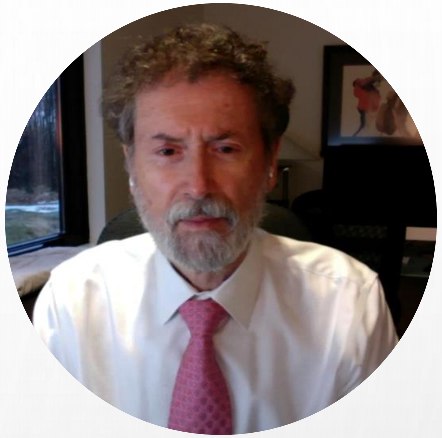


3D DOSIMETRY OF PROTON BEAMS AND INFLUENCES ON RESPONSE

Geoffrey Ibbott, PhD, and
Mitchell Carroll, PhD

OUTLINE

1) BENEFITS OF 3D DOSIMETRY IN PROTON THERAPY

2) EXPERIENCE WITH 3D DOSIMETERS WITH PROTON BEAMS

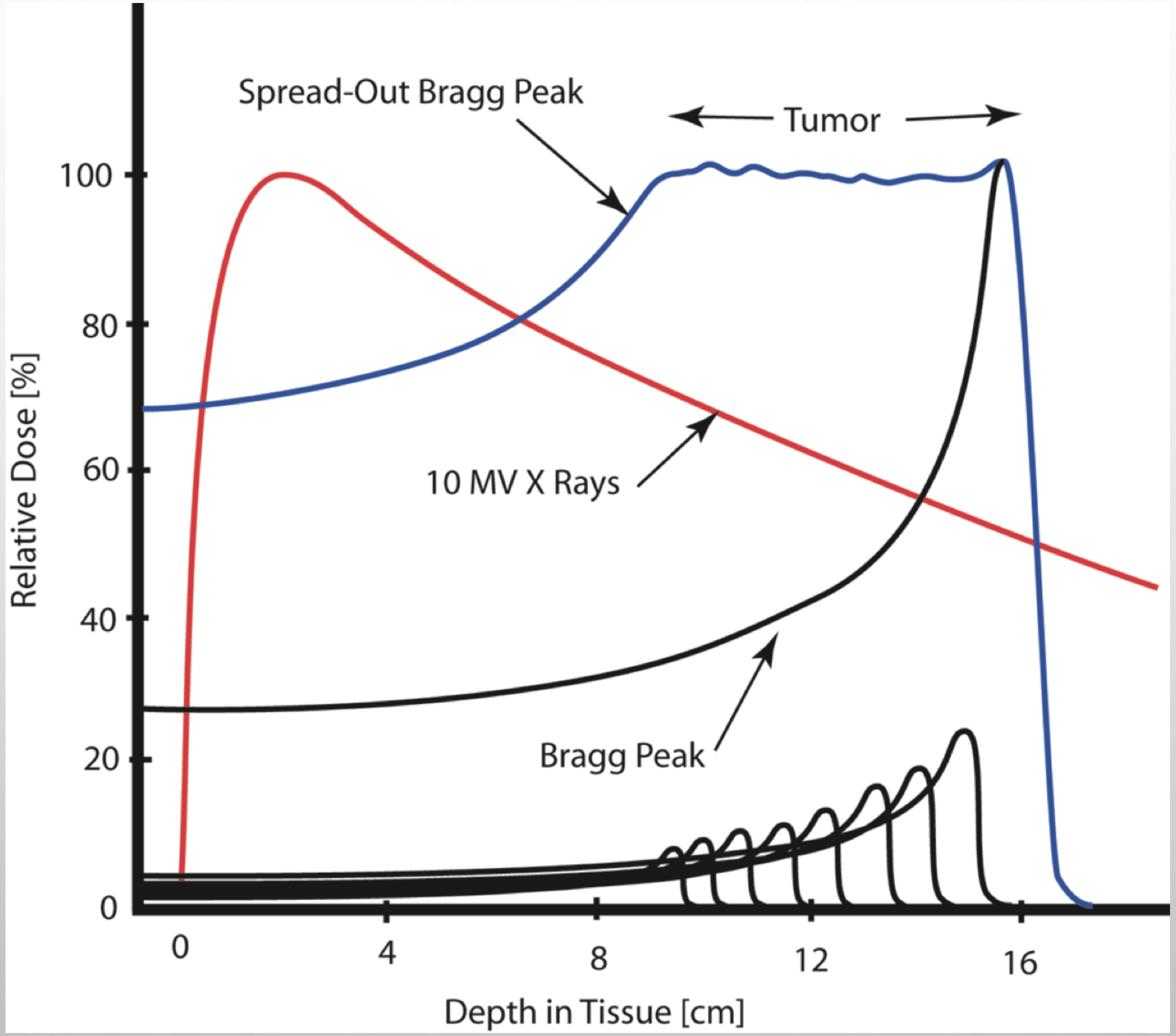
3) COMPLICATIONS TO USE OF 3D DOSIMETRY

4) SOLUTIONS TO THESE COMPLICATIONS

ERRORS IN RADIOTHERAPY

- "RADIATION OFFERS NEW CURES, AND WAYS TO DO HARM"
  - WALT BOGDANICH, NYTIMES, 2010
  - PUBLISHED A SERIES OF ARTICLES REGARDING HISTORY OF MEDICAL ERRORS IN RT
- THESE CASES LEAD THE HEADLINES, BUT MOST MISADMINISTRATIONS GO UNDETECTED
- DEMONSTRATES THE NEED FOR COMPREHENSIVE QA:
  - INCREASING COMPLEXITY OF MODERN EQUIPMENT AND TECHNIQUES
    - MANUFACTURER'S "BLACK BOX"
  - MAINTAINING CLINICAL EFFICIENCY

CHARACTERISTICS OF PROTON BEAMS



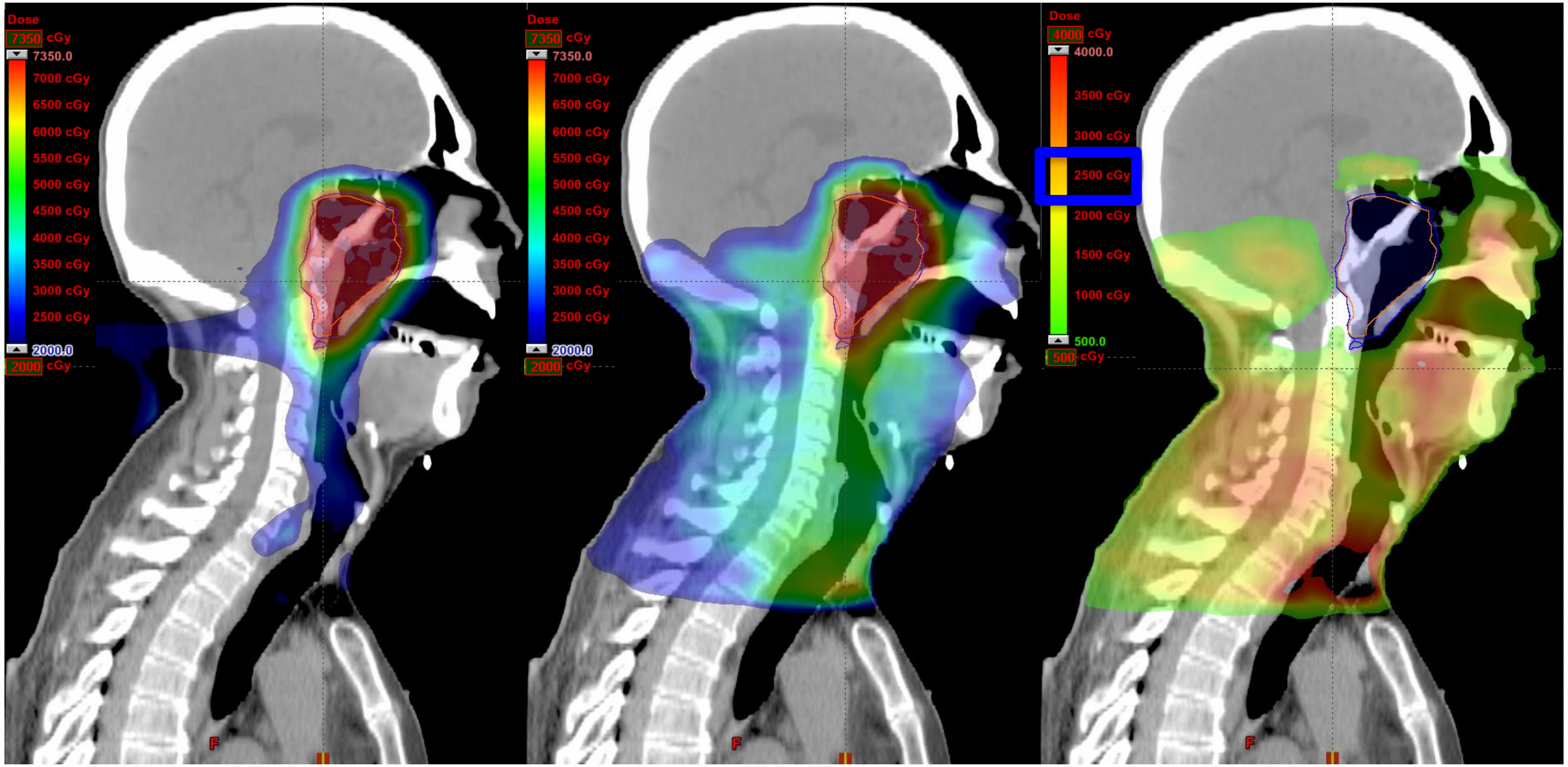
WHY PROTONS?

