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Deformable 3D Polymer Gel Dosimetry for the Validation of Motion Management and Deformable Dose Accumulation

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Motion during Radiotherapy

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- Inter- and Intrafractional motion decreases treatment precision, especially in the thoracic and abdominal regions
- Creates dose blurring
  - Increases healthy tissue dose
  - Decreases tumor dose
- Translational motion and deformation can be on the order of several centimeters[1]

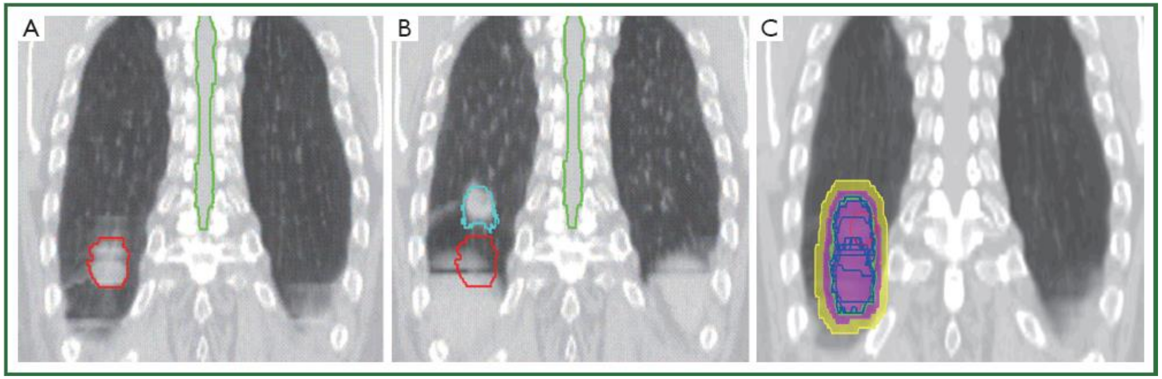

Image source: C K Gilde-Hurst et al., *JTD*, 6, 2014

1. D Jaffray *Nat Rev Clin Oncol*, 9, 2012

Real-Time Image Guided Radiotherapy (IGRT)

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- Monitor target intrafractional motion with imaging and gate or track the treatment beam accordingly
- Image guidance during treatment allows for increased tumor dose while sparing healthy tissue[1]
- Commercial systems:
  - MRI guidance
    - ViewRay MRIdian
    - Elekta Unity MR-Linac
  - Ultrasound guidance
    - Elekta Clarity® Autoscan System
  - External/optical surface tracking
    - VisionRT GateRT®
    - C-RAD Catalyst
    - Varian RPM

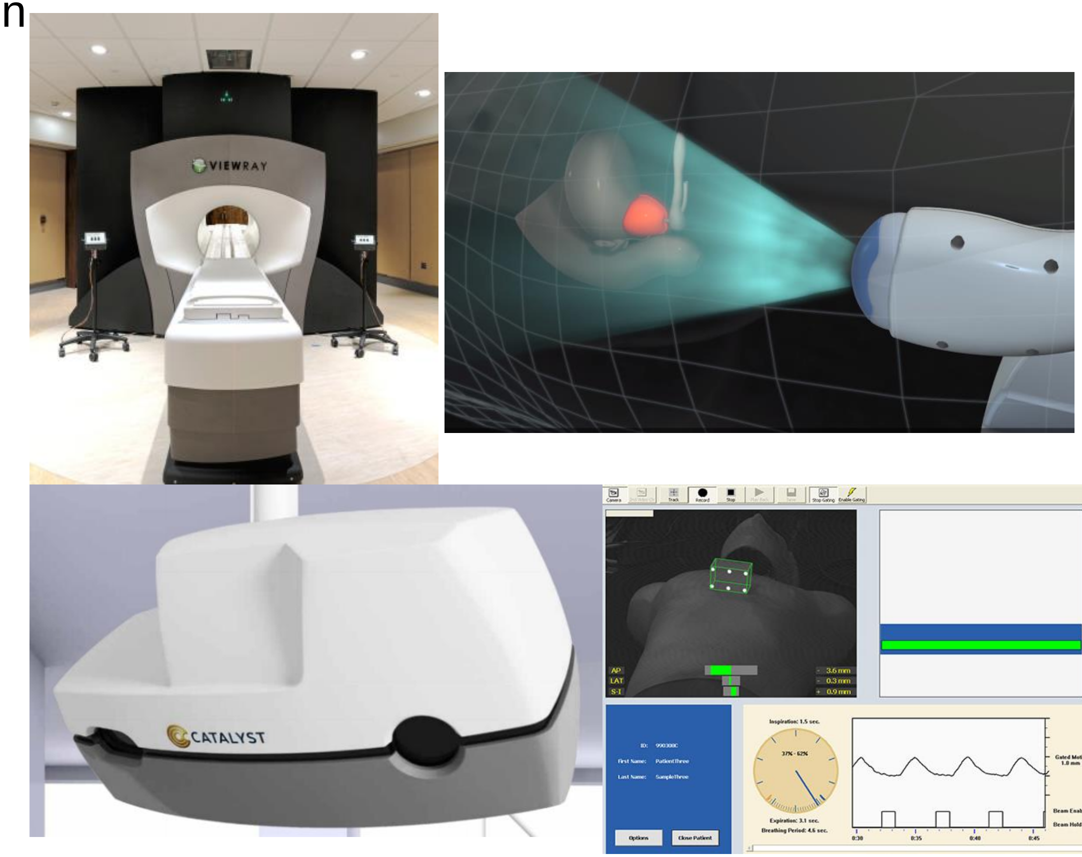

Image Source(clockwise): medicalphysicsweb.org, elekta.com, varian.com, c-rad.se

1. P Keall et al., *Med Phys*, 33, 2006

Deformable Dose Accumulation

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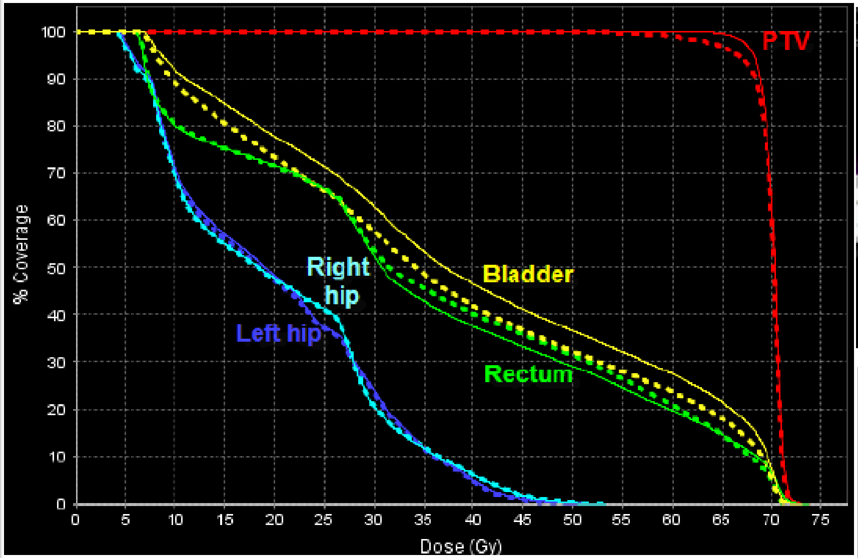
- Track target and organ dose changes due to interfractional motion through deformable image registration
- Requires daily imaging for daily dose calculations
- Deformable registration relates day-to-day dose calculations back to initial planned dose



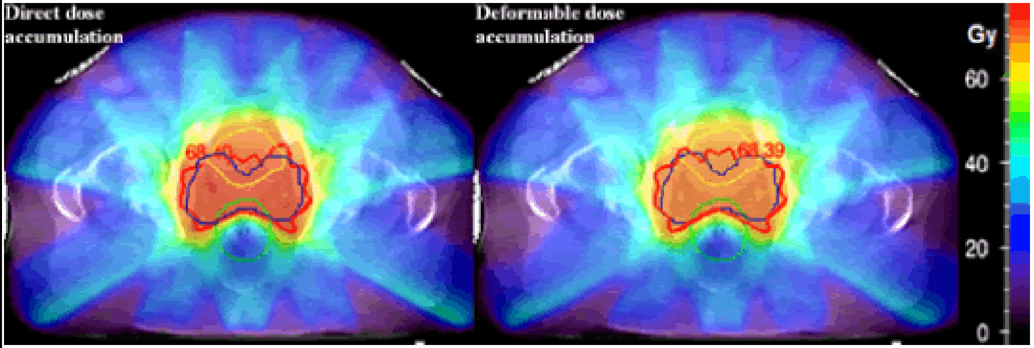


Image source: Y Cui et al., *J Nucl Med Radiat Ther*, 2011

QA Phantoms

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- Clinical implementation of real-time IGRT systems and deformable dose accumulation algorithms requires accuracy verification

