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3D Dosimetry in the Clinic and Research

VALIDATING SPECIAL TECHNIQUES

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Stanford MEDICINE

DUKE UNIVERSITY MEDICAL PHYSICS GRADUATE PROGRAM

Learning objectives

1: 3D Dosimetry in the Clinic: Background and Motivation

2: 3D Dosimetry in the Clinic: Motion interplay effects in dynamic radiotherapy

3: 3D Dosimetry in the Clinic and Research: Validating Special Techniques

- Understand the potential for 3D dosimetry in validating dose accumulation in deformable systems.
- Observe the benefits of high resolution measurements for precision therapy in SRS and in microSBRT for small animal irradiators.

4: 3D Dosimetry in end-to-end dosimetry QA

BACKGROUND DOSE DEFORMATION

- Dose accumulation with deformable image registration (DIR)
  - ▸ Deform patient image at time of treatment to a common reference image
  - ▸ Apply the same deformation vector field to the **calculated dose** for that treatment
  - ▸ Add up cumulative dose and adjust treatment accordingly

MIRADA medical

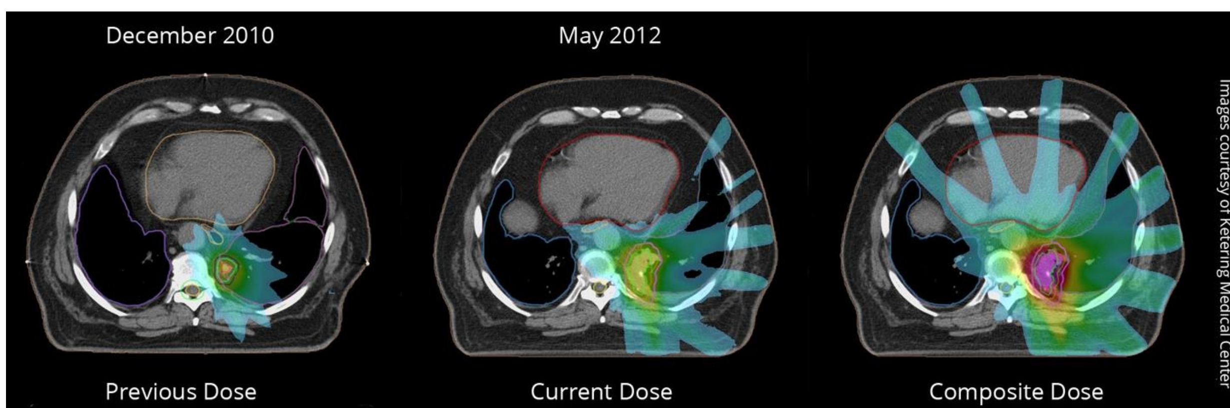


Image Credit: http://www.mirada-medical.com/solutions/dose-deformation-and-summation/

BACKGROUND DOSE DEFORMATION

MIRADA medical

"Utilizing accurate deformable registration between the previous and current planning CTs, the dose warping feature can account for variations in positioning or weight-loss. Dose summation extends this capability to produce cumulative doses over multiple planning volumes and multiple courses of radiation therapy."

mim Maestro unlimited

Dose Accumulation

As combined therapy and retreatments became commonplace in RT planning, MIM introduced the first method for deformable dose summation.

This innovation has made the careful evaluation of overlapping dose fields practical. With the recent introduction of biological effective dose (BED) conversion, dose from multiple treatment modalities can be even more accurately combined.

Velocity

Deform dose. Sum dose.

Deform delivered dose from different time-points, regardless of change in position of the patient during imaging. Sum doses over multiple plans, courses, and deliveries of radiation therapy.

