Introduction of MRgRT: What, How and Why?

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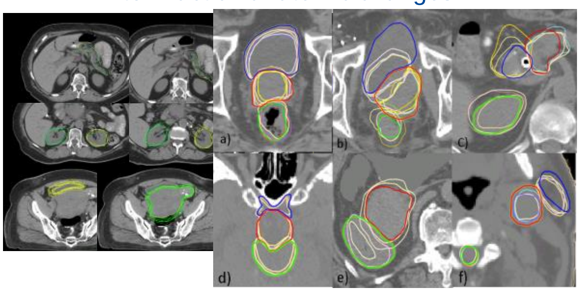
Professor and Chief Physicist

AAPM, Tu-HI-301-1, July 16th, 2019

knowledge changing life   RADIATION ONCOLOGY

Inter-fraction anatomic changes:



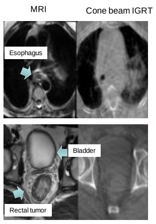
Problems in current CT/CBCT-based IGRT

- ❑ Insufficient image quality
  - ➢ Lack of soft-tissue contrast
- ❑ Incapable of visualizing tumor
  - ➢ Only can see organ/anatomy so far
- ❑ Lack of real-time 3D images for intrafraction motion
  - ➢ CBCT acquisition time is limited to "pre-treatment" or "periodic"
- ❑ Incapable of assessing treatment response during the course of RT delivery
  - ➢ Lack of functional/biologic information

⇨ MRI

Why MRI-guided RT

- Better image quality (high SNR, soft tissue contrast)
- No imaging dose
- Possible fast imaging
- Able to provide all anatomy and biological data
- Real-time imaging (intrafraction motion)
  - Treat the patient simultaneously while being imaged by MRI
- Capable of online adaptive planning
- Possible adaptation based on treatment response



Cont……Why MRgRT?

High soft tissue contrast improves:

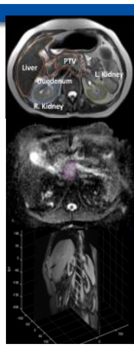
- **target/OAR delineation**
- **auto-segmentation**
- **Deformable registration**
- **Workflow and throughput**

Motion management with real-time MRI reduces:

- **margins account for motion and delineation uncertainty**

High-field MRI allows

- **Adaptation based on tumor and/or normal tissue responses**

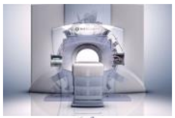


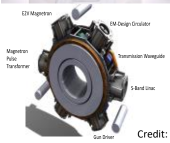
Integrated MRgRT systems

- ViewRay (0.35T, Co-60 or 6MV Linac)
- Elekta Unity MR-Linac (1.5T, 7MV)
- Aurora RT MR-Linac (Edmonton) (0.5T, 6MV)
- Australian MR-Linac (1.0T, 6MV)

ViewRay MR-Linac system

- **RT components:**
  - **Un-flattened nominal 6MV beam**
  - **Double stack double focused 138 leaf MLC**
- **MRI components:**
  - **Split superconducting MRI (0.345 T)**
  - **50cm FOV with 70cm bore size**
  - **Imaging isocenter matches with RT system**
  - **Zero boil-off**





Credit: ViewRay

David Geffen School of Medicine

Slide courtesy of Yingli Wang

UCLA RADIATION ONCOLOGY Division of Medical Physics

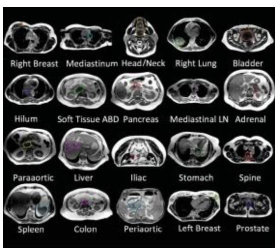
ViewRay: Real-Time Motion Management

- Revolutionary targeting accuracy
- What you see is what you get

✓ 4 Frames per second
✓ bSSFP sequence (T2/T1) weighting
✓ Imaging a single sagittal plane (you choose the plane)
✓ Future: 8 frames per second (FDA cleared, not yet installed for any customer)

Courtesy James Lamb, UCLA

Clinical uses of ViewRay systems



Courtesy Yingli Yang

Clinical uses:

- > 5 years
- 4500 patients
- 6500 on-table adaptation fractions
- 50 disease sites

