University of Maryland
Department of Radiation Oncology

Intensity Modulated Arc Therapy

History and Principles

Cedric Yu

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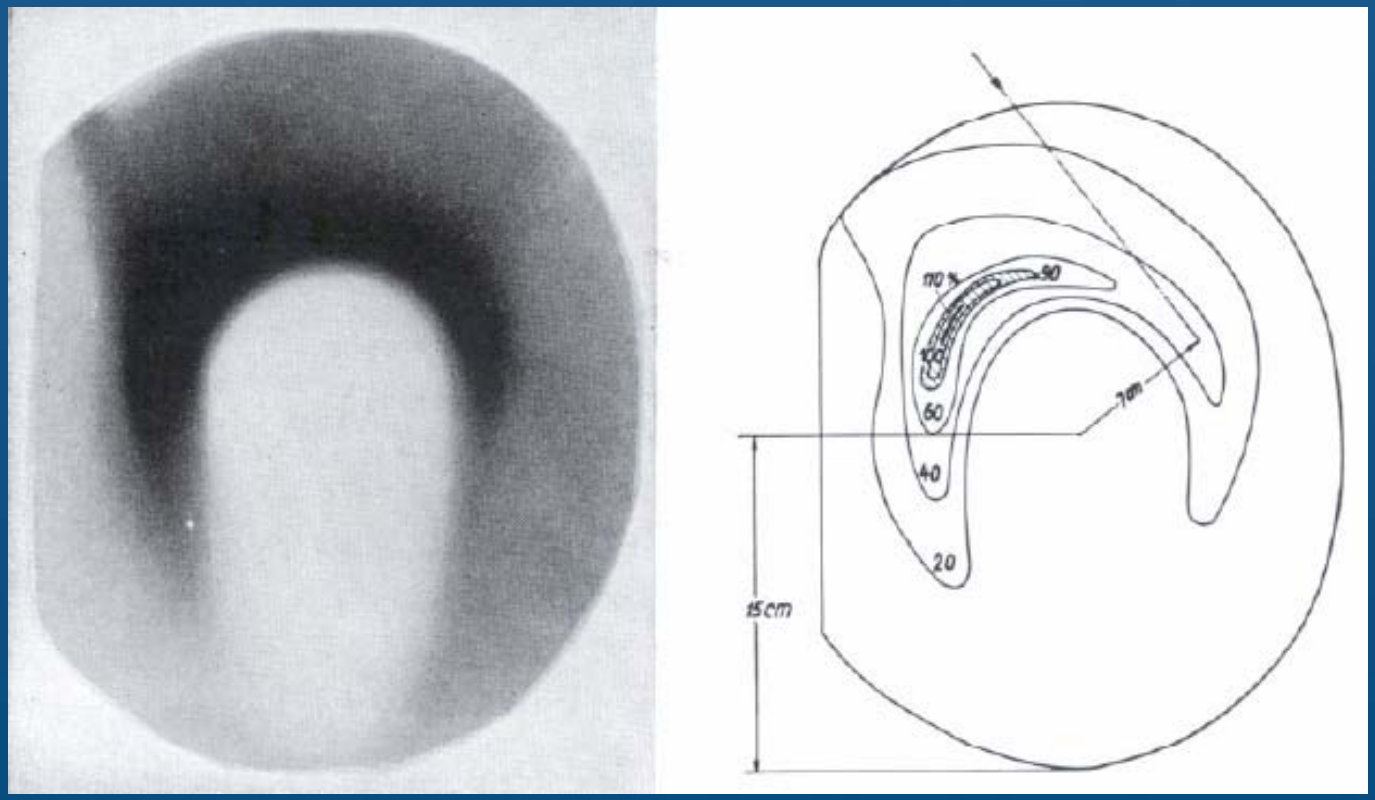
Arc therapy

Wachsman F and Barth G. Moving field radiation therapy. University of Chicago Press. Chicago 1962 1-265.



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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.

