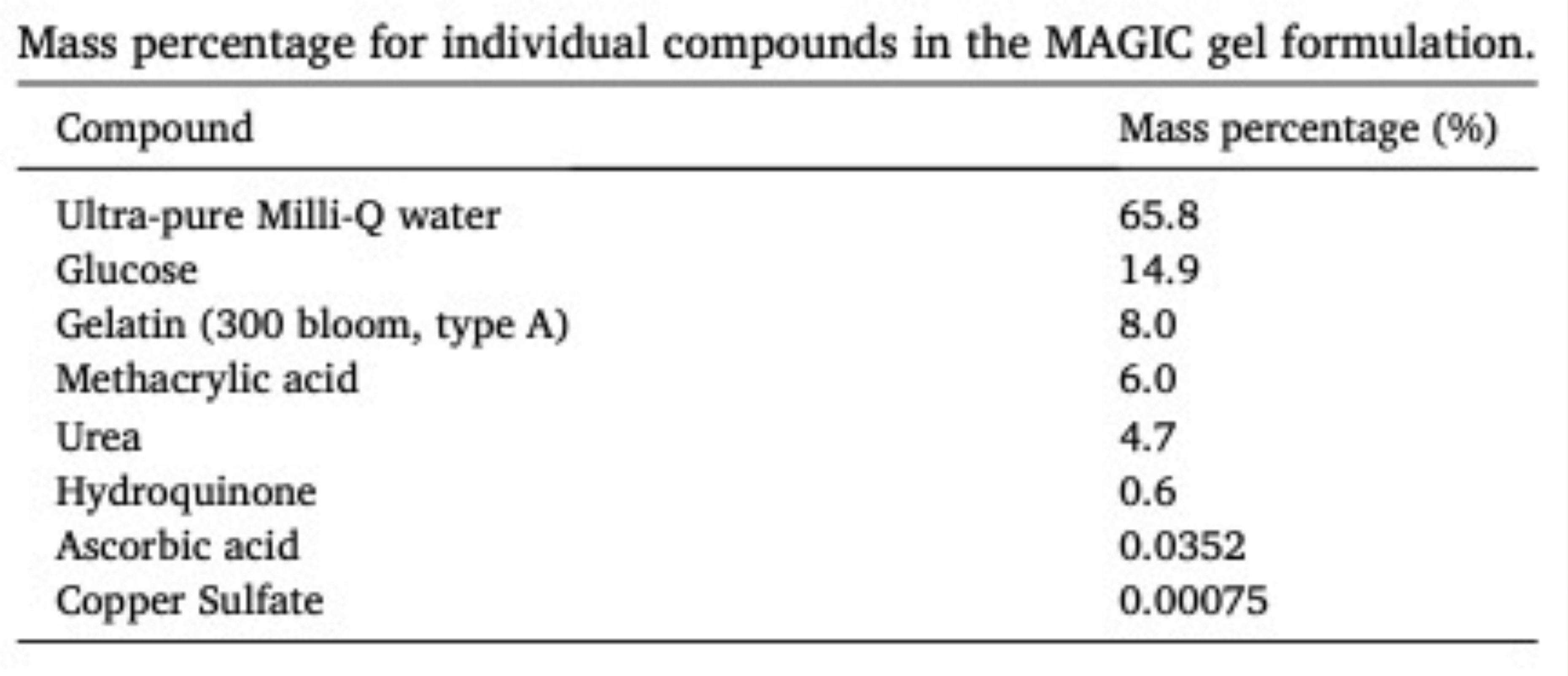


Radiochromic films vs Planning system



Luis Olivares M.Sc. UNAM 2019

3D gel dosimetry



Mass percentage for individual compounds in the MAGIC gel formulation.

Compound	Mass percentage (%)
Ultra-pure Milli-Q water	65.8
Glucose	14.9
Gelatin (300 bloom, type A)	8.0
Methacrylic acid	6.0
Urea	4.7
Hydroquinone	0.6
Ascorbic acid	0.0352
Copper Sulfate	0.00075

TG-?

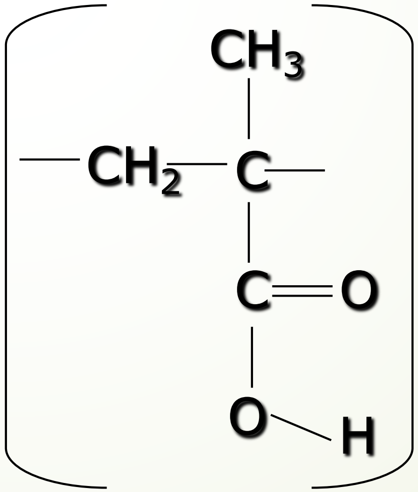
Radiation induced polymerization

It is a 4 step processes

1. **Ionizing radiation induces the radiolysis of water**
2. **Polymethacrylic acid undergoes free-radical polymerization**