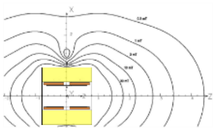
Elekta Unity MRI-Linac

Fully integrated three subsystems

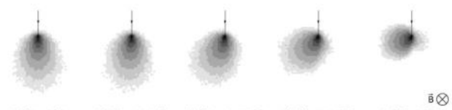
- State of the art radiotherapy delivery system
  - Linac rotates around the MRI magnet
  - Modified to make it compatible with the MR environment
  - Delivery of radiotherapy conformal to MRI-defined anatomy
- 1.5T MRI system
  - Modified to make it compatible with Linac based radiotherapy
  - 3D/4D pre-treatment MRI, 2D/3D beam-on MRI
- Real-time and Online adaptive workflow
  - Real-time motion management
  - Online adaptive replanning

Specially designed MR magnet

- Designed to maintain normal 1.5T operation in the imaging volume
- Minimize material in the beam path and ensure it is homogeneous
- Minimise magnetic field at the Linac
- Built using ‘normal’ process to ensure manufacturability and reliability



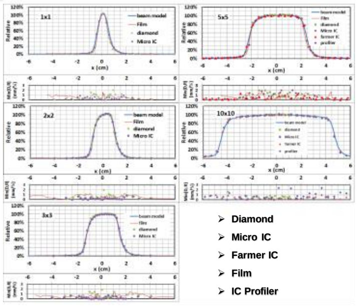
Electron Return Effect (ERE)



(a) B = 0 T (b) B = 0.2 T (c) B = 0.75 T (d) B = 1.5 T (e) B = 3 T

Raaijmakers *et al. Phys Med Biol* 2008;53:909

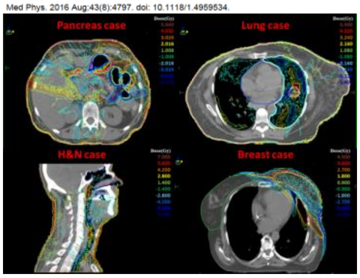
Cross plane beam profiles: measurements vs. beam model



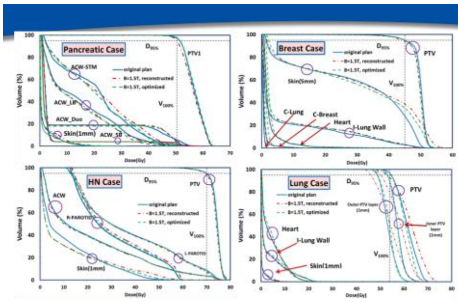
Chen X, Paulson ES, Ahunbay E, Sanli A, Klawikowski S, Li XA. Measurement validation of treatment planning for a MR-Linac. J Appl Clin Med Phys. 2019 Jul;20(7):28-38.

- Diamond
- Micro IC
- Farmer IC
- Film
- IC Profiler

Technical Note: Dose effects of 1.5 T transverse magnetic field on tissue interfaces in MRI-guided radiotherapy.
Chen X, Prior P, Chen GP, Schultz CJ, **Li XA**.
Med Phys. 2016 Aug;43(8):4797. doi: 10.1118/1.4959534.



Dose difference maps w/o 1.5T

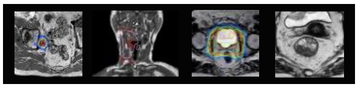


Dose effect of 1.5T can be substantially reduced or eliminated, by including B-field in plan optimization, resulting in no deterioration in plan quality.

Clinical highlights

From Aug 2018 – June 2019

11 Unity machines in clinical operation



>230	>50%	16 min	12
patients completed treatment	SBRT adoption	minimum session time	different indications treated

For internal use only.

Elekta

Unity @ F-MCW

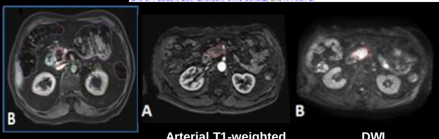
Sept. 17, 2016

April 28, 2017, handover

Jan 17, 2019, 1st Tx

Pancreas

Medical Physics 42, 28 (2015); doi: 10.1118/1.4896096
Comprehensive MRI simulation methodology using a dedicated MRI scanner in radiation oncology for external beam radiation treatment planning
Eric S. Paulson, Beth Erickson, Chris Schultz, and X. Allen Li

