Overview of IMRT and Arc-Based Techniques

David Shepard
AAPM Annual Meeting - Austin
July 21, 2014

The Beginnings of IMRT


IMRT

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

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

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.

Clinical Example

Dose coverage is virtually identical with compensator- or MLC-modulation.
Compensators - Advantages

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

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.

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.

Confidential Information

ViewRay

System Components
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.

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.
Sliding Window

- Advantages
  - Does not suffer from intersegment delay time.

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

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%

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

Lung SBRT

Dong et al. JROBP 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

Automated 4p delivery

6x speed playback, delivery time <10 minutes

IMRT Delivery Techniques

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

Fixed field
Rotational
## Why rotational delivery?

C-shaped Target Simulations

<table>
<thead>
<tr>
<th># Angles</th>
<th>Obj. Funct. Value</th>
<th>Std. Dev. in target dose</th>
<th>d$_{90}$</th>
<th>Mean dose to RAR</th>
<th>Total integral dose</th>
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<td>2543.5</td>
</tr>
</tbody>
</table>

![Images of C-shaped Target Simulations](image)
Tomotherapy: A new concept for the delivery of dynamic conformal radiotherapy

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.

The text is from a paper titled "Tomotherapy: A new concept for the delivery of dynamic conformal radiotherapy" by T. Rock, M. A. Zois, T. S. Swartz, P. W. S. Baker, and J. O. Bears. The paper includes images and diagrams illustrating the concept of Tomotherapy.
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
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.
Prostate Treatment - Movie

Tomotherapy Treatments

<table>
<thead>
<tr>
<th>SRS/SRT</th>
<th>SBRT</th>
<th>TBI/TMI</th>
<th>Craniospinal</th>
</tr>
</thead>
</table>

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 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
Helical IMRT - Disadvantages

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

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.
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.

**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
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.

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

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

Example 2: Spinal Ependymoma

5 arc treatments

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.
We developed two IMAT inverse planning approaches:

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.
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
Vancouver Cancer Centre, BC Cancer Agency, Vancouver, British Columbia V5Z 4H4, Canada
(Received 23 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 adaption have resulted in an increase in overall treatment times. Intensity-modulated radiation therapy (IMRT) has also increased treatment time by requiring a large 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°. The technique is similar to tomotherapy in that a full 360° of beam directions are available for optimization but is fundamentally different in that the entire dose volume is delivered in a single gantry rotation. The new technique is referred to as volumetric modulated arc therapy (VMAT). Multifield collimation (MLC) leaf motion and number of MUs per

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

Head & Neck Case #1

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

<table>
<thead>
<tr>
<th></th>
<th>IMRT</th>
<th>VMAT</th>
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<tbody>
<tr>
<td>Delivery Efficiency</td>
<td>Slow 😞</td>
<td>Fast 😊</td>
</tr>
<tr>
<td>MU efficiency</td>
<td>Low 😞</td>
<td>High 😊</td>
</tr>
<tr>
<td>Planning Time?</td>
<td>Short 😞</td>
<td>Long 😊</td>
</tr>
<tr>
<td>Constraints</td>
<td>Fewer 😞</td>
<td>More 😞</td>
</tr>
</tbody>
</table>

Fixed Field IMRT-VS-VMAT
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.

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

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 continue to change.
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

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.
Cylindrical phantom delivery

Arc Sequencer

- Algorithm that converts optimized fluence maps into deliverable IMAT plans:
  1. A step-and-shoot treatment plan is created in the Pinnacle 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 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 $51 \times 64 = 3,264$ 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.

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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

---

Helical Delivery

**Fusion of a Linear Accelerator and a Helical CT Scanner**

![Diagram of Helical Delivery](image)
Treatment Geometry Overview:

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

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

Under the Covers

- Gun Board
- Linac
- Circulator
- Magnetron
- Pulse Forming Network and Modulator
- Data Acquisition System
- High Voltage Power Supply
- Beam Stop
- Detector
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

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 Cseko 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

Inverse planning for intensity modulated arc therapy using direct aperture optimization

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

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

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

**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”

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...