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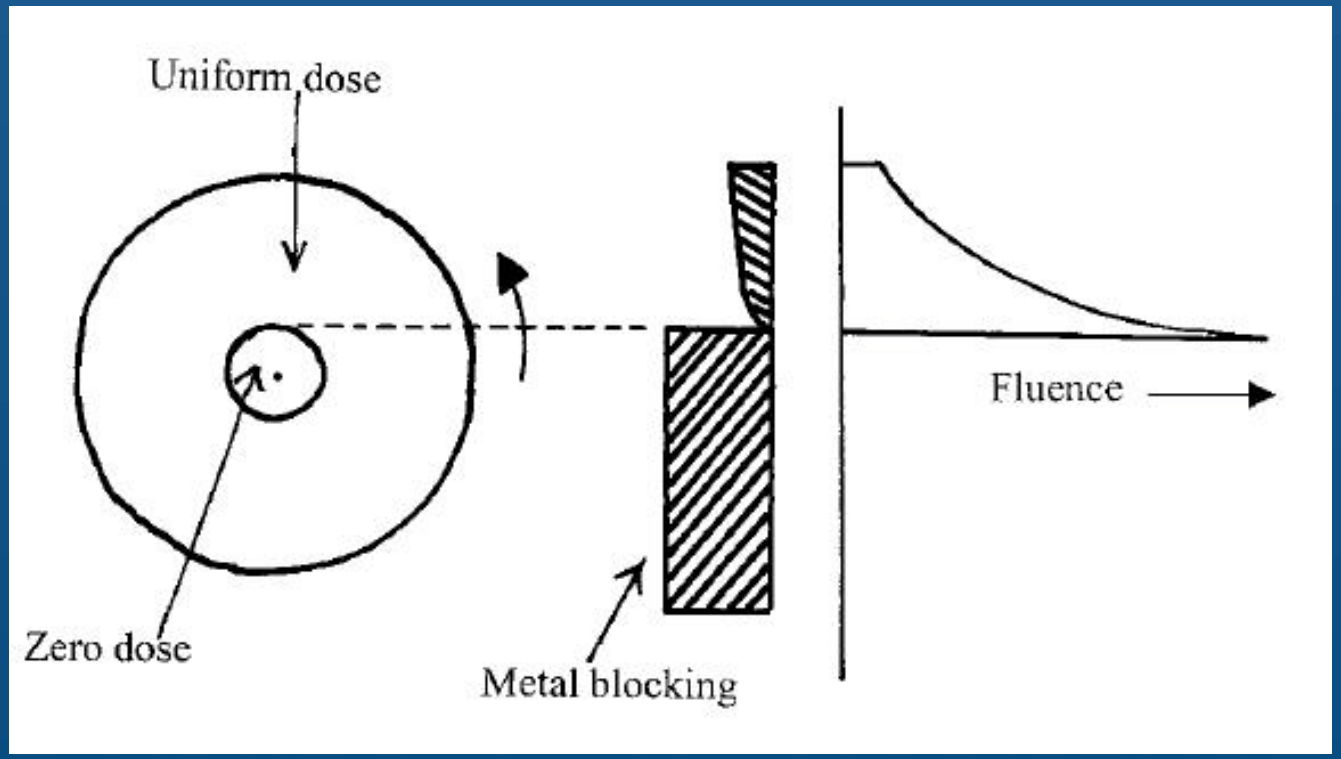
IMRT Inverse Planning

- Brahme A. Optimisation of stationary and moving beam radiation therapy techniques. Radiother Oncol 1988;12: 129–40.
- Webb S. Optimisation of conformal dose distributions by simulated annealing. Phys Med Biol 1989; 34:1349–69.

