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

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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

¹ D Jaffray Nat Rev Clin Oncol, 9, 2012
Real-Time Image Guided Radiotherapy (IGRT)

- 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

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

- 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

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.

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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

Applications of Gel Dosimetry

- 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\(^3,4,5\)

1. C Baldock et al., PMB, 55, 2010
2. H Lee et al., J Phys: Conference Series, 847, 2017
4. Y De Deene et al., PMB, 60, 2015

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\(^4\)

2. C Ceberg et al., *PMB*, 55, 2010
3. D Adliene et al., *Application of Dose Gels in HDR Brachytherapy*, 2015
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\(^2\)

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1. Y De Deene et al., *PMB*, 51, 2006
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\(^1\)

nPAG poured into latex membranes and molded into cylinders

Water equivalent
- Density of 0.969±0.024 g/cm^3
- 1.5% maximum Z\text{eff} discrepancy from water

Repeated deformation doesn’t alter gel
- 150 deformations of 2.3 cm

OCT readout
- 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


3. C Baldock et al., PMB, 55, 2010
DEFGEL Deformability

a) Irradiation scheme

b) Scenario 1

Max: 8.65 Gy

Dose (Gy)

1 2 3 4 5 6 7 8

y

x

A A'

Max: 8.65 Gy

y

x

1 2 3 4 5 6 7 8

A A'

y

x

1 2 3 4 5 6 7 8

2 4 6 8 10 12 14

C C'

Max: 14.66 Gy

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.
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

- 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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Four-Field Box QA

Treatment Plan

Gel Dosimeter
Four-Field Box QA

- 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

Four-Field Box QA

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

Reference Dosimeter
Deformed Dosimeter

Site of deformation
Deformable Abdominal Phantom

- Motion Stage
- Gel Dosimeter
- Organ Inserts
PVCP Phantom

Front/Inferior View
- Gel Cavity
- Spine

Back/Superior View
- Bowel
- Spleen
- Kidneys
- 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

- 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

Gel Dosimeter

Treatment Plan
Profile

![Graph showing dose vs position with oxygen inhibition indicated](image-url)

Oxygen Inhibition

Dose (Gy)

Position (mm)
- 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

<table>
<thead>
<tr>
<th>Region</th>
<th>3%/3 mm</th>
<th>3%/5 mm</th>
<th>5%/5 mm</th>
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<tr>
<td>Full Volume</td>
<td>84.6%±2.1%</td>
<td>97.0%±0.5%</td>
<td>97.5 %±0.2%</td>
</tr>
<tr>
<td>Central Slice</td>
<td>96.6%±1.8%</td>
<td>99.7%±0.5%</td>
<td>100.0%±0.0%</td>
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</tbody>
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Future Phantom Applications

- 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
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.
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