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Overview of IMRT and Arc-Based Techniques

David Shepard
AAPM Annual Meeting - Austin

July 21, 2014

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The Beginnings of IMRT

- Brahme, A., J.E. Roos, and I. Lax (1982), “Solution of an integral equation encountered in rotational therapy.” Phys. Med. Biol. 27:1221-1229.
- Brahme, A. (1988). “Optimization of stationary and moving beam radiation therapy techniques.” Radioth. Oncol. 12:129-140.

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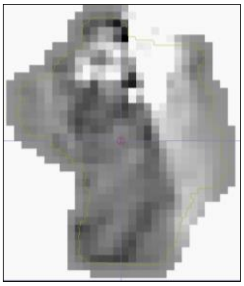

IMRT

- IMRT is characterized by highly conformal dose distributions achieved by delivering non-uniform intensity patterns determined using inverse planning.

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IMRT Delivery Techniques

- Compensators
- Step-and-shoot
- Sliding Window
- Tomotherapy
- IMAT

Compensators, Step-and-shoot, Sliding Window: Fixed field

Tomotherapy, IMAT: Rotational

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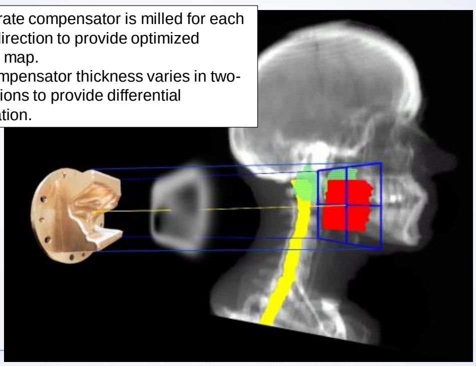
Compensators

- A separate compensator is milled for each beam direction to provide optimized fluence map.
- The compensator thickness varies in two-dimensions to provide differential attenuation.

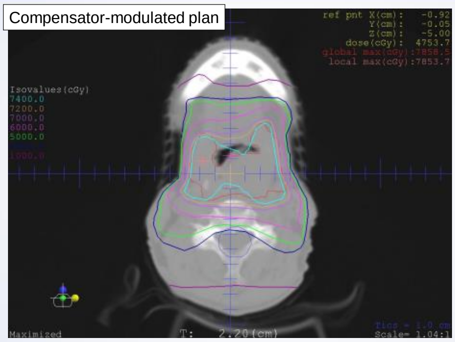


Early Clinical Example

- Squamous cell carcinoma of the oral pharynx
- Planning goals:
  - Primary target: 70 Gy to 95%
  - Spinal cord: < 50 Gy
  - Patient is in extreme pain; treatment time must be as short as possible
- Plan selection:
  - 5 beams
  - Treatment time
    - 7.0 min for compensator-modulation
    - 19.3 min for MLC-modulation (may vary; dependent on MLC vendor)
  - ***Compensator modulation was chosen due to short treatment time.***

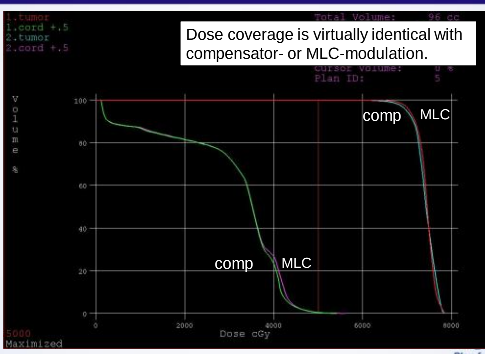
CMS Plan for More

Clinical Example



CMS Plan for More

Clinical Example



CMS Plan for More

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Compensators - Advantages

- No MLC required
- No field splitting (full 40x40cm fields)
- Works well with gated beam delivery

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Compensators - Disadvantages

- Production is labor intensive and time consuming.
- Therapists must enter room and change the compensator for each field of the treatment.
- It is difficult to obtain high spatial variation in an intensity pattern.
- Compensators are a source of unwanted scatter.
- Beam hardening effects and scattered photons must be accounted for in the dose calculation.

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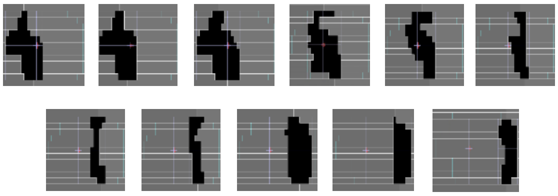
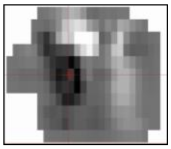
Step-and-shoot

- Multiple beam segments (apertures) delivered from each beam angle.
- The radiation is turned off between segments.

Step and Shoot

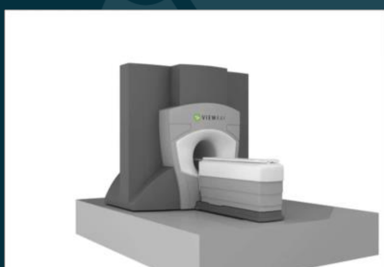


11 segments delivered to replicate the Intensity map.



CMS

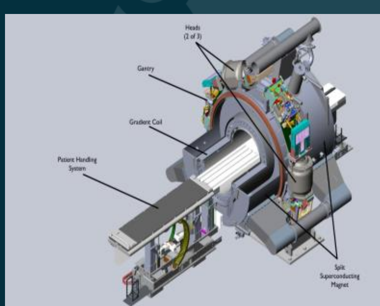
ViewRay



VIEWRAY | Visibly Different

Confidential Information

System Components



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Siteman Cancer Center - BJC

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Step-and-Shoot - Advantages

- No radiation delivered while MLC is moving.

Step-and-Shoot - Disadvantages

- Can be time consuming if a large number of segments are used.

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Dynamic MLC (Sliding Window)

- Each leaf pair of the MLC are moved independently but unidirectionally across the treatment field while the beam is on, effectively sweeping apertures of variable width across the field.
- Pairs of MLC leaves are in continuous movement across the field with the intensity at a point equal to the total exposure time of the leaf pair above it.

Courtesy of Rock Mackie

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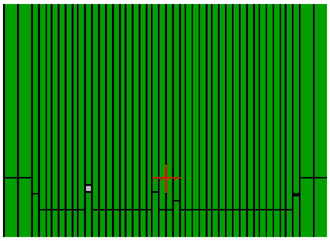
Sliding Window



Courtesy of Paul Keall

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Sliding Window - Advantages

- Does not suffer from intersegment delay time.

Sliding Window - Disadvantages

- Increased wear and tear on MLC.
- More difficult to correctly predict dose.

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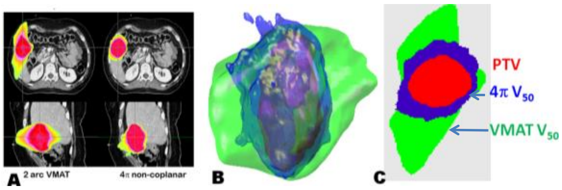
Automated Non-Coplanar Delivery

- Researchers are exploring the dosimetric benefits of using large numbers of non-coplanar beams.
- This would require the development:
  - Comprehensive optimization tools including beam angle selection
  - Sophisticated collision prediction and detection algorithms
  - Automated delivery tools

Dosimetric comparison for a liver SBRT treatment

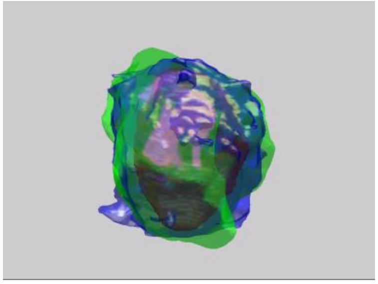
Minimum isodose 50%



Dong, P., P. Lee, R. Dan, T. Long, E. Romeijn, Y. Yang, D. Low, P. Kupelian, and **K. Sheng***, 4pi Non-Coplanar Liver SBRT: A Novel Delivery Technique. Int J Radiat Oncol Biol Phys, 2013. 85(5): p. 1360-1366.

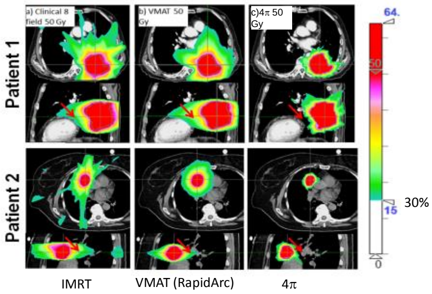
Courtesy of Ke Sheng

3D isodose cloud comparison between non-coplanar and coplanar plans



Courtesy of Ke Sheng

Lung SBRT



Dong et al. IJROBP 2013 July 1; 86 (3):407–413.

Courtesy of Ke Sheng

Implementation

- Delivery is being tested on a Varian TrueBeam
- Automated beam delivery:
  - Most 4π plans have >20 beams
  - Most beams required different couch angles
  - Couch translation also required

Courtesy of Ke Sheng

Automated 4p delivery

6x speed playback, delivery time <10 minutes

Courtesy of Ke Sheng

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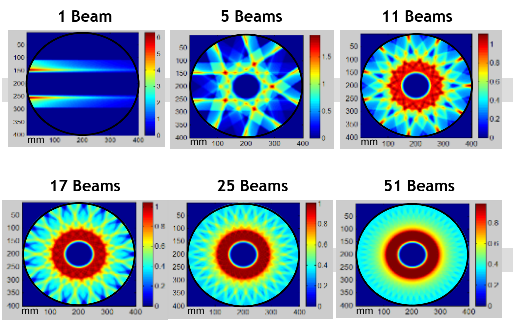
Why rotational delivery?