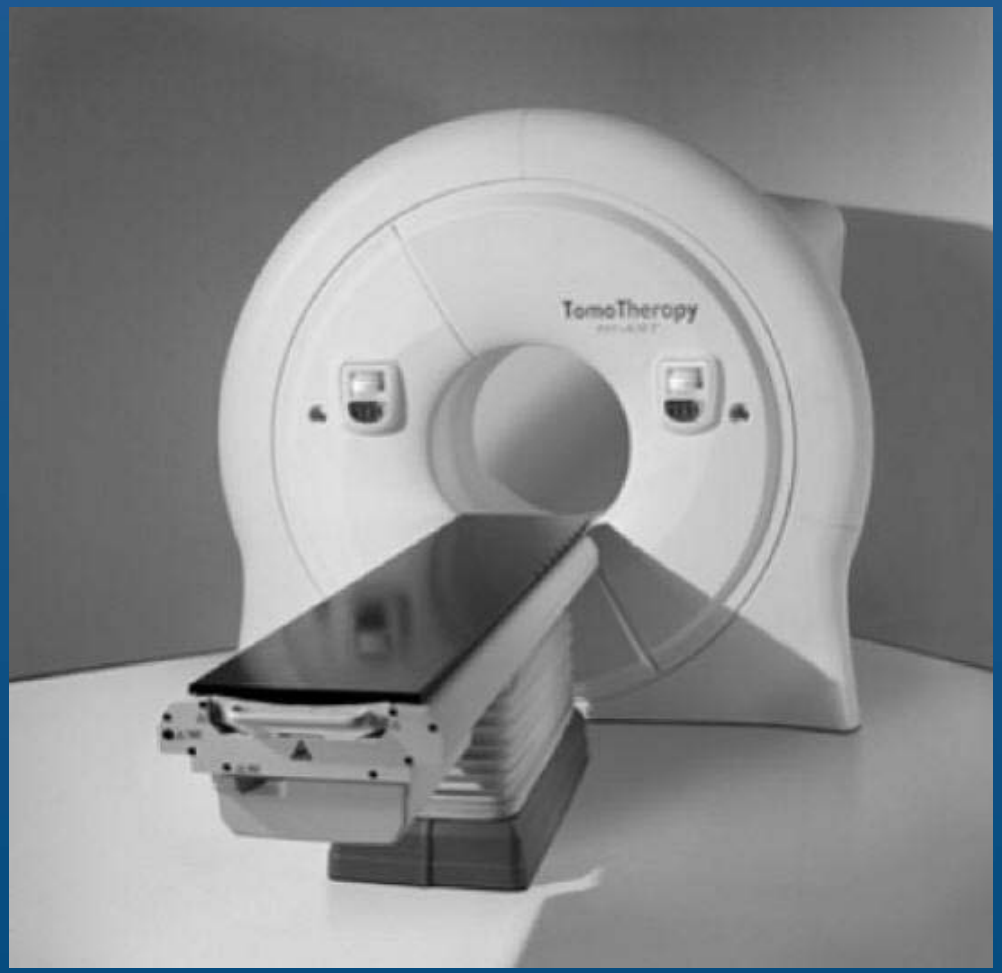
A Brahme, J E Roos and I Lax. Solution of an integral equation encountered in rotation therapy. Phys Med Biol, vol. 27, no. 10, pages 1221–9, 1982.



Rotational IMRT

- Brahme A, et al. "Solution of an integral equation encountered in rotation therapy". *Phys Med Biol*. **27** 1221-9, 1982
- Chin LM, et al. "Dose optimization with computer-controlled gantry rotation, collimator motion and dose-rate variation". *Int J Radiat Oncol Biol Phys*. **9** 723-9,1983.
- Mackie T R, et al: Tomotherapy: a new concept for the delivery of dynamic conformal radiotherapy. Med Phys 20(6): 1709-19,1993.
- M. Carol et al. "An automated 3D treatment planning and implementation system for optimised conformal therapy" in *Three-Dimensional Treatment Planning* (Liege: Minet) pp. 173-87,1993
- Yu, CX: Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy. Phys. Med. Biol., 40: 1435-49, 1995

Mackie T R, et al: Tomotherapy: a new concept for the delivery of dynamic conformal radiotherapy. Med Phys 20(6): 1709-19,1993