- HAS RAPID DOSE FALL OFF BEYOND THE RANGE
- CAN LEAD TO LESS DOSE TO NORMAL TISSUE AND CRITICAL ORGAN
- POSSIBLE TO ESCALATE THE TARGET DOSE
- WILL LEAD TO BETTER THERAPEUTIC GAIN
- PATIENTS CAN BETTER TOLERATE COMBINED THERAPY

WHY PROTON THERAPY?

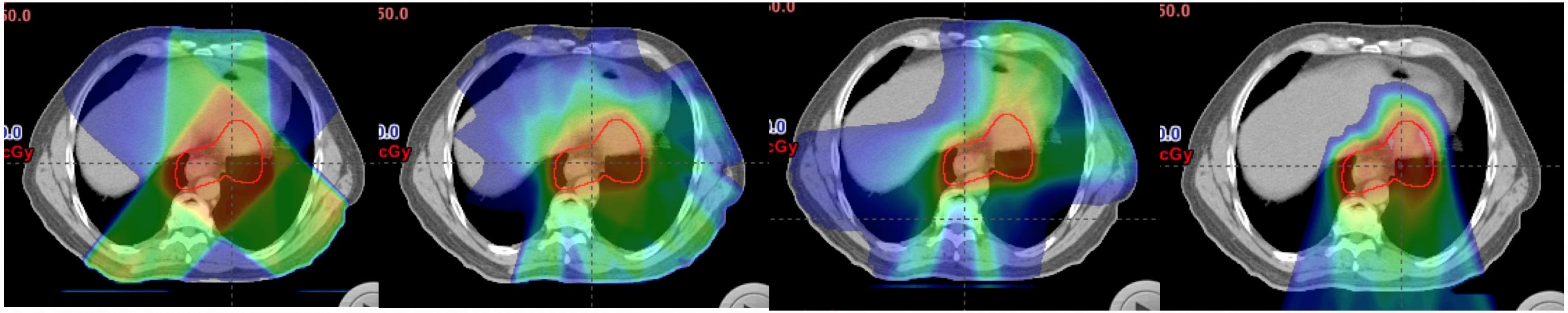
Elimination of Unnecessary Radiation with Proton Therapy

<u>Proton</u> Therapy (IMPT) | <u>X-Ray</u> Therapy (IMRT) | Added Radiation w/ X-Rays



WHY PROTON THERAPY?

3D-CRT X-RAYS	IMRT X-RAYS	VMAT X-RAYS	IMPT PROTONS



HEARTDOSE (cGy):

3D-CRT X-RAYS	IMRT X-RAYS	VMAT X-RAYS	IMPT PROTONS
2833	1933	2200	**943**

LUNG DOSE (cGy):

3D-CRT X-RAYS	IMRT X-RAYS	VMAT X-RAYS	IMPT PROTONS
1747	1324	1103	**775**

LIVER DOSE (cGy):

3D-CRT X-RAYS	IMRT X-RAYS	VMAT X-RAYS	IMPT PROTONS
1184	1141	986	**235**

CONVENTIONAL DOSIMETRY FOR PROTON BEAMS

- CALIBRATION:
  - CALORIMETERS, ION CHAMBERS, TLDS, ALANINE, FRICKE SOL'N
- COMMISSIONING, ROUTINE QA:
  - MULTILAYER IONIZATION CHAMBER
- 2D MEASUREMENTS:
  - FILM, PLANAR ARRAYS

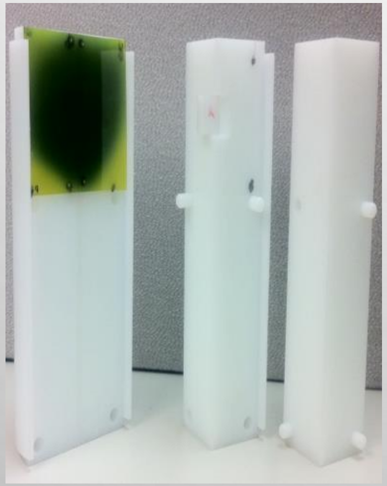
IROC PHANTOM LIBRARY

- IROC SUPPLIES A NUMBER OF PHANTOMS TO CREDENTIAL INSTITUTIONS PARTICIPATING IN NIH TRIALS.
  - PROVIDE PHANTOMS FOR TESTING OF A VARIETY OF ANATOMICAL SITES AND CLINICAL TECHNIQUES
  - DOSIMETRY SYSTEMS USING CROSS-SECTIONAL FILMS WITH TLD OR OSLD INSERTS
  - PHANTOMS TREATED END-TO-END FOLLOWING SAME CLINICAL PROTOCOL



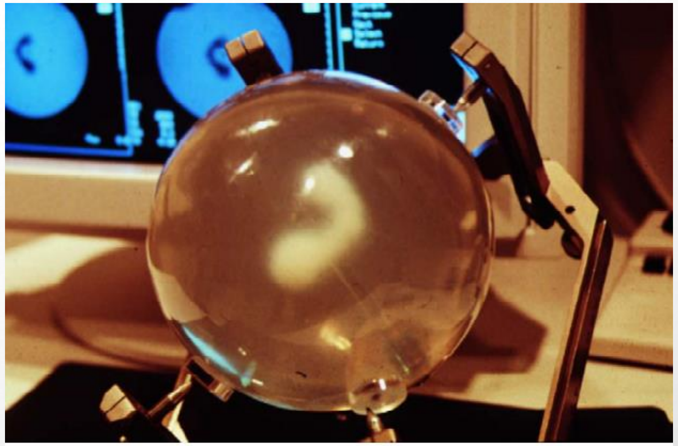
PHANTOMS

- A STRAIGHTFORWARD PROCESS ADAPTING EXISTING ANTHROPOMORPHIC PHANTOMS TO 3D SYSTEMS



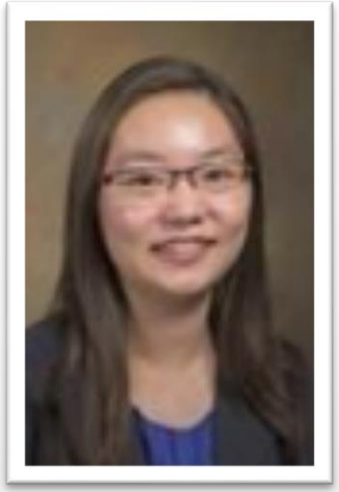
GEL DOSIMETRY

- DOSE REPORTERS:
  - POLYMERS GELS: CONVERSION OF LOCAL MONOMERS TO POLYMER CLUSTERS
  - FRICKE: CONVERSION OF FERROUS (FE^{2+}) TO FERRIC (FE^{3+}) IONS
- OFFLINE READOUT:
  - MRI
  - X-RAY CT
  - OPTICAL CT (OCT)
  - 0.5 MM OR BETTER SPATIAL RESOLUTION
- LIMITATIONS:
  - OXYGEN SENSITIVITY
  - SIGNAL DIFFUSION
  - CONTAINER REQUIREMENT
  - DOSE RATE DEPENDENCE (CERTAIN POLYMER GELS)