RayStation

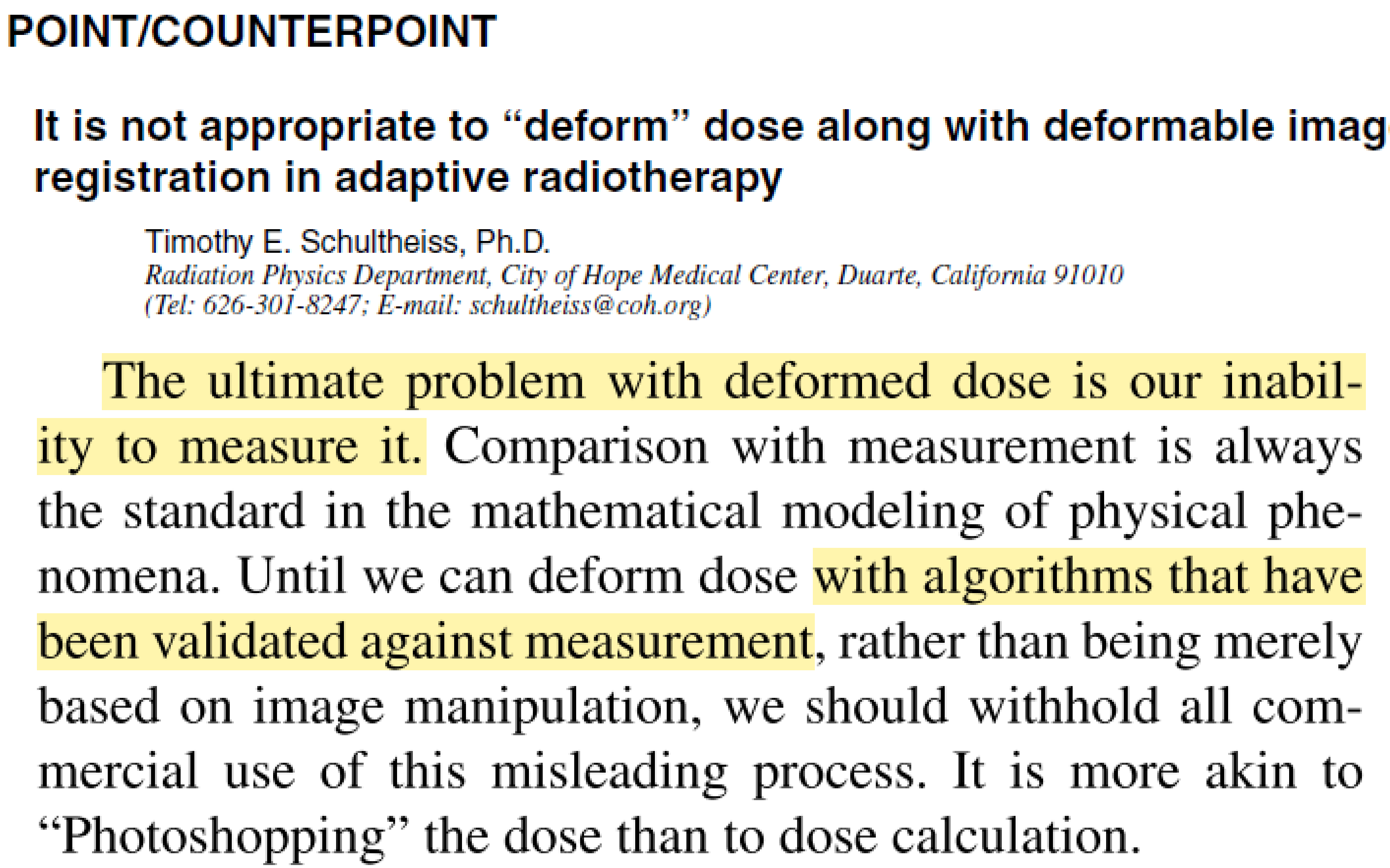
rayTracker

Dose Tracking

By combining dose calculation capabilities (for any modality) and deformable registration, it becomes possible to accumulate dose over changing anatomy within a single system, i.e. without imports or exports to other systems. This includes computing dose on CBCT.

BACKGROUND DOSE DEFORMATION

Currently no established method of validating DIR algorithm accuracy with physical measurement


POINT/COUNTERPOINT

It is not appropriate to "deform" dose along with deformable image registration in adaptive radiotherapy

Timothy E. Schultheiss, Ph.D.
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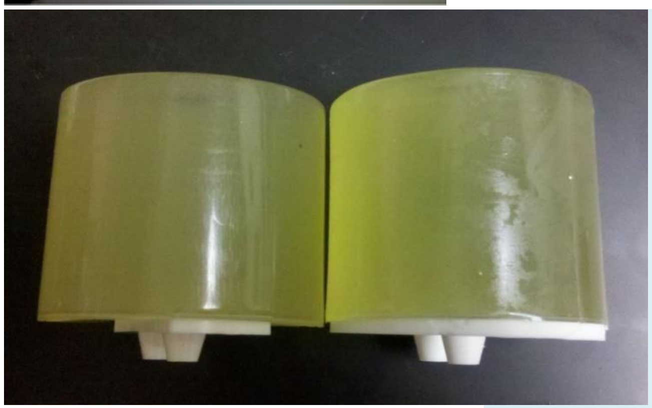
(Tel: 626-301-8247; E-mail: schultheiss@coh.org)

The ultimate problem with deformed dose is our inability to measure it. Comparison with measurement is always the standard in the mathematical modeling of physical phenomena. Until we can deform dose with algorithms that have been validated against measurement, rather than being merely based on image manipulation, we should withhold all commercial use of this misleading process. It is more akin to "Photoshopping" the dose than to dose calculation.

SOLUTION DEFORMABLE 3D DOSIMETERS

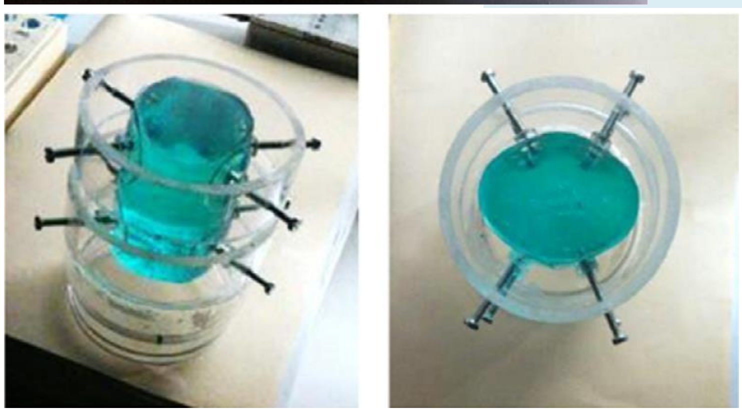
DEFGEL (Yeo, et al.)

- Normoxic polymer gel (modified nPAG)
- Contained in elastic latex membrane



Presage-Def (Juang, et al.)

- Radiochromic polyurethane
- Can be cast in desired 3D geometry

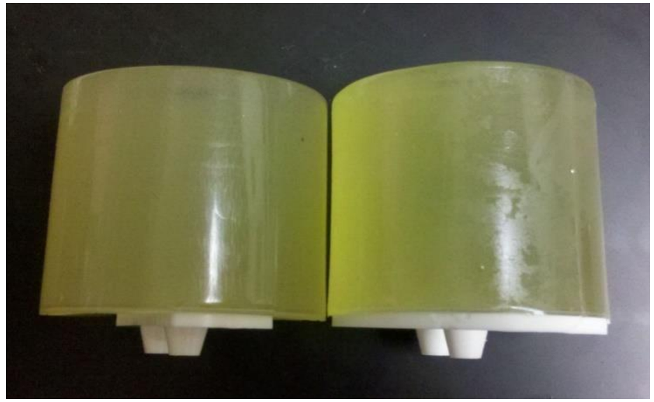


FlexyDos3D (De Deene, et al.)