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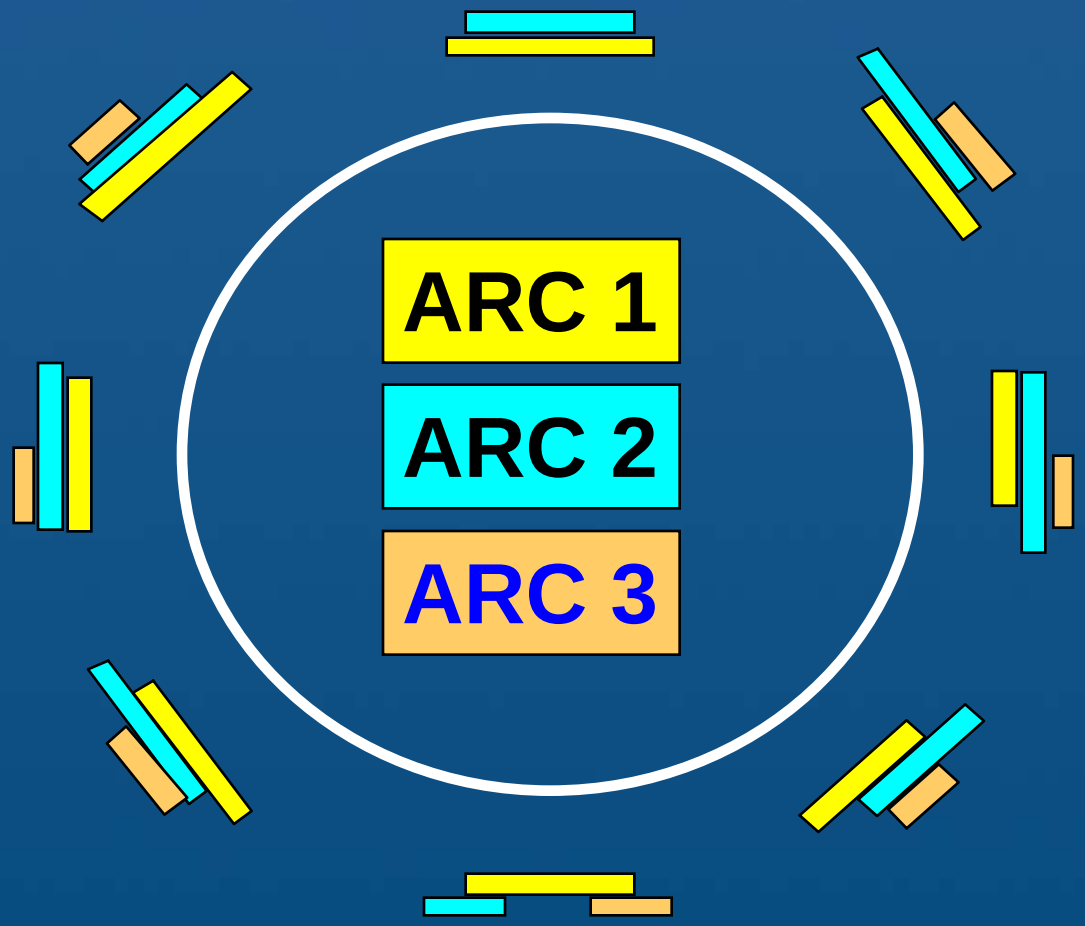
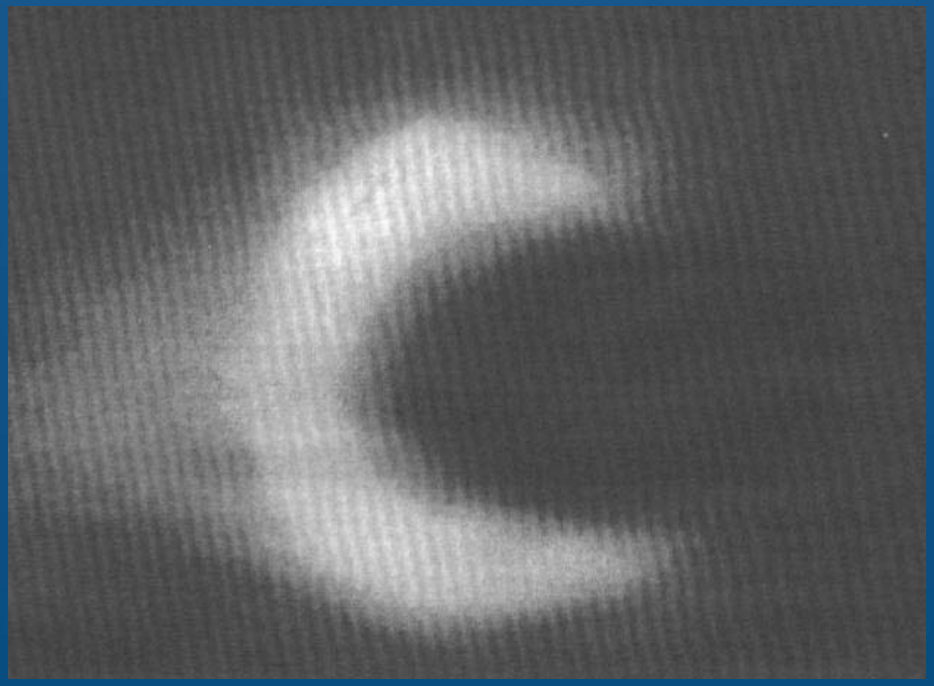
What is IMAT?



