Intensity Modulated Arc Therapy
Principles and Perspectives

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Conflict Disclosure

- Advisory Council on Advanced Treatment Delivery, Varian Medical Systems, Inc.
- Patent License:
  - Varian: Single arc dose painting
  - Prowess & Varian: Direct Aperture Optimization
- Board of Directors, Prowess, Inc.

Rotational IMRT


Arc therapy


Dynamic Arc therapy

- Takahashi S. “Conformation Radiotherapy, rotation techniques as applied to radiography and radiotherapy of cancer”. Acta Radiol Suppl 142, 1965
  - Introduces conformal therapy: MLC-shaped fields matches the beams-eye-view of target
  - Describes conformal arc therapy using MLC to outline the tumour through 360° rotation.

IMRT

- Development of MLC around 1990
- Convery and Rosenbloom, 1993
- Bortfeld & Boyer, Yu et al, 1994
The Peacock System


Nomos Peacock System

IMRT

- Development of MLC around 1990
- Convery and Rosenbloom, 1993
- Bortfeld & Boyer, Yu & Wong, 1994

IMRT Delivery

- NOMOS MIMiC delivery technique at Baylor College of Medicine, Houston Texas in March 1994.
- The first dMLC treatments were those at Memorial Sloan Kettering Cancer Institute and Hospital starting in April 1996.
- By 2000 commercial MLC/Linac manufacturers had made available sMLC and dMLC technique linked to inverse planning;
- In 2004 the MIMiC has still delivered the most IMRT but the MLC techniques are catching up;

Rotational IMRT


Commercial Tomotherapy System: 2002

What is IMAT?

- Take a NOMOS tomo plan, convert to 36 2D intensity maps
- Sequence the intensity maps to overlapping apertures
- Convert overlapping apertures into multiple arcs, and
- Deliver by arcing and dynamic MLC motion

Clinical Applications: Pre Single Arc IMAT


Publications on IMAT

- 173 publications on IMAT since 1995.
### Plan Quality and the Number of Beams

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<th>Obj. Funct. Value</th>
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### Works on single arc IMAT


### Commercial Adoption

- Varian first commercialized Otto’s VMAT with RapidArc
- Elekta Developed their single arc solution and called it VMAT
- Philips has recently announced their solution called SmartArc
- Other acronyms: AMAT (aperture modulated arc therapy), AMRT (arc-modulated radiation therapy)

### No.1 Principle of IMAT

"The DVHs or subsequently derived biological scores depend on the total number of strata, which is defined as the product of the number of beams and the intensity levels within each beam. As the number of beams increases, the number of intensity levels required to obtain optimal dose distribution should be reduced."


What matters is the total number of shape changes!

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### Multi-arc to Single arc

“As the speed of delivery and level of integration increases, the superior dose distributions and optimization of numerous beam angles will push IMRT toward intensity-modulated arc therapy paradigms.”

Converting multiple arcs to a single arc ...

Stacked -> Spaced

Same total number of strata (shape change), same plan quality

Stacked v.s. Spaced

Same number of apertures, same plan quality

Stack v.s. Spaced DVH

Observation:
Rotational IMRT is insensitive to small angular errors
Understanding Single Arc

- By using a large number (100+) of shape variations, intensity modulation is effectively achieved at the target level.
- It is, therefore, capable of achieving IMRT-like plan quality for simple as well as complex cases.

so,

Is it the same as 36 beam IMRT?
In principle: Yes.
In practice: No quite.

This picture ignored deliverability!

Delivery Requirements

- Neighboring shapes must be geometrically connected.
  - Because deliverability takes priority, shapes are forced to connect in the optimization process, leading to lower plan quality
- Dose rate has to vary in order to maintain (more or less) constant gantry speed.

What if I have a fast MLC and fast dose rate variation?

Static Planning for Dynamic Delivery

- All aperture shapes and weights are optimized at fixed angles
- At delivery, the shape is changing continuously, and the dose rate varies to deliver the MUs

Therefore, an optimized shape only appears at an instant, and the MUs for the aperture is delivered through different aperture shapes.

Continuous v.s. static beams

Static beam’s Ripple artifact
**Planning vs. Delivery**

*Calculated*

Planned as static beams

*Measured*

Delivered as continuous arc

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**Typical Cases – small differences**

- Finger-like artifacts
- Smooth isodose

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**Some Cases – noticeable Differences**

- Plan A

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**Some Cases – Large Differences**

- Plan B

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**Reason 1: Too much MLC movement**

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**Reason 2: Too Much Dose Rate Variation**
Large MLC motion and dose rate variation can cause:

Delivered ≠ Planned

Your machine can do it does not mean you should allow it!