- AAPM Task Groups 76 and 132 both recommend end-to-end testing using a quality assurance (QA) phantom[1,2]
  - Measure dose distribution using real-time IGRT system and compare to planned dose
  - Estimate cumulative dose over multiple fractions using deformable dose accumulation algorithm and compare to measured dose

- An ideal QA phantom for this purpose would have the following features:
  - Translational motion and deformation
  - Imaging compatibility
  - Reusability
  - Robust dosimetry, preferably 3D

- Many available options, but all miss some traits
  - Don't incorporate 3D dosimetry
  - Lack deformability

1. K Brock et al., *Med Phys*, 44, 2017
2. P Keall et al., *Med Phys*, 33, 2006

Gel Dosimeters

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- Solution of radiation sensitive chemicals suspended in a gel matrix
- Undergoes a chemical reaction as a function of dose
  - Color changes in methylene blue[1]
  - Ionic changes in ferrous sulfate[2]
  - Polymerization of monomers
- Data acquired using MRI, Optical CT (OCT), or X-ray CT
- 3D dosimeters

Image Source: IASA

1. M J Day and G Stein, *Nature*, 166, 1950
2. H Fricke and S Morse, *Am. J. Roent. Rad. Ther.*, 18, 1927

Applications of Gel Dosimetry

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- Measure 3D dose distributions from:
  - Stereotactic Radiosurgery (SRS) [1]
  - Intensity-Modulated Radiation Therapy (IMRT) [1]
  - Brachytherapy[1]
  - Internal Dosimetry[1]
  - Neutron Dose[1]
  - Heavy particles[1]
  - Electron Return Effect[2]
- QA complex treatment plans
- Deformable gel dosimetry[3,4,5]

Image Source: G S Ibbott, *J Phys: Conference Series*, 3, 2004

1. C Baldock et al., *PMB*, 55, 2010
2. H Lee et al., *J Phys: Conference Series*, 847, 2017
3. C J Niu et al., *Med Phys*, 39, 2012
4. Y De Deene et al., *PMB*, 60, 2015
5. U. J. Yeo, et al., *Med Phys*, 39, 2012

Normoxic Polyacrylamide Gel (nPAG)

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- Gel dosimeter based on polymerization of acrylamide (AA) and N,N'-methylene-bis-acrylamide (Bis)
- Antioxidant (THPC) added to the gel scavenges oxygen[1]
  - Oxygen inhibits polymerization
  - Can be manufactured in normoxic environments
  - Easily poured into unique molds
  - THPC decreases dose sensitivity
- Used as a 3D dosimetry device for a variety of applications
  - EBRT[2]
  - Brachytherapy[3]
  - Internal dosimetry[4]

Image Source: De Deene, *J Phys: Conference Series*, 444, 2013

1. Y De Deene, *MRM*, 43, 2000
2. C Ceberg et al., *PMB*, 55, 2010
3. D Adliene et al., *Application of Dose Gels in HDR Brachytherapy*, 2015
4. K Braun et al., *J Phys: Conference Series*, 164, 2009

Benefits of nPAGs

- Radiologically water equivalent above 100 keV[1]
- Mostly dose rate independent
  - 5% dose rate dependence from 25 cGy/min-400 cGy/min[1]
- Mostly Energy independent
  - No energy dependence 6 MV-25 MV[1]
- High spatial resolution[2]
- High spatial integrity[2]

1. Y De Deene et al., *PMB*, 51, 2006
2. M Maryanski et al., *MRI*, 11, 1993

Uncertainties in Gel Dosimetry

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- Since this is a 3D dosimeter, there is both dose uncertainty and spatial uncertainty

- Some sources of uncertainty are:
  - Physico-chemical mechanisms (<2%)[1]
  - Stochastic noise in dose maps (<1%)[1]
  - Linac calibration and stability(<1%)[2]
  - MRI scanner uncertainties (<3%)[1] or Imaging artifacts in OCT scanners
  - Gel temperature deviations during scanning[1]
  - Oxygen contamination

- Combined uncertainties are below 5% (k=1) on an individual voxel basis[1]

1. Y De Deene and A Jirasek, *J Phys: Conference Series*, 573, 2015
2. M McEwen. COMP/AAPM Joint Meeting, Vancouver, 2011

DEFGEL[1]

- nPAG poured into latex membranes and molded into cylinders
- Water equivalent
  - Density of 0.969±0.024 g/cm^3
  - 1.5% maximum Z_{eff} discrepancy from water
- Repeated deformation doesn’t alter gel
  - 150 deformations of 2.3 cm
- OCT readout[3]
  - Low cost alternative to MRI
  - Able to achieve very low noise in short scans
  - Sensitive to artifacts from light scatter and refraction
  - Limited to cylindrical dosimeters

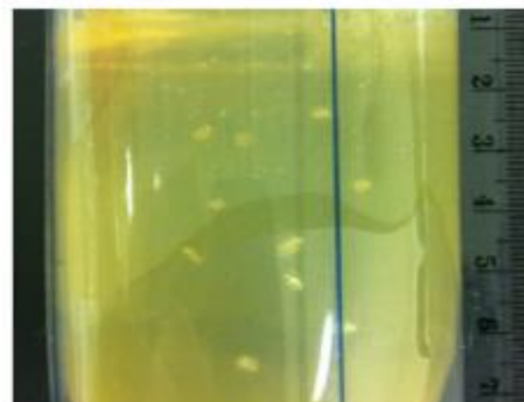

Image Source: U. J. Yeo, et al., *Med Phys*, 39, 2012

1. U. J. Yeo, et al., *Med Phys*, 39, 2012
2. M. L. Taylor et al., *Australas Phys Eng Sci Med*, 31, 2008
3. C Baldock et al., *PMB*, 55, 2010

DEFGEL Deformability[1]

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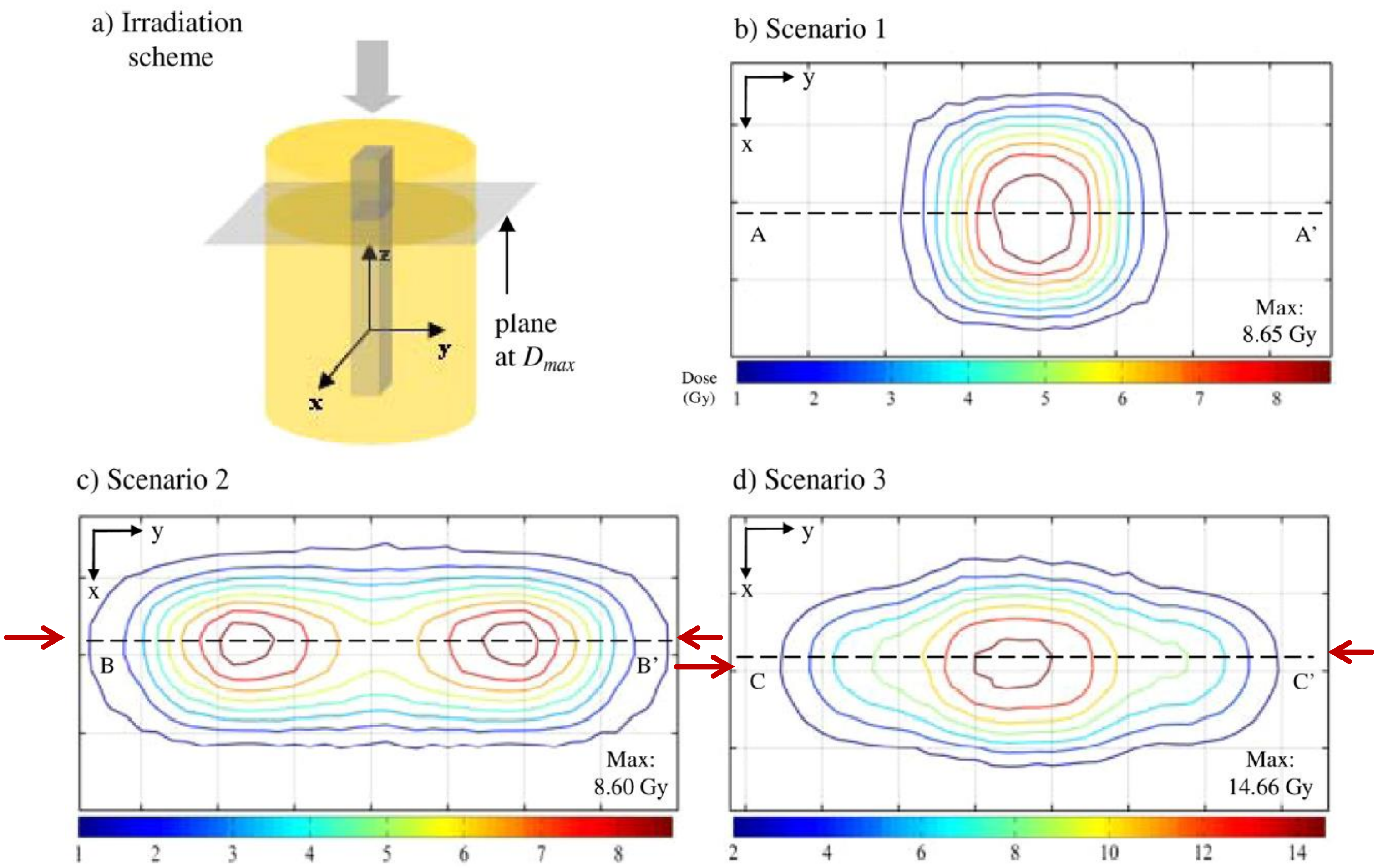