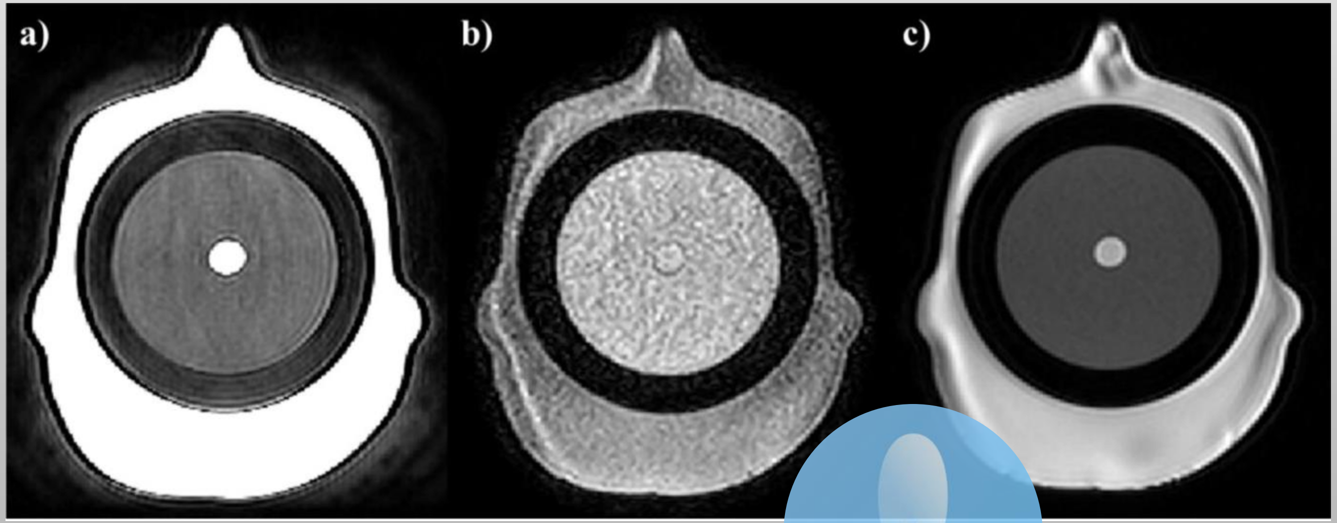


Ibbott, 1997, 2004
Baldock, 2010

END-TO-END TESTS WITH GEL DOSIMETRY

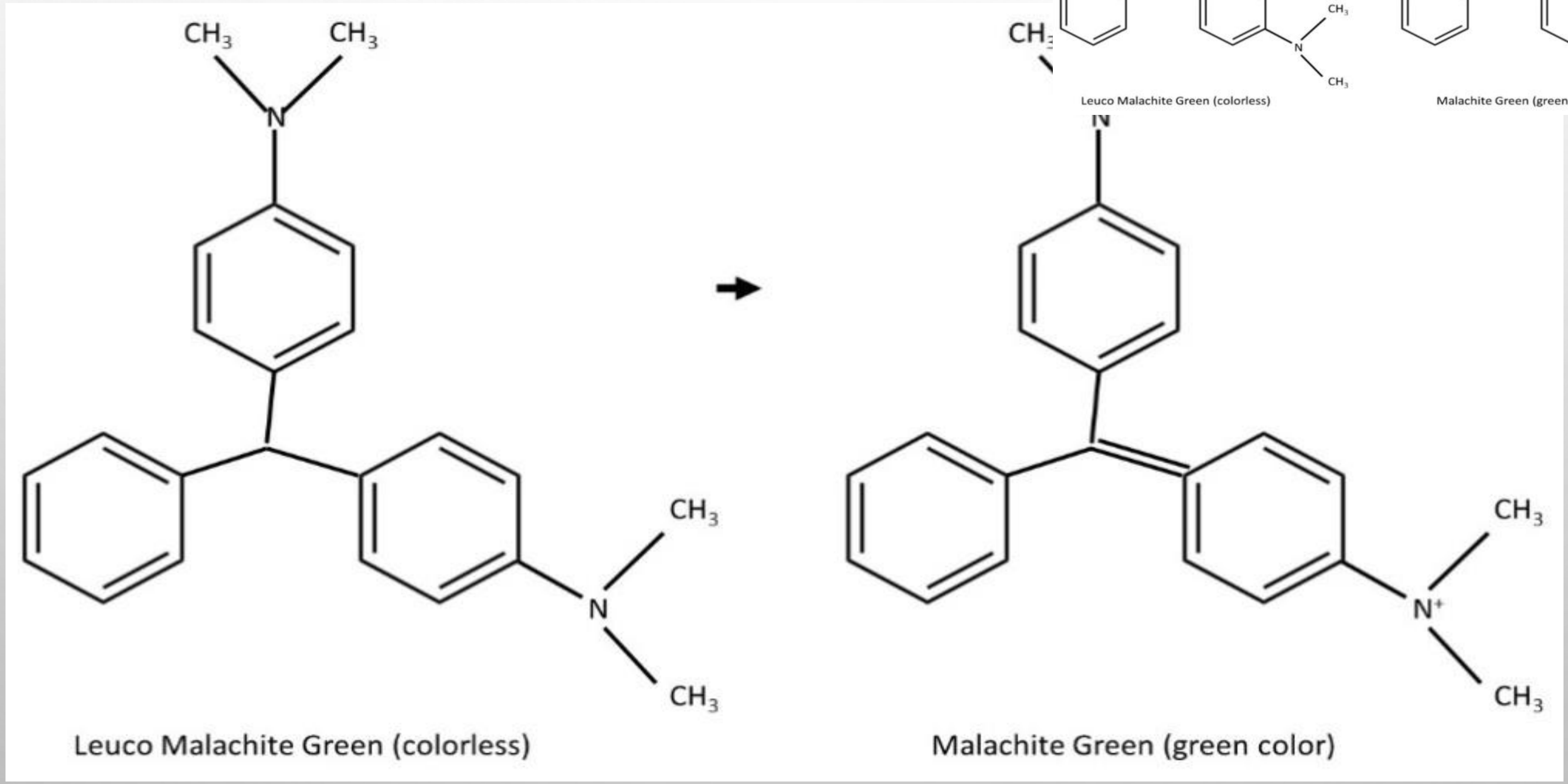


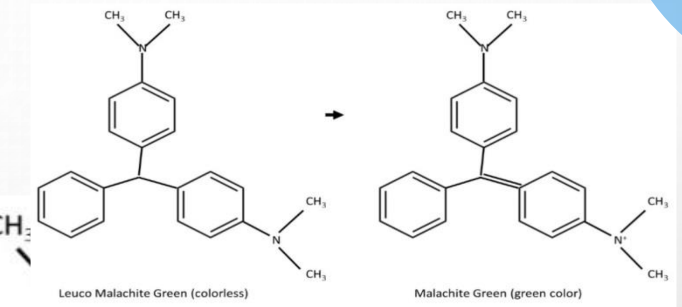
Hannah J. Lee, Ph.D,



PRESAGE®

- A RADIOCHROMIC, POLYURETHANE DOSIMETER
  - HOUSING LEUCO DYE RECORDER AND RADICAL INITIATOR (RI) ACTIVATOR.





PRESAGE®

- ADVANTAGES:
  - LITTLE OXYGEN SENSITIVITY*
  - NO SIGNAL DIFFUSION
  - NO CONTAINER REQUIREMENTS
  - CAN BE MACHINED AND MOLDED INTO ANY SHAPE OR SIZE
- DISADVANTAGES:
  - DIFFICULTY IN MANUFACTURING
  - OPTICAL CT READOUT ONLY

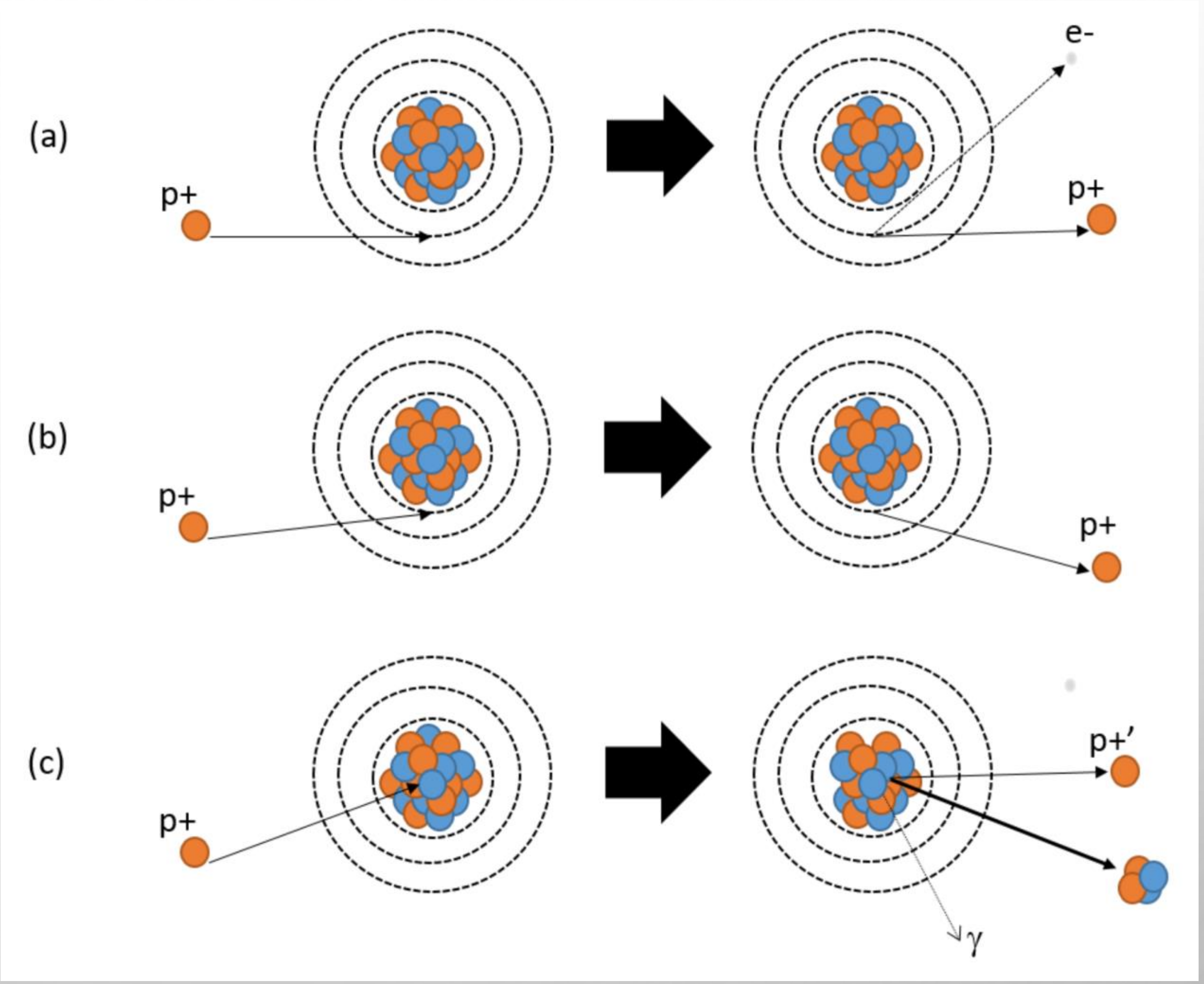
*Alqathami M, Blencowe A, Ibbott G. Experimental determination of the influence of oxygen on the PRESAGE(®) dosimeter. Phys Med Biol 61(2):813-824, 1/2016,