Strongly hydrophobic methyl group

Ionizing radiation + water ⇒ $H^+ + OH^- + e^-$

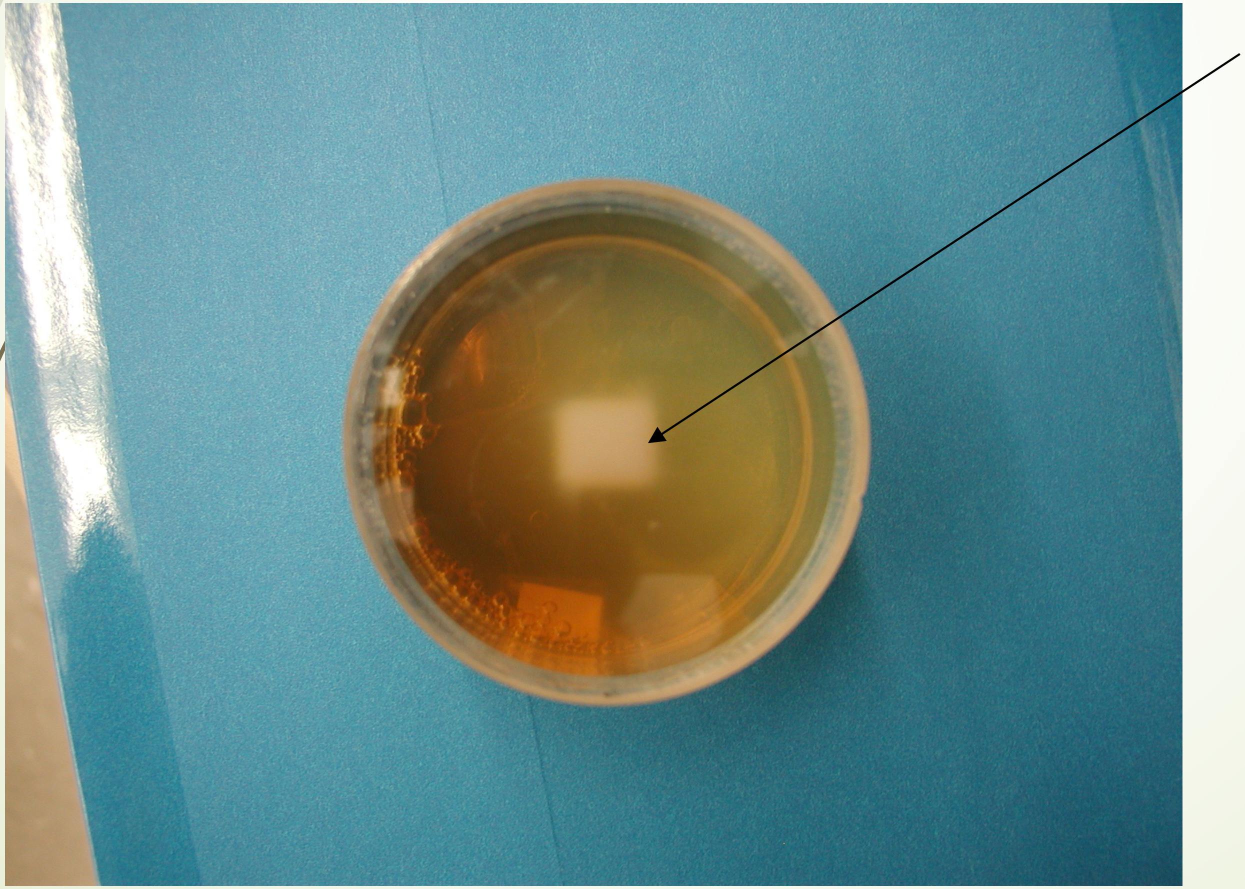


= chain polymerization

Strongly hydrophilic carboxylic group

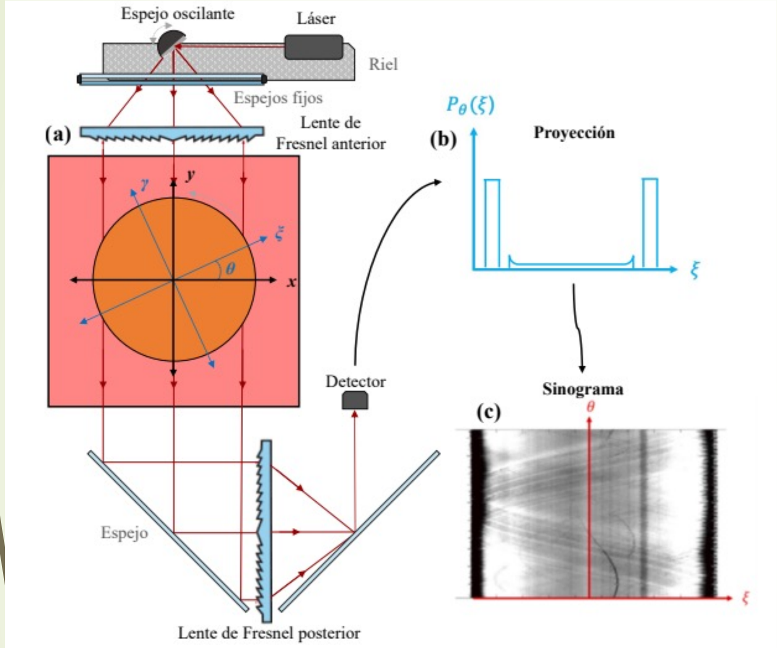
Radiation induced polymerization

2. Polymer chains aggregate in the pores of the gel
3. Formation of various microscopic (submicron size) particles that precipitate from the liquid phase



Irradiated area

Dose-response mechanism



A) 635 nm polarized diode laser at 0.8mW
B) Focusing convex lens
C) Rotating mirror
D) Translucent sphere filled with gel mounted in a turntable
E) Diffuser
F) 1 cm^2 silicon photodiode detector