C-shaped Target Simulations

# Angles	Obj. Funct. Value	Std. Dev. in target dose	d_{95}	Mean dose to RAR	Total integral dose
3	0.665	0.124	0.747	0.488	2732.5
5	0.318	0.090	0.814	0.215	2563.3
7	0.242	0.064	0.867	0.206	2596.8
9	0.222	0.064	0.855	0.192	2598.3
11	0.202	0.058	0.879	0.186	2570.2
15	0.187	0.053	0.908	0.180	2542.9
21	0.176	0.049	0.912	0.171	2545.1
33	0.151	0.038	0.933	0.155	2543.5



Courtesy of Accuray Inc.

Tomotherapy: A new concept for the delivery of dynamic conformal radiotherapy

T. Rock Mackie
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Timothy Holmes and Stuart Swerdloff
Department of Medical Physics, University of Wisconsin, Madison, Wisconsin
Paul Reckwerdt and Joseph O. Deasy
Department of Medical Physics and Human Oncology, University of Wisconsin, Madison, Wisconsin
James Yang
Department of Medical Physics, University of Wisconsin, Madison, Wisconsin
Bhudatt Paliwal
Department of Medical Physics and Human Oncology, University of Wisconsin, Madison, Wisconsin
Timothy Kinsella
Department of Human Oncology, University of Wisconsin, Madison, Wisconsin
(Received 20 July 1992; accepted for publication 14 June 1993)

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Tomotherapy

- Intensity modulated delivery using a fan beam.
- Can be delivered in either a serial or a helical fashion.

Serial Tomotherapy

- Add on binary MLC introduced by NOMOS in 1994.

Courtesy Walter Grant

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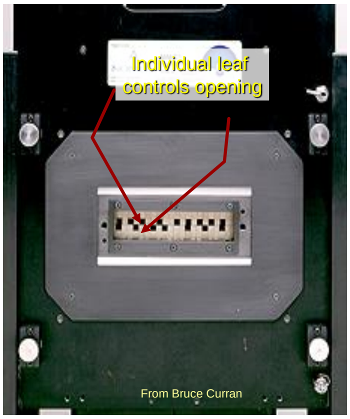
Serial Tomotherapy

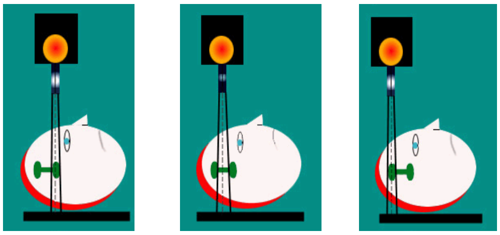
- The leaves of the binary MLC open and close as the gantry rotates.
- Two slices are treated during each rotation.
- Couch must be indexed between rotations.
- In early years of IMRT, more patients were treated with serial tomotherapy than any other technology.

MIMiC

Multileaf
Intensity
Modulating
Collimator



NOMOS MIMiC Delivery



Serial Tomotherapy - Advantages

- Tight dose conformity provided by rotational IMRT delivery.

Serial Tomotherapy - Disadvantages

- Need to purchase add on MLC.
- Very sensitive to accurate couch translation.

Helical Tomotherapy

- Dedicated treatment unit using a rotating fan beam of radiation and a binary MLC.

Helical Tomotherapy

- 2002 – 1st patient treated at the University of Wisconsin
- 2014 - 500th system installed

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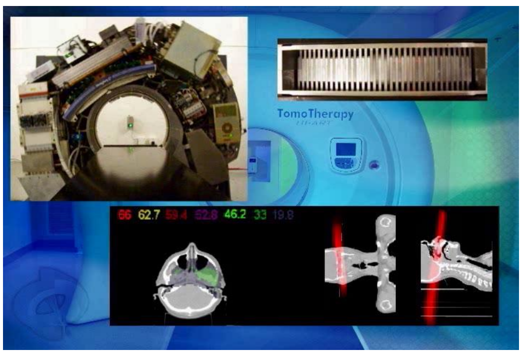
Helical Tomotherapy

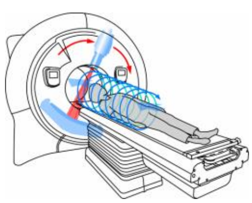
- In-line linac mounted on CT-style gantry
- Fan beam (up to 40cm wide) is divided into 64 “beamlets” by the binary multileaf collimator
- Helical delivery using 6 MV beam
- MV fan-beam CT scanning



Treatment Geometry Overview

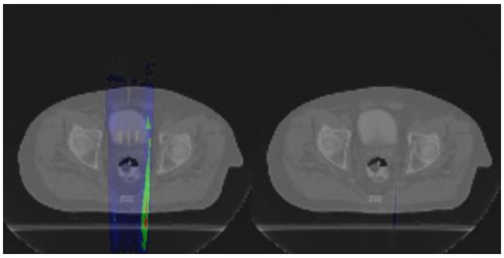
Helical Delivery

- Couch travels continuously in the superior direction.
- Gantry rotates at a constant rate.

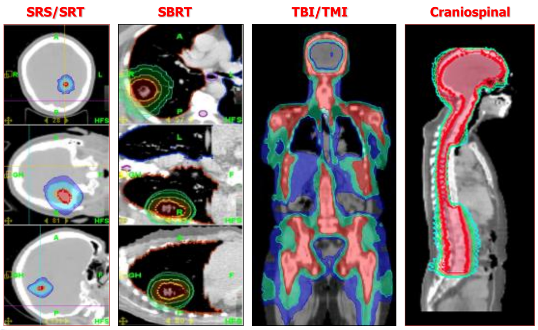


TomoTherapy

Prostate Treatment - Movie



Tomotherapy Treatments



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Additional Tools

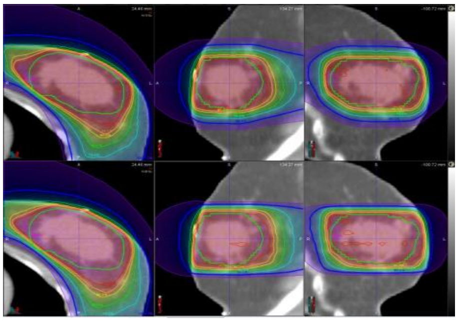
- TomoDirect – Deliver 3DCRT or IMRT with fixed beam angle delivery.
- Dynamic Jaws – running start and stop provides improved dose conformity and in some cases will allow users to select a wider jaw setting leading to a more efficient delivery.

Helical 3D Breast Boost – Comparison of 5 cm Dynamic Jaw vs. 2.5 cm Static Jaw for 14 Gy Boost

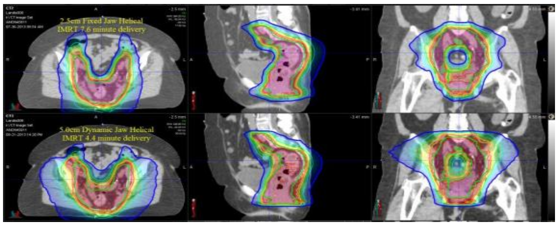
2.5 cm Fixed

5 cm Dynamic

30% Time reduction



Dynamic Helical IMRT vs Fixed Jaw Helical IMRT



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Helical IMRT - Advantages

- Delivery to entire volume in one continuous field
- Overlapping helical strips provide for high degree of modulation
- Rotational delivery provides highly conformal Tx plans
- System fits in low-energy vaults

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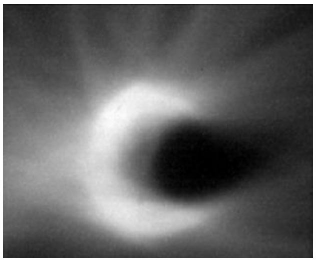
Helical IMRT - Disadvantages

- Need to purchase dedicated treatment system
- Non-coplanar delivery is not an option
- Respiratory gating is challenging

Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy

C X Yu 1995 *Phys. Med. Biol.* **40** 1435-1449 doi:10.1088/0031-9155/40/9/004



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IMAT: 1995-2007

- Over this time, the IMAT delivery technique largely withered on the vine.
- Linac manufacturers did not have control systems capable of delivering IMAT.
- No treatment planning system had robust inverse planning tools for IMAT.

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IMAT: 2008-Today

- Elekta and Varian introduced control systems that are capable of delivering IMAT.
- Key innovation is that the dose rate, gantry speed, and MLC leaf positions can be changed dynamically during rotational beam delivery.
- The term VMAT has been adopted.

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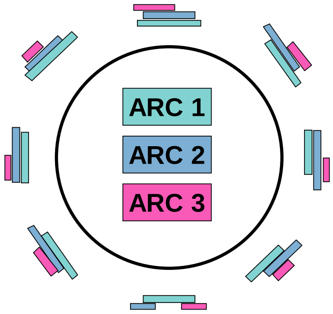
IMAT Basics

- An arced-based approach to IMRT that can be delivered on a conventional linear accelerator with a conventional MLC.
- During each arc, the leaves of the MLC move continuously as the gantry rotates.
- The degree of intensity modulation is related to the number of beam shapes per arc and the number of arcs.