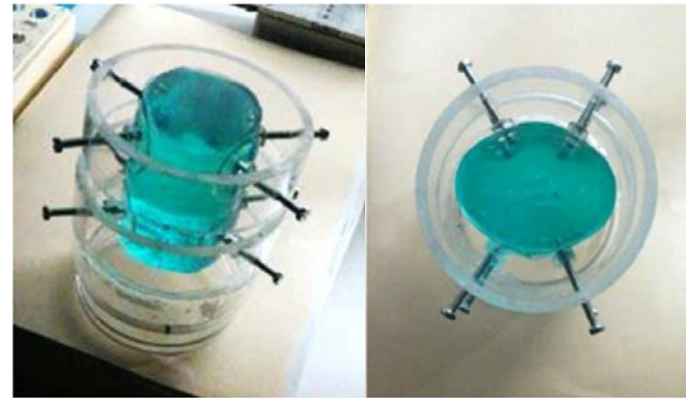
- Radiochromic silicone
- Can be cast in desired 3D geometry

SOLUTION DEFORMABLE 3D DOSIMETERS

DEFGEL



Presage-Def



FlexyDos3D

- Tissue-equivalent
- Optical-CT readout
- Provides full 3D, high-resolution physical measurement of dose under deformation
  - Validate DIR algorithms for dose accumulation

DIR ALGORITHM VALIDATION

International Journal of Radiation Oncology biology • physics
www.redjournal.org

Physics Contribution

On the Need for Comprehensive Validation of Deformable Image Registration, Investigated With a Novel 3-Dimensional Deformable Dosimeter

Titania Juang, BS,*,† Shiva Das, PhD,† John Adamovics, PhD,‡ Ron Benning,‡ and Mark Oldham, PhD†

**Medical Physics Graduate Program and †Department of Radiation Oncology Physics, Duke University Medical Center, Durham, North Carolina; and ‡Department of Chemistry and Biology, Rider University, Lawrenceville, New Jersey*

Received Dec 3, 2012, and in revised form May 15, 2013. Accepted for publication May 27, 2013

IJROBP 87(2), 2013

Duke University

- **DIR Algorithm**
  Intensity-based B-splines algorithm combined with mutual information metric
  (VelocityAI, version 2.8.1)

pro practical radiation oncology ASTRO

July–August, 2015 Volume 5, Issue 4, Pages e401–e408

Utility and validation of biomechanical deformable image registration in low-contrast images

Michael Velec, PhD, Titania Juang, BSc, Joanne L. Moseley, BMath, Mark Oldham, PhD, Kristy K. Brock, PhD

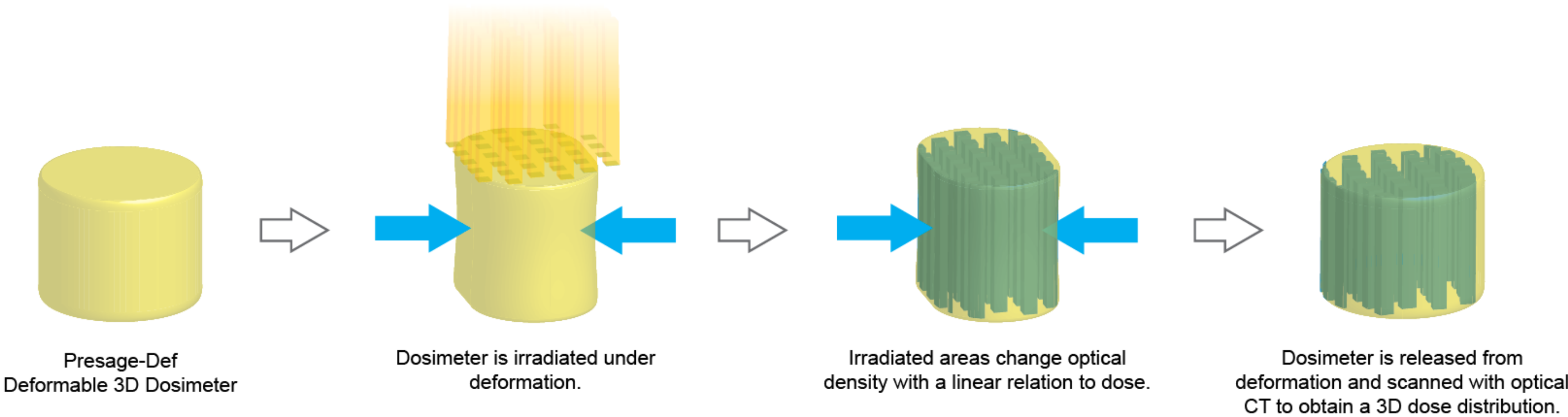
DOI: http://dx.doi.org/10.1016/j.prro.2015.01.011 | CrossMark