IMAT

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



From Yu 1995 PMB

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."

Yu, CX: Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy. Phys. Med. Biol., 40: 1435-49, 1995

What matters is the total number of shape changes!

Where to place these apertures does not matter.

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Works on single arc IMAT

- MacKenzie MA, Robinson DM. 2002 Intensity modulated arc deliveries approximated by a large number of fixed gantry position sliding window dynamic multileaf collimator fields. *Med Phys.* **29** 2359-65.
- Crooks SM, et al. 2003 Aperture modulated arc therapy. *Phys. Med. Biol.* **48** 1033-1044.
- Earl MA, et al, 2003 Inverse planning for intensity-modulated arc therapy using direct aperture optimization *Phys. Med. Biol.* **48**, 1075-1089
- Cameron C. 2005 Sweeping-window arc therapy: an implementation of rotational IMRT with automatic beam-weight calculation. *Phys Med Biol.* **50** 4317-36.
- Ulrich S, et al. 2007 Development of an optimization concept for arc-modulated cone beam therapy. *Phys. Med. Biol.* **52** 4099-4119.
- G. Tang, M. Earl, S. Luan, S. Naqvi and C.X. Yu, "Converting multiple-arc Intensity-modulated Arc Therapy into a single arc for efficient delivery," *Int. J. Rad. Oncol. Biol. Phys* ***69(3,)*** *Sup*, S673 (2007)
- Otto K 2008 Volumetric modulated arc therapy: IMRT in a single gantry arc. *Med Phys.* **35** 310-317.
- Wang C, Luan S, Tang G, Chen DZ, Earl MA, Yu CX, 2008 Arc-Modulated Radiation Therapy (AMRT): A Single-Arc Form of Intensity-Modulated Arc Therapy. *Phys. Med. Biol.* **53** 6291-6303.