1. U. J. Yeo, et al., *Med Phys*, 39, 2012

Goal

Develop a dynamically deformable anthropomorphic phantom that incorporates gel dosimetry and use this phantom to measure 3D dose distributions to validate real-time IGRT systems and deformable dose accumulation algorithms.

3D Dosimetry Workflow

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- Fabricate gel and pour into dosimeter mold
  - Airtight mold
  - Allow gel to set in fridge
- Irradiate gel dosimeter
  - Often comparing to a calculated dose distribution
- Image dosimeter using MRI or OCT
  - Construct R_2 map based MRI data
  - Construct optical density map based on OCT data
- Calibrate response to dose
  - Calibration vials
  - Calibration phantom
  - Self-calibration

Gel Calibration

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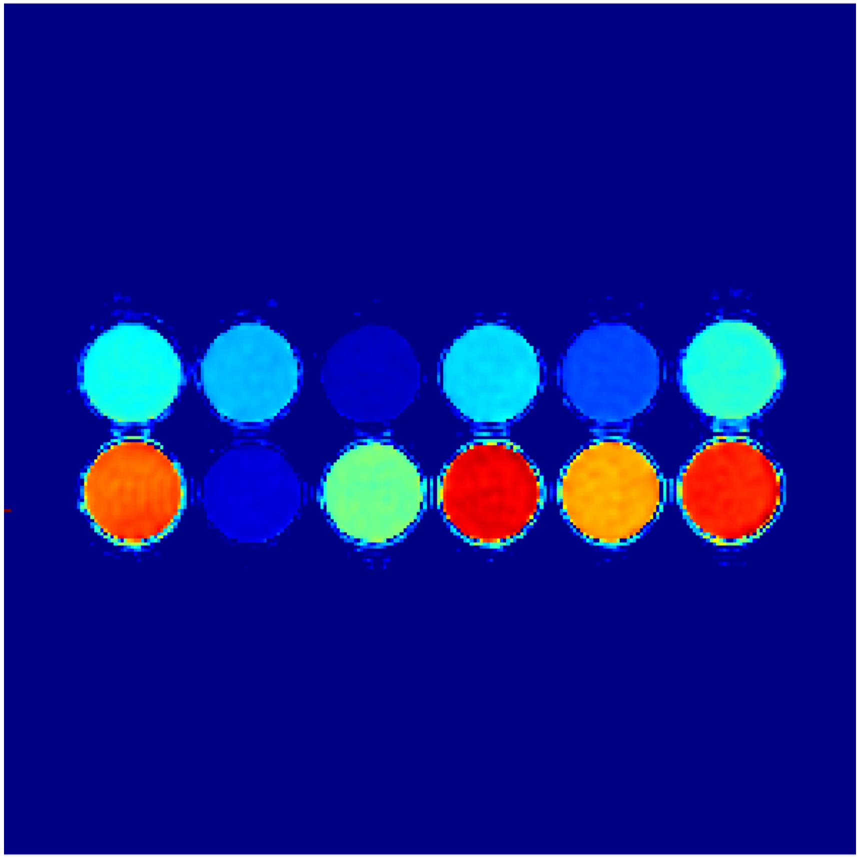
- Calibration vials
  - Create vials of gel from same gel batch
  - Irradiate to known doses
  - Small vials can have different dose response from large phantoms
- Calibration phantom
  - Create phantom identical to experimental phantom from same gel batch
  - Irradiate with simple dose distribution
  - Uncertainty in coregistration of gel and planned distributions
- Self Calibration
  - Create additional section of experimental phantom and irradiate with simple dose distribution
  - Renormalize gel distribution based on multiple known dose points



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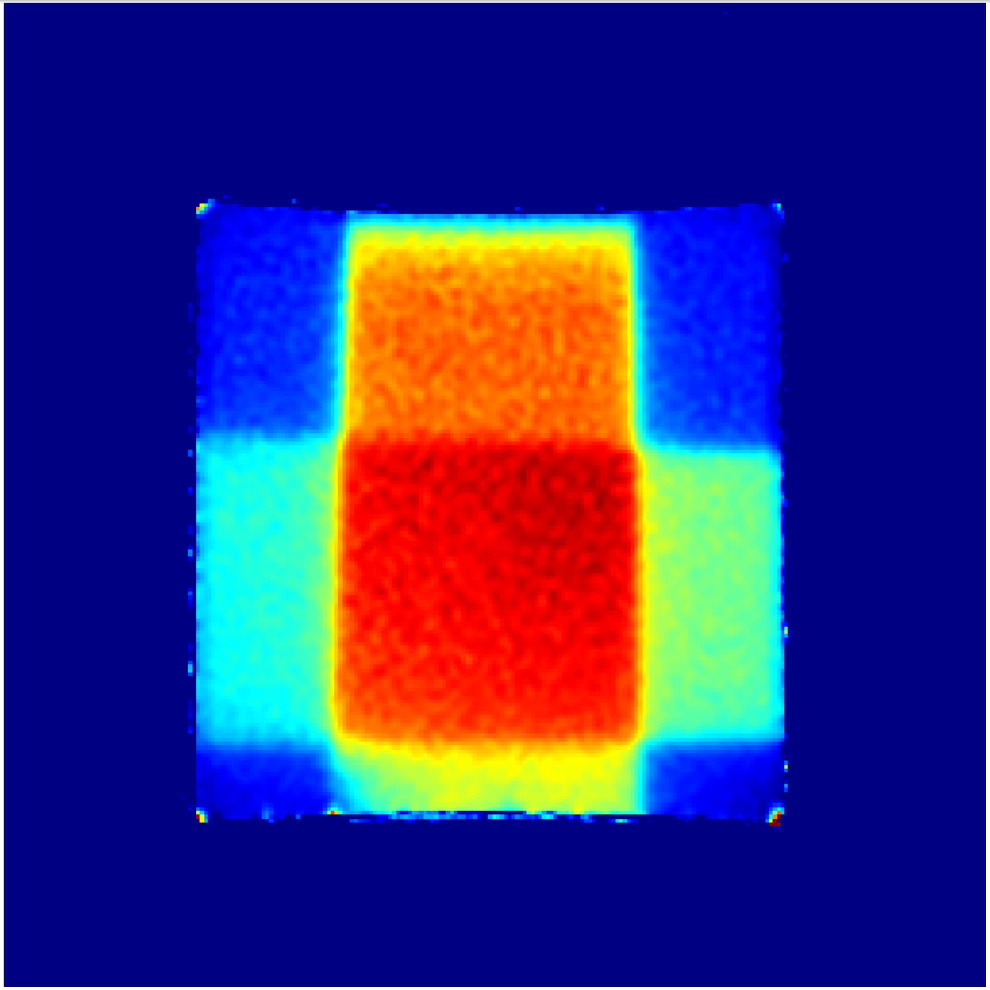

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Image Source: W Campbell et al., *Med Phys*, 41, 2014