IMAT Delivery



From Cedric Yu

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Efforts to Revive Interest in IMAT

University of Maryland School of Medicine

- We developed tools for delivering rotational IMRT on a Elekta SL20 linac.
- Conducted a clinical trial to demonstrate that IMAT could be delivered safely and accurately on a conventional linac.

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2000 – Phase I Clinical Trial

University of Maryland School of Medicine

- 50 patient trial using IMAT delivered under an IRB protocol.
- Two key limitations were:
  1. Constant dose rate during rotation
  2. No inverse planning solution

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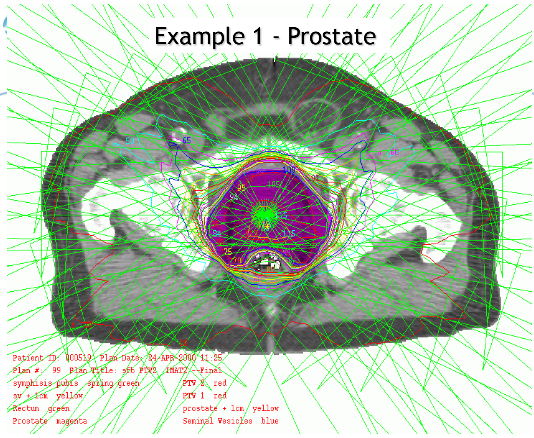
Example 1 - Prostate

- Two sets of bilateral arcs.
- 1 set of arcs matches BEV of prostate.
- 1 matches BEV of prostate – rectum.
- Weights of arcs are optimized.

Example 1 - Prostate



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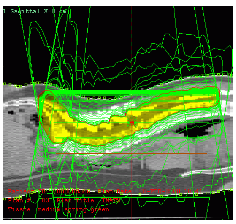
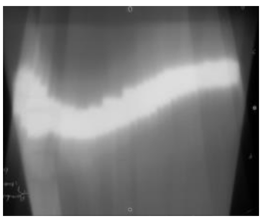
Example 2: Spinal Ependymoma





5 arc treatments

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IMAT - Initial Experience

- 50 patients were treated in this trial: central nervous system (17 patients), head and neck (25 patients) and prostate (8 patients).
- Average treatment time was 7.5 minutes.
- Demonstrated IMAT is an efficient approach to delivering rotational IMRT.

IMAT - Forward Planning

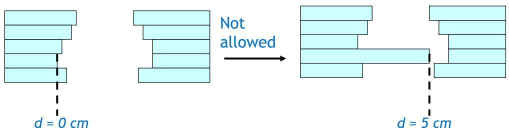
- Dosimetrists used iterative trial-and-error approach to determine starting and stopping angles, the beam shapes, and beam weights.
- Planning was time consuming.
- No guarantee that a plan was close to optimal.

Inverse Planning for IMAT

- The complex nature of IMAT treatment planning has was a primary barrier to routine clinical implementation of IMAT.
- From one angle to the next in each IMAT arc, one must account for the interconnectedness of the beam shapes.

Interconnectedness of Beam Shapes

- Leaf motion between adjacent angles is limited by leaf travel speed and gantry rotation speed.
- For example, if the gantry speed is 10 degree/sec and the leaf travel speed is 3 cm/sec, then the maximum leaf travel distance between two adjacent angles is 3 cm.



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IMAT Treatment Planning

- We developed two IMAT inverse planning approaches:
  1. Direct Aperture Optimization for IMAT (2003).
  2. An “arc-sequencing” algorithm (2006).

Published 2007

Int. J. Radiation Oncology Biol. Phys., Vol. 69, No. 1, pp. 240–250, 2007

ELSEVIER

doi:10.1016/j.ijrobp.2007.04.073

PHYSICS CONTRIBUTION

COMPARISON OF PLAN QUALITY PROVIDED BY INTENSITY-MODULATED ARC THERAPY AND HELICAL TOMOTHERAPY

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*Swedish Cancer Institute, Seattle, WA; and †Department of Radiation Oncology, St. Agnes Hospital, Baltimore, MD

Purpose: Intensity-modulated arc therapy (IMAT) is an arc-based approach to intensity-modulated radiotherapy (IMRT) that can be delivered on a conventional linear accelerator using a conventional multileaf collimator. In a previous work, we demonstrated that our arc-sequencing algorithm can produce highly conformal IMAT plans. Through plan comparisons, we explored the ability of IMAT to serve as an alternative to helical tomotherapy.
Methods and Materials: The IMAT plans were created for 10 patients previously treated with helical tomotherapy. Treatment plan comparisons, according to the target dose coverage and critical structure sparing, were performed to determine whether similar plan quality could be achieved using IMAT.
Results: In 8 of 10 patient cases, IMAT was able to provide plan quality comparable to that of helical tomotherapy. In 2 of these 8 cases, the use of non-axial coplanar or non-coplanar arcs in IMAT planning led to significant improvements in normal tissue sparing. The remaining 2 cases posed particular dosimetric challenges. In 1 case, the target was immediately adjacent to a spinal cord that had received previous irradiation. The second case involved multiple target volumes and multiple prescription levels. Both IMAT and tomotherapy were able to produce clinically acceptable plans. Tomotherapy, however, provided a more uniform target dose and improved critical structure sparing.
Conclusions: For most cases, IMAT can provide plan qualities comparable to that of helical tomotherapy. For some intracranial tumors, IMAT's ability to deliver non-coplanar arcs led to significant dosimetric improvements. Helical tomotherapy, however, can provide improved dosimetric results in the most complex cases.

Intensity-modulated arc therapy, IMAT, Tomotherapy, Intensity-modulated radiotherapy, IMRT, Arc sequencing, Inverse planning.

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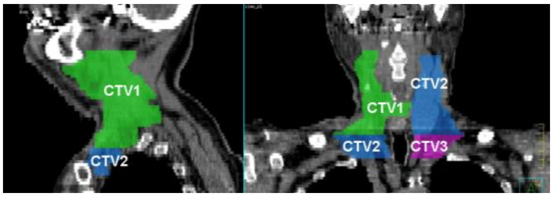
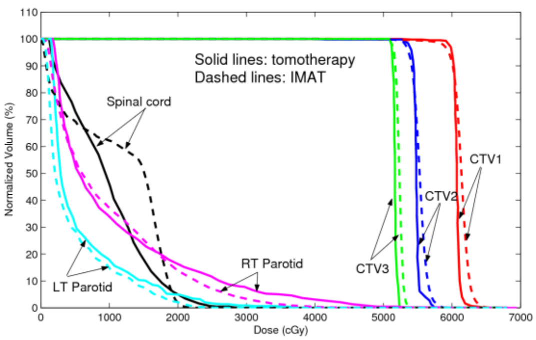
IMAT vs. Tomotherapy

Plan Comparison

- Dr. Tim Holmes from St. Agnes Hospital in Baltimore provides us with 10 tomotherapy treatment plans.
- Plan comparisons were made between IMAT and tomotherapy.

H&N Example





Results of Initial Comparison Study

- This study showed the IMAT can provide similar plan quality as helical tomotherapy for a range of clinical cases.
- At this point, no delivery control system existed capable of delivering these IMAT plans.

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IMAT Commercial Introduction

- In 2008, Elekta and Varian introduced control systems that are capable of delivering IMAT.
- Key innovation is that the dose rate, gantry speed, and MLC leaf positions can be changed dynamically during rotational beam delivery.
- The term VMAT was coined by Karl Otto and became widely adopted.

Volumetric modulated arc therapy: IMRT in a single gantry arc

Karl Otto[a)]
Vancouver Cancer Centre, BC Cancer Agency, Vancouver, British Columbia V5Z 4E6, Canada

(Received 25 June 2007; revised 21 September 2007; accepted for publication 5 November 2007; published 26 December 2007)

In this work a novel plan optimization platform is presented where treatment is delivered efficiently and accurately in a single dynamically modulated arc. Improvements in patient care achieved through image-guided positioning and plan adaptation have resulted in an increase in overall treatment times. Intensity-modulated radiation therapy (IMRT) has also increased treatment time by requiring a larger number of beam directions, increased monitor units (MU), and, in the case of tomotherapy, a slice-by-slice delivery. In order to maintain a similar level of patient throughput it will be necessary to increase the efficiency of treatment delivery. The solution proposed here is a novel aperture-based algorithm for treatment plan optimization where dose is delivered during a single gantry arc of up to 360 deg. The technique is similar to tomotherapy in that a full 360 deg of beam directions are available for optimization but is fundamentally different in that the entire dose volume is delivered in a single source rotation. The new technique is referred to as volumetric modulated arc therapy (VMAT). Multileaf collimator (MLC) leaf motion and number of MU per

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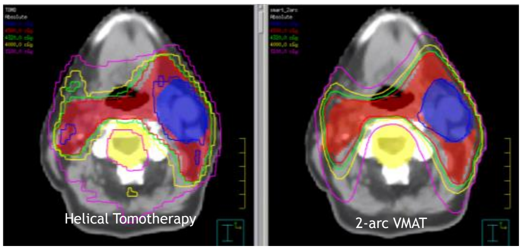
New Study:
VMAT vs. Tomotherapy

- Collaborative study between Swedish Cancer Institute and University of Virginia.
- 6 prostate, 6 head-and-neck, and 6 lung cases were selected for this study.
- Fixed field IMRT, VMAT, and Tomotherapy were compared in terms of plan quality, delivery time, and delivery accuracy.