PROTON INTERACTIONS

- INELASTIC COULOMBIC INTERACTIONS WITH ELECTRONS

- ELASTIC COULOMBIC INTERACTIONS WITH NUCLEI

- NUCLEAR COLLISIONS



3D DOSIMETRY

- FRICKE GELS
- POLYMER GELS
- RADIOCHROMIC PLASTIC (PRESAGE)
- LIQUID SCINTILLATOR

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- Bäck SA, Medin J, Magnusson P, Olsson P, Grusell E, Olsson LE. Ferrous sulphate gel dosimetry and MRI for proton beam dose measurements. *Phys Med Biol*. 1999;44(8):1983-1996.
- Heufelder J, Stiefel S, Pfaender M, Lüdemann L, Grebe G, Heese J. Use of BANG® polymer gel for dose measurements in a 68 MeV proton beam. *Med Phys*. 2003;30(6):1235-1240. doi:10.1118/1.1575557
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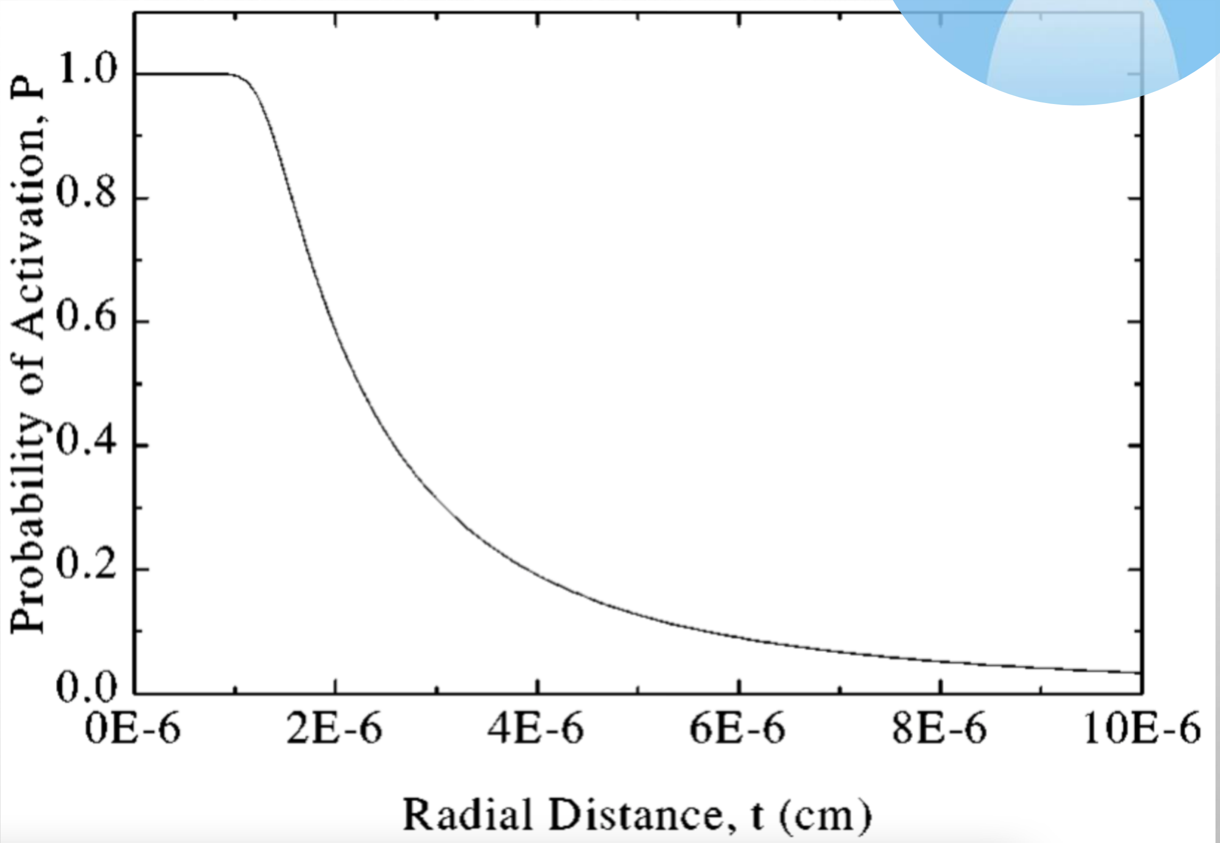
- Robertson D, Mirkovic D, Sahoo N, Beddar S. Quenching correction for volumetric scintillation dosimetry of proton beams. *Phys Med Biol*. 2013;58(2):261-273. doi:10.1088/0031-9155/58/2/261
- Nadrowitz R, Coray A, Boehringer T, Dunst J, Rades D. A liquid fluorescence dosimeter for proton dosimetry. *Phys Med Biol*. 2012;57(5):1325-1333. doi:10.1088/0031-9155/57/5/1325
- Al-Nowais S, Doran S, Kacperek A, Krstajic N, Adamovics J, Bradley D. A preliminary analysis of LET effects in the dosimetry of proton beams using PRESAGE^{TM} and optical CT. *Appl Radiat Isot*. 2009;67(3):415-418. doi:10.1016/J.APRADISO.2008.06.032
- Nowais S Al, Kacperek A, Brunt JNH, Adamovics J, Nisbet A, Doran SJ. An investigation of the response of the radiochromic dosimeter PRESAGE to irradiation by 62 MeV protons. *J Phys Conf Ser*. 2010;250(1):012034. doi:10.1088/1742-6596/250/1/012034

MECHANISMS OF SIGNAL LOSS

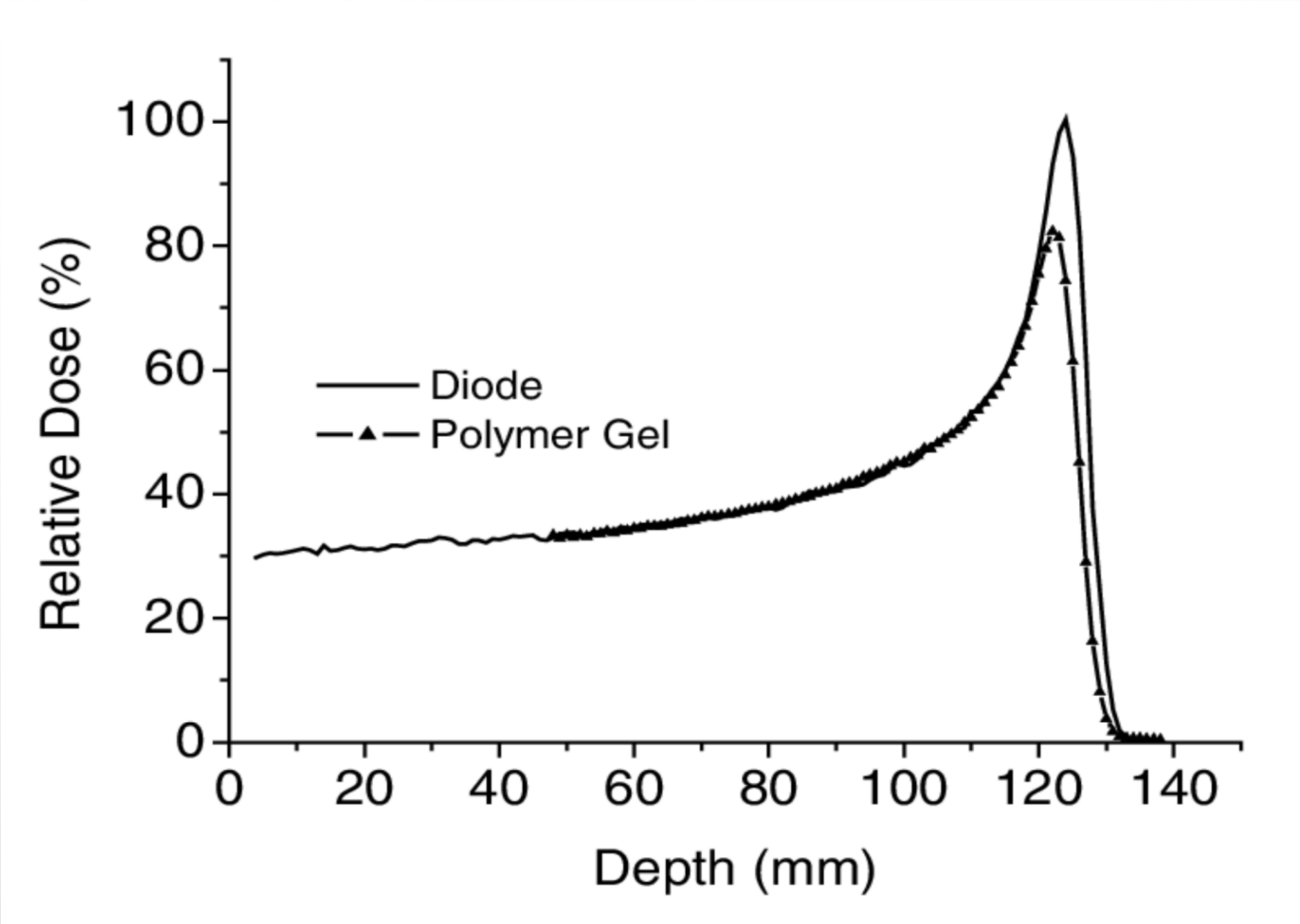
Jirasek & Duzenli: High dose deposition close to proton track saturates activation sites in gel



Jirasek A, Duzenli C. Relative effectiveness of polyacrylamide gel dosimeters applied to proton beams: Fourier transform Raman observations and track structure calculations. *Med Phys.* 2002;29(4):569-577. doi:10.1118/1.1460873