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

IMAT Delivery: C-shaped Target

From Cedric Yu

IMAT - advantages

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

- $$$
- No patients treated yet.

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

Dynamic MLC

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

Why Helical?

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

Helical Delivery Benefit:
Resolution over width

Pitch = 1

Single "beam" with 5 "beamlets"

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
Helical Delivery Benefit: Resolution over length

Pitch = 0.5

Single “beam” with 5 “beamlets”

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

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.
Single vs. Multiple Arc VMAT

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).

- 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.
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

<table>
<thead>
<tr>
<th>Treatment</th>
<th>V95 (%)</th>
<th>V90 (%)</th>
<th>CTV coverage</th>
<th>OAR avoidance</th>
<th>Delivery time</th>
</tr>
</thead>
<tbody>
<tr>
<td>single arc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>two arc</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tbody>
</table>

No significant difference
92% increase in delivery time

Single arc is preferable for relatively simple cases

Head-&-Neck Case (I)

- The single-arc plan has a total of 175 control points.
- The three-arc plan has 35 control points per arc (105 total).
The average V95 are 97.6% and 98.8% for the single-arc and three-arc plans, respectively. Delivery times are 4.9 and 5.63 minutes for the single-arc and three-arc plans, respectively.

Summary of More Complex Cases

- Better target dose coverage
- Better target dose uniformity
- 30% increase in delivery time
- Multiple arcs can provide better target dose coverage with less compromise in delivery efficiency for more complex cases.
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.

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%. 

**PhysicaL Contributions**

**DYNAMIC JAWS AND DYNAMIC COUCH IN HELICAL TOMOTHERAPY**

Florent Steinzig, M.D.,* Matthias Uhl, M.D.,* B. Heiko Haag, M.D.,* Kai Stober, Ph.D.,* Gabriele Scholz-Penz, Ph.D.,* Yo-Chin, Ph.D.,* Whang Le, Ph.D.,* R. Michael, Ph.D.,* Jurgen Diers, M.D., Ph.D.,* Klaus Heywang, M.D.,* and Gustavo Oliveira, Ph.D.†

*Department of Radiation Oncology, University of Heidelberg, Germany, and †Tomotherapy Incorporated, Madison, Wisconsin
Breast Cancer and Funnel Chest

Courtesy of Dr. Florian Sterzing, Heidelberg University

<table>
<thead>
<tr>
<th>Treatment Time</th>
<th>Regular 2.5cm</th>
<th>Dynamic Jaw Dynamic Couch 5cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12 minutes</td>
<td>3.5 minutes</td>
</tr>
</tbody>
</table>

Whole Abdominal Irradiation

<table>
<thead>
<tr>
<th>Treatment Time</th>
<th>Regular 2.5cm</th>
<th>Dynamic Jaw Dynamic Couch 5cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17 minutes</td>
<td>5.5 minutes</td>
</tr>
</tbody>
</table>

Dynamic Jaws - SCI

Delivery time reduced from 8.5 to 5 minutes.
Recent VMAT Developments

- Flattening filter free (FFF) VMAT
- Gated VMAT

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.
**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)