Head & Neck Case #1



- Two targets with prescription levels of 5040 and 4500 cGy

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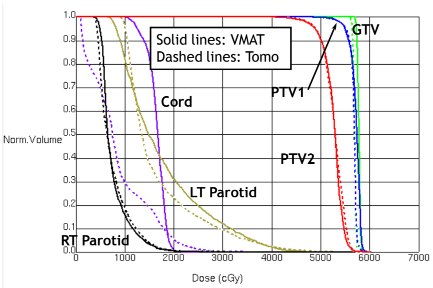
Head & Neck Case #1



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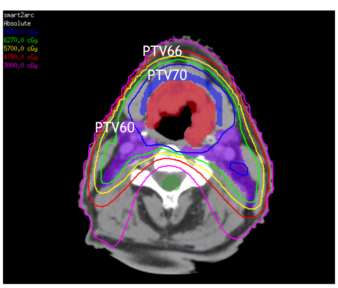
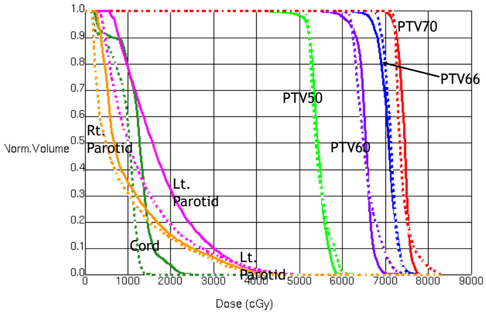
H&N Example #2

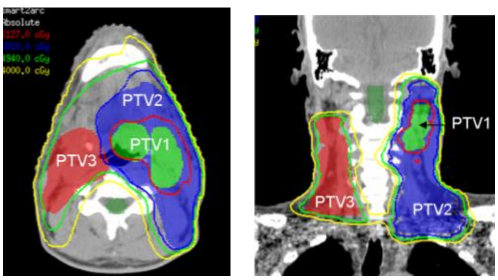


- 2 arcs, 512 monitor units
- Deliver time = 4 minutes 7 seconds

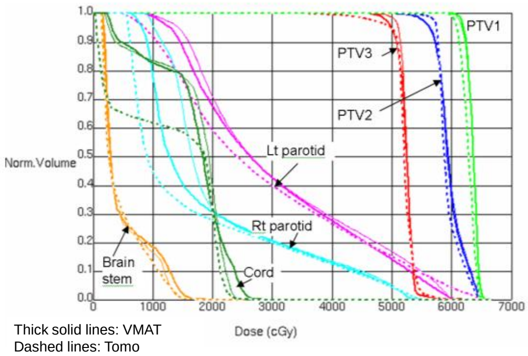
H&N Example #2



H&N Example #3



VMAT Plan



Thick solid lines: VMAT
Dashed lines: Tomo
Thin solid: 9 Field IMRT

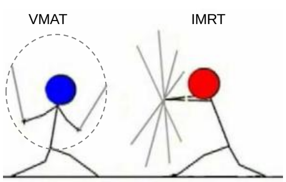
IMAT/VMAT - Advantages

- Highly efficient delivery – approx. 1.5 minutes per arc
- Strong dose shaping capabilities

IMAT/VMAT - Disadvantages

- Interconnectedness of beam shapes from one beam angle to the next.

When does IMRT beat VMAT?



Picture from: aniboom.com

Fixed Field IMRT-VS-VMAT

	Step-N-Shoot IMRT	VMAT
Delivery Efficiency	Slow ☹	Fast ☺
MU efficiency	Low ☹	High ☺
Planning Time?	Short ☺	Long ☹
Constraints	Fewer ☺	More ☹

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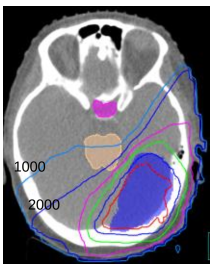
VMAT/Fixed Field IMRT Comparison

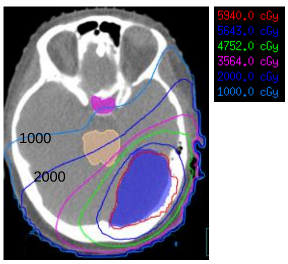
- We prospectively tested fixed field IMRT and VMAT plan quality on 100 consecutive IMRT patients.
- The physician selected the plan that he/she felt was most appropriate for the individual patient based on plan quality and delivery efficiency.
- In 95 out of 100 cases, the VMAT plan was selected.

Partial Brain: Fixed Field Selected

IMRT: 6 fields (one couch kick)



VMAT (Single-arc: no couch kick)



IMRT plan has lower dose in brain stem and chiasm.

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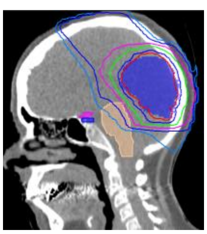
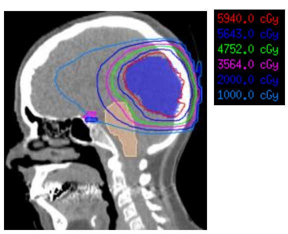
Partial Brain: Fixed Field Selected

Sagittal View

IMRT: 6 fields (one couch kick)



VMAT (Single-arc: no couch kick)



IMRT plan spares more brain stem and chiasm.

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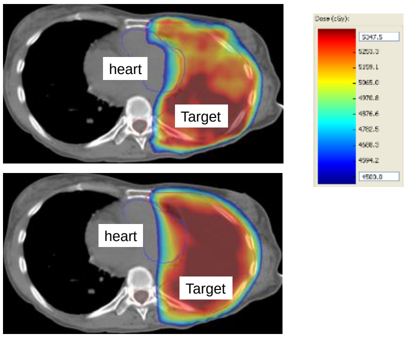
Mesothelioma: Fixed Field Selected

IMRT

VMAT



IMRT plan provided better conformality perhaps due to higher degree of intensity modulation.

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Summary

- All IMRT delivery techniques provide highly conformal dose distributions.
- With each, a balance must be struck between plan quality and delivery efficiency.
- As technology evolves, views on which technique is the best choice will continues to change.

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Factors that Impact VMAT Quality

1. More gantry angles➔ large volume being irradiated to low dose
2. Segment shapes are connected➔ limited Leaf motion➔ limited modulation
3. Gantry continuous moving➔ limited modulation at good angles

88

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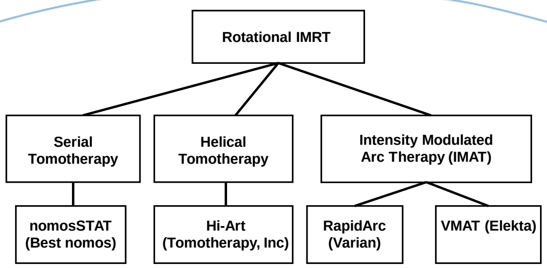
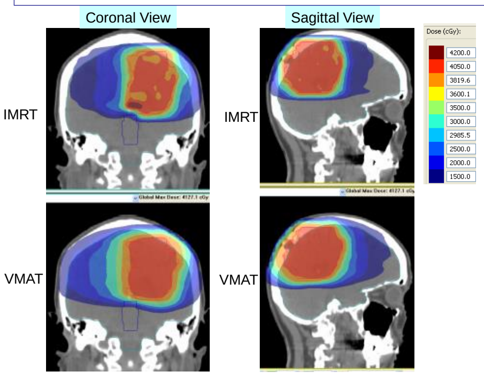


Case#1: Partial Brain: Fixed field has smaller low dose volume



VMAT = more uniform target dose. IMRT = smaller low dose volume.

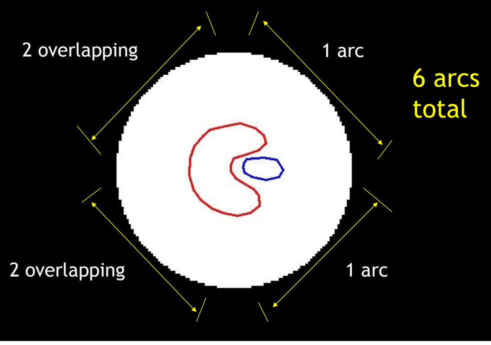
IMAT Advantages

- The rotational nature of IMAT delivery provides additional flexibility in shaping the dose distribution.
- IMAT is an efficient delivery technique due to the continuous nature of the delivery.

Direct Aperture Optimization (DAO)

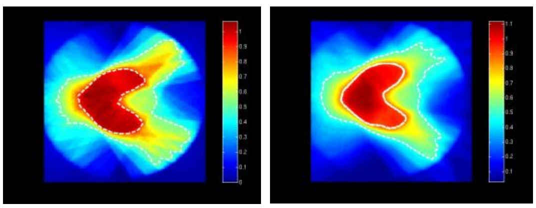
- The number apertures per beam angle is specified in the prescription.
- All of the MLC delivery constraints are included in the optimization.
- The optimized plan is ready for delivery (no leaf sequencing).
- Can be used for both step-and-shoot and IMAT planning.

Cylinder -Arc configuration



Cylindrical phantom delivery

Planned Delivered



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Arc Sequencer

- Algorithm that converts optimized fluence maps into deliverable IMAT plans:
  1. A step-and-shoot treatment plan is created in the Pinnacle[3] TPS with beams separated by 10 degrees.
  2. The optimized intensity maps are extracted and sent to our arc-sequencing algorithm.
  3. The sequencer produces an IMAT plan that is read back into Pinnacle[3] for a final dose calculation.