Four-Field Box QA

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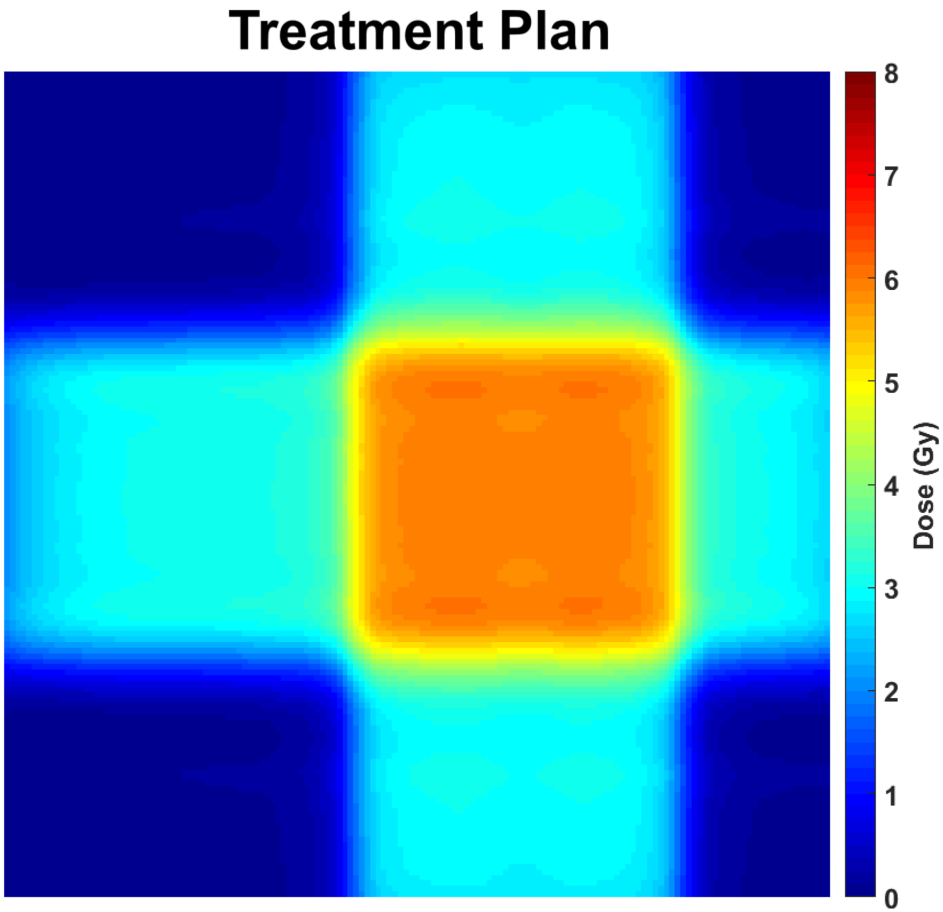

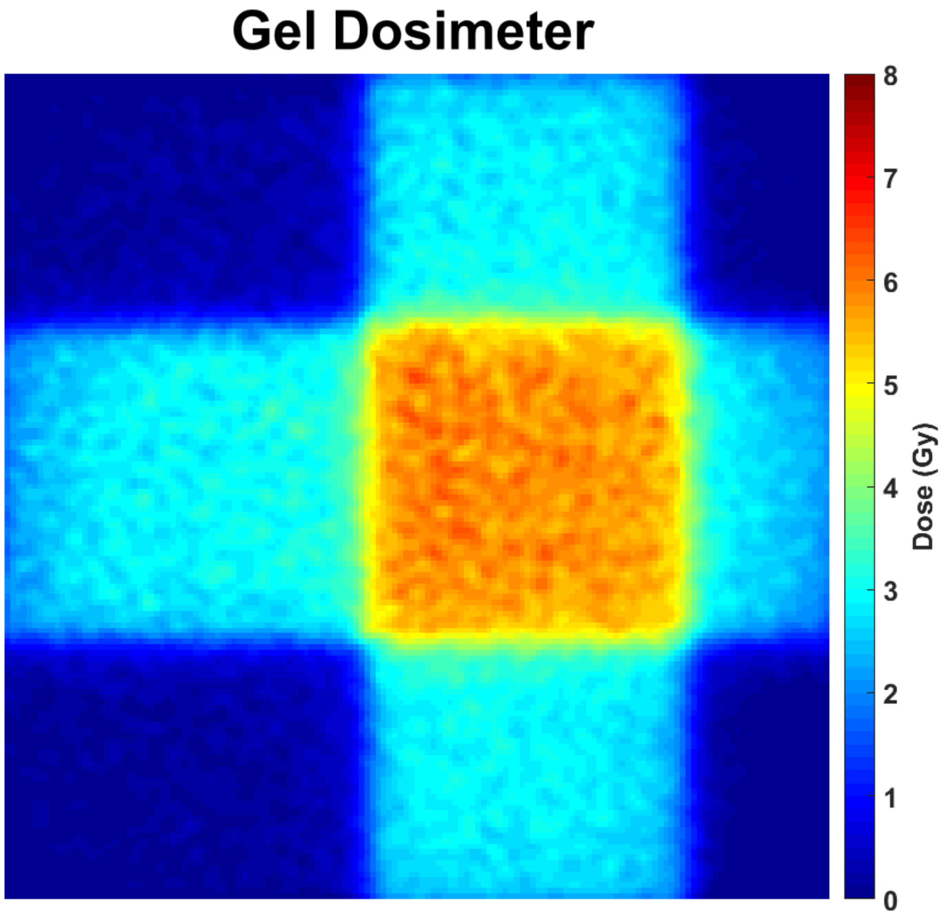

Four-Field Box QA

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- 3D 3%/3 mm gamma analysis used to compare distributions
  - 3% of maximum planned dose (6.03 Gy) used as dose-difference threshold
  - 3 mm distance to agreement threshold
- Gel dose map as reference for analysis, treatment plan used as evaluated dose map[1,2]
  - Ensures that the noise of the gel dose map is considered in analysis
- Overall pass rates and 10% maximum dose threshold pass rates are calculated

1. J Vandecasteele and Y De Deene, *PMB*, 58, 2013
2. D A Low and J F Dempsey, *Med Phys*, 30, 2003

Four-Field Box QA

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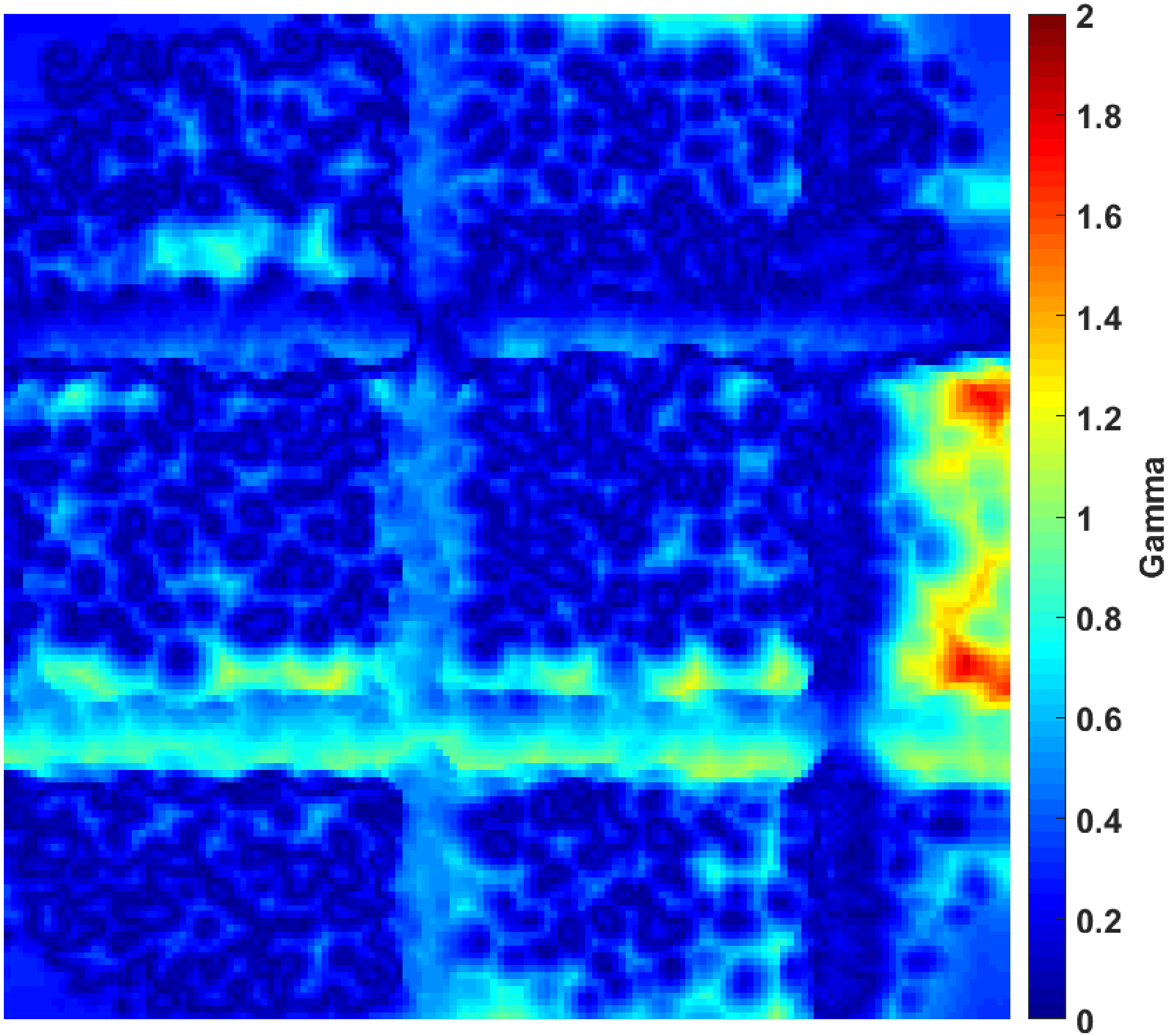