---

**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

Entire Procedure < 15 minutes
Gated VMAT

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

Gated VMAT

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

<table>
<thead>
<tr>
<th></th>
<th>IMRT</th>
<th>VMAT</th>
<th>HT</th>
<th>Wilcoxon matched-pair signed rank test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V95 (%)</td>
<td>V95 (%)</td>
<td>V95 (%)</td>
<td>V95 (%)</td>
</tr>
<tr>
<td>PTV</td>
<td>96.5 (95.0-100)</td>
<td>96.5 (95.0-100)</td>
<td>96.0 (97-100)</td>
<td>0.375</td>
</tr>
<tr>
<td>SD (0.5)</td>
<td>1.4 (0.7-2.1)</td>
<td>1.6 (0.8-2.3)</td>
<td>1.5 (0.7-3.2)</td>
<td>0.438</td>
</tr>
<tr>
<td>Lung</td>
<td>9.8 (2.0-17.5)</td>
<td>10.0 (2.2-18.0)</td>
<td>10.0 (2.3-17.0)</td>
<td>0.844</td>
</tr>
<tr>
<td>Vmean (Gy)</td>
<td>15.3 (4.5-28.3)</td>
<td>15.4 (4.9-28.8)</td>
<td>15.8 (3.8-30.0)</td>
<td>0.625</td>
</tr>
<tr>
<td>Cord</td>
<td>19.8 (6.7-39.2)</td>
<td>19.9 (4.1-42.2)</td>
<td>19.9 (3.8-41.8)</td>
<td>0.563</td>
</tr>
<tr>
<td>D95 (Gy)</td>
<td>5.6 (1.0-15.4)</td>
<td>5.7 (1.6-15.8)</td>
<td>5.3 (1.8-11.6)</td>
<td>0.844</td>
</tr>
<tr>
<td>Total body</td>
<td>3.9 (1.0-9.0)</td>
<td>4.0 (1.3-9.3)</td>
<td>4.2 (1.3-8.7)</td>
<td>0.563</td>
</tr>
<tr>
<td>MU (per fraction)</td>
<td>569 (340-1108)</td>
<td>476 (348-904)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Delivery time (minutes)</td>
<td>7.9 (6.3-9.5)</td>
<td>2.1 (2.0-2.3)</td>
<td>5.4 (3.4-10.0)</td>
<td>0.031</td>
</tr>
<tr>
<td>QA passing rate (%)</td>
<td>99.3 (99.2-99.4)</td>
<td>99.0 (98.6-99.5)</td>
<td>99.6 (99.5-99.7)</td>
<td>-</td>
</tr>
</tbody>
</table>

Abbreviations: PTV = planning target volume; V95 = volume of PTV receiving 95% of prescription; SD = standard deviation of PTV dose; Vmean = volume of structure receiving X Gy; 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

<table>
<thead>
<tr>
<th></th>
<th>IMRT</th>
<th>VMAT</th>
<th>HT</th>
<th>Wilcoxon matched-pair signed rank test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V95 (%)</td>
<td>V95 (%)</td>
<td>V95 (%)</td>
<td>V95 (%)</td>
</tr>
<tr>
<td>PTV</td>
<td>99.5 (97.3-99.7)</td>
<td>98.7 (97.3-99.7)</td>
<td>98.3 (96.2-99.8)</td>
<td>0.653</td>
</tr>
<tr>
<td>SD (0.5)</td>
<td>1.0 (0.7-1.3)</td>
<td>1.0 (0.6-1.6)</td>
<td>1.2 (0.7-1.6)</td>
<td>0.048</td>
</tr>
<tr>
<td>Rectum</td>
<td>56.7 (45.0-69.1)</td>
<td>56.1 (45.1-67.1)</td>
<td>57.3 (45.8-71.0)</td>
<td>0.156</td>
</tr>
<tr>
<td>D95 (Gy)</td>
<td>24.5 (17.7-31.4)</td>
<td>26.3 (15.3-30.3)</td>
<td>26.9 (16.9-34.6)</td>
<td>0.048</td>
</tr>
<tr>
<td>Ddseg (Gy)</td>
<td>47.2 (27.2-57.9)</td>
<td>48.6 (27.2-58.6)</td>
<td>47.5 (27.2-91.4)</td>
<td>1.000</td>
</tr>
<tr>
<td>Bladder</td>
<td>58.0 (46.8-58.5)</td>
<td>57.4 (46.6-78.4)</td>
<td>58.6 (46.4-76.3)</td>
<td>0.438</td>
</tr>
<tr>
<td>Ddseg (Gy)</td>
<td>20.1 (15.1-26.1)</td>
<td>18.9 (15.1-20.1)</td>
<td>20.7 (15.4-26.2)</td>
<td>0.119</td>
</tr>
<tr>
<td>Femoral head</td>
<td>25.5 (16.2-61.6)</td>
<td>24.3 (15.4-41.4)</td>
<td>25.6 (16.1-42.4)</td>
<td>0.033</td>
</tr>
<tr>
<td>Ddseg (Gy)</td>
<td>16.5 (10.1-30.1)</td>
<td>16.7 (9.7-33.9)</td>
<td>16.1 (11.1-28.3)</td>
<td>0.844</td>
</tr>
<tr>
<td>Total body</td>
<td>4.6 (3.3-8.1)</td>
<td>4.8 (3.3-8.1)</td>
<td>4.9 (3.4-8.1)</td>
<td>0.313</td>
</tr>
<tr>
<td>MU (per fraction)</td>
<td>639 (595-731)</td>
<td>549 (469-603)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Delivery time (minutes)</td>
<td>8.1 (7.8-8.6)</td>
<td>2.2 (1.9-2.7)</td>
<td>4.0 (3.3-4.9)</td>
<td>0.031</td>
</tr>
<tr>
<td>QA passing rate (%)</td>
<td>98.5 (97.3-99.3)</td>
<td>98.9 (95.5-99.5)</td>
<td>99.0 (99.0-99.9)</td>
<td>-</td>
</tr>
</tbody>
</table>