Treatment Geometry Overview

Projections, Beamlets, and Rays

- 51 **projections** (beam delivery angles) per rotation
  - The Treatment Planning System (TPS) assumes that radiation is delivered from 51 discrete angles centered on each projection.
  - Actual gantry rotation is continuous.
- 64 **beamlets** per projection (one for each MLC leaf).
  - A single gantry rotation has 51 x 64 = 3,264 beamlets.
  - A treatment with 30 rotations would have 97,920 beamlets.
  - The MLC is binary; each leaf is either fully open or fully closed.
  - However, individual leaf open times vary within a projection, allowing for many intensity levels across the radiation field.

TomoTherapy

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Helical TomoTherapy

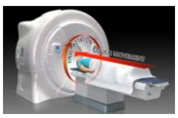
Fast Binary MLC

\+

Continuous Gantry Rotation

\+

Simultaneous Couch Movement



- MLC leaves that move at 250 cm/s to open or shut in milliseconds
- Thousands of beamlets throughout multiple 360 degree rotations
- Coverage of a target extent up to 160 cm in length with no matching

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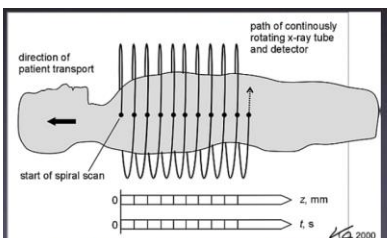
Helical Delivery

Fusion of a Linear Accelerator and a Helical CT Scanner



from: W. Kalender, Computed Tomography: Fundamentals, System Technology, Image Quality, Applications

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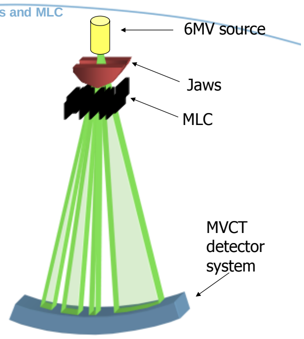
Treatment Geometry Overview:

Jaws and MLC

- Jaws define the field size along the *y*-axis: 1.05, 2.50, or 5.02 cm FWHM at iso.
- Leaves open and close to shape the intensity distribution across the beam.
  - Binary MLC: Leaves are open, closed, or switching very quickly between states.



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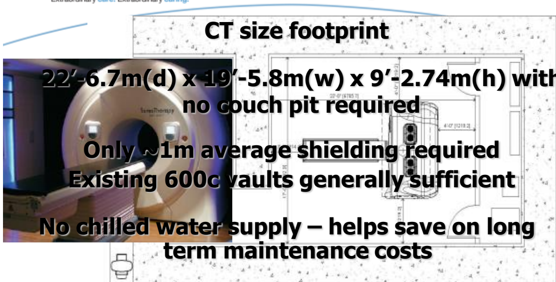
Minimal Bunker Requirements



CT size footprint

22'-6.7m(d) x 19'-5.8m(w) x 9'-2.74m(h) with no couch pit required

Only ~1m average shielding required

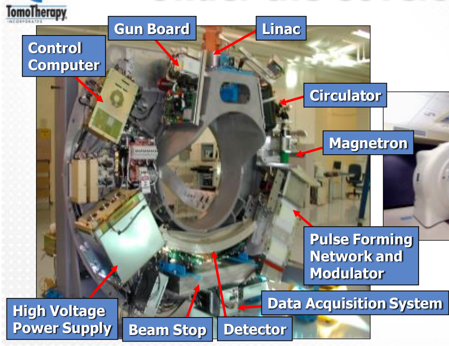
Existing 600c vaults generally sufficient

No chilled water supply – helps save on long term maintenance costs

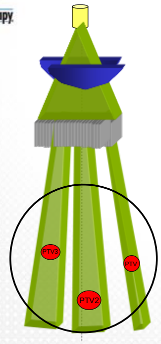
30 day typical install of pre commissioned machine

TomoTherapy

Under the Covers



Reshaping Radiation Therapy



MLC

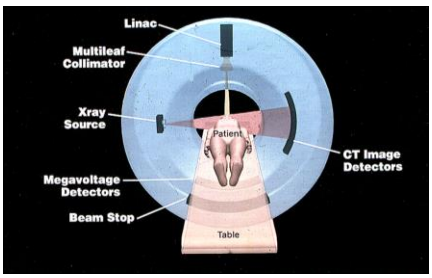
64 binary
pneumatically driven MCL leaves
(no MLC motors)

Leaf size: 0.625 cm
Leaf speed: 20 msec

Isocenter placement not
significant for treatment

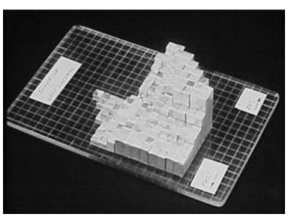
Reshaping Radiation Therapy

Helical Tomotherapy



- Dedicated treatment unit using a rotating fan beam of radiation and a binary MLC.

Custom Compensators

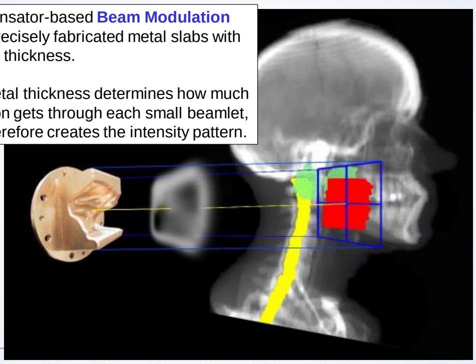


- A separate compensator is milled for each beam direction to provide optimized fluence map.
- The compensator thickness varies in two-dimensions to provide differential attenuation.

From Cedric Yu

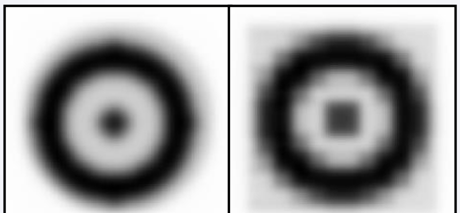
Compensators

- Compensator-based **Beam Modulation** uses precisely fabricated metal slabs with varying thickness.
- The metal thickness determines how much radiation gets through each small beamlet, and therefore creates the intensity pattern.



Advantages of Compensator-Based IMRT

Painting with a "finer" paint brush…



Brass modulator | segmented MLC modulator

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INSTITUTE OF PHYSICS PUBLISHING — PHYSICS IN MEDICINE AND BIOLOGY
Phys. Med. Biol. 48 (2003) 1–15 — PII: S0031-9155(03)57398-5

Inverse planning for intensity modulated arc therapy using direct aperture optimization

M A Earl, D M Shepard, S Naqvi, X A Li and C X Yu

Department of Radiation Oncology, University of Maryland School of Medicine, Baltimore, MD 21201, USA

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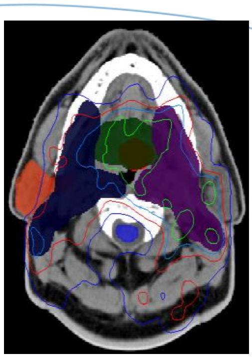
NOMOS Corvus System

- Isodose
  - Green - 66 Gy
  - Light Blue - 60 Gy
  - Red - 54 Gy
  - Blue - 45 Gy
- Structures
  - Orange - Parotid
  - Red - PTV66
  - Green - PTV60
  - Blue - PTV54
  - Purple - PTV60 nodes



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Acknowledgments

- Thomas Bortfeld
- Martijn Engelsman
- Alexei Trofimov
- Lei Dong
- Daniel Ollendorf
- Daniel Lessler

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Types of IMRT Delivery

- **Custom Compensators**
- **Step-and shoot**
- **Dynamic MLC (sliding window)**
- **Intensity Modulated Arc Therapy (IMAT)**
- **Tomotherapy**
  - Serial Tomotherapy (NOMOS Peacock™)
  - Helical Tomotherapy
- **Robotic Pencil Beam IMRT Delivery**

Advantages of Compensator-Based IMRT

- Inverse planning with compensator-based modulation can transform ANY linear accelerator into an IMRT machine
  - *Therefore, almost all clinics already have the hardware to deliver IMRT*
- Compensator-based IMRT requires fewer total monitor units
  - *Less than half the MUs required for MLC based IMRT*
  - *Less treatment time, compared to MLC*
  - *Important for patients in pain*
- Each compensator can be visually inspected to ensure proper placement in the beam
  - *Hands-on "sanity checks"*

CMS Plan for More

USA • Europe • China • Japan • Australia • cmsrtp.com

Advantages of Compensator-Based IMRT

- Shielding is not required if Brass filters are used as adequate shielding is provided by the filter.
- "Unlimited" Field size. Up to max collimator settings on Linac
  - *No need for Head and Neck junctions*
  - *No issues with jaw over travel*
  - *No field splitting*
- Compensator-based IMRT is better when treatments are "gated" for breathing
  - *Moving modulators (MLC) do not work well with moving targets*
- Metal compensators do not break down…

CMS Plan for More

USA • Europe • China • Japan • Australia • cmsrtp.com

Disadvantages of Compensator-Based IMRT

- A radiation therapist must enter the treatment room to change the IMRT compensator for each irradiation beam.
  - *This is a common practice, quick, and a good way to check on the patient and make sure they are comfortable and still.*
- Requires ordering or fabricating the compensators
  - *1- to 2-day turnaround (within the USA)*
- Expendable component (the compensators) have a recurring cost
  - *How this compares to the cost of acquiring and maintaining an MLC-based system depends on the patient load.*

CMS Plan for More

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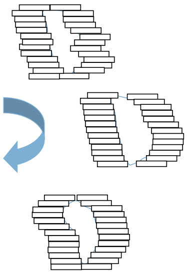
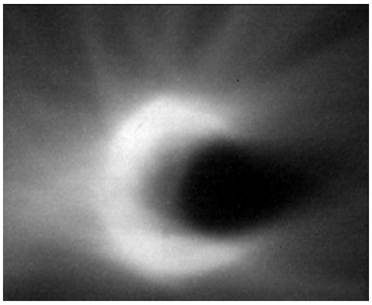
IMAT



Field shape changes dynamically during rotation. Multiple rotations may be necessary.