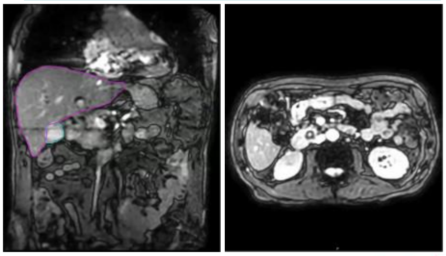


Arterial T1-weighted
Resectable

Arterial T1-weighted DWI
Unresectable

Recommendations for MRI-based contouring of gross tumor volume and organs at risk for radiation therapy of pancreatic cancer.
Heerkens HD, Hall WA, **Li XA**, Knechtges P, Dalah E, Paulson ES, van den Berg CA, Meijer GJ, Koay EJ, Crane CH, Aitken K, van Vulpen M, Erickson BA.
Pract Radiat Oncol. 2017 Mar - Apr;7(2):126-136. doi: 10.1016/j.prro.2016.10.006. Epub 2016 Oct 17.

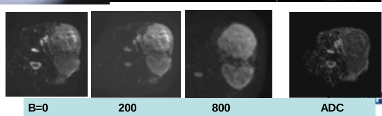
Motions: respiration and peristalsis in abdomen



Oct 10, 2017
Starting imaging patients

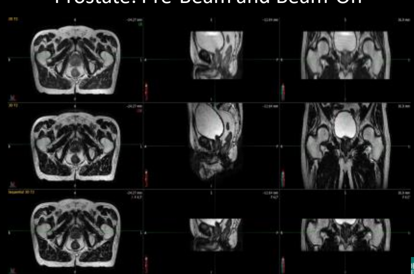
1st patient

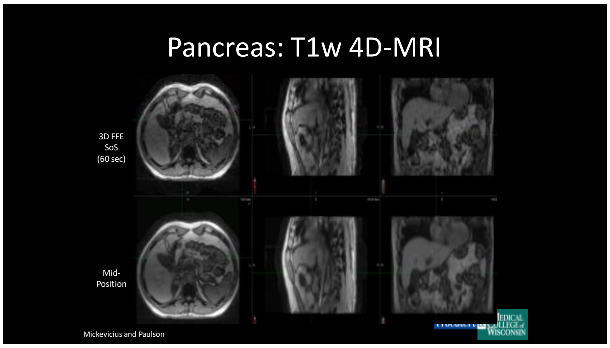
DWI

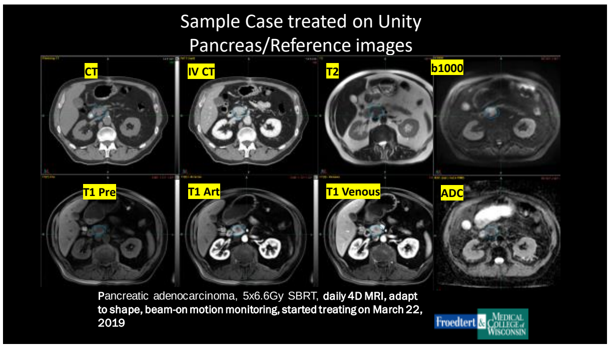


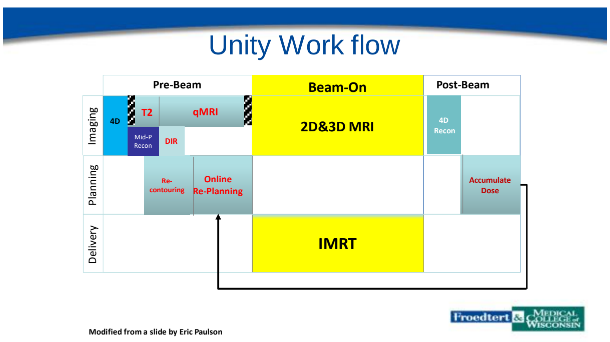
B=0 | 200 | 800 | ADC

Prostate: Pre-Beam and Beam-On

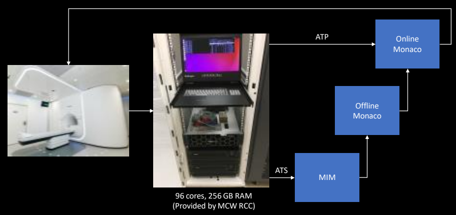



Pancreas: T1w 4D-MRI
3D FFE
SoS
(60 sec)
Mid-
Position
Mickevicius and Paulson


Sample Case treated on Unity
Pancreas/Reference images
CT
IV CT
T2
b1000
T1 Pre
T1 Art
T1 Venous
ADC
Pancreatic adenocarcinoma, 5x6.6Gy SBRT, daily 4D MRI, adapt to shape, beam-on motion monitoring, started treating on March 22, 2019