The dose response is related to the exponential attenuation of the light caused by scattering of micro particles resulting from the polymerization process as follow:

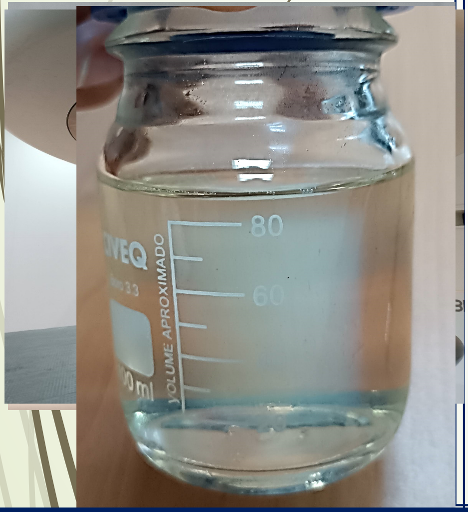
1. The laser beam passes through the lens.
2. The rotating mirror reflects the light to scan the interior of the sphere with focused and parallel paraxial rays at a focal length, *f = r/(n-1), (r, n radius and refractive index of the cylinder)*
3. The photodetector collects the transmitted light to produce the projection data, as the sphere rotates in small-angle increments between projections
4. The response is obtained by the relation:

$$I(x) = I_0 e^{-\int u(x,y)dy}$$

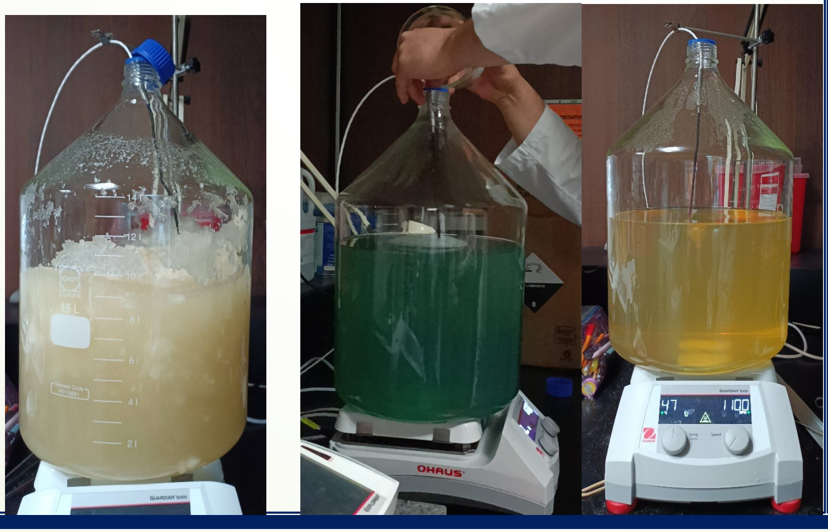
Where *I(x)* is the intensity exiting the sample at position x, I_0 the incident intensity and *u(x,y)* is the optical attenuation coefficient per unit length in a section of the gel