From Rock Mackie

IMAT Delivery: C-shaped Target



From Cedric Yu

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IMAT - advantages

- Spreads out dose to normal tissue.
- Provides rotational IMRT with conventional MLC.
- Efficient delivery.

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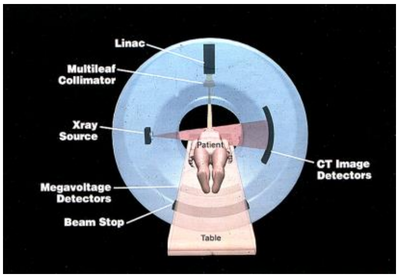
IMAT - disadvantages

- Complicated due to simultaneous motion of MLC leaves and gantry.
- Inverse planning is complicated due to increased number of delivery constraints.

Helical Tomotherapy



Partial Assembly of the UW Clinical Prototype

From Rock Mackie

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Helical Tomotherapy - disadvantages

- $$$
- No patients treated yet.

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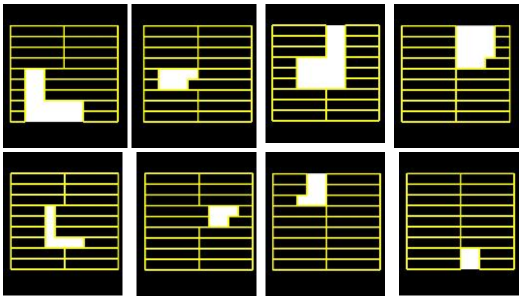
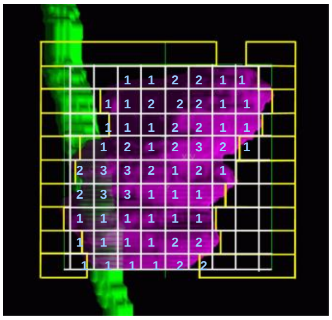
IMAT Development
Outline

- IMAT basics
- Efforts to revive interest in IMAT
- Commercial IMAT solutions
- Future directions for IMAT

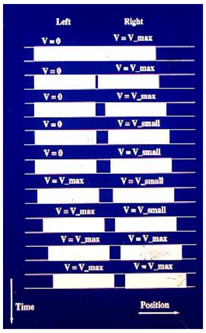
Eight step and shoot segments...

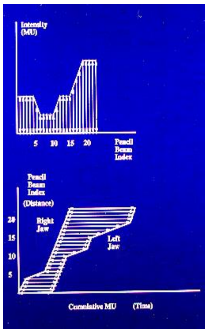


Summed together …



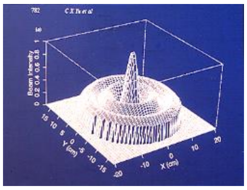
Sliding Window

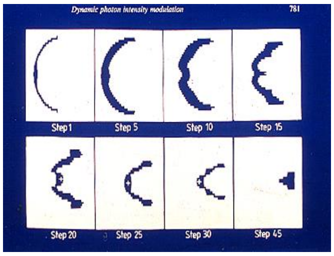




From Rock Mackie

Dynamic MLC





- This 2-D Sinc Function can be delivered with the MLC pattern shown on the right

From Cedric Yu

What is IMRT?

- A delivery technique where a nonuniform intensity of radiation is delivered from each beam direction.
- By optimizing the intensity pattern delivered from each beam direction it is possible to achieving highly conformal dose distributions.

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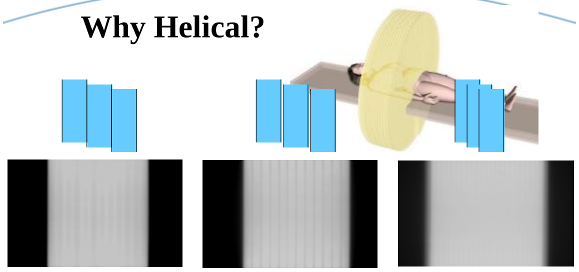
Why Helical?



Axial correct table indexing | Axial 0.2 mm error in table indexing | Helical pitch 0.5

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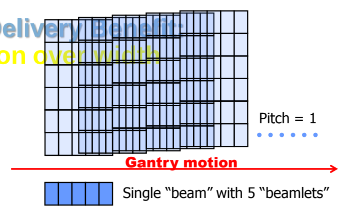
Helical Delivery Benefit:
Resolution over width

“Width”



In this example:
51 angles x 5 beamlets x 6 rotations = 1530 total beamlets

Note: Effective beamlet width is reduced due to close angular spacing

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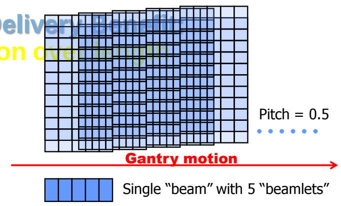
Helical Delivery Benefits: Resolution over length

“Length”



In this example:
51 angles x 5 beamlets x 11 rotations = 2805 total beamlets

Note: Effective beamlet width and height is reduced due to close angular spacing and small pitch

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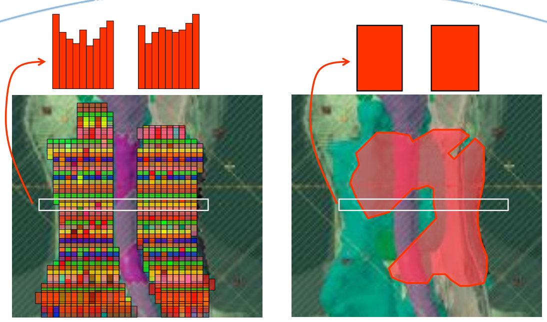

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Initial IMAT Investigations @ Swedish

- Single-arc vs. multiple arc VMAT: plan quality and delivery efficiency
- Elekta VMAT vs. Helical tomotherapy
- Comparison of VMAT QA Techniques
- Impact of systematic and random error on the plan quality and delivery accuracy for VMAT and IMRT techniques.

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Single vs. Multiple Arc VMAT

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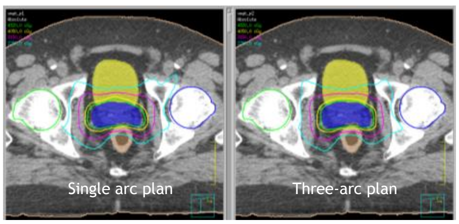
Prostate case



- The single-arc plan has a total of 60 control points.
- The three-arc plan has 35 control points per arc (105 total).

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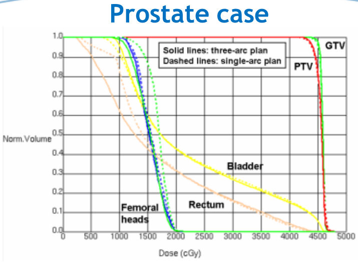
Prostate case



- The V95 (target volume covered by 95% prescribed dose) are 99.1% and 99.6% for the single-arc and three-arc plans, respectively
- Delivery times are 2.5 and 5.1 minutes for single-arc and three-arc plans, respectively

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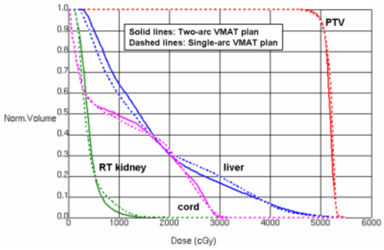
Pancreas Case



- The V95 are 98.7% and 99.1% for the single-arc and two-arc plans, respectively
- Delivery times are 2.6 and 3.8 minutes for single-arc and two-arc plans, respectively

Summary for Relatively Simple Cases

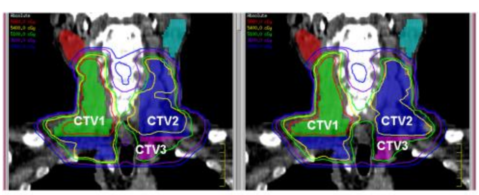
Treatment site	V95 (%)		σ_{PTV} (cGy/fraction)		OAR mean/max dose (cGy)			MU/fraction		Delivery time (minute)	
	1 arc	multi-arc	1 arc	multi-arc	OAR	1 arc	multi-arc	1 arc	multi-arc	1 arc	multi-arc
lung	99.8	99.9	3.4	3.3	lung	793	791	356	412	2.8	5.5
					cord	1984	1881				
prostate #1	99.3	99.6	4.1	2.8	rectum	2959	2773	597	581	2.5	5.1
					bladder	3531	3758				
					femoral heads	2482	2560				
prostate #2	99.8	100	2.3	1.9	rectum	1642	1591	571	642	2.0	3.6
					bladder	507	500				
					femoral heads	974	1006				
partial brain (GBM) #1	98.9	99.5	4.0	3.6	brainstem	1906	1955	252	278	2.4	6.1
					chiasm	554	549				
partial brain (GBM) #2	100	100	2.0	1.7	brainstem	3053	3162	244	273	2.1	3.7
					chiasm	710	694				
pancreas	98.7	99.1	4.0	3.6	liver	1676	1709	363	470	2.6	3.8
					RT kidney	1923	1789				
					cord	3158	3030				

No significant difference

92% increase in delivery time

- Single arc is preferable for relatively simple cases

Head-&-Neck Case (I)

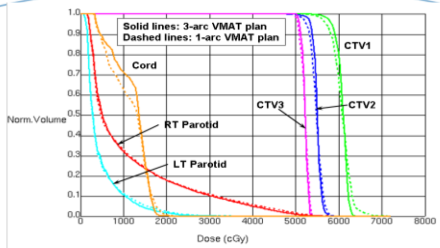


Single-Arc

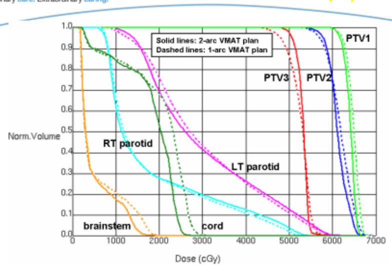
Three-arc

- The single-arc plan has a total of 175 control points.
- The three-arc plan has 35 control points per arc (105 total).