- 98.39% pass rate overall
- 93.44% pass rate with a 10% maximum dose threshold

Deformation of nPAG

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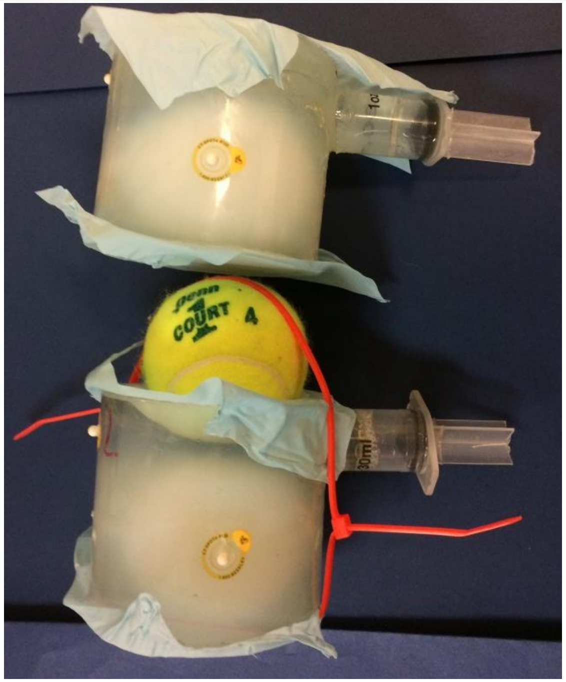

- Two 8 cm thick cylindrical phantoms made with acrylic cylinders and nitrile windows at ends
- Depressed one dosimeter with tennis ball 1.25 cm during irradiation then allowed it to return to original shape (right)
- Identical coplanar 5-beam treatment plans with a 6 Gy target dose
- Used identical undeformed phantom as reference and for calibration

Deformation of nPAG

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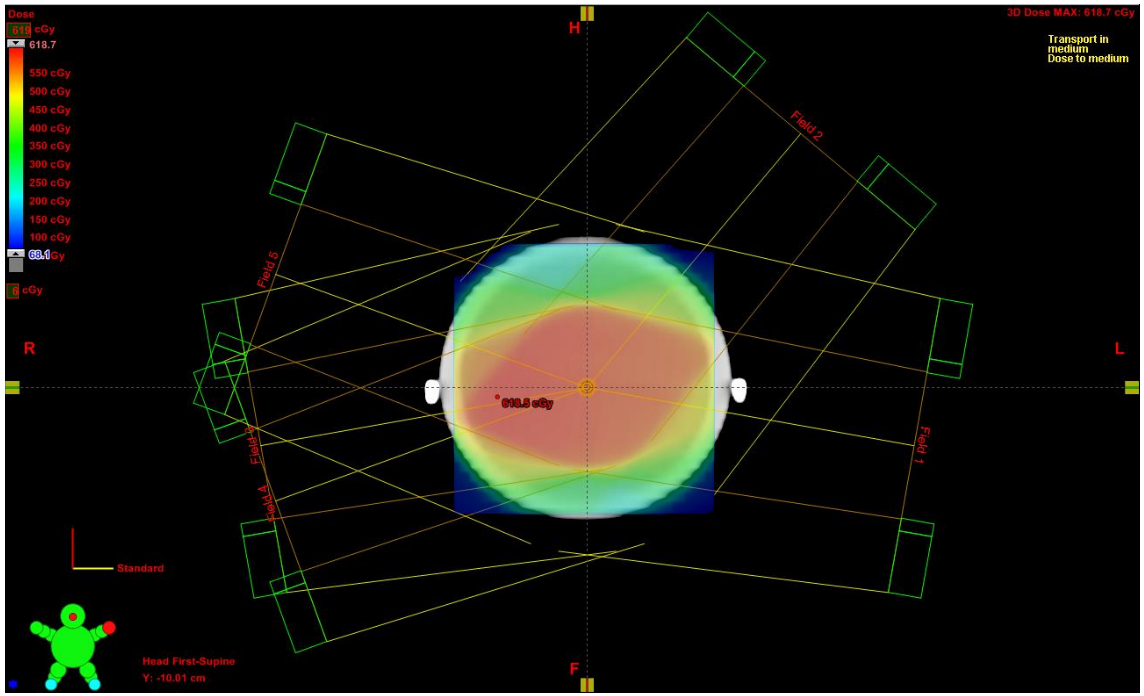

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Deformation of nPAG

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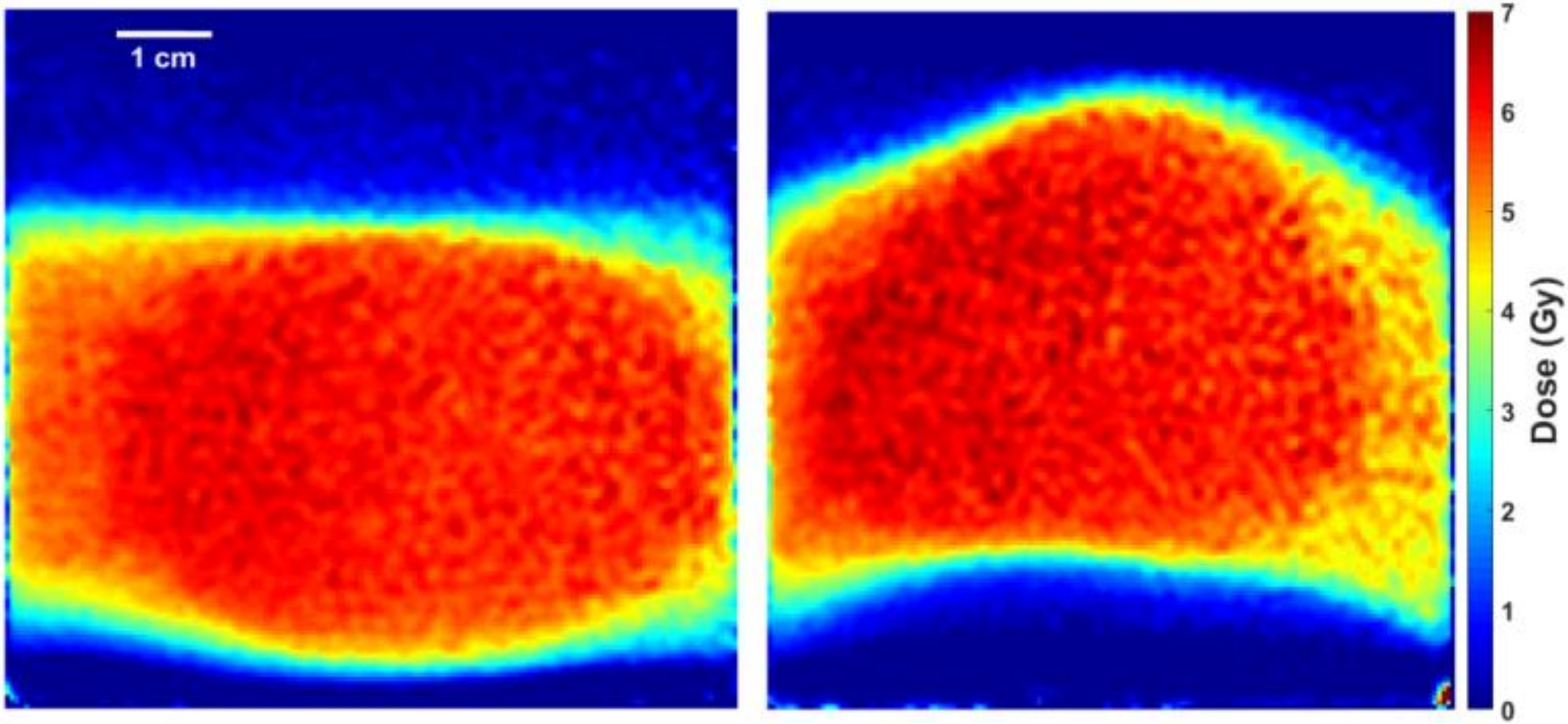
Site of deformation