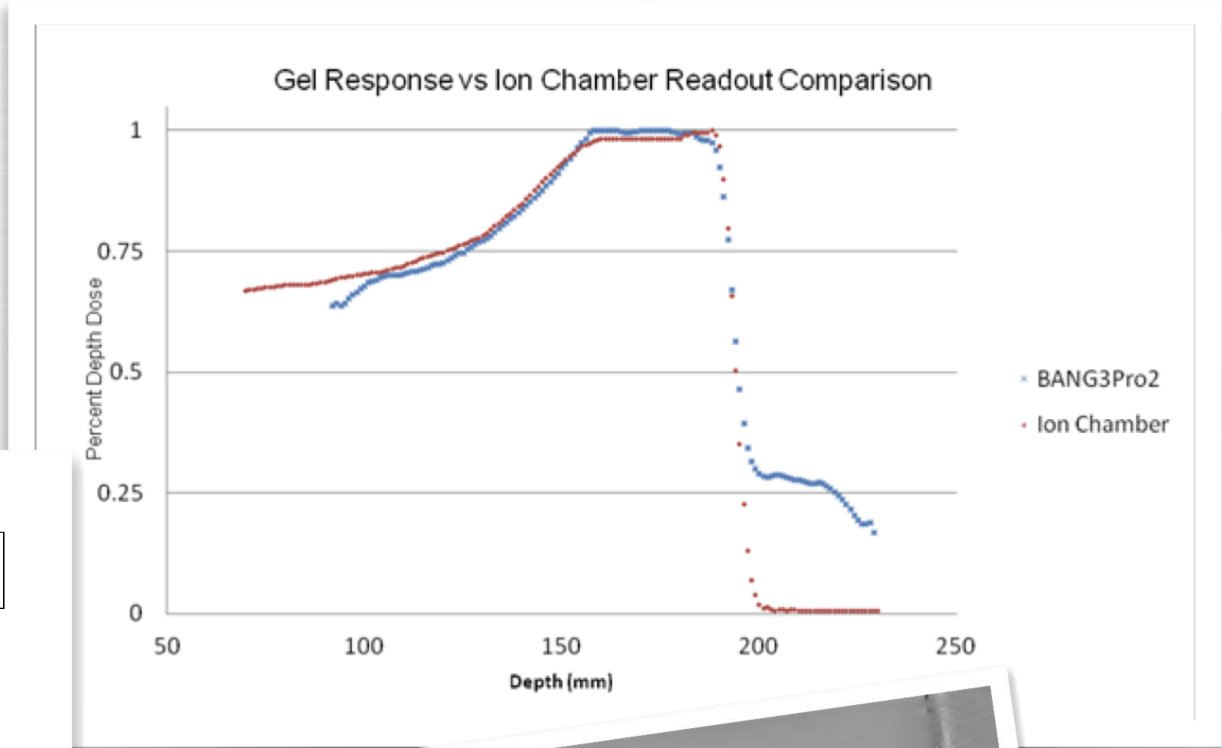
SIGNAL QUENCHING IN POLYMER GEL

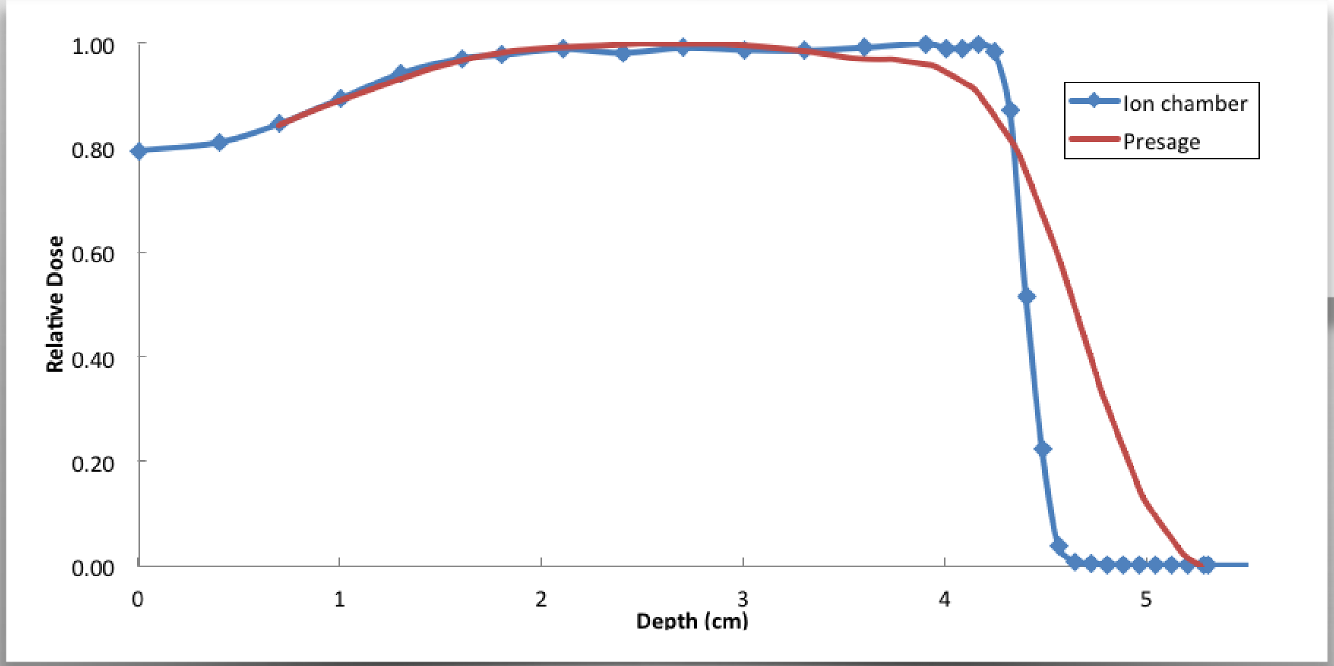
GUSTAVSSON: HIGH CONCENTRATION OF RADICALS LEADS TO RECOMBINATION

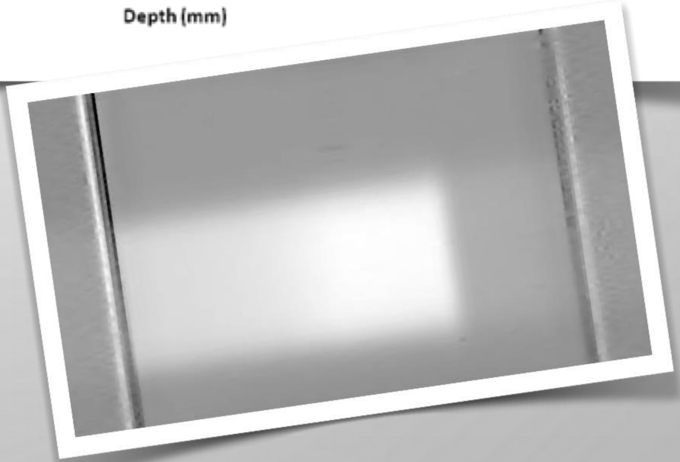


Gustavsson H, Bäck SAJ, Medin J, Grusell E, Olsson LE. Linear energy transfer dependence of a normoxic polymer gel dosimeter investigated using proton beam absorbed dose measurements. *Phys Med Biol*. 2004;49(17):3847-3855.