Commercial Adoption

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

1. Compare single arc, multiple arc, and 7-field IMRT

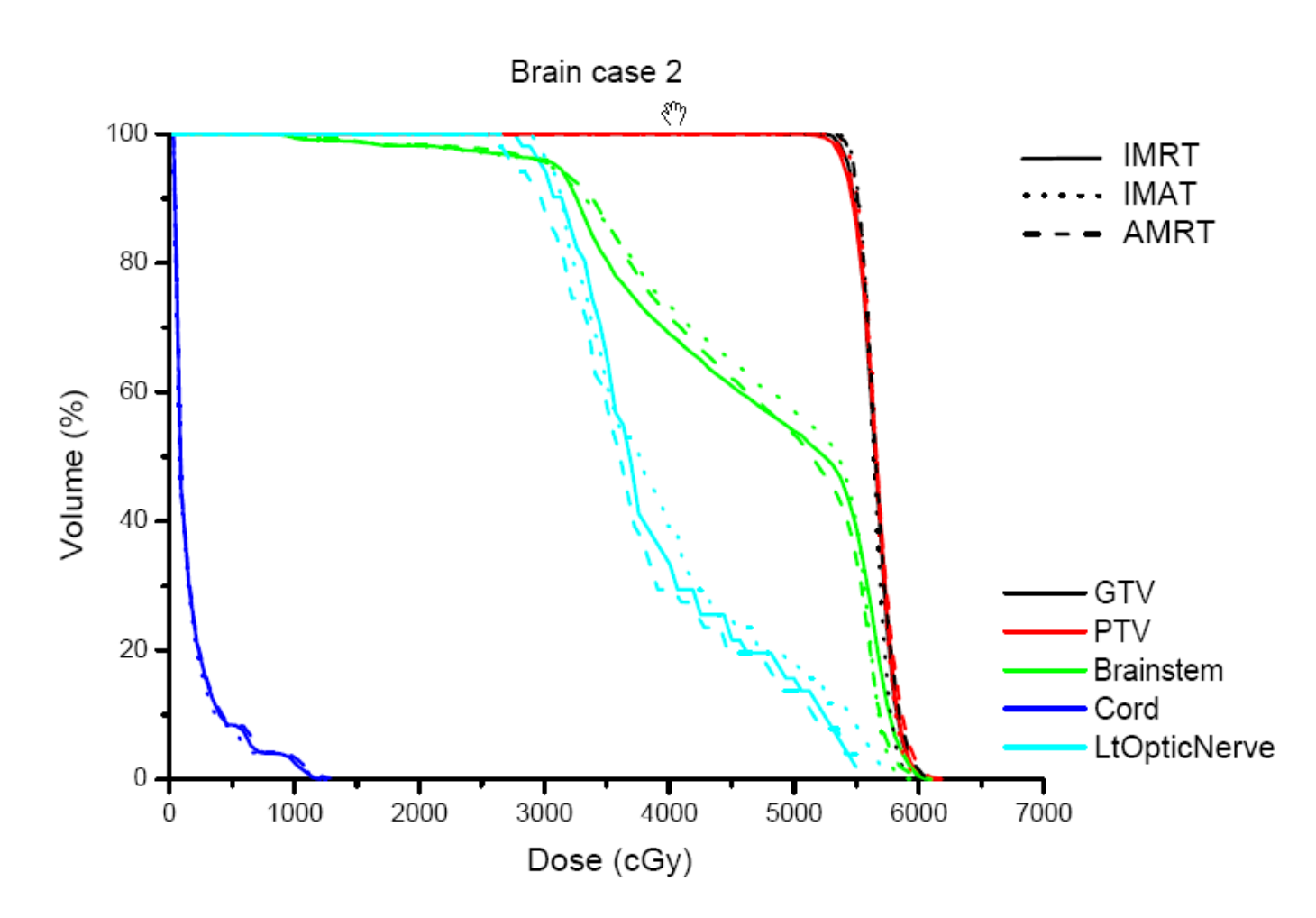
All optimized with the same planning system, with the same objectives, the same Monte-Carlo based calculation, and the same DVH analysis.