MAGIC gel

Pre-fabrication test



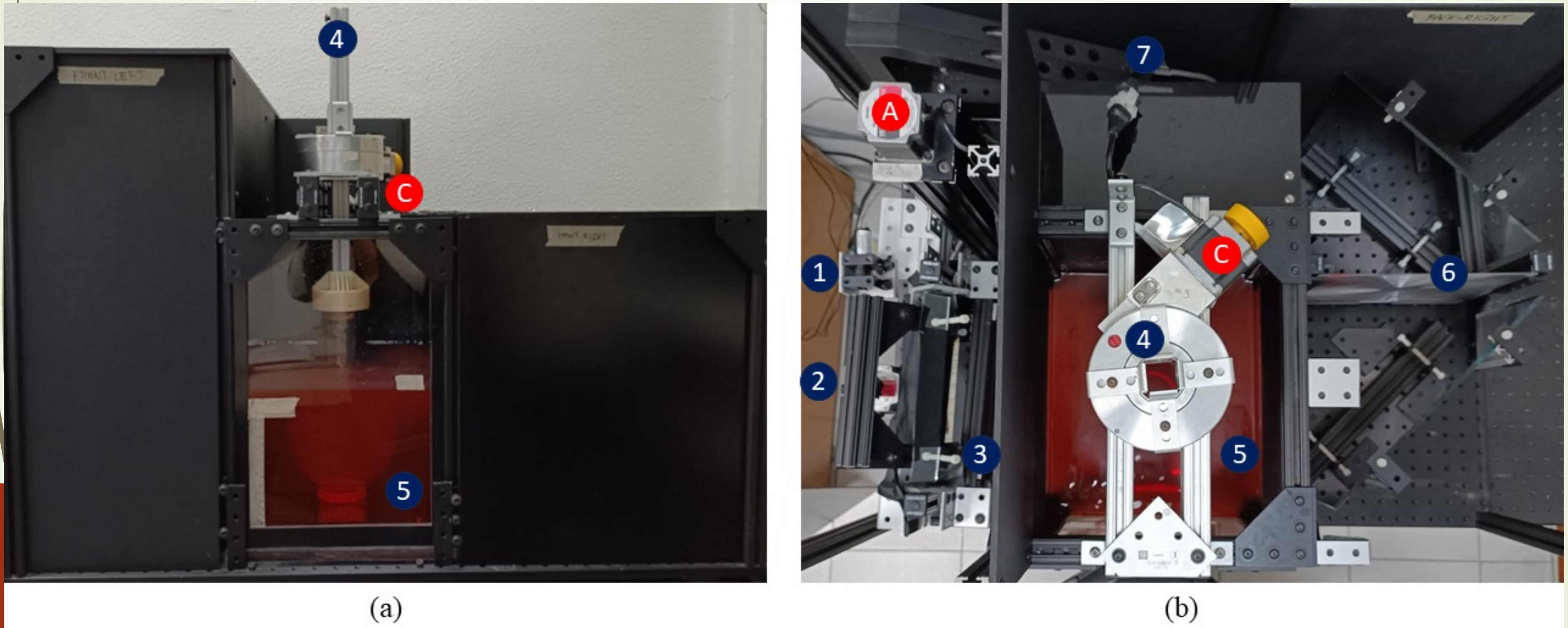
- Preparation



Fabricated gel batch :

Reader: Optical computed tomography scanner

Acquisition software (Octopus-RR laser CT DAQ, R2019b) and reconstruction software (LCT Data and 3D Reconstruction), developed by the manufacturer MGS Research, Inc.



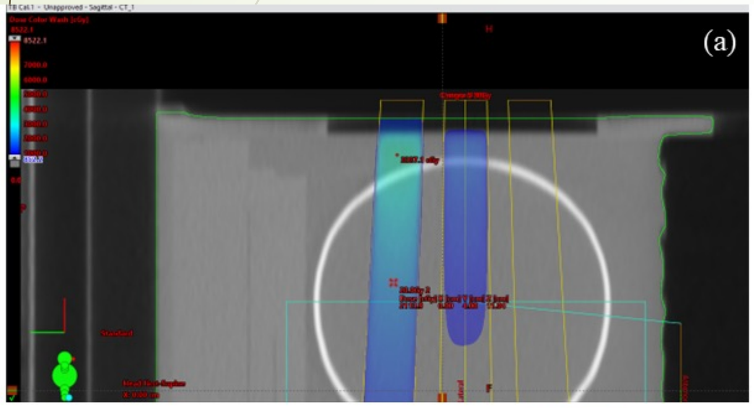
(a) (b)

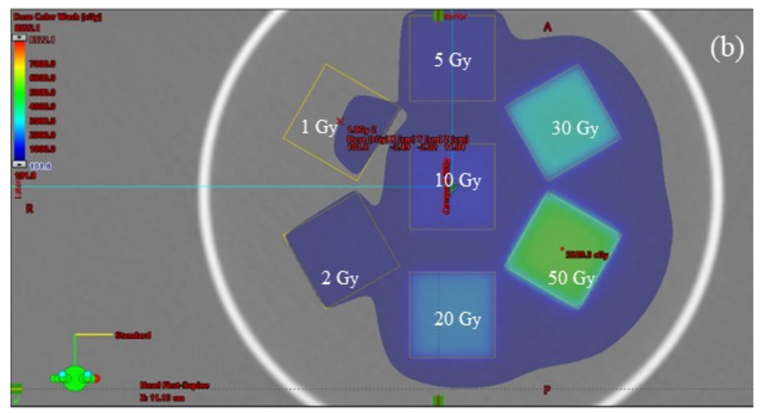
OCT OCTOPUS-RR: (1) laser, (2) oscillating mirror, (3) anterior Fresnel lens, (4) rotation axis, (5) immersion tank, (6) posterior Fresnel lens, (7) detector, (A) engine 1, (B) engine 2, (C) engine 3.

Optical computed tomography scanner for 3D gel dosimetry

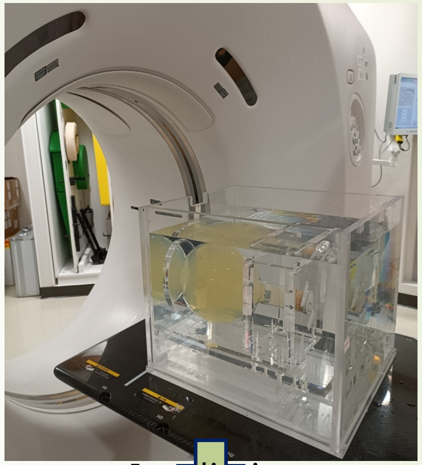
Gel calibration

Calibration was performed in a liquid water phantom of one glass sphere flask phantom filled with gel