Unity Work flow
Pre-Beam
Beam-On
Post-Beam
Imaging
Planning
Delivery
4D
T2
qMRI
Mid-P Recon
DIR
2D&3D MRI
4D Recon
Re-contouring
Online Re-Planning
Accumulate Dose
IMRT
Modified from a slide by Eric Paulson

4D MRI workflow



Mickevicius & Paulson, ASTRO 2019

Investigation of undersampling and reconstruction algorithm dependence on respiratory correlated 4D-MRI for online MR-guided radiation therapy.
Mickevicius NJ, **Paulson ES**.
Phys Med Biol. 2017 Apr 21;62(8):2910-2921. doi: 10.1088/1361-6560/aa54f2. Epub 2016 Dec 20.

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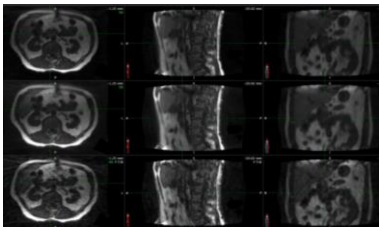
Daily 4DMRI

Motion Averaged

Mid Position

Respiratory Binned



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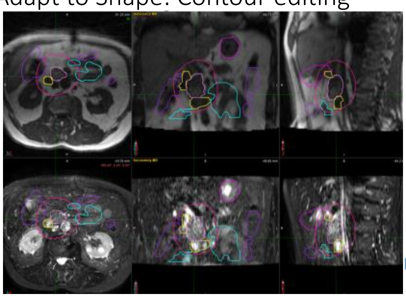
Adapt to Shape: Contour editing



Motion Averaged 4D

Respiration triggered 3D T2

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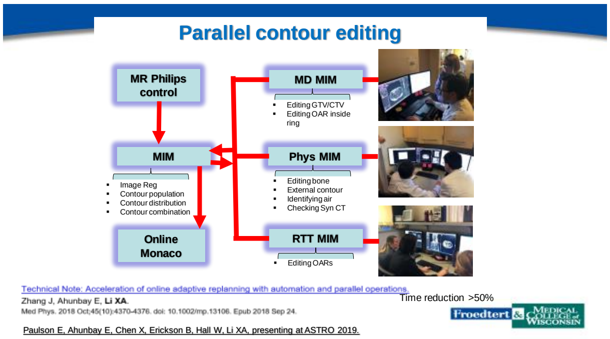
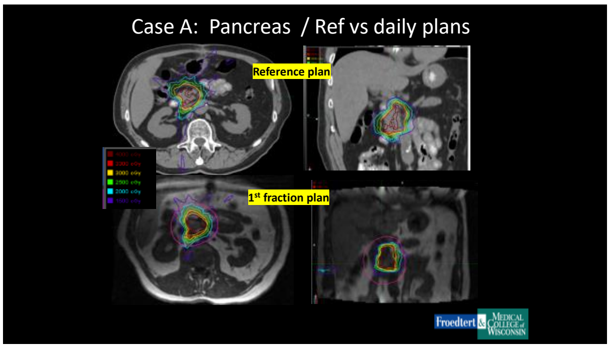
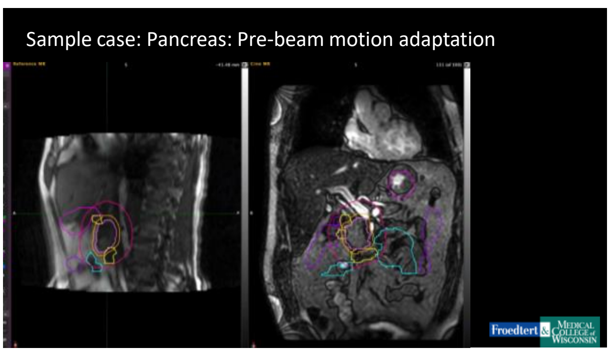
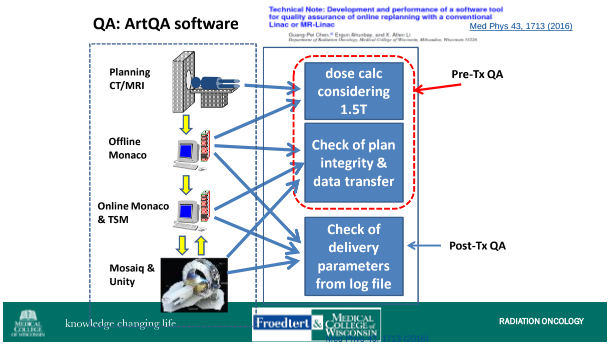