Head-&-Neck Case (I)



Head-&-Neck Case (II)



Summary of More Complex Cases

Treatment site	V95 (%)		σPTV (cGy/fraction)		OAR mean/max dose (cGy)			MU/fraction		Delivery time (minute)	
	1 arc	multi-arc	1 arc	multi-arc	OAR	1 arc	multi-arc	1 arc	multi-arc	1 arc	multi-arc
pelvis	98.2	99.2	6.3	4.4	rectum	1747	1732	564	728	2.5	4.4
					bladder	2909	2849				
					femoral heads	1886	1952				
H & N #1	97.8	99.2	5.4	4.2	LT parotid	461	441	439	498	4.9	5.6
					RT parotid	1104	1094				
					cord	2173	2271				
H & N #2	95.6	98.8	7.3	5.2	LT parotid	3037	3011	507	577	2.5	3.7
					RT parotid	1796	1817				
					cord	3072	2723				
					brainstem	2050	1932				
H & N #3	97.2	98.9	6.8	5.4	LT parotid	1638	1607	400	481	4.8	5.4
					RT parotid	5232	5311				
					cord	3362	3644				
					brainstem	3495	3229				

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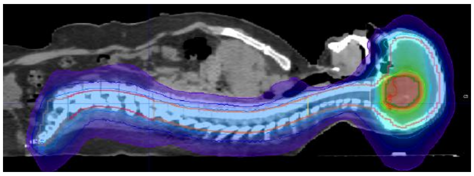
Tomotherapy – Complex Irradiations



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Tomotherapy Developments

- With the HiArt system, the jaw width and the couch speed are set to constant values for each plan.
- A new option with dynamic jaw motion and dynamic couch motion (TomoEDGE) is now available that should improve the efficiency of delivery and the quality of the plans.

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ELSEVIER

Int. J. Radiation Oncology Biol. Phys., Vol. ■, No. ■, pp. 1–8, 2009

0360-3016/09/$–see front matter

doi:10.1016/j.ijrobp.2009.07.1686

PHYSICS CONTRIBUTIONS

DYNAMIC JAWS AND DYNAMIC COUCH IN HELICAL TOMOTHERAPY

Florian Sterzing, M.D.,* Matthias Uhl, M.D.,* Henrik Hauswald, M.D.,* Kai Schubert, Ph.D.,* Gabriele Sroka-Perez, Ph.D.,* Yu Chen, Ph.D.,† Weiguo Lu, Ph.D.,† Rock Mackie, Ph.D.,† Jürgen Debus, M.D., Ph.D.,* Klaus Herfarth, M.D.,* and Gustavo Oliveira, Ph.D.†

*Department of Radiation Oncology, University of Heidelberg, Germany; and †Tomotherapy Incorporated, Madison, Wisconsin

- DJ/DC couch plans were developed for 10 nasopharyngeal patients.
- As compared with a 2.5 cm fixed jaw setting, the mean integral dose was reduced by 6.3% and the average delivery time was reduced by 66%.

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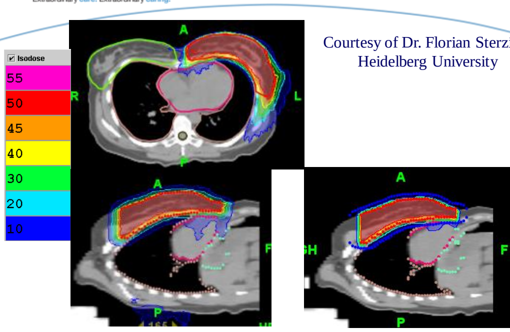
Breast Cancer and Funnel Chest

Courtesy of Dr. Florian Sterzing, Heidelberg University



treatment time **regular 2.5** 12 minutes → **Djdc 5**: 3.5 minutes

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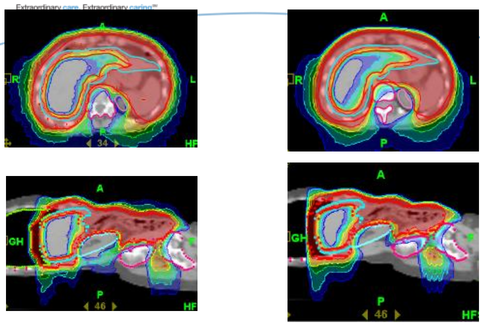
Whole Abdominal Irradiation



treatment time **regular 2.5cm** 17 minutes → **Dynamic jaw Dynamic Couch 5cm:** 5.5 minutes

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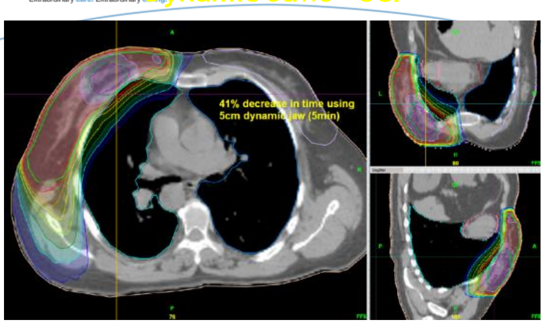
Dynamic Jaws - SCI



- Delivery time reduced from 8.5 to 5 minutes.

Recent VMAT Developments

- **Flattening filter free (FFF) VMAT**
- **Gated VMAT**

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Flattening Filter Free (FFF)

- Varian TrueBeam accelerators offer FFF delivery.
- When the filter is removed from the photon beam, the intensity increases by a factor of 2 for 6 MV photons and by a factor of 4 for 10 MV.
- Using FFF mode, the dose rate increases from 6 Gy/min to 14 Gy/min for 6 MV and 24 Gy/min for 10 MV beams.

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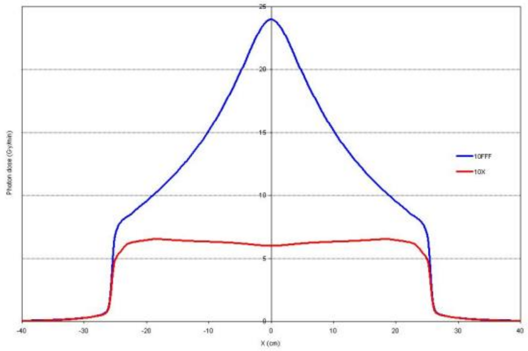

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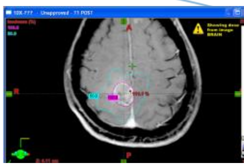
Oligometastatic Melanoma

4 brain mets
6 Gy x 5 (frameless)
Conformity index 1.2 (average)
10X FFF @ 2400 MU/minute, RapidArc
Treatment time= 61 seconds



Pink = 100% (6 Gy), light blue = 50% (3 Gy)

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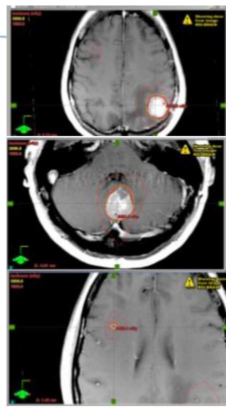
Metastatic Breast Cancer

- 3 tumors
- 6 Gy x 5 fractions
- 2 arcs (axial and vertex)
- 10X FFF (2400 MU/min)
- 3536 MU
- Treatment time 3:12
- Beam time 1:50



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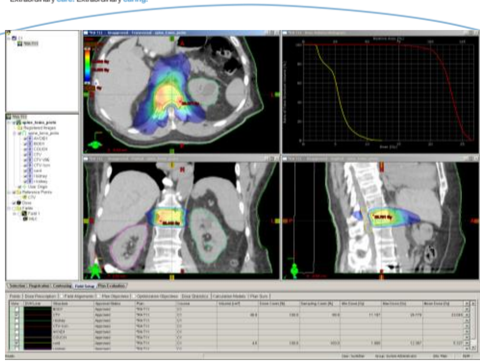