Planning

1. IMRT Plan on 36 fields, export the plan
   - Convert to deliverable single arc IMAT
   - Convert to deliverable multi-arc IMAT
2. IMRT Plan on 7 fields
3. Dose calculation with Monte-Carlo method
4. Import doses into Pinnacle for DVH analysis

Results – Brain

Same objectives, same dose engine



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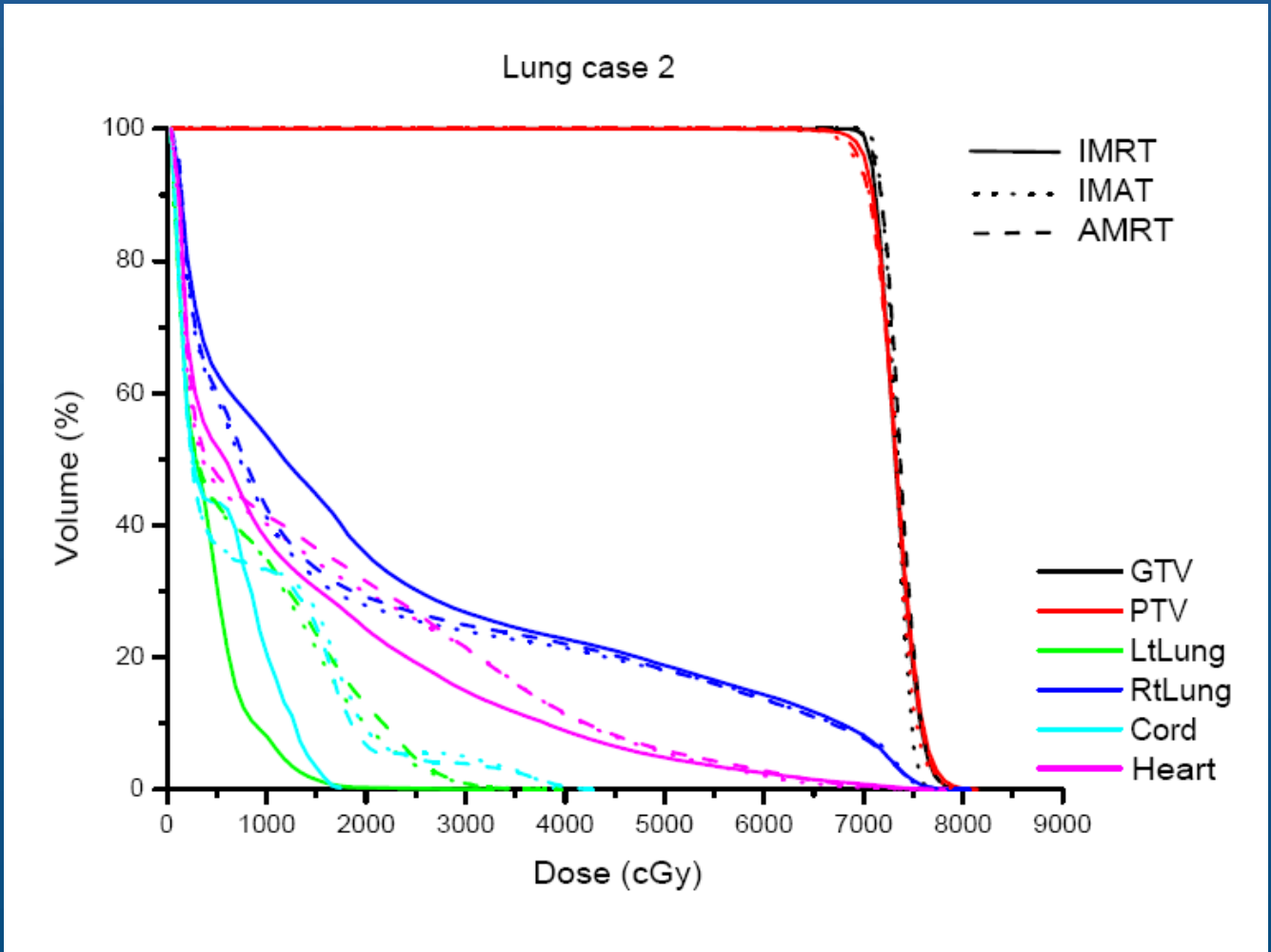
Results - lung