Reference Dosimeter

Deformed Dosimeter

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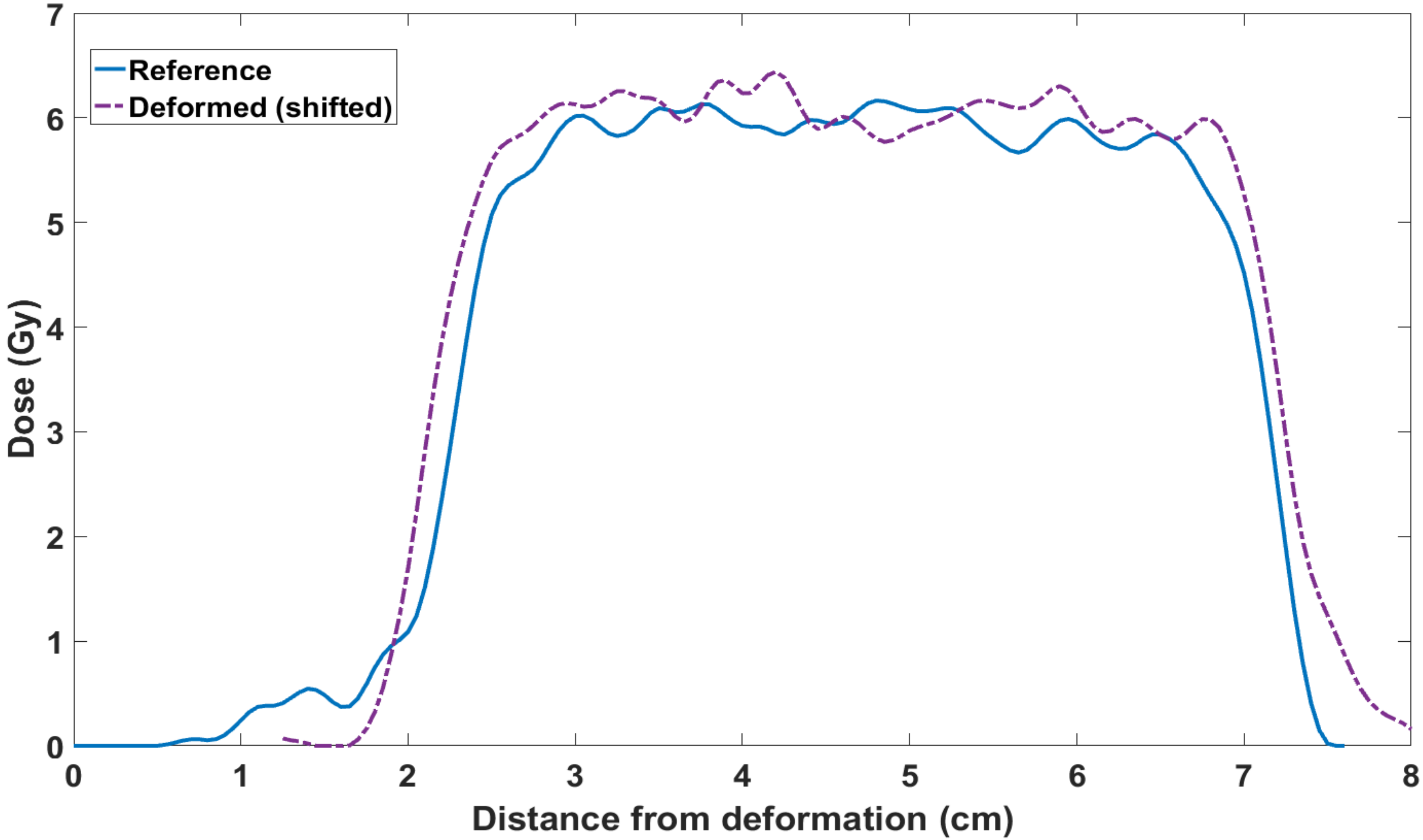
Deformation of nPAG



Deformable Abdominal Phantom

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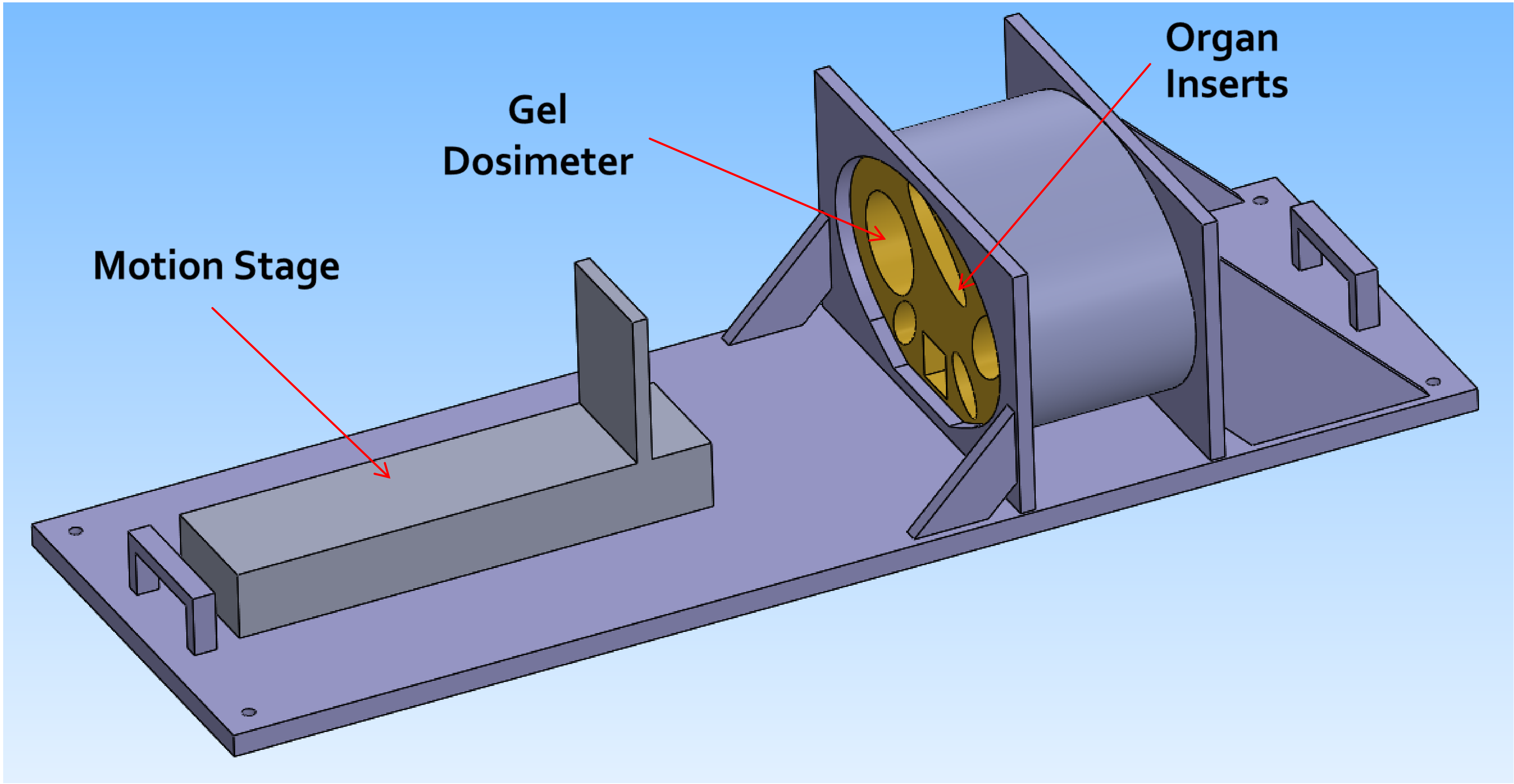