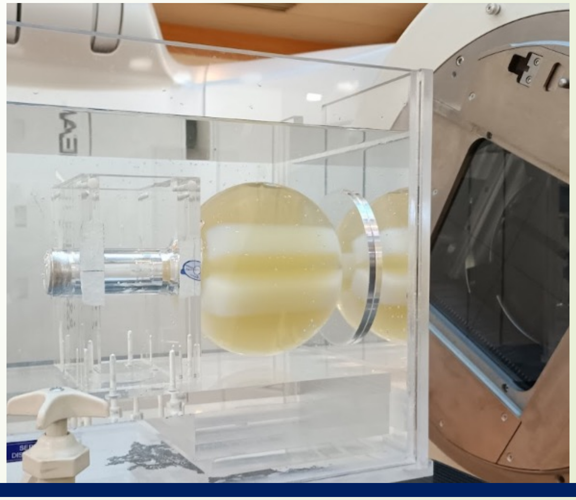




Simulation



Irradiation

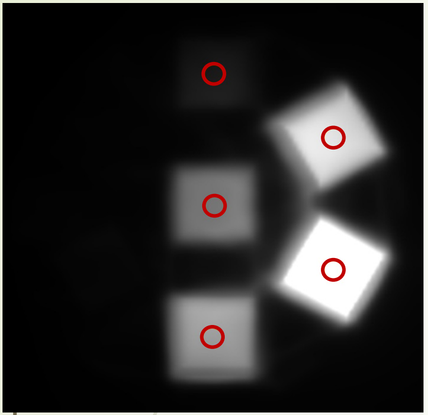


P. J. Guadarrama-Huerta *et al.*, *Radiat. Meas.* 175 (2024) 107166

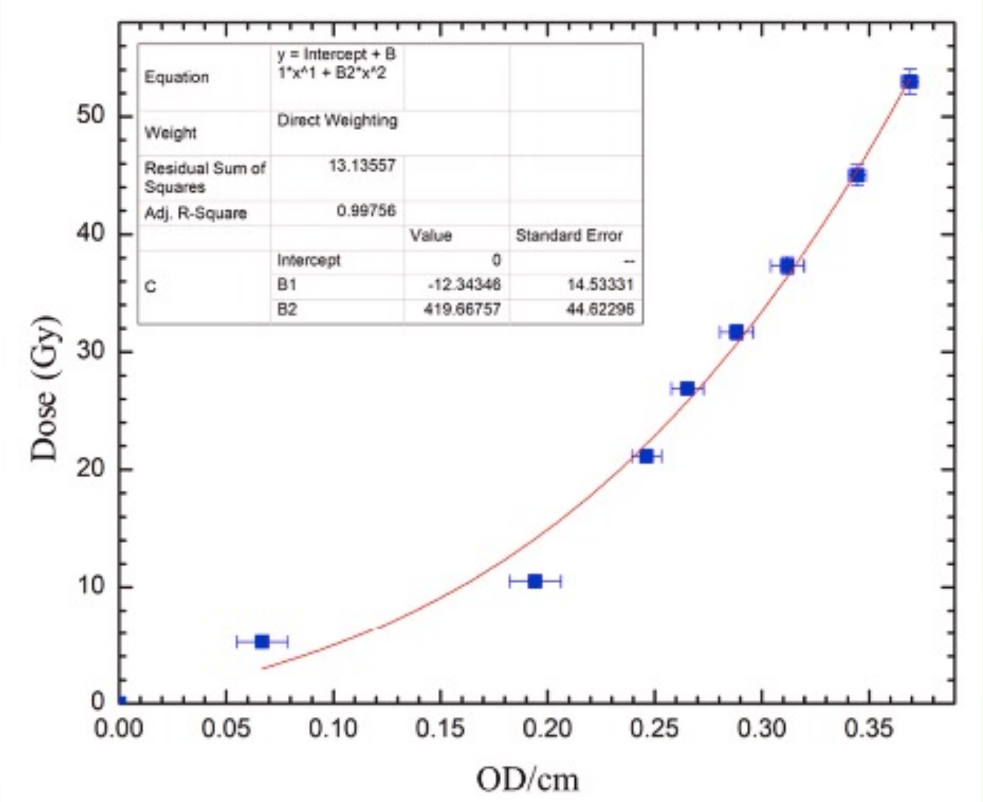
Results

P. J. Guadarrama-Huerta *et al.*, *Radiat. Meas.* 175 (2024) 107166

Calibration curve



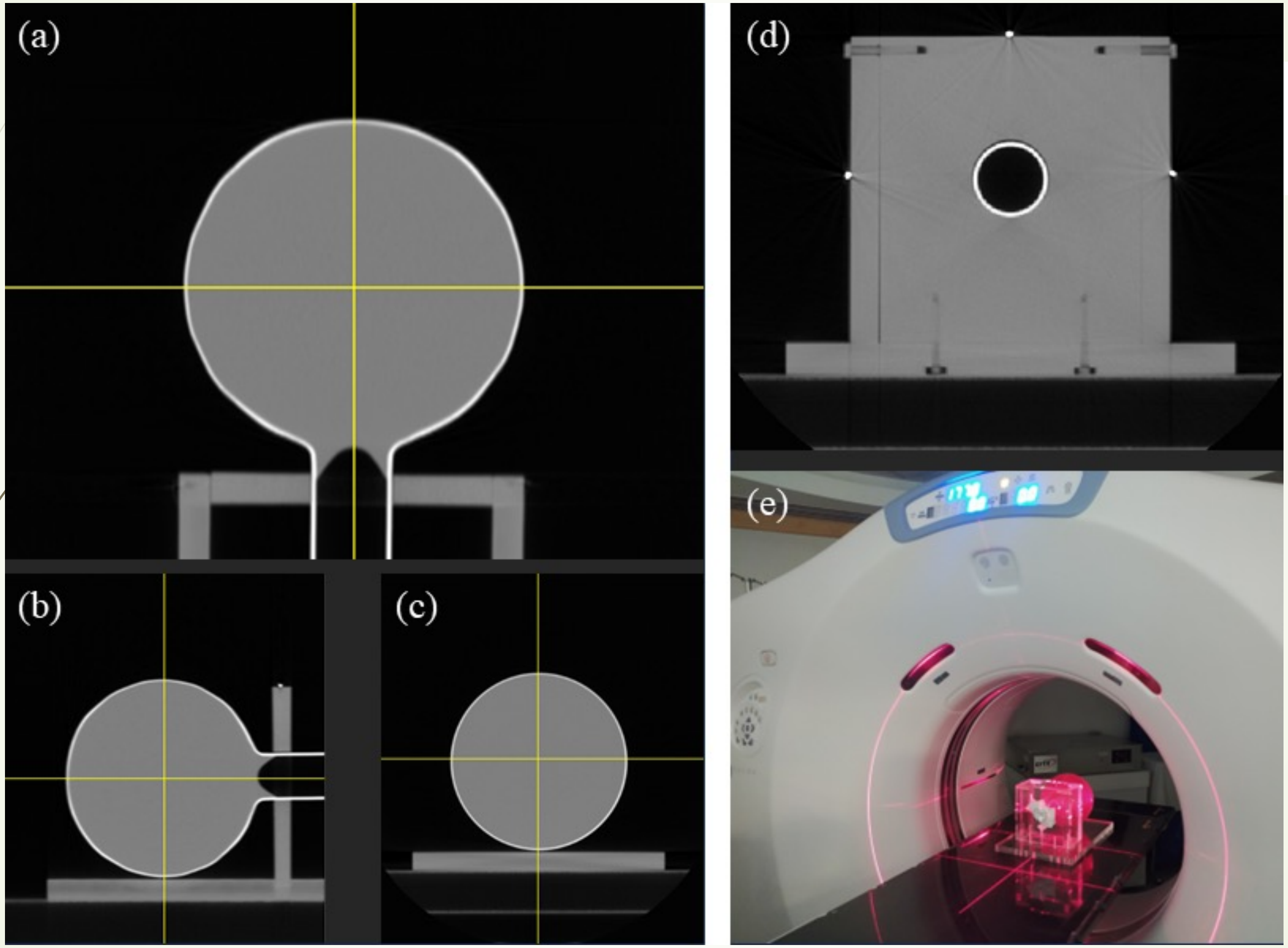
(a) (b)