Abbreviations: Ddseg = minimal dose to 5% of structure; Ddseg = 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 IN cases (6 patients): Plan comparison between fixed-field IMRT, VMAT and HT

<table>
<thead>
<tr>
<th></th>
<th>IMRT</th>
<th>VMAT</th>
<th>HT</th>
<th>Wilcoxon matched-pair signed rank test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>V95 (%)</td>
<td>98.3 (96.7–99.6)</td>
<td>98.6 (97.1–99.7)</td>
<td>98.9 (98.4–99.7)</td>
<td>0.625</td>
<td></td>
</tr>
<tr>
<td>SD (Gy)</td>
<td>1.6 (1.4–1.7)</td>
<td>1.6 (0.9–2.1)</td>
<td>1.5 (0.1–2.9)</td>
<td>0.844</td>
<td></td>
</tr>
<tr>
<td>Spinal cord D95 (Gy)</td>
<td>26.8 (18.1–36.6)</td>
<td>27.3 (20.8–39.9)</td>
<td>28.0 (14.4–34.4)</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>Dmean (Gy)</td>
<td>13.2 (9.5–20.8)</td>
<td>13.3 (8.5–25.6)</td>
<td>11.7 (8.6–16.6)</td>
<td>0.438</td>
<td></td>
</tr>
<tr>
<td>Brain stem D95 (Gy)</td>
<td>47.8 (27.3–61.6)</td>
<td>46.6 (23.3–62.6)</td>
<td>48.3 (26.8–65.9)</td>
<td>0.156</td>
<td></td>
</tr>
<tr>
<td>Dmean (Gy)</td>
<td>19.9 (13.0–24.8)</td>
<td>17.9 (11.8–24.8)</td>
<td>16.5 (10.3–21.8)</td>
<td>0.094</td>
<td></td>
</tr>
<tr>
<td>Total body D95 (Gy)</td>
<td>36.4 (23.5–42.7)</td>
<td>36.0 (16.9–47.0)</td>
<td>31.1 (6.3–46.4)</td>
<td>0.844</td>
<td></td>
</tr>
<tr>
<td>Dmean (Gy)</td>
<td>11.4 (2.3–18.9)</td>
<td>11.3 (2.7–20.2)</td>
<td>9.8 (1.8–19.0)</td>
<td>0.031</td>
<td></td>
</tr>
<tr>
<td>MU per fraction</td>
<td>777 (607–1120)</td>
<td>620 (495–683)</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Delivery time (min)</td>
<td>11.1 (10.9–12.6)</td>
<td>4.6 (3.7–6.0)</td>
<td>7.6 (4.0–9.3)</td>
<td>0.031</td>
<td></td>
</tr>
<tr>
<td>QA passing rate (%)</td>
<td>97.7 (96.1–99.3)</td>
<td>98.3 (94.0–99.8)</td>
<td>99.3 (99.0–99.6)</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

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.

Case 2 Partial Brain: effect of couch kick

- IMRT plan spares more Brain stem and Chiasm.
Case#1 Partial Brain: Low dose volume

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