PVCP Phantom

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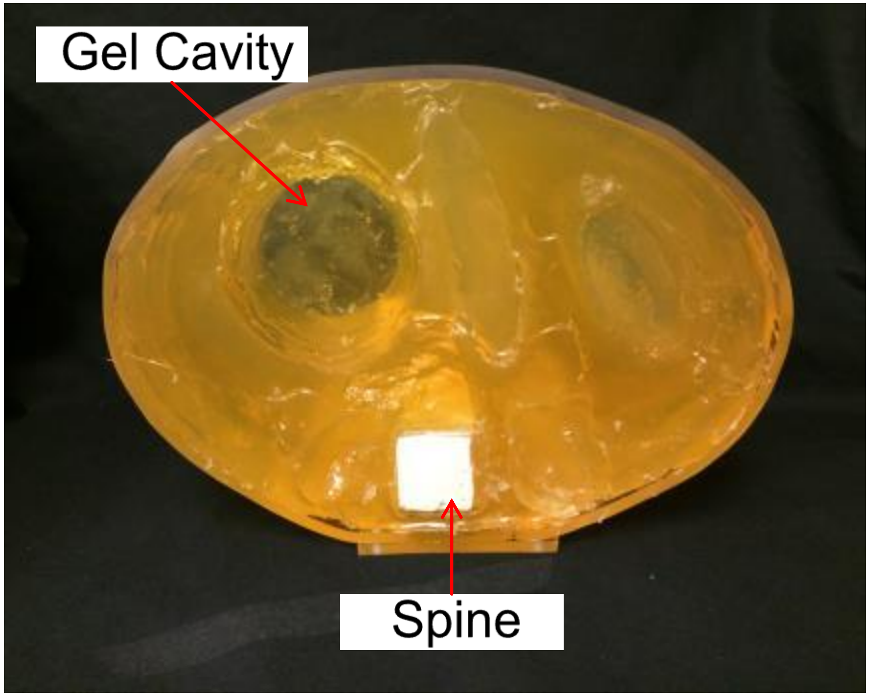
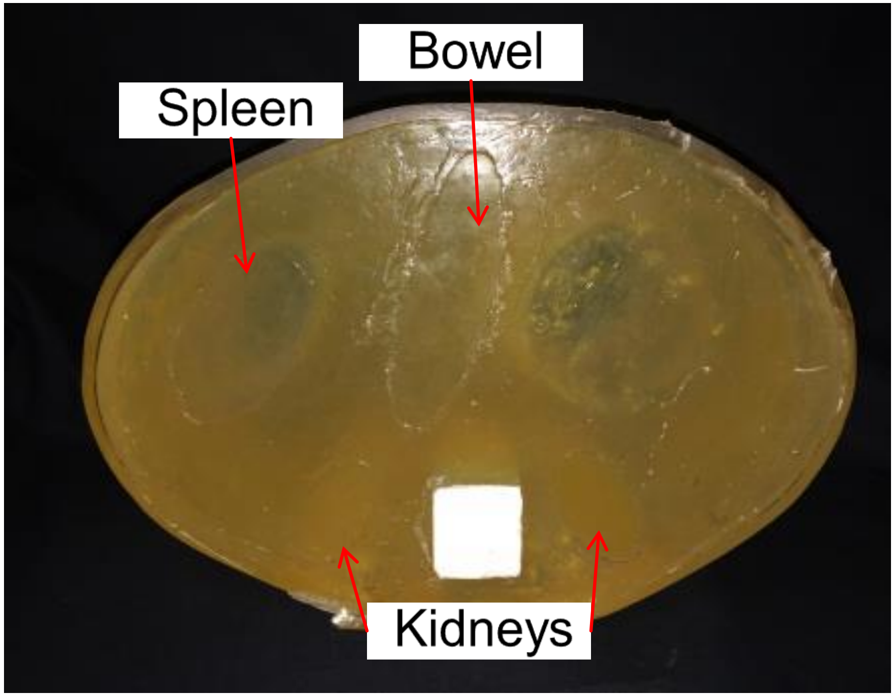


Front/Inferior View



Back/Superior View

Deformable Gel Dosimeter

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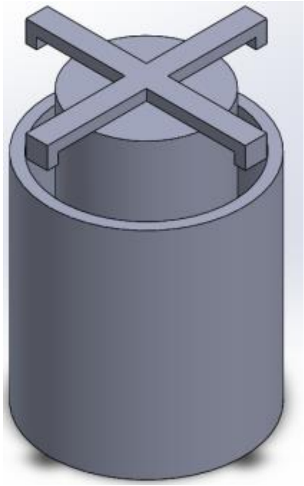
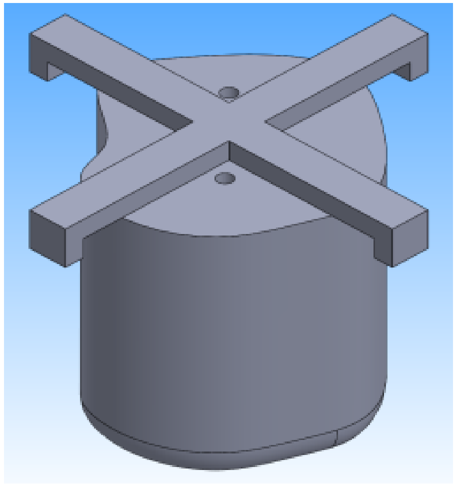
- Developed a deformable nPAG mold
- PVCP outer shell with PVCP cap placed over gel
  - Molded using acrylic outer ring with 3-D printed insert
  - Cap fused to shell using fishing lure repair liquid
- Asymmetric inner cavity shape allows for more accurate PTV representation





Liver SBRT Treatment Study

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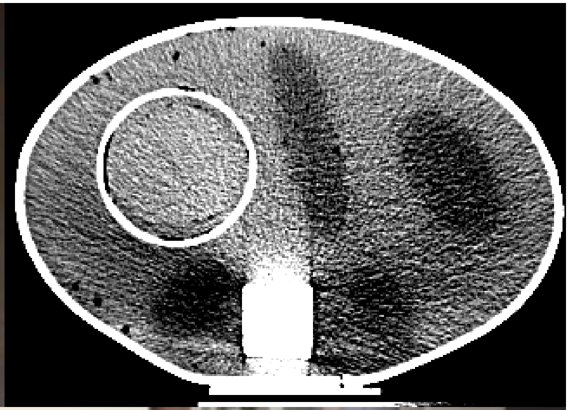
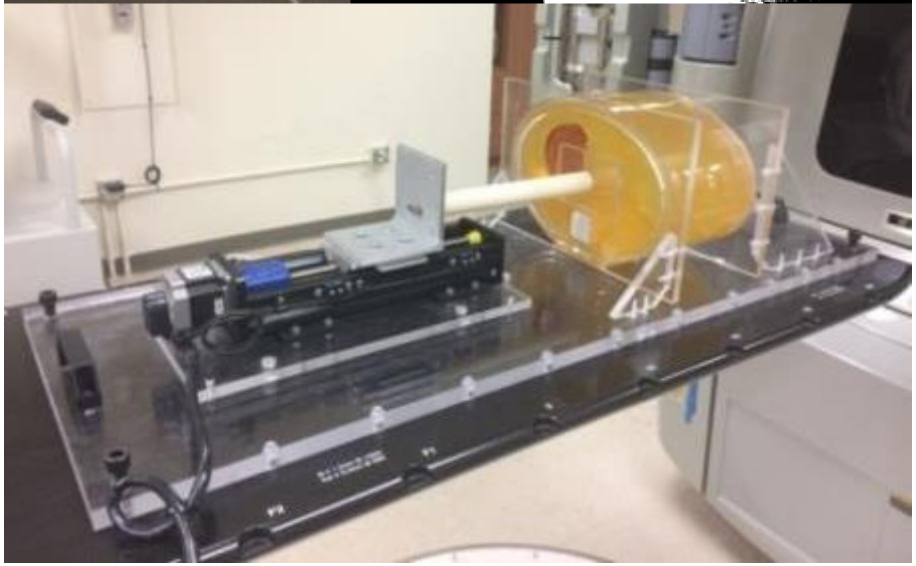
- Created four deformable gel dosimeters
  - 1 calibration gel
  - 3 SBRT gels
- CT data gathered with each gel in phantom
- Liver SBRT Treatment fraction planned with 12 Gy target dose
  - No motion or deformation
  - PTV defined as 1.7 cm reduction of gel dosimeter
  - Used UW DHO protocol for target dose and OAR limits