Equation	y = Intercept + B1*x^1 + B2*x^2		
Weight	Direct Weighting		
Residual Sum of Squares	13.13557		
Adj. R-Square	0.99756		
		Value	Standard Error
C	Intercept	0	--
	B1	-12.34346	14.53331
	B2	419.66757	44.62296

$$Dose(Gy) = -12.34\left(\frac{OD}{cm}\right) + 419.67\left(\frac{OD}{cm}\right)^2$$

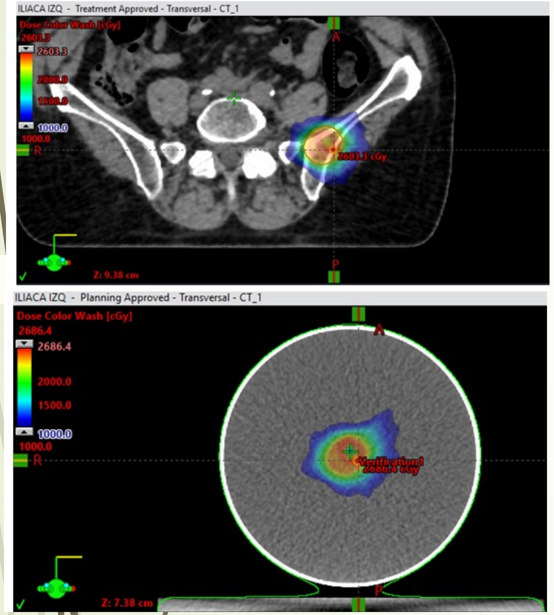
Verification of the treatment plans using the CT scanner