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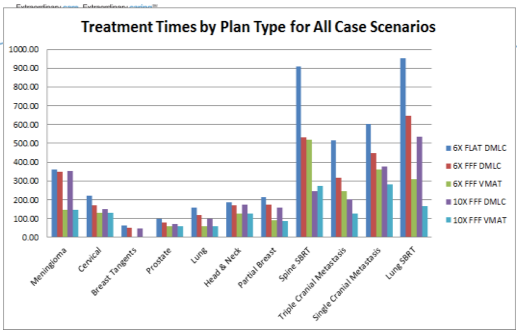

E. Thomas, JB Fiveash, RA Popple, manuscript in preparation. ISRS 2010

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Gated VMAT

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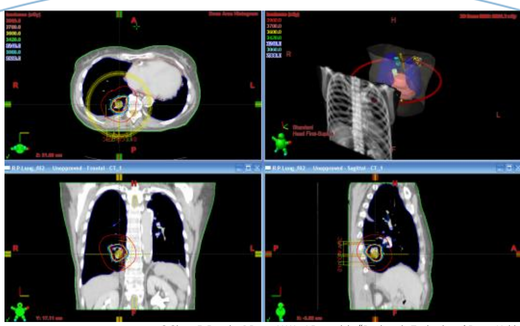

S Shen, R Popple, J Duan, X Wu, I Brezovich, "Dosimetric Evaluation of Beam-Hold Interruption in Respiratory Gated RapidArc Delivery," AAPM 2011 meeting SU-E-T-517

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Elekta VersaHD

- VersaHD received FDA approval April 2013
- Includes FFF and gated delivery capabilities.
- Elekta Response FDA approved in August 2013

Table 1 Lung cases (6 patients): Plan comparison between fixed-field IMRT, VMAT and HT

	IMRT	VMAT	HT	Wilcoxon matched-pair signed rank test *p*
PTV				
V95 (%)	98.5 (95.0–100)	98.5 (95.0–100)	98.0 (91.7–100)	0.375
SD (Gy)	1.4 (0.7–2.1)	1.6 (0.8–2.5)	1.5 (0.7–3.2)	0.438
Lung				
D_{mean} (Gy)	9.8 (2.0–17.5)	10.0 (2.2–18.0)	10.0 (2.3–17.0)	0.844
V_{20Gy} (%)	15.3 (4.5–28.3)	15.4 (4.9–28.8)	15.8 (3.8–30.0)	0.625
Cord				
D_{max} (Gy)	19.8 (4.7–39.2)	19.9 (4.1–42.2)	19.9 (3.8–41.8)	0.563
D_{mean} (Gy)	5.6 (1.0–15.4)	5.7 (1.6–15.8)	5.3 (1.8–11.6)	0.844
Total body				
D_{mean} (Gy)	3.9 (1.0–9.0)	4.0 (1.3–9.3)	4.2 (1.3–8.7)	0.563
MU per fraction	569 (340–1108)	476 (348–904)	-	-
Delivery time (minutes)	7.9 (6.3–9.5)	2.1 (2.0–2.3)	5.4 (3.4–10.0)	0.031
QA passing rate (%)	99.3 (99.2–99.4)	99.0 (98.6–99.5)	99.6 (99.5-99.7)	-

Abbreviations: PTV = planning target volume; V95 = volume of PTV receiving 95% of prescription; SD = standard deviation of PTV dose; V_{nGy} = volume of structure receiving ≥ nGy. QA passing rate was obtained using gamma analysis with 3 mm/3% limit. Values expressed as mean (range). The Wilcoxon matched-pair signed rank test is listed for VMAT vs. HT.

Table 2 Prostate cases (6 patients): Plan comparison between fixed-field IMRT, VMAT and HT

	IMRT	VMAT	HT	Wilcoxon matched-pair signed rank test *p*
PTV				
V95 (%)	98.5 (97.3–99.7)	98.7 (97.3–99.7)	98.3 (96.2–99.8)	0.063
SD (Gy)	1.0 (0.7–1.3)	1.0 (0.6–1.4)	1.2 (0.5–1.6)	0.688
Rectum				
D_{max} (Gy)	56.7 (45.0–69.1)	56.1 (45.1–67.1)	57.3 (45.0–71.0)	0.156
D_{mean} (Gy)	25.7 (15.6–38.8)	24.5 (17.7–31.4)	26.5 (15.3–39.3)	0.688
$D_{20\%}/D_{pres}$ (%)	47.2 (27.2–87.9)	48.0 (27.2–88.6)	47.9 (27.2–91.8)	1.000
Bladder				
D_{max} (Gy)	58.0 (46.8–69.5)	57.4 (46.6–70.4)	58.6 (46.1–70.3)	0.438
D_{mean} (Gy)	20.1 (5.4–28.6)	19.9 (5.1–29.1)	20.5 (5.6–28.2)	0.219
Femoral head				
D_{max} (Gy)	25.5 (16.2–41.6)	24.3 (15.4–41.4)	25.6 (16.1–42.4)	0.031
D_{mean} (Gy)	16.5 (10.1–30.1)	16.7 (9.7–33.9)	16.1 (11.2–28.8)	0.844
Total body				
D_{mean} (Gy)	4.6 (3.3–8.1)	4.8(3.3–8.6)	4.9 (3.6–8.4)	0.313
MU per fraction	639 (595–731)	549 (449–603)	-	-
Delivery time (minutes)	8.1 (7.9–8.6)	2.2 (1.9–2.7)	4.0 (3.1–4.9)	0.031
QA passing rate (%)	98.5 (97.6–99.3)	98.9 (98.5–99.5)	99.9 (99.9-99.9)	-

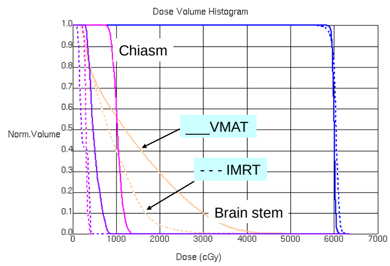
Abbreviations: $D_{n\%}$ = minimal dose to n% of structure, D_{pres} = prescription to PTV; other abbreviations as in Table 1. Values expressed as mean (range). The Wilcoxon matched-pair signed rank test is listed for VMAT vs. HT.

Table 3 HN cases (6 patients): Plan comparison between fixed-field IMRT, VMAT and HT

	IMRT	VMAT	HT	Wilcoxon matched-pair signed rank test *p*
PTV				
V95 (%)	98.3 (96.7–99.6)	98.6 (97.1–99.7)	98.9 (98.4–99.7)	0.625
SD (Gy)	1.6 (1.4–1.7)	1.6 (0.9–2.1)	1.5 (1.1–2.0)	0.844
Spinal cord				
D_{max} (Gy)	26.8 (18.1–36.6)	27.3 (20.8–39.9)	28.0 (14.4–34.4)	1.000
D_{mean} (Gy)	13.2 (9.5–20.8)	13.3 (8.5–23.6)	11.7 (8.6–16.4)	0.438
Parotid				
D_{max} (Gy)	47.8 (27.3–61.6)	46.6 (25.3–62.6)	48.5 (26.8–65.9)	0.156
D_{mean} (Gy)	19.0 (13.0–24.8)	17.9 (12.6–24.8)	16.5 (10.5–22.8)	0.094
Brain stem				
D_{max} (Gy)	30.4 (13.7–42.7)	30.6 (16.0–47.0)	31.1 (6.3–46.4)	0.844
D_{mean} (Gy)	11.4 (2.3–18.9)	11.3 (2.7–20.2)	9.8 (1.8–19.0)	0.031
Total body				
D_{mean} (Gy)	9.9 (5.3–18.1)	9.7 (5.5–17.2)	10.0 (5.7–18.0)	0.156
MU per fraction	777 (607–1229)	620 (495–683)	-	-
Delivery time (minutes)	11.1 (10.9–12.4)	4.6 (3.7–6.0)	7.0 (6.0–9.1)	0.031
QA passing rate (%)	97.7 (96.1–99.3)	98.3 (96.0–99.8)	99.3 (99.0-99.6)	-

Values expressed as mean (range). The Wilcoxon matched-pair signed rank test is listed for VMAT vs. HT.

Case#2 Partial Brain: effect of couch kick



• IMRT plan spares more Brain Stem and Chiasm.

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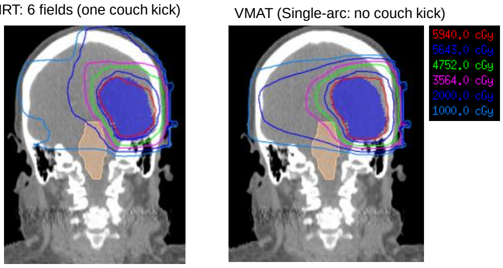
Case#2 Partial Brain: effect of couch kick

Coronal View

IMRT: 6 fields (one couch kick)

VMAT (Single-arc: no couch kick)



• IMRT plan spares more brain stem and chiasm.

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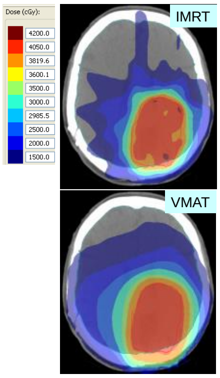
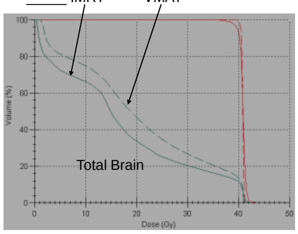
Case#1 Partial Brain: Low dose volume



_____ IMRT - - - - VMAT



- VMAT ↑ better target dose uniformity
- IMRT ↓ volume receiving a low dose.

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