Dose Maps

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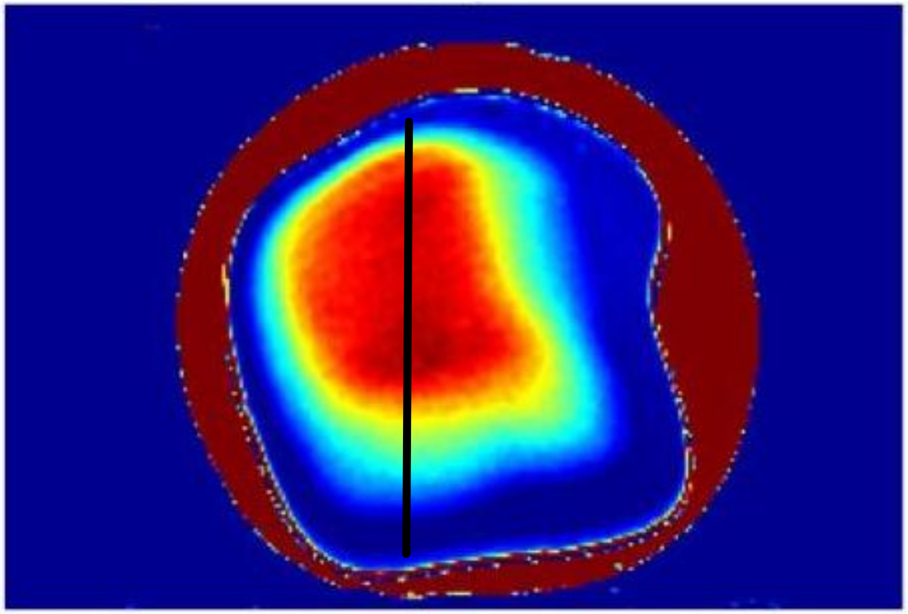
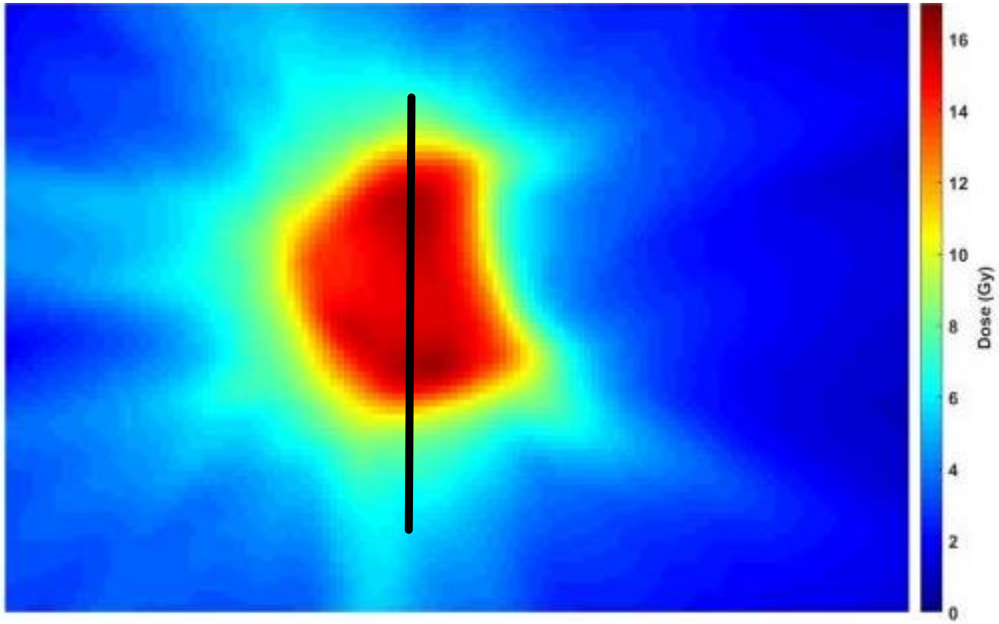


Gel Dosimeter



Treatment Plan

Profile

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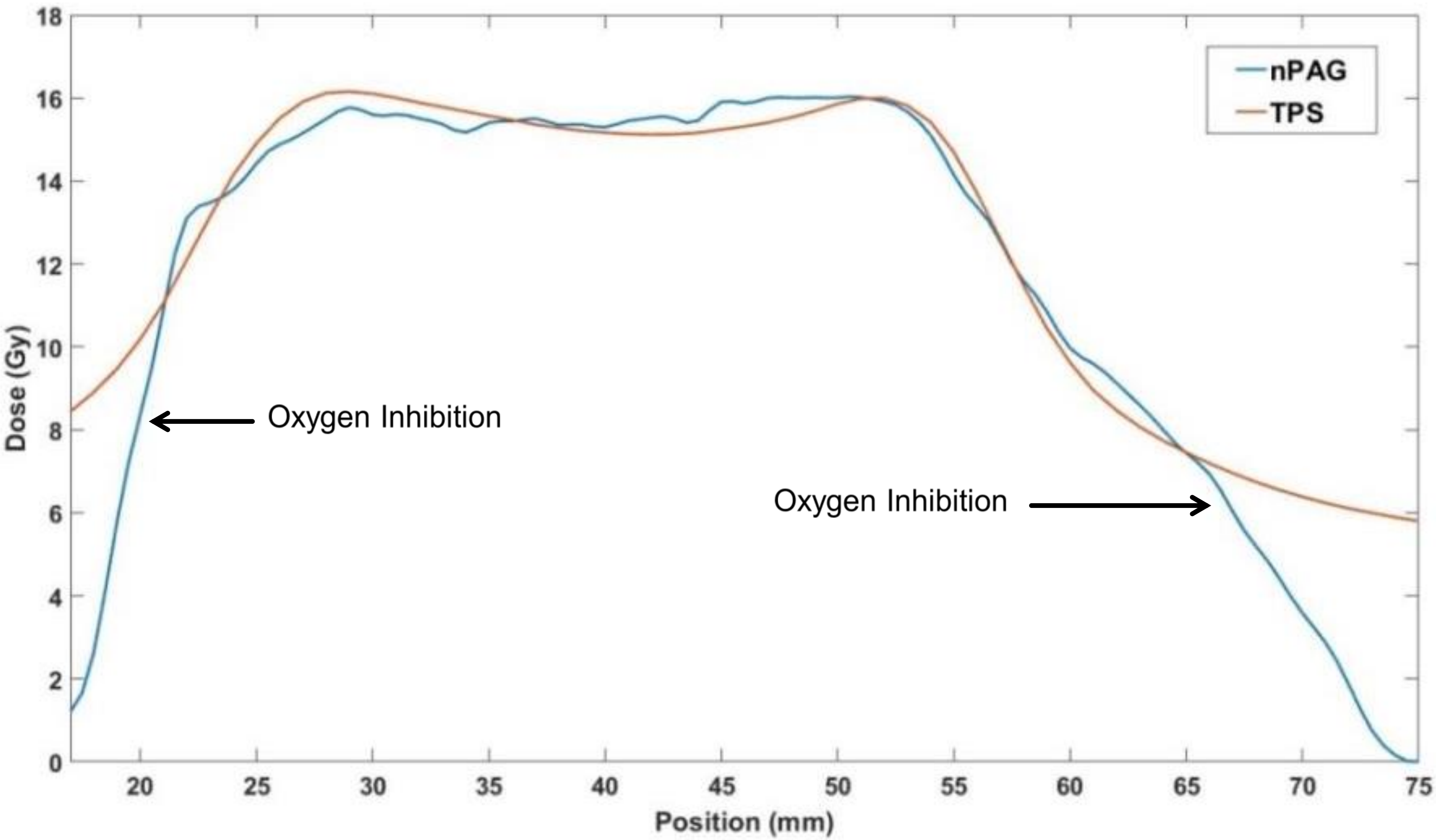

Gamma Analysis

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- Performed 3%/3 mm, 3%/5 mm, and 5%/5 mm analyses
  - Note gel map slice thickness is 3 mm
  - 20% maximum dose threshold on both maps to remove oxygen contamination and low dose regions
  - Performed for all three gels and averaged results

Region	3%/3 mm	3%/5 mm	5%/5 mm
Full Volume	84.6%±2.1%	97.0%±0.5%	97.5 %±0.2%
Central Slice	96.6%±1.8%	99.7%±0.5%	100.0%±0.0%

Future Phantom Applications

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- Quantify dosimetric effects of gated vs. ungated treatment
- Validate a deformable dose accumulation algorithm over multiple treatment fractions
- Validate a novel real-time IGRT system being developed by UW and GE Global Research Center

Conclusions

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- Gel dosimetry shows potential as a method to test and validate intrafractional motion management with real-time IGRT and interfractional motion management with deformable dose accumulation algorithms
- Incorporating deformable gel dosimeters in deformable phantoms can allow for realistic testing, allowing for clinical implementation of these systems

Acknowledgements

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Thank you for your attention!