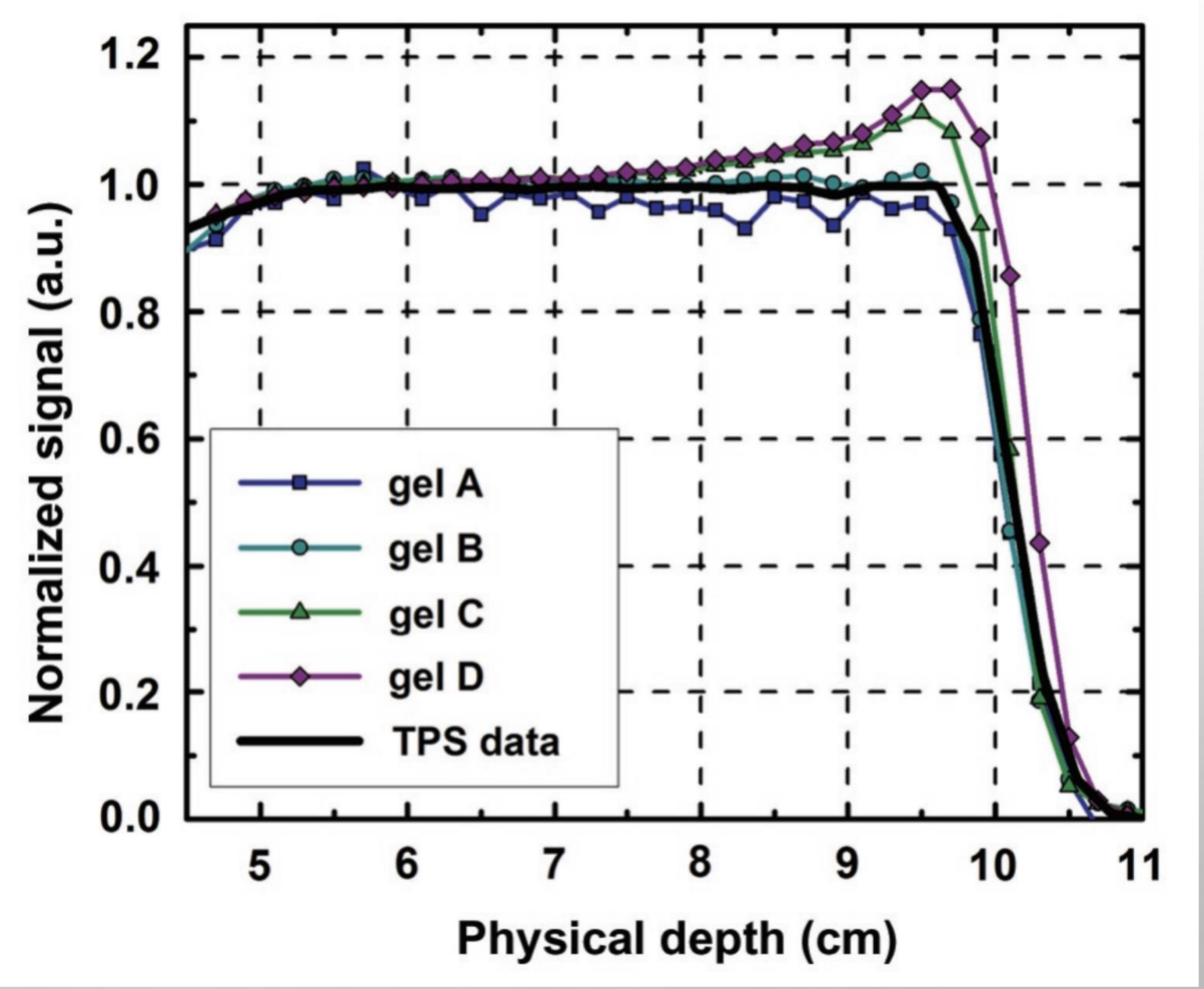
PROTON DOSIMETRY





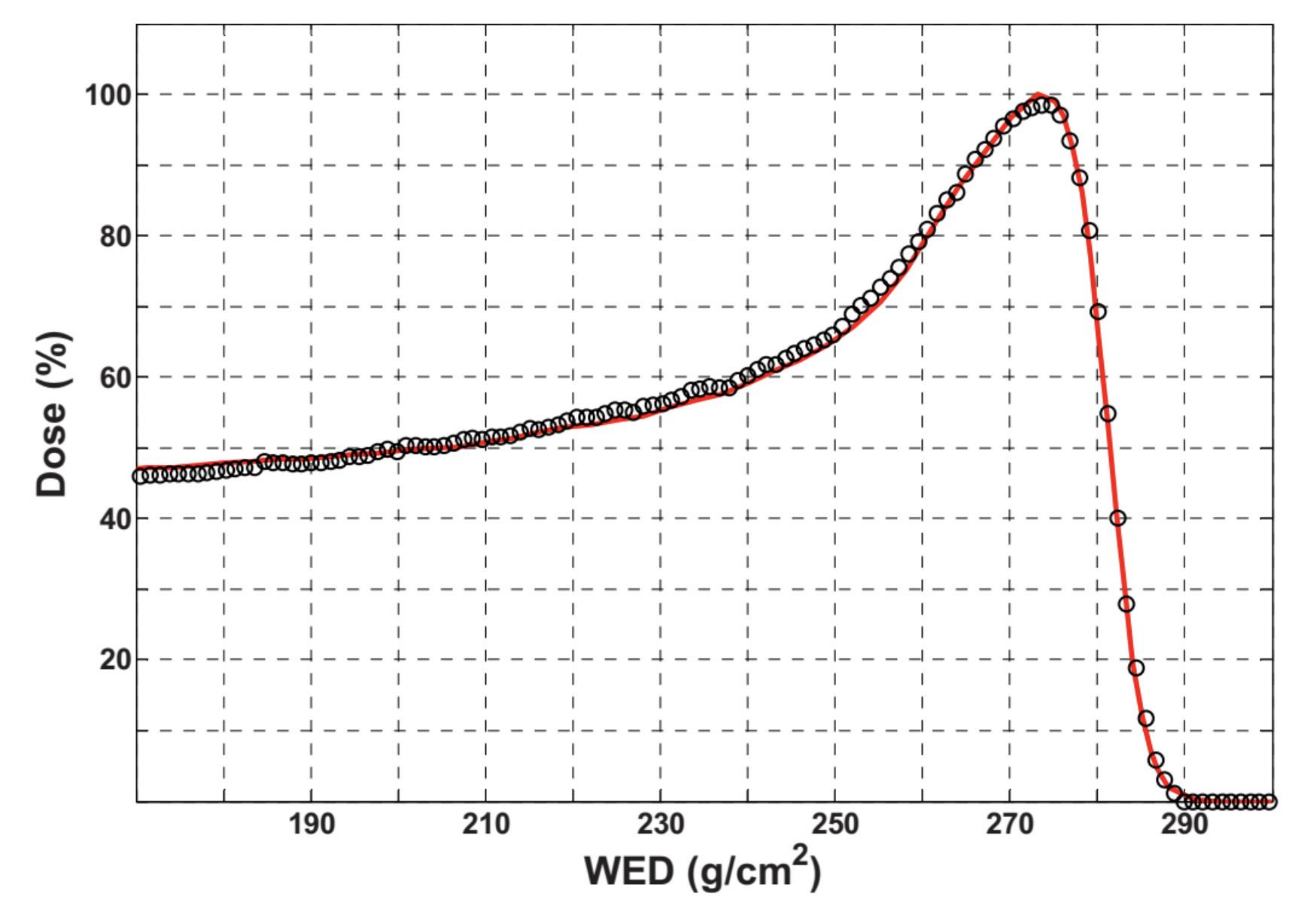


MODIFIED GEL: BANG3



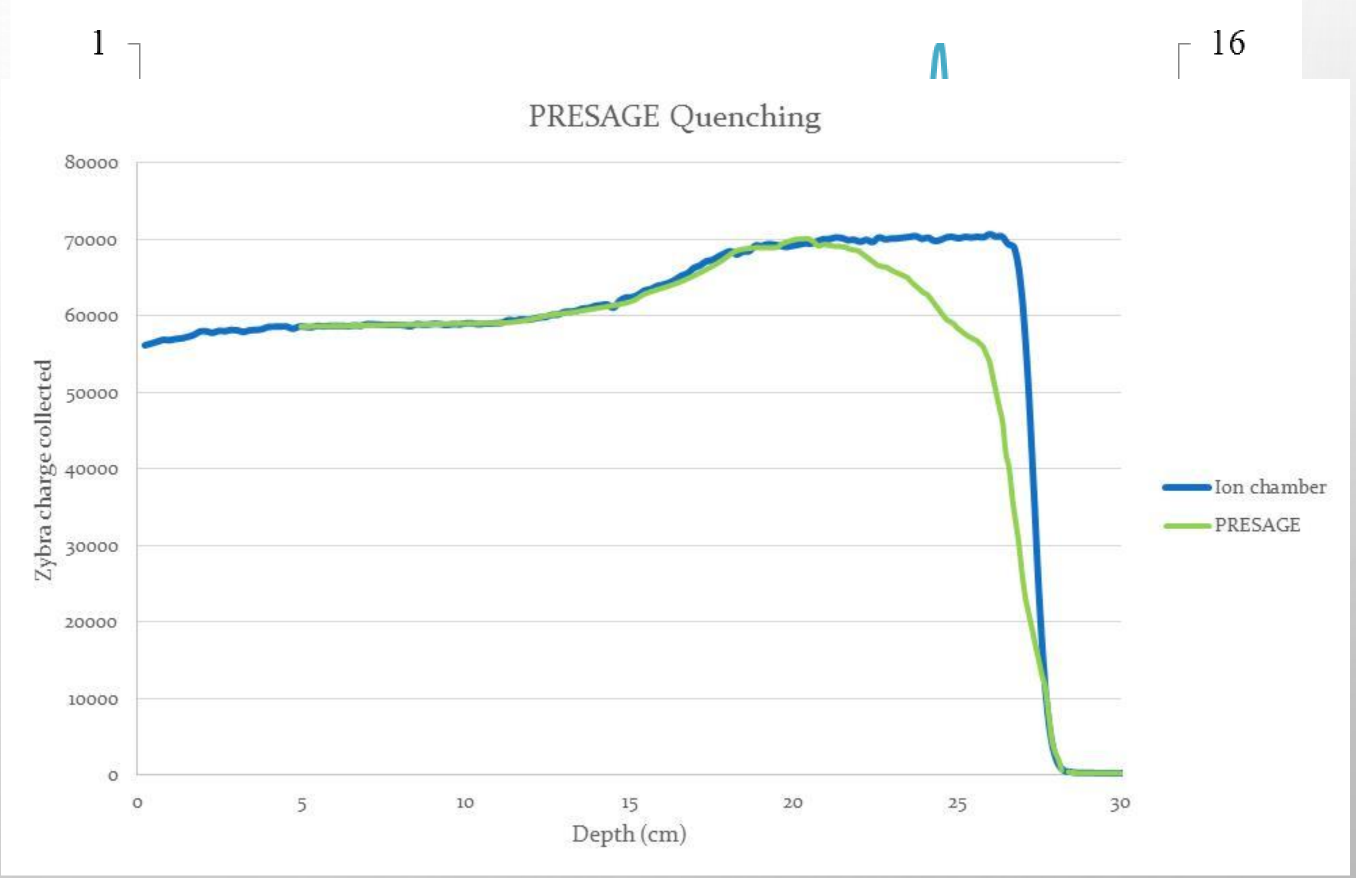
Zeidan O et al: Dosimetric evaluation of a novel polymer gel dosimeter for proton therapy, Medical Physics | 10.1118/1.3388869