PRO 5(4), 2015

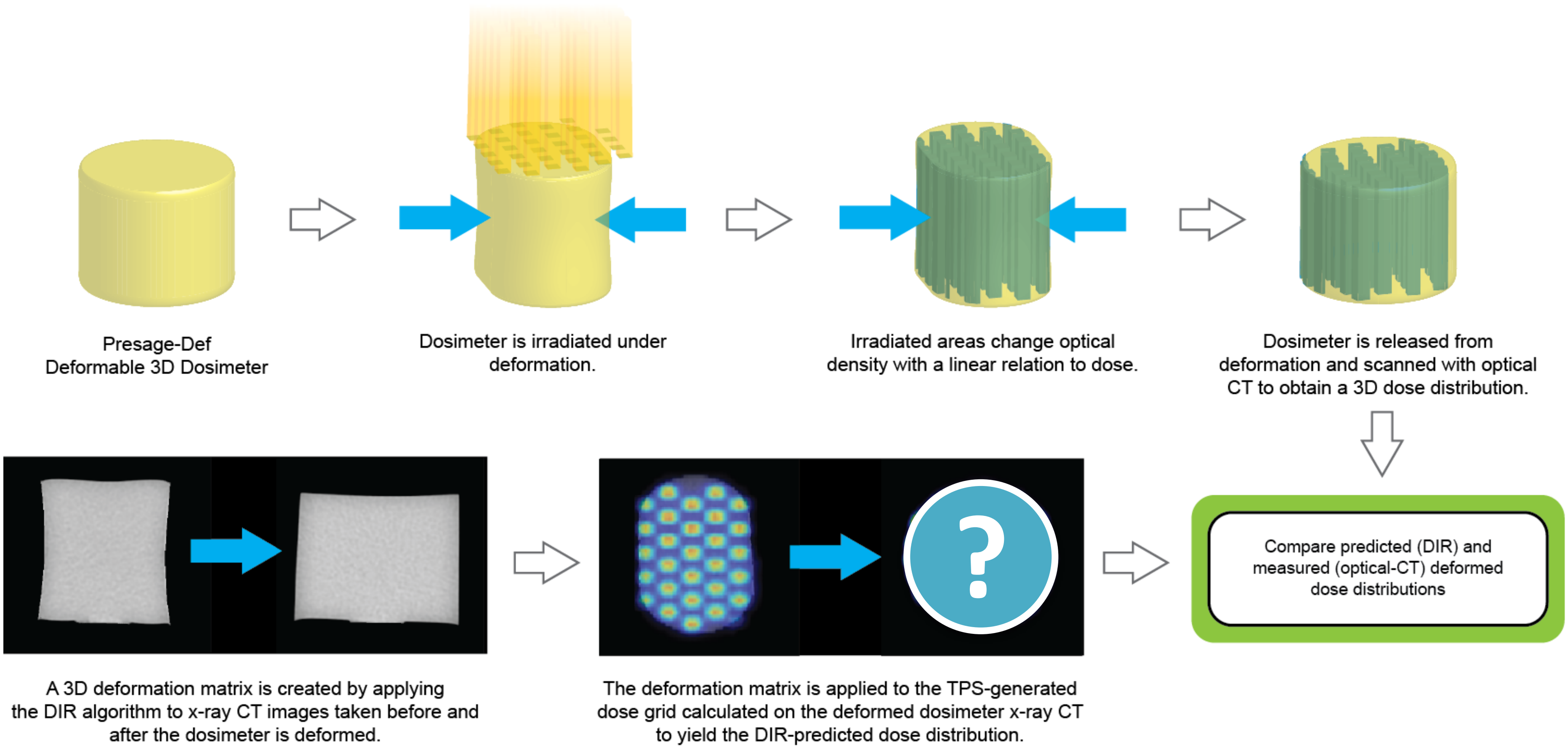
Princess Margaret Cancer Centre
Duke University

- **DIR Algorithm**
  Biomechanics-based algorithm using finite element modeling (MORFEUS)

METHODS DIR ALGORITHM VALIDATION



METHODS DIR ALGORITHM VALIDATION



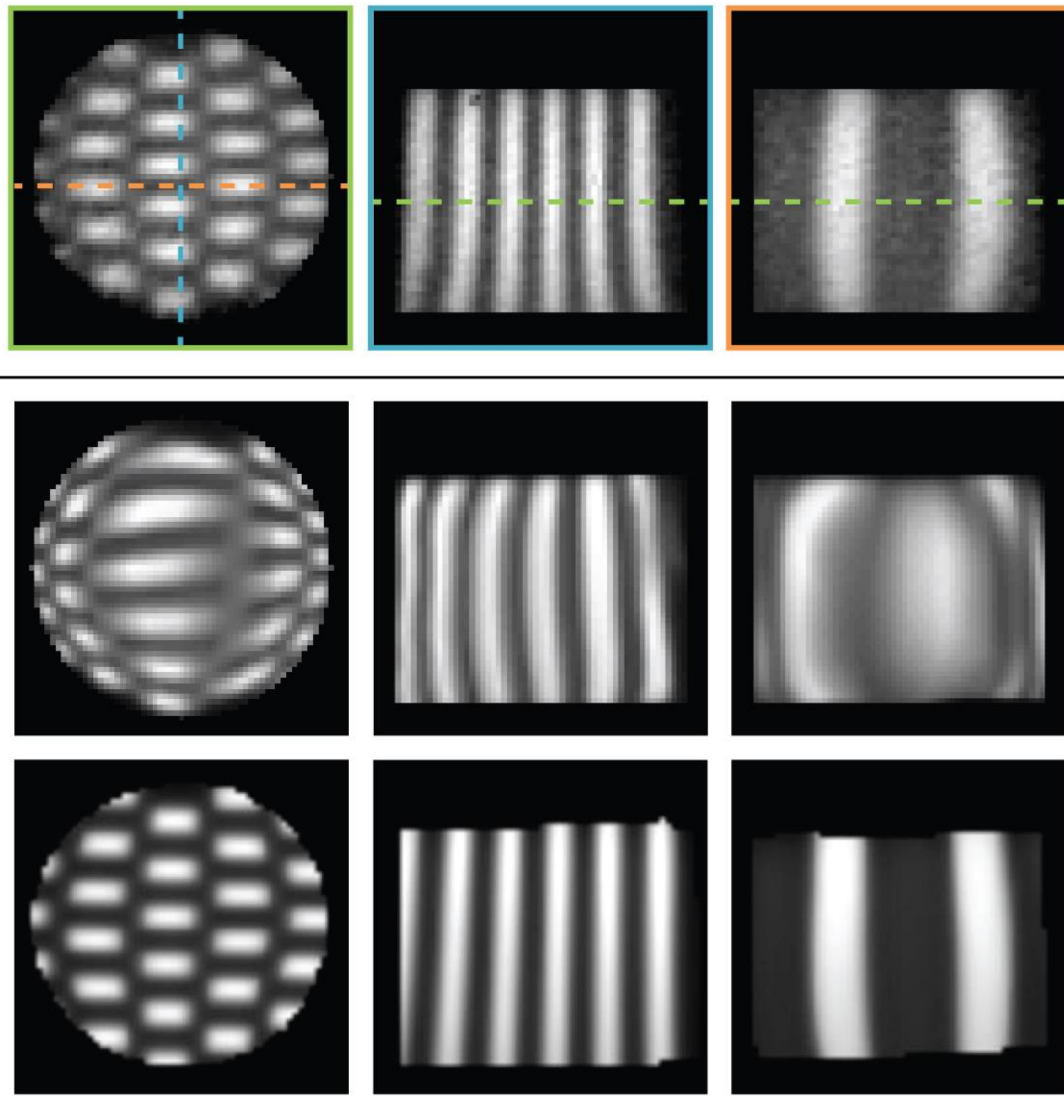
RESULTS DIR ALGORITHM VALIDATION

Coronal | Axial | Sagittal

Measured 3D Dosimetry (Presage-Def/Optical CT)