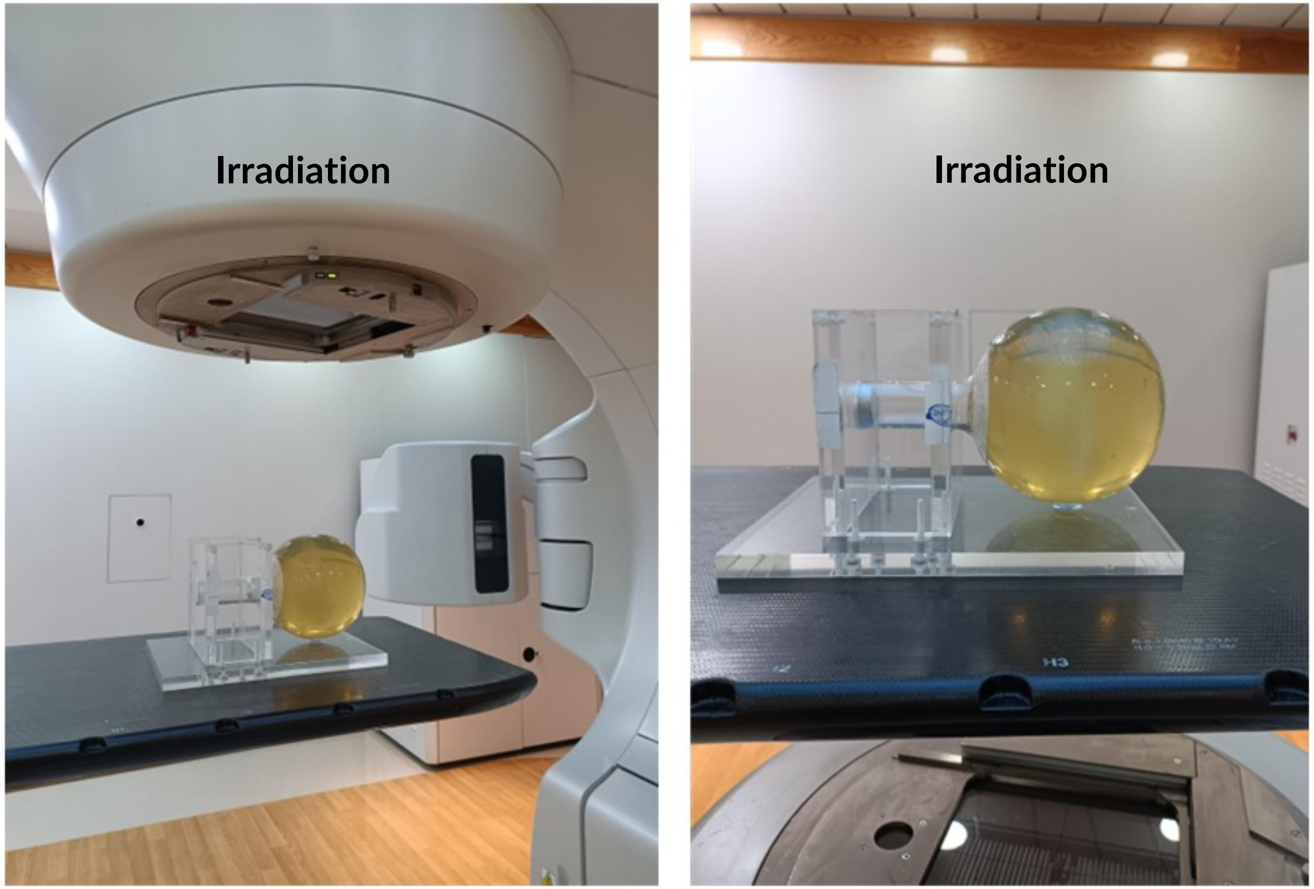


P. J. Guadarrama-Huerta, Thesis UNAM 2024

Verification of the treatments

Treatment plan in the gel

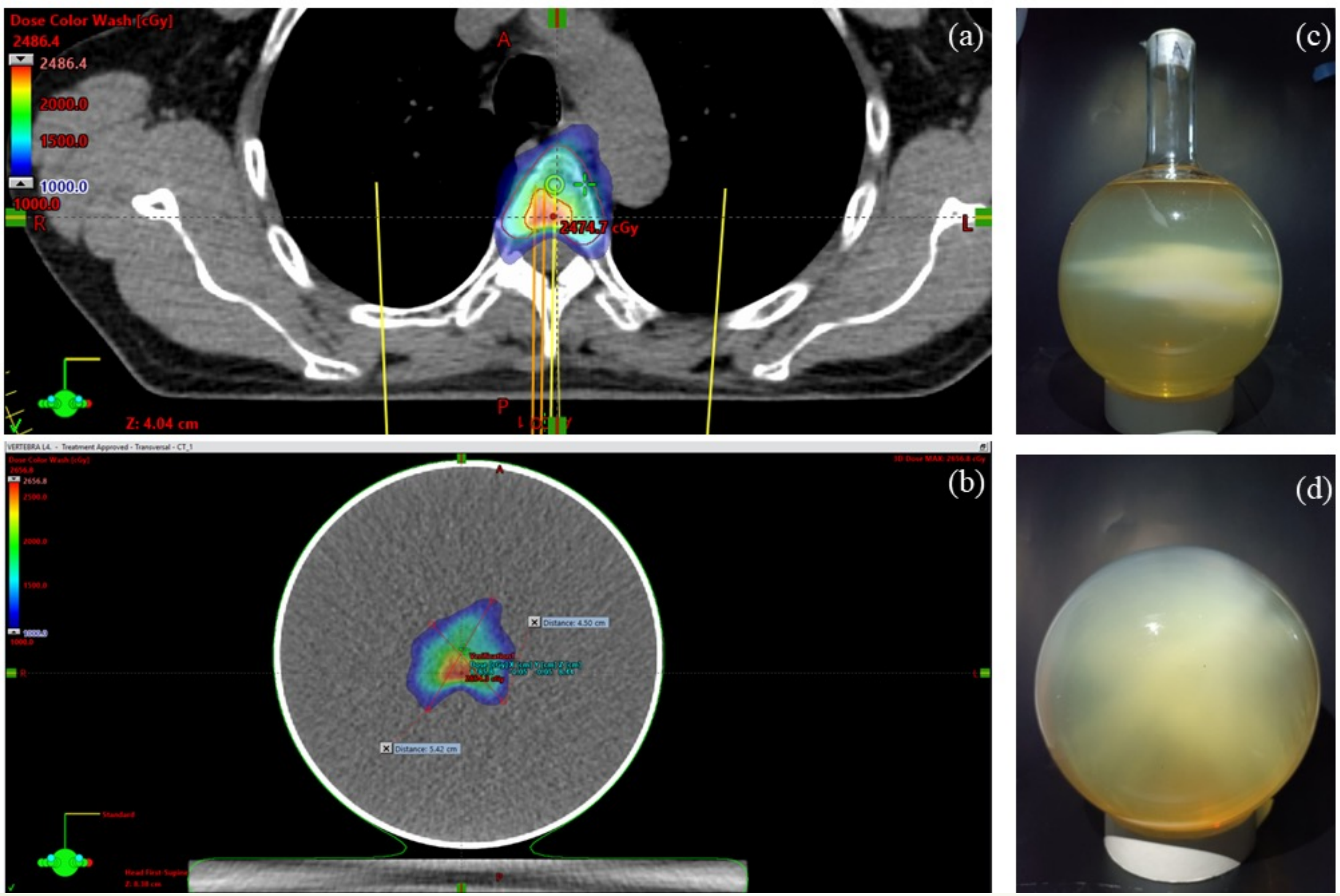




(a) (b)

P. J. Guadarrama-Huerta, Thesis UNAM 2024

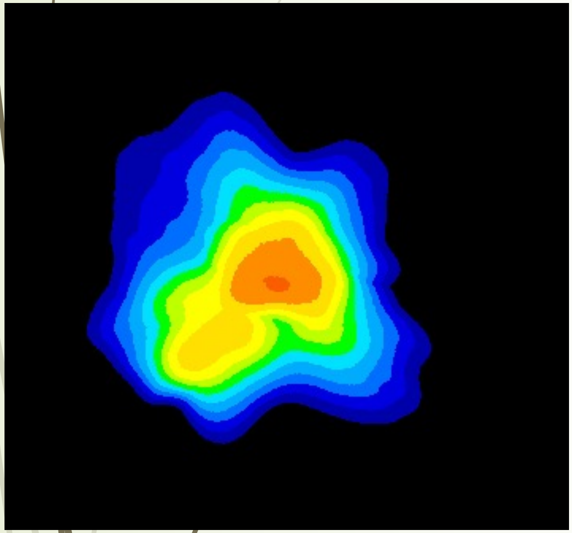
SBRT vertebral



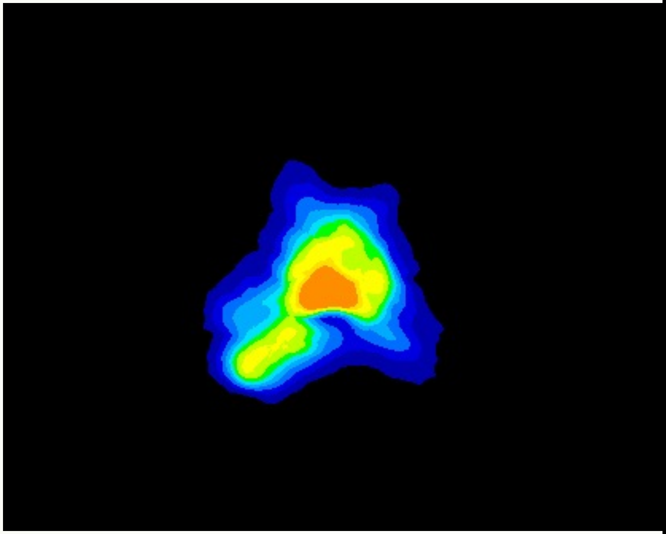
P. J. Guadarrama-Huerta *et al.*, *Radiat. Meas.* 175 (2024) 107166

3D projection of the dose distribution

3D OD/cm

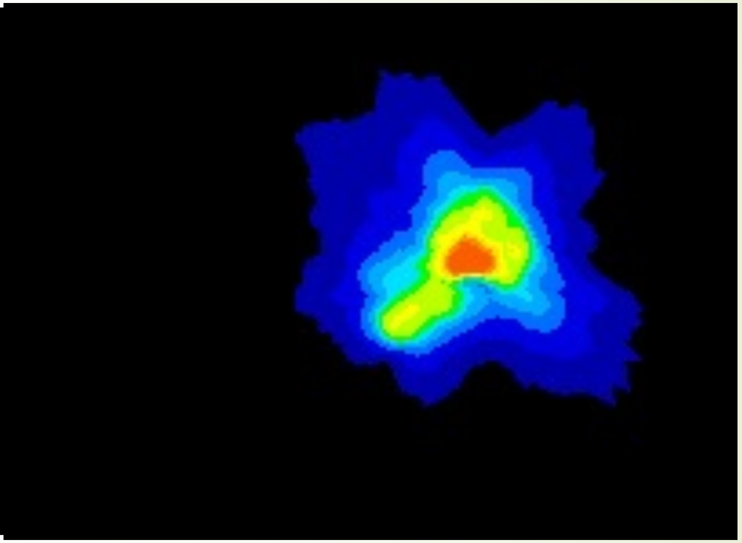


Measured dose distribution



vs

Calculated dose distribution, TPS



P. J. Guadarrama-Huerta, Thesis UNAM 2024

Summary

- Radiochromic films can be used to measure absorbed dose rate within combined uncertainty of less than 1.5% if a strict protocol is followed, besides the low cost of this system.

- TLD-100 should not be used for absorbed dose greater than 1 Gy for Medical application due to the supralinearity effect

- Optimizing the gel's sensitivity for doses under 10 Gy is imperative.

- Enhance the thermal stability of the gel and optimize the procedures for manufacturing, reading, calibration, and results analysis will be important.