Dose Rate Variation

- Not all machines support variable dose rate
- Large dose rate fluctuation can also lead to delivery errors
- Forcing all apertures to have the same weighting will degrade plan quality!

It would be nice if we could use constant dose rate without limiting the freedom.

Scheme: Similar to AM & FM radio

Observation: Rotational IMRT is insensitive to small angular error.

Proof of the idea

- Convert RapidArc Plan (variable dose rate) to Constant Dose Rate delivery
  1. Change even aperture spacing to variable aperture spacing
  2. Apertures with high weights occupy larger angular interval
  3. Limiting angle error to 5 degrees
  4. Re-write the control points for delivery

Converting VDR RA to CDR delivery

H&N 1

Converting VDR RA to CDR delivery

H&N 2
How does IMAT (single or multiple arcs) stack up against other IMRT methods?

(No trying to be fashionable)
Two Step Arc Planning

Results – Brain
Same objectives, same dose engine

Results – Lung

Results – H&N

Results – H&N 2

Results – Prostate
Compare IMAT and IMRT for 10 Cases

- Multiple arc IMAT wins every time, but not by much.
- Single arc IMAT performs better than 7-field IMRT in most of the cases.
  
  both single arc and multi-arc IMAT is homegrown

Compare RapidArc™ with Tomotherapy™

Helical tomotherapy vs. Varian RapidArc: A dosimetric comparison between two institutes

Yi Rong¹, Grace Tang², James Welsh¹, Majid Mohiuddin², Bhudatt Paliwal¹, Cedric Yu²

¹University of Wisconsin Cancer Center Riverview
²University of Maryland School of Medicine

Plan After Unblinding
Perform N delivery QAs for each site before going clinical.

Start with a simple site, generate an IMRT plan and an IMAT plan to build the team’s confidence.

Perform N delivery QAs for each site before going clinical.

For a given case, there are preferred angles and locations to aim the radiation to the target. There are many ways to take advantage of such angular and location preferences.

Tomotherapy or multi-arc IMAT are subject to less physical constraints. Theoretically, they have more freedom to obtain the optimal solution.

However, there are many solutions rival such optimal solutions.

IMAT in either single arc or multi arc form performs at least as well as 7-field IMRT.

Clinical Implementation

Same as IMRT implementation

For RapidArc or SmartArc, no new machine commissioning is required if the same planning system is used.

Start with a simple site, generate an IMRT plan and an IMAT plan to build the team’s confidence.

Perform N delivery QAs for each site before going clinical.

Dose Calculation

Calculation time is proportional to the number of beams with current algorithms.

Vendors are forced to make shortcuts.

Typical patient specific QA using a homogeneous phantom to compare the calculated and measured doses cannot catch dose calculation errors.

Must commission with inhomogeneous phantoms!

Monte-Carlo methods have been shown to out perform with large number of beams.
IMAT QA

IMAT involves gantry rotation, dMLC, and variable dose rate. Is it less reliable by default?
– Aperture shape change is enslaved to MUs, proven with dMLC IMRT.
– Both dose rate error and gantry speed error only cause angular errors, to which rotational delivery is known to be insensitive.
– Therefore, if a linac can delivery arc and dynamic IMRT, it can delivery IMAT reliably. (passing rates)

What is more likely to go wrong?
– MLC positioning accuracy
– If planning system is not from the linac vendor, be careful about large MLC travel and large dose rate variations
– Phantoms: MapCheck embedded phantoms or similar phantoms (fancy ones require more work and not as intuitive). 3%/3mm pass rate: ~95%
– Couch (stiffening bar) attenuation.

What we learnt?
• The geometric arrangement of the target and ORAs dictates angular and positional preferences.
• Large number of independent apertures are required to take advantage of “the geometry”.
• These apertures can be arranged in one arc, multiple arcs, or in a number of fixed fields: “All roads lead to Rome”.
• We have only seen improvements in efficiency, not plan quality, over the years.

Conclusion
• IMAT came a long way from Takahashi’s dynamic arc in 1965 to today’s single arc solutions.
• IMAT has been proven to improve efficiency without sacrificing quality for both simple and complex cases.
• The success lies in the large number of aperture variations (or quanta) and the increased freedom through dose rate or angular spacing variation.
• Plan with static beams may not accurately approximate dynamic delivery, if large MLC travel and dose rate fluctuations are allowed.
• Delivery is not less reliable than dynamic IMRT, but careful commissioning and regular QA is needed.