Predicted Intensity-Based DIR (VelocityAI)

Predicted Biomechanical DIR (MORFEUS)



Predicted Intensity-Based DIR (VelocityAI)

Displacement

- Max **9.0 mm**
- Mean **4.2 mm**

3D Gamma **(3%/3mm)**

- **60%**

Predicted Biomechanical DIR (MORFEUS)

Displacement

- Max **1.7 mm**
- Mean **0.9 mm**

3D Gamma **(3%/3mm)**

- **90%**

ONGOING DEVELOPMENTS

Implementation in deforming phantoms

From IC3DDose 2014 (8th International Conference on 3D Radiation Dosimetry)

Reproducibility assessment of dynamically deforming DEFGEL in a respiratory motion phantom

R D Franich[1], J R Supple[1], B Lindsay[1], U J Yeo[1], P Lonski[1,2], R L Smith[1,3], M L Taylor[1], L Dunn[1] and T Kron[1,2]
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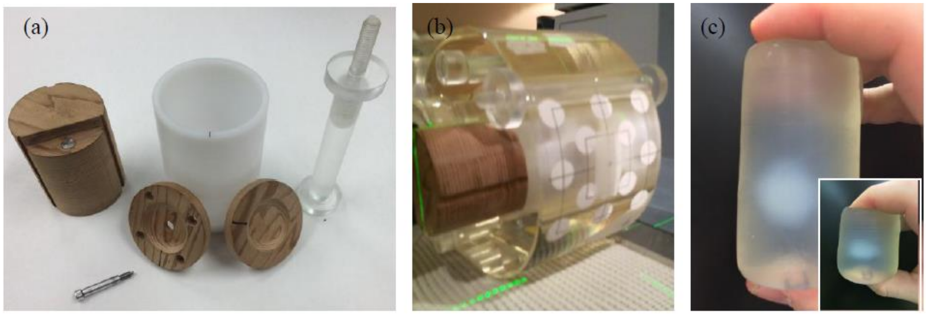

Figure 1. (a) Components used in the modification of the QASAR phantom, (b) the assembly with cylinder liner clamp in place, and (c) a deformable DEFGEL phantom.

Flexydos3D: A new deformable anthropomorphic 3D dosimeter readout with optical CT scanning

Yves De Deene[1,2], Robin Hill[3], Peter S Skyt[2,4] and Jeremy Booth[5]
[1]Dept. of Engineering, Faculty of Science, Macquarie University, Sydney, Australia
[2]Institute of Medical Physics, University of Sydney, Sydney, Australia
[3]Chris O'Brien Lifehouse, Sydney, Australia
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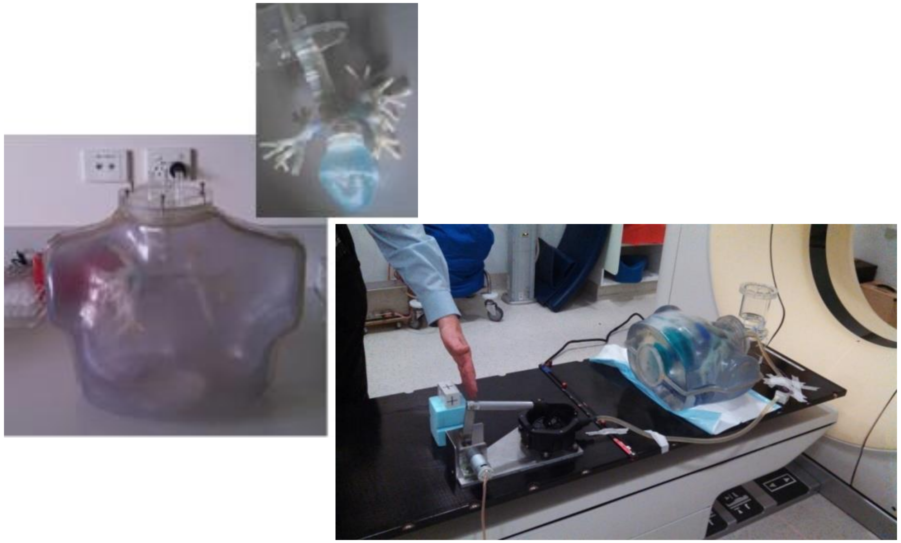


TAKE-HOME MESSAGES

Learning Objective #1

Understand the potential for 3D dosimetry in validating dose accumulation in deformable systems.

- Physical measurement of dose deformation in high-resolution 3D
- Can be implemented in anthropomorphic, deforming phantoms
- Potential to validate DIR algorithms and dose accumulation through comparison against measurement in clinically relevant situations

LEARNING OBJECTIVES

1. Understand the potential for 3D dosimetry in validating dose accumulation in deformable systems.

2. Observe the benefits of high resolution measurements for precision therapy in SRS and in microSBRT for small animal irradiators.

HIGH-RESOLUTION 3D DOSIMETRY

- High-resolution capabilities in 3D dosimetry

  Examples in published and presented work

Isotropic Resolution	Clinical/Research Application
1 mm	SRS
0.5 mm	MicroSBRT
0.2 mm	Small animal irradiator commissioning
0.1 mm	Hippocampal sparing in rat whole-brain RT
0.05 mm	Microbeam radiation

- Why is this useful?
  - ▶ Comprehensive validation of SRS/SBRT techniques
  - ▶ Enables study of advanced RT techniques in preclinical setting

EXAMPLES HIGH-RES 3D DOSIMETRY

1. Multi-target, single isocenter VMAT SRS
2. Small-field irradiator commissioning
3. MicroSBRT with rodent-morphic dosimeters
4. Hippocampal sparing in rat whole-brain RT

MULTITARGET SINGLE ISOCENTER VMAT SRS

A comprehensive investigation of the accuracy and reproducibility of a multitarget single isocenter VMAT radiosurgery technique

Andrew Thomas, Michael Niebanck, Titania Juang, Zhiheng Wang, and Mark Oldham[a)]
Duke University Medical Center, Durham, North Carolina 27710

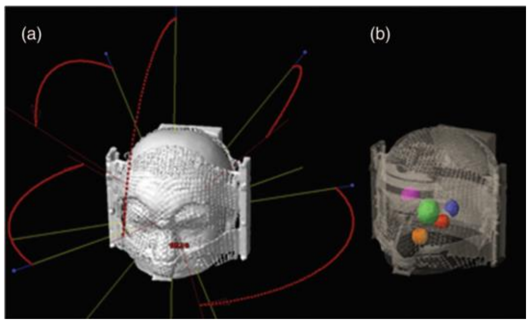
(Received 25 May 2013; revised 24 October 2013; accepted for publication 26 October 2013; published 26 November 2013)

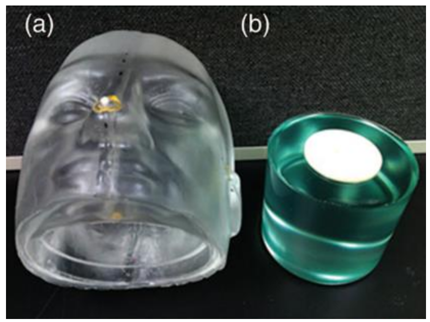
Purpose: Recent trends in stereotactic radiosurgery use multifocal volumetric modulated arc therapy (VMAT) plans to simultaneously treat several distinct targets. Conventional verification often involves low resolution measurements in a single plane, a cylinder, or intersecting planes of diodes

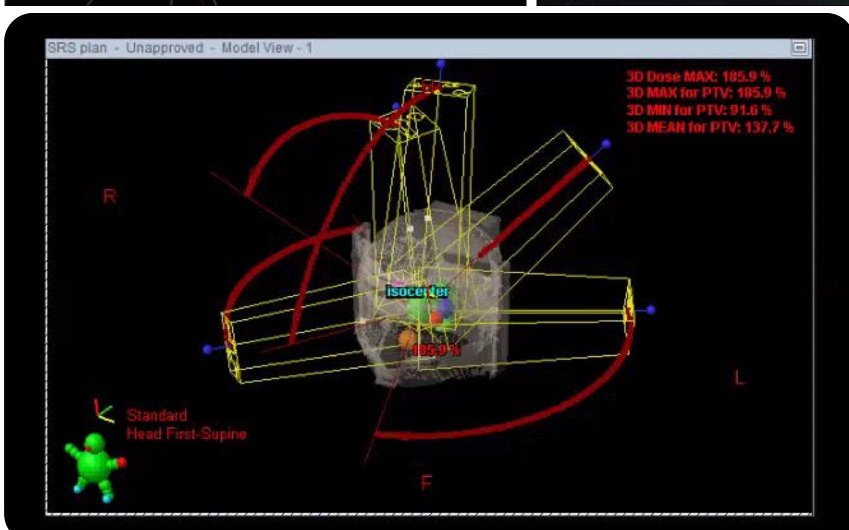
Med. Phys. 40(12), 2013

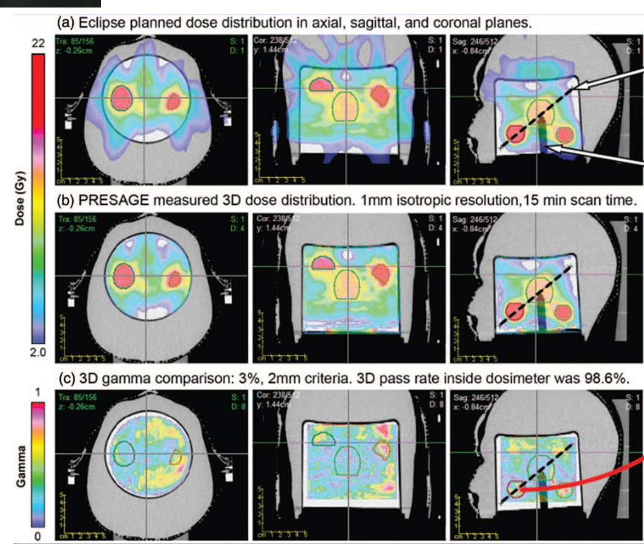
Thomas, et al. (Duke University)

- **1 mm isotropic** 3D dosimetry
- **5 SRS targets** (5-24 cm^3)
- **5 arcs, 1 isocenter**
- **Verified end-to-end accuracy & reproducibility**









3D Gamma (3%/3mm)
98.0% Passing

<3% deviation
between dosimeters

SMALL-FIELD IRRADIATOR COMMISSIONING

Commissioning a small-field biological irradiator using point, 2D, and 3D dosimetry techniques

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Department of Radiation Oncology, Duke University, Durham, North Carolina 27710 and Department of Pharmacology and Cancer Biology, Duke University, Durham, North Carolina 27710