BANG3 PRO2 POLYMER GEL



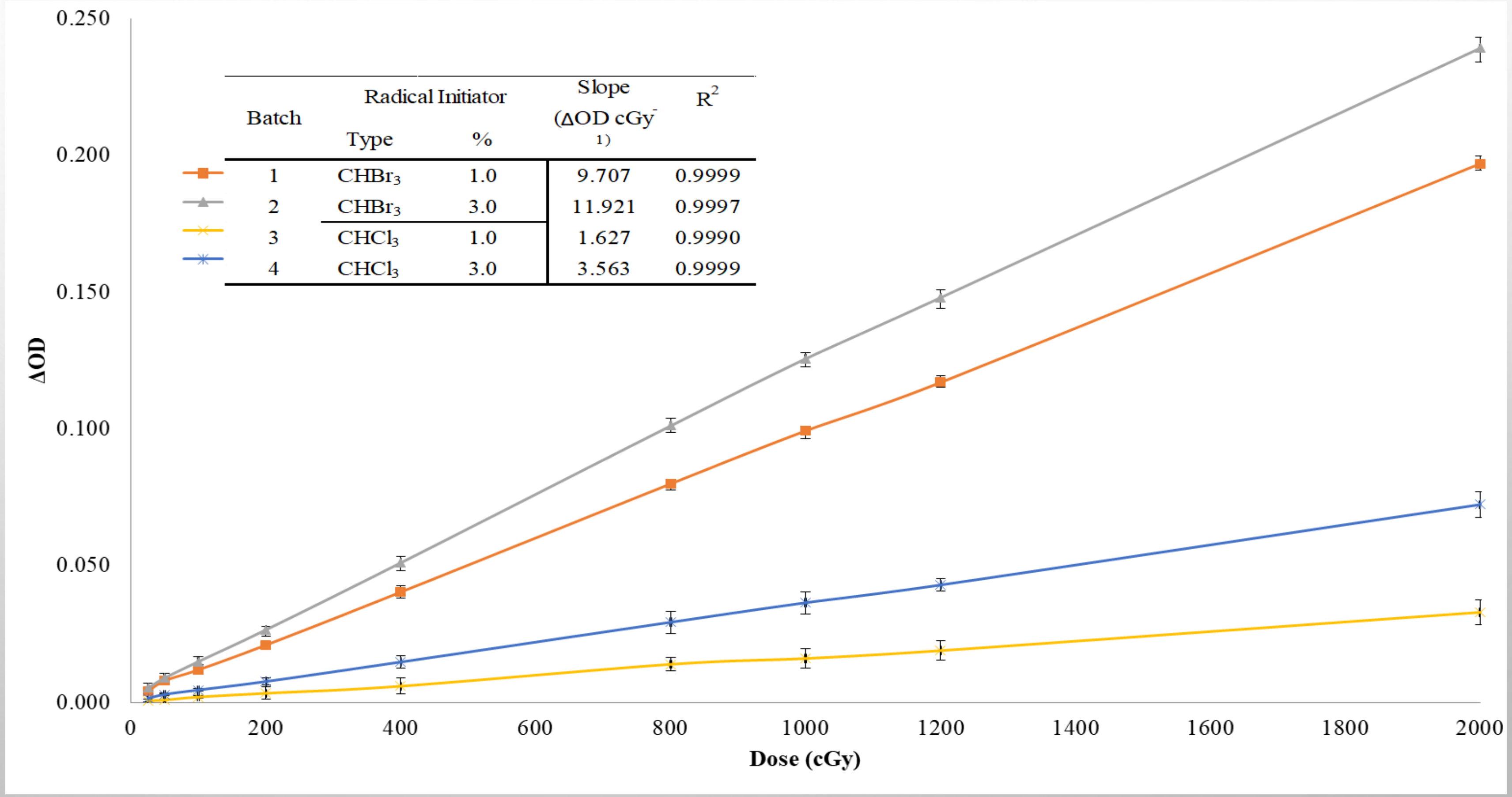
SIGNAL QUENCHING IN PRESAGE

- SIGNAL QUENCHING LEADING TO DOSE SIGNAL UNDER-RESPONSE
- ATTRIBUTED TO HIGH LET OF PROTONS
- OBSERVED IN NEARLY ALL CHEMICAL DOSIMETERS
  - >20% IN PRESAGE



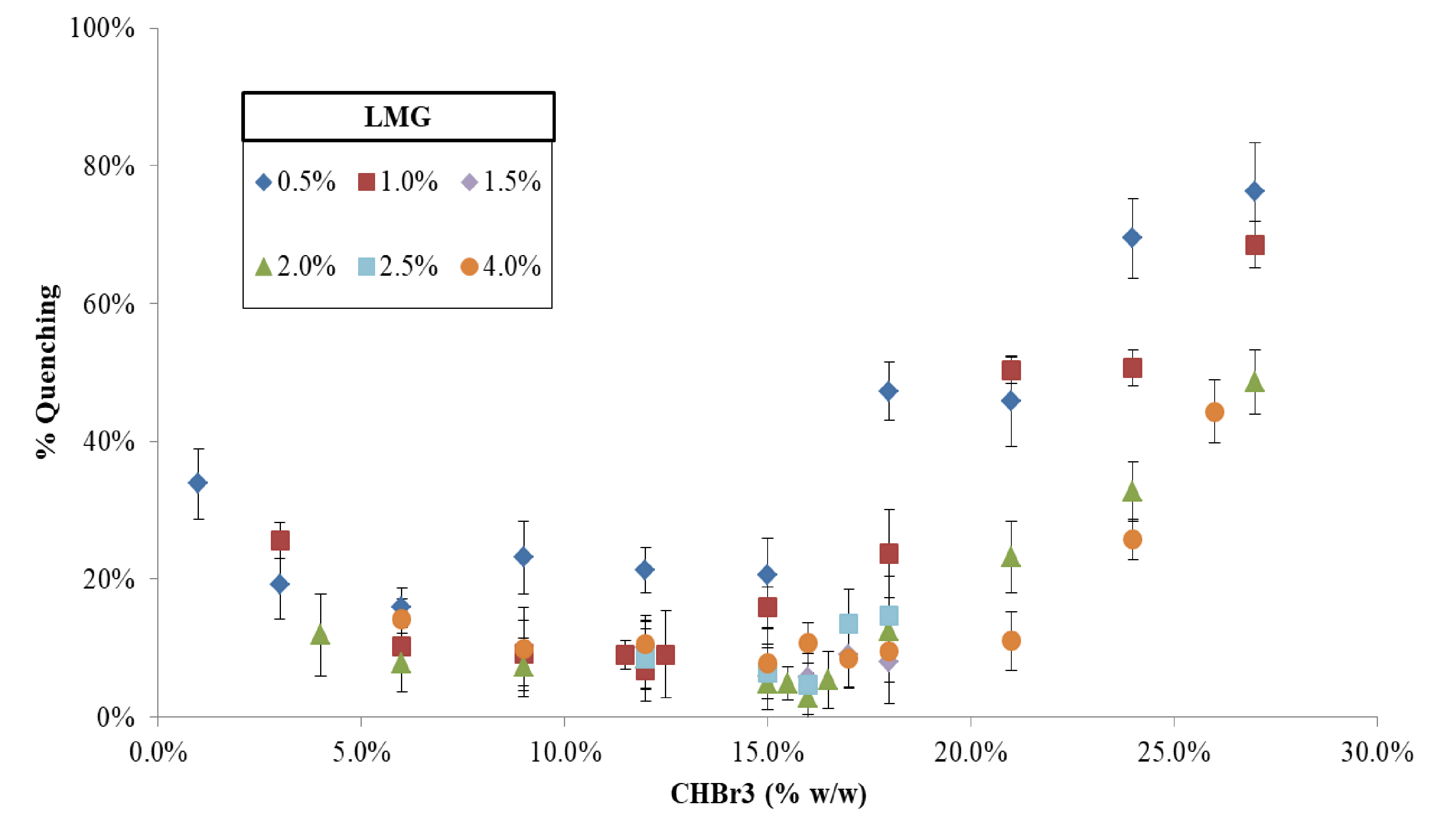
DOSE SENSITIVITY

- DOSE RESPONSE SENSITIVITY: (10^{-5} ΔOD CGY^{-1} (% W/W)$^{-1}$)
  - LMG CONCENTRATION: 142.1%±8.3%
  - RADICAL INITIATOR: 110.7%±3.2% (CHBR3) 96.8%±2.1% (CHCL3)



Batch	Radical Initiator Type	%	Slope (ΔOD cGy^{-1})	R^2
1	$CHBr_3$	1.0	9.707	0.9999
2	$CHBr_3$	3.0	11.921	0.9997
3	$CHCl_3$	1.0	1.627	0.9990
4	$CHCl_3$	3.0	3.563	0.9999

FORMULATION DEPENDENCE OF QUENCHING



QUENCHING CORRECTION

- QUENCHING CORRECTION FACTOR (QCF):
  - PRESAGE® CORRELATION COEFFICIENT (r_p) IS DERIVED FROM THE QUENCHING:

$$r_P(d,E) = \frac{\varepsilon_{IC}^{P}(E) * M_P(d,E)}{M_{IC}^{norm}(d,E)}$$

$$QCF(d,E) = \frac{1}{r_P(d,E)}$$

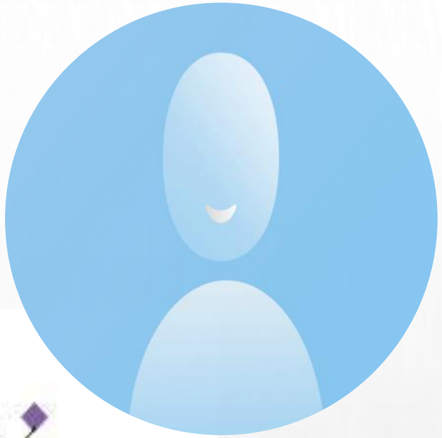
ε_{IC}^{P}=PRESAGE® CALIBRATION FACTOR

M_P=PRESAGE® DOSE SIGNAL

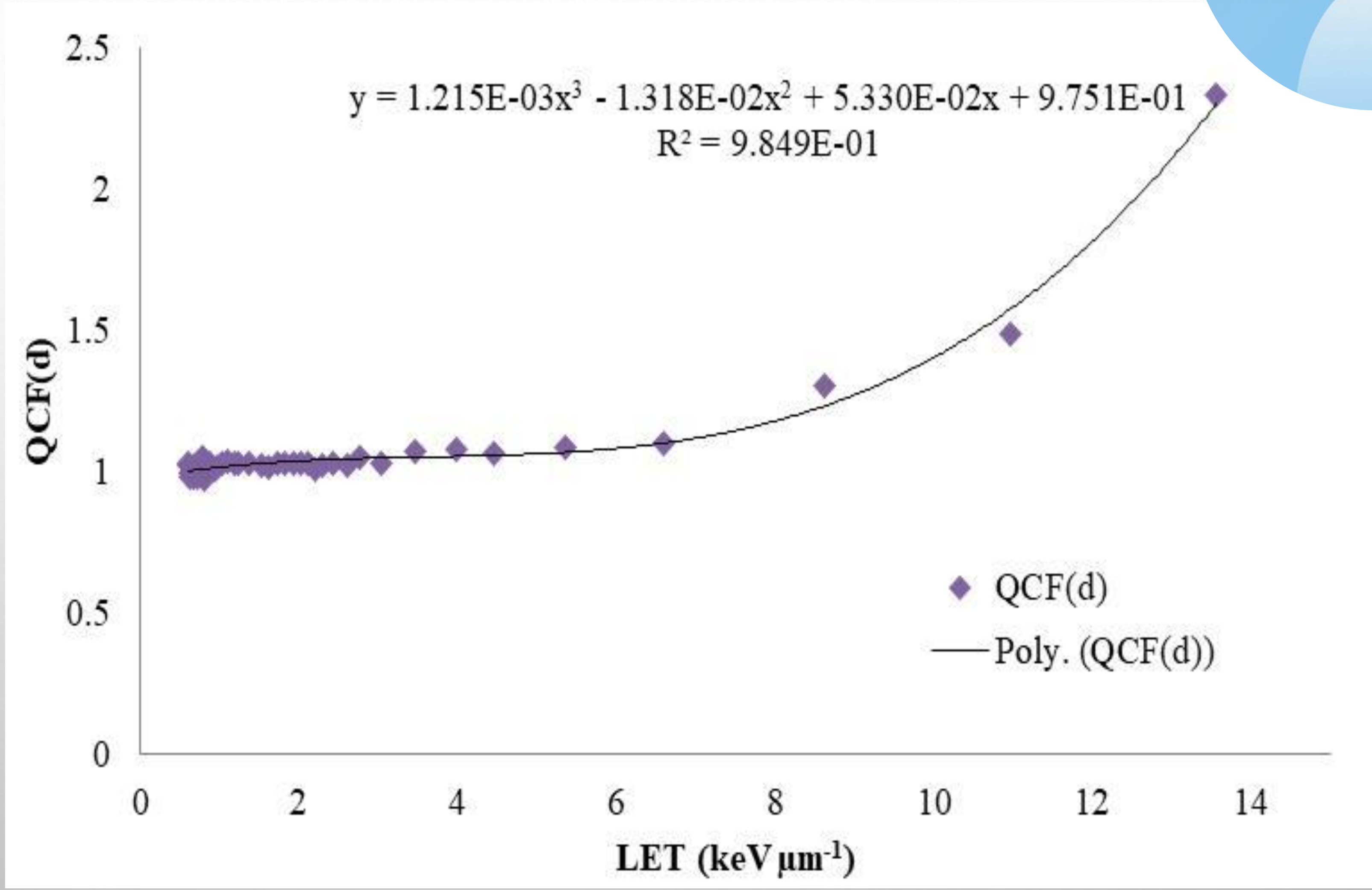
M_{IC}^{norm}=NORMALIZED ION CHAMBER MEASUREMENT

  - QCF(LET$_{\Phi}$) DERIVED FROM FITTING TO LET$_{\Phi}$ CALCULATIONS

RESULTS



- THE QCF AS A FUNCTION OF LET:

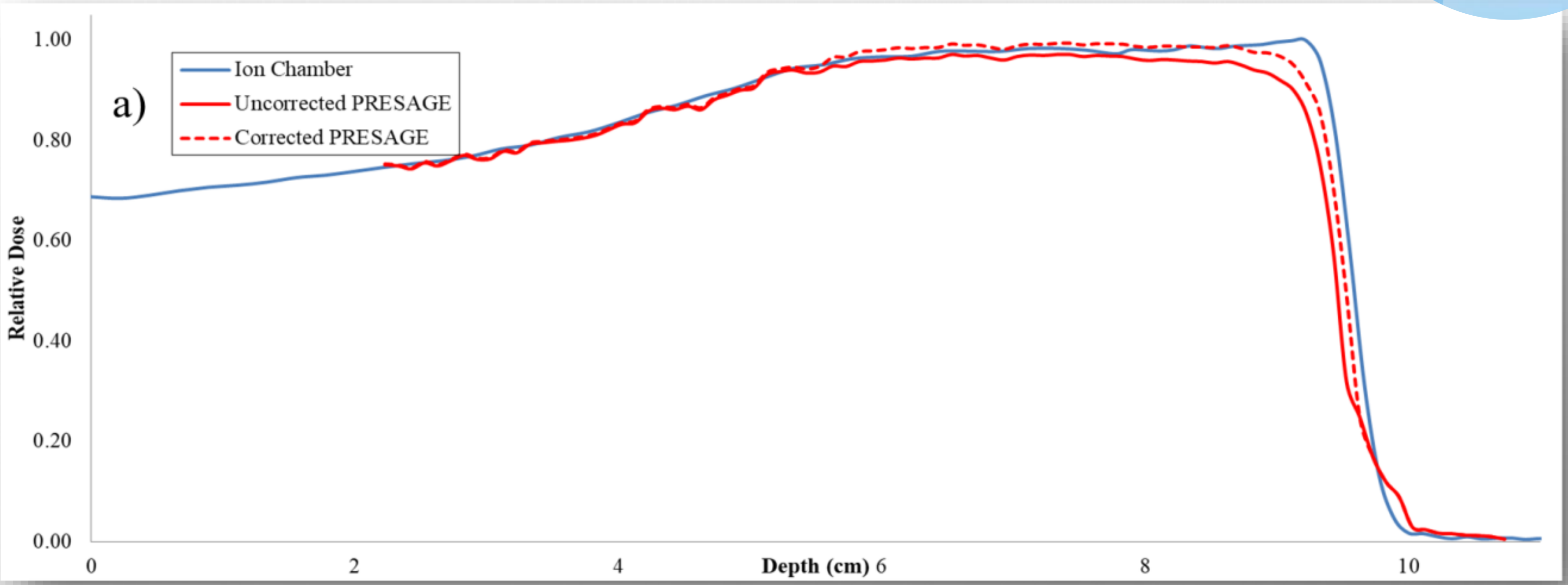


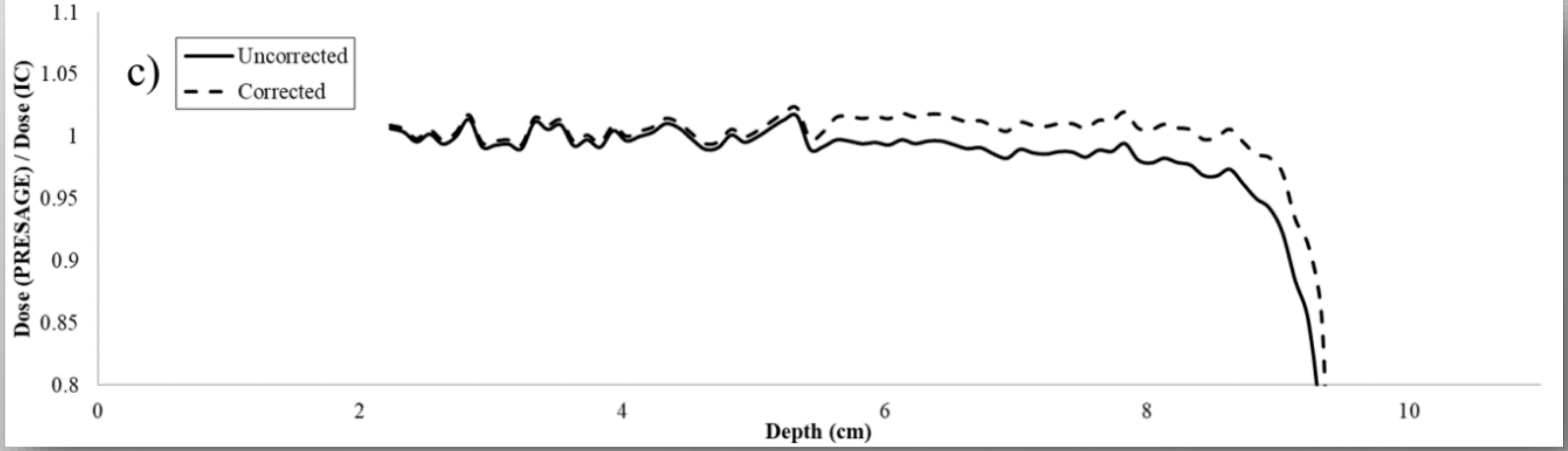
APPLICATION OF THE QCF

- DOSE DISTRIBUTIONS OF MODULATED SOBP IRRADIATED PRESAGE WERE MODELED USING MCNP CALCULATIONS AND LET USED FOR QUENCHING CORRECTION.

- THE QUENCHING CORRECTION RESULTED IN NOTEWORTHY IMPROVEMENTS TO DOSE ACCURACY IN THE BRAGG PEAK
  - UNCORRECTED: 79.1%
  - CORRECTED 92.7%

- NEXT UP:
  - APPLICATION TO IMPT PLANS
  - AUTOMATION OF QUENCHING CORRECTION





SUMMARY

- 3D DOSIMETERS OFFER MANY BENEFITS BEYOND CONVENTIONAL DOSIMETERS BOTH IN REMOTE AUDITS AND DIRECTLY IN THE CLINIC
  - MORE COMPREHENSIVE DOSE ANALYSIS
  - POTENTIAL FOR TIME AND RESOURCE EFFECTIVENESS.
- DEMONSTRATED APPLICATIONS IN NEARLY ALL FACETS OF RADIOTHERAPY: IMRT, SRS, HDR BRACHY, MRGIMRT, AND ION THERAPY.

ACKNOWLEDGEMENTS:

- Mitchell Carroll
- Hannah Lee
- Yvonne Roed
- Ryan Lafratta
- Mamdooh Alqathami
- Jihong Wong

THANK YOU!