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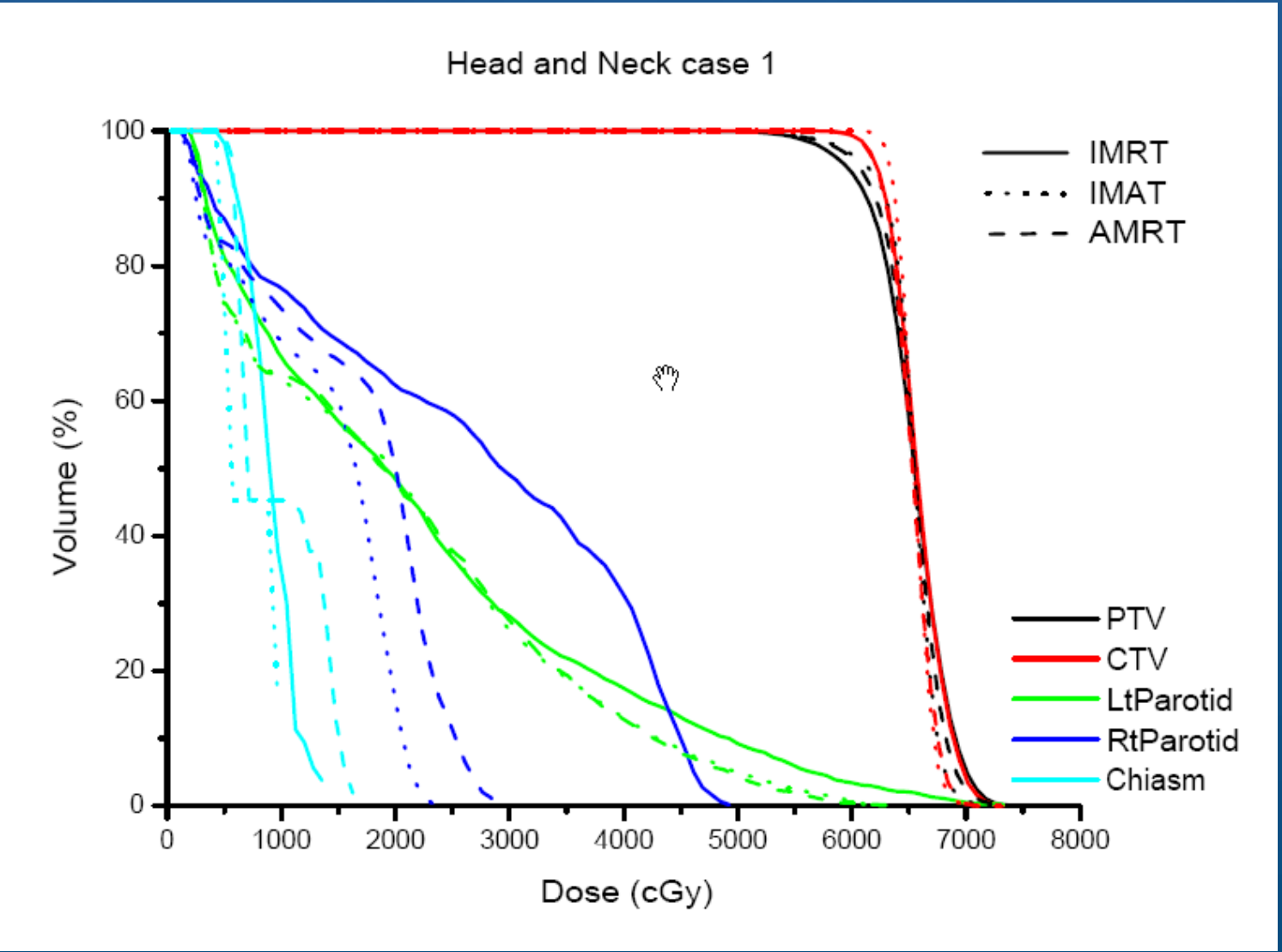
Results – H&N



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