Parallel contour editing
MR Philips control
MIM
Image Reg
Contour population
Contour distribution
Contour combination
Online Monaco
MD MIM
Editing GTV/CTV
Editing OAR inside ring
Phys MIM
Editing bone
External contour
Identifying air
Checking Syn CT
RTT MIM
Editing OARs
Technical Note: Acceleration of online adaptive replanning with automation and parallel operations.
Zhang J, Ahunbay E, Li XA.
Med Phys. 2018 Oct;45(10):4370-4376. doi: 10.1002/mp.13106. Epub 2018 Sep 24.
Time reduction >50%
Froedtert & Medical College of Wisconsin
Paulson E, Ahunbay E, Chen X, Erickson B, Hall W, Li XA, presenting at ASTRO 2019.


Case A: Pancreas / Ref vs daily plans
Reference plan
1st fraction plan
Froedtert & Medical College of Wisconsin


Sample case: Pancreas: Pre-beam motion adaptation
Froedtert & Medical College of Wisconsin



QA: ArtQA software
Technical Note: Development and performance of a software tool for quality assurance of online replanning with a conventional Linac or MR-Linac
Med Phys 43, 1713 (2016)
Planning CT/MRI
Offline Monaco
Online Monaco & TSM
Mosaiq & Unity
dose calc considering 1.5T
Check of plan integrity & data transfer
Check of delivery parameters from log file
Pre-Tx QA
Post-Tx QA
knowledge changing life
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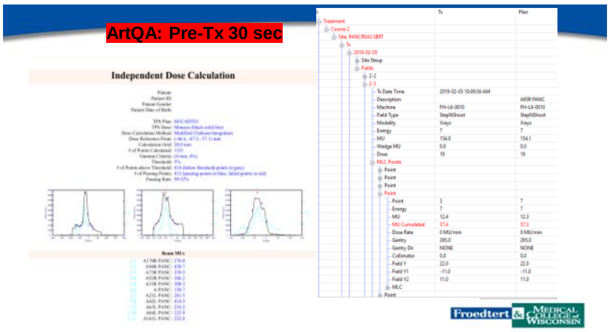
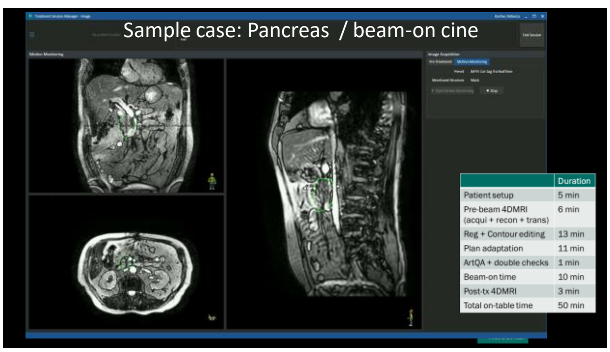
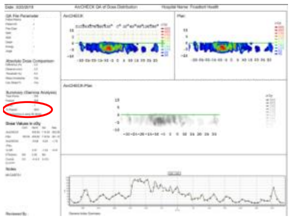


ArtQA: Pre-Tx 30 sec
Independent Dose Calculation
Froedtert & Medical College of Wisconsin