Shiva Das
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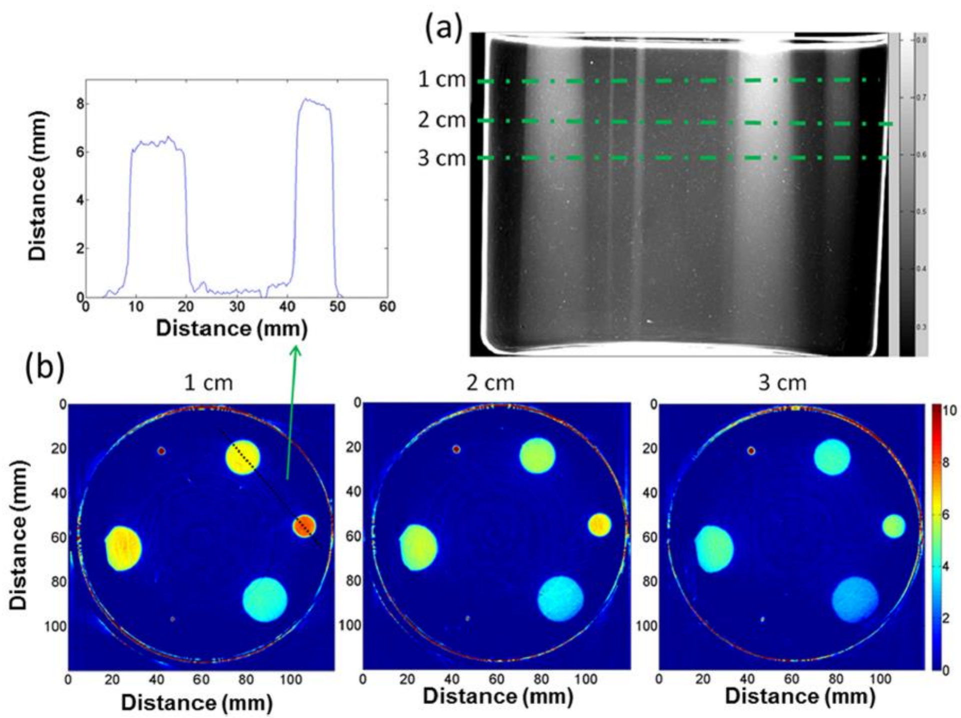
(Received 24 June 2011; revised 3 November 2011; accepted for publication 4 November 2011; published 30 November 2011)

Purpose: To commission a small-field biological irradiator, the XRad225Cx from Precision x-Ray, Inc., for research use. The system produces a 225 kVp x-ray beam and is equipped with collimating



Med. Phys. 38(12), 2011

Newton, et al. (Duke University)

- **0.2 mm isotropic** 3D dosimetry
- **XRad225Cx** small animal irradiator
  - **Field sizes: 1-40 mm**
- **Independent verification** of **PDDs, profiles, and output factors** with 3D dosimetry
  - Can measure and characterize field sizes as small as 1 mm
  - Single dosimeter and scan for all parameters

MICROSBRT WITH RODENT-MORPHIC DOSIMETERS

Investigating the accuracy of microstereotactic-body-radiotherapy utilizing anatomically accurate 3D printed rodent-morphic dosimeters

Steven T. Bache, Titania Juang, and Matthew D. Belley
Duke University Medical Physics Graduate Program, Durham, North Carolina 27705

Bridget F. Koontz
Duke University Medical Center, Durham, North Carolina 27710

John Adamovics
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Terry T. Yoshizumi, David G. Kirsch, and Mark Oldham[a)]
Duke University Medical Center, Durham, North Carolina 27710

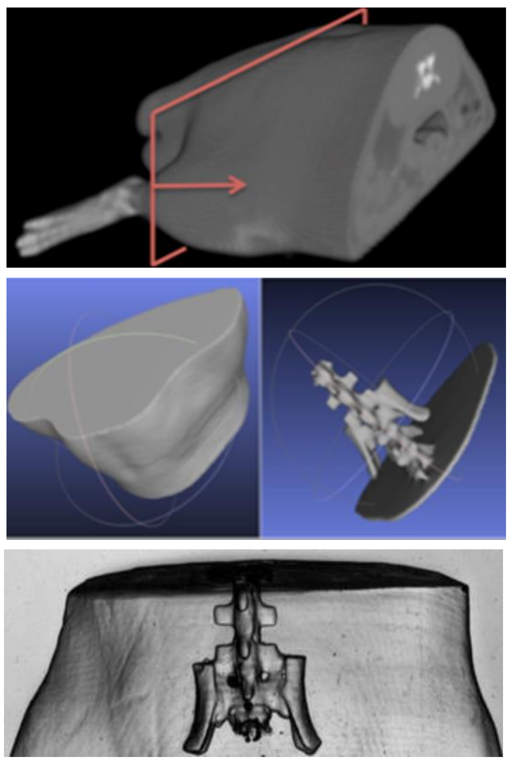
(Received 19 May 2014; revised 1 December 2014; accepted for publication 22 December 2014; published 22 January 2015)

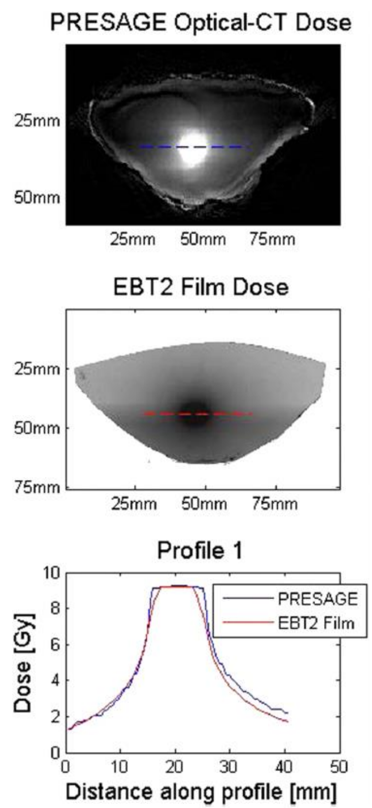
Purpose: Sophisticated small animal irradiators, incorporating cone-beam-CT image-guidance, have recently been developed which enable exploration of the efficacy of advanced radiation treatments

Med. Phys. 42(2), 2015

Bache, et al. (Duke University)

- **0.5 mm isotropic** 3D dosimetry
- **MicroSBRT + cone-beam CT image guidance**
- **Verification of arc treatment delivery accuracy**
- Demonstrates use of 3D printing for anatomically accurate 3D dosimetry phantoms





HIPPOCAMPAL SPARING IN RAT WHOLE-BRAIN RT

27-30 June, London UK
iccr2016.org
ICCR 2016

Feasibility of a micro-radiotherapy technique to investigate hippocampal sparing in whole-brain radiotherapy in rats

Devin Miles, Suk Whan Yoon, Christina Cramer, Michael Reinsvold, David Kirsch, Mark Oldham†
Duke University Medical Center, 201 Trent Drive, Durham, NC, USA 27710

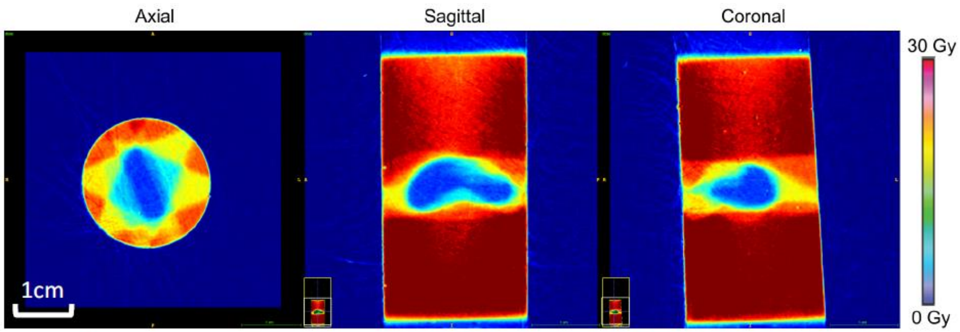


Figure 2: Orthogonal slices of dose readout from irradiated PRESAGE dosimeter.

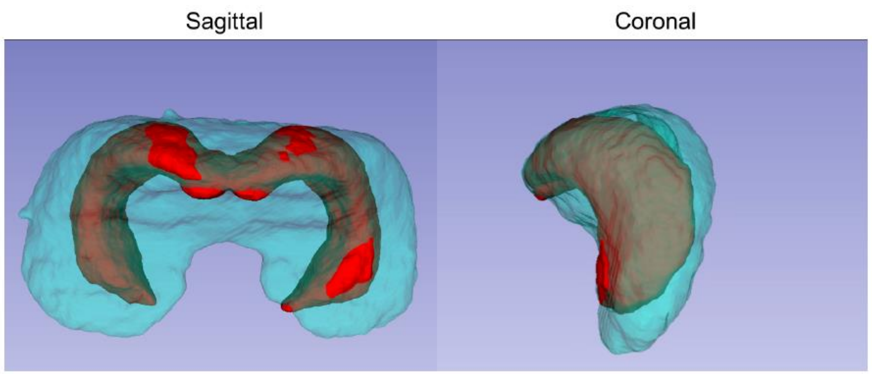


Figure 3: Overlaid 3D rendering of atlas rat hippocampus (red) and measured 30% isodose line (blue).

ICCR 2016 Poster

Miles, et al. (Duke University)

- **0.1 mm isotropic** 3D dosimetry
- **Rodent protocol comparable to RTOG protocol for whole-brain RT with hippocampal avoidance**
- **Verified hippocampal sparing** in conformal 8-field whole-brain rat treatment
  - 3D-printed tungsten blocks to shield hippocampus
  - Hippocampus volume
    0.08 cm^3
    + 1 mm margin
    0.36 cm^3

TAKE-HOME MESSAGES

Learning Objective #2

Observe the benefits of high resolution measurements for precision therapy in SRS and in microSBRT for small animal irradiators.

- Comprehensive, full 3D dose validation for complex SRS plans
- Dosimetry option for small radiation fields down to 1 mm diameter
- Treatment delivery verification for preclinical small animal studies, including models of advanced radiation treatment techniques

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3D DOSIMETRY EDUCATIONAL COURSE

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Mark Oldham
Shiva Das
Andy Thomas
Michael Niebanck
Zhiheng Wang
Joe Newton
Yifan Li
David G. Kirsch
Steve Bache
Matt D. Belley
Bridget F. Koontz
Terry Yoshizumi
Devin Miles
Suk Whan (Paul) Yoon
Christina Cramer
Michael Reinsvold

RIDER UNIVERSITY

John Adamovics
Ron Benning

PMCC / UNIVERSITY OF MICHIGAN

Michael Velec
Joanne Moseley
Kristy Brock

DEFGEL

U. J. Yeo
M. L. Taylor
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R. L. Smith
R. D. Franich
J. R. Supple
B. Lindsay
P. Lonski

FLEXYDOS3D

Y. De Deene
P. S. Skyt
R. Hil
J. T. Booth
C. O. B. Lifehouse

PAPERS (1/2)

- T. E. Schultheiss, W. A. Tomé, and C. G. Orton, “It is not appropriate to ‘ deform ’ dose along with deformable image registration in adaptive radiotherapy,” *Med. Phys.*, vol. 39, no. November, pp. 6531–6533, 2012.
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- M. Velec, T. Juang, J. L. Moseley, M. Oldham, and K. K. Brock, “Utility and validation of biomechanical deformable image registration in low-contrast images,” *Pract. Radiat. Oncol.*, vol. 5, no. 4, pp. e401–e408, 2015.

PAPERS (2/2)

- Y. De Deene, P. S. Skyt, R. Hil, and J. T. Booth, “FlexyDos3D: a deformable anthropomorphic 3D radiation dosimeter: radiation properties,” *Phys. Med. Biol.*, vol. 60, no. 4, pp. 1543–1563, 2015.
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- S. T. Bache, T. Juang, M. D. Belley, B. F. Koontz, J. Adamovics, T. T. Yoshizumi, D. G. Kirsch, and M. Oldham, “Investigating the accuracy of microstereotactic-body-radiotherapy utilizing anatomically accurate 3D printed rodent-morphic dosimeters,” *Med. Phys.*, vol. 846, pp. 1–11, 2015.