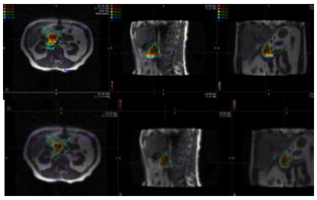


Sample case: Pancreas / beam-on cine
Duration
Patient setup 5 min
Pre-beam 4DMRI (acqui + recon + trans) 6 min
Reg + Contour editing 13 min
Plan adaptation 11 min
ArtQA + double checks 1 min
Beam-on time 10 min
Post-tx 4DMRI 3 min
Total on-table time 50 min

Post-Treatment IMRT QA



Post-Tx dose reconstruction



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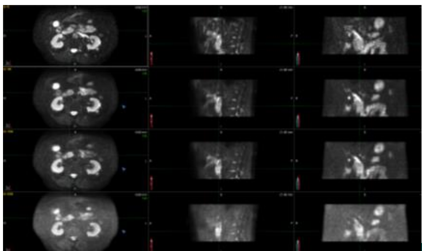
Daily DWI

b=0 s/mm^2

b=30 s/mm^2

b=150 s/mm^2

b=550 s/mm^2



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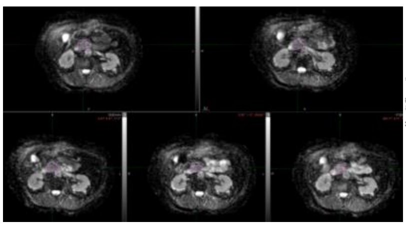
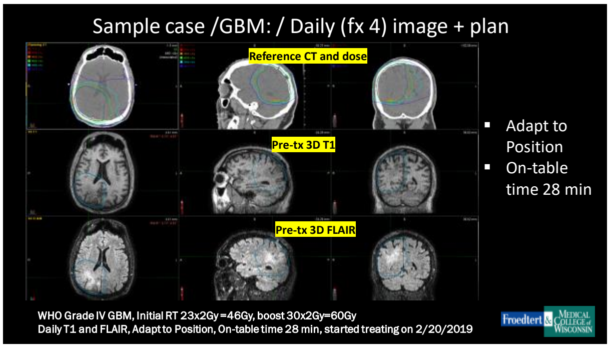
Changes of ADC during RT (SBRT, 5 fr)



36 NCT03500081, STIM, Bill Hall, PI


Sample case /GBM: / Daily (fx 4) image + plan
Reference CT and dose
Pre-tx 3D T1
Pre-tx 3D FLAIR
Adapt to Position
On-table time 28 min
WHO Grade IV GBM, Initial RT 23x2Gy=46Gy, boost 30x2Gy=60Gy
Daily T1 and FLAIR, Adapt to Position, On-table time 28 min, started treating on 2/20/2019
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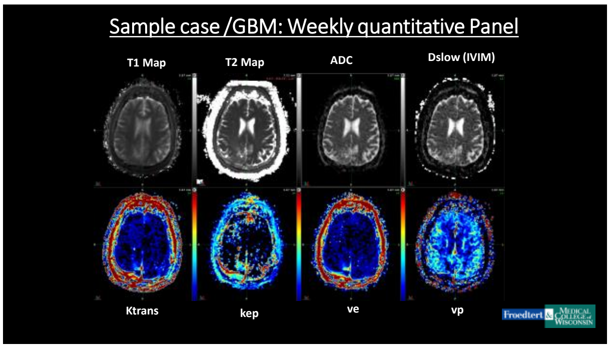
Sample case /GBM: Weekly quantitative Panel
T1 Map
T2 Map
ADC
Dslow (IVIM)
Ktrans
kep
ve
vp
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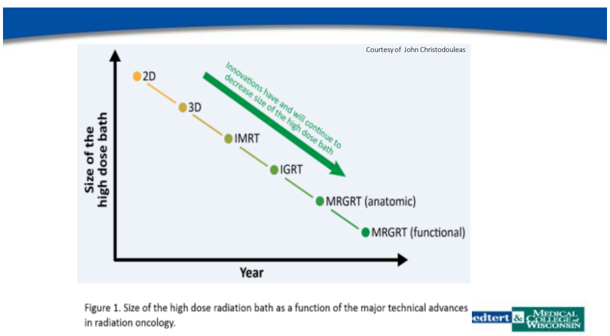
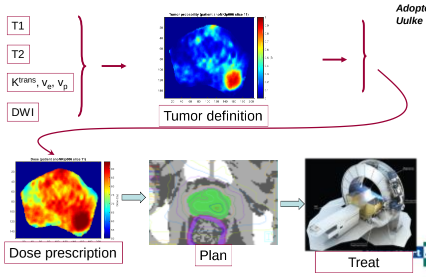
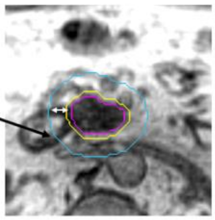

Courtesy of John Christodouleas
Size of the high dose bath
Year
2D
3D
IMRT
IGRT
MRGRT (anatomic)
MRGRT (functional)
Innovations have and will continue to decrease size of the high dose bath
Figure 1. Size of the high dose radiation bath as a function of the major technical advances in radiation oncology.
edtert & Medical College of Wisconsin

Response-guided adaptive dose painting

Adopted from: Uulke van der Heide

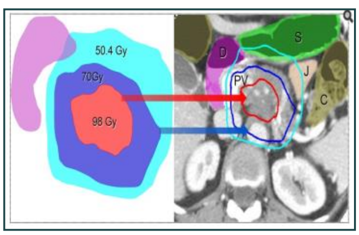




Different PTV expansions into duodenum from pancreatic tumor, yellow represents a tighter PTV volume enabled by real time MRI utilization

Hall et al, EJC 2019

Pancreatic cancer RT

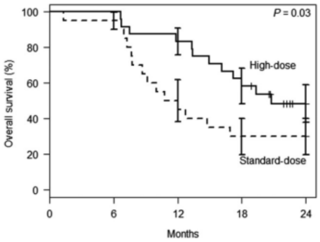


Crane J Rad Research 57(1):53-57,2016

Cancer Med. 2019 May;8(5):2123-2132. doi: 10.1002/cam4.2100. Epub 2019 Apr 1.

Using adaptive magnetic resonance image-guided radiation therapy for treatment of inoperable pancreatic cancer.

Rudra S[1], Jiang N[2], Rosenberg SA[3], Olsen JR[1], Roach MC[1], Wan L[1], Portelance L[4], Mellon EA[4], Bruynzeel A[5], Lagerwaard F[5], Bassetti MF[3], Parikh PJ[1], Lee PP[2].



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MRgRT

Not just an IGRT
Disruptive Innovation

Paradigm Shift

- Improve tumor definition and characterization and management of motion and response, leading to adaptive dose painting, increasing local control.
- Improve OAR definition, better avoidance, decreasing toxicities.
- More SBRT, hypofractionation, ablative RT, transferring the success of SBRT for lung and liver to other tumor sites.
- Online planning and real-time image guided dose delivery, making RT as an intervention.
- Replace surgery with radiotherapy for more situations.
- More affordable RT

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MRgRT

Not just an IGRT
Disruptive Innovation

Paradigm Shift

- **Re-define RT (margin, fractionation, dose homogeneity, tumor heterogeneity, response-based adaptation, …)**
  - *Varying daily radiation dose based on tumor/OAR location*
  - *Varying total radiation dose based on early response assessment during treatment by MR*
  - *Adjusting therapy during treatment based on early markers of disease response*
  - *Monitoring normal tissue damage during RT from MR changes*
- **Possibility to treat novel diseases (e.g. kidney, cardiac)**

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Acknowledgements

F-MCW Unity Clinical Team

MRgRT research team

knowledge changing life

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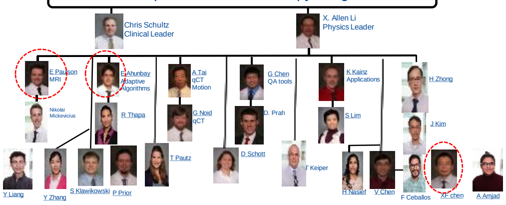
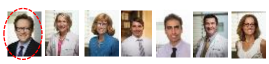
Adaptive Radiation Therapy Program



MCW Radiation Oncologists

W Hall, B Erickson, C Lawton, M. Straza, M. Awan, A Currey, E Gore



Other Institutions

Paul Knechtges, MD
Kiyoko Oshima, MD
Entesar Dalah, Ph.D
Mei Feng, MD
Hui Wu, MD
Wei Huang, MD
Dingjie Li
Taly Schmidt, Ph.D
Cheng Zheng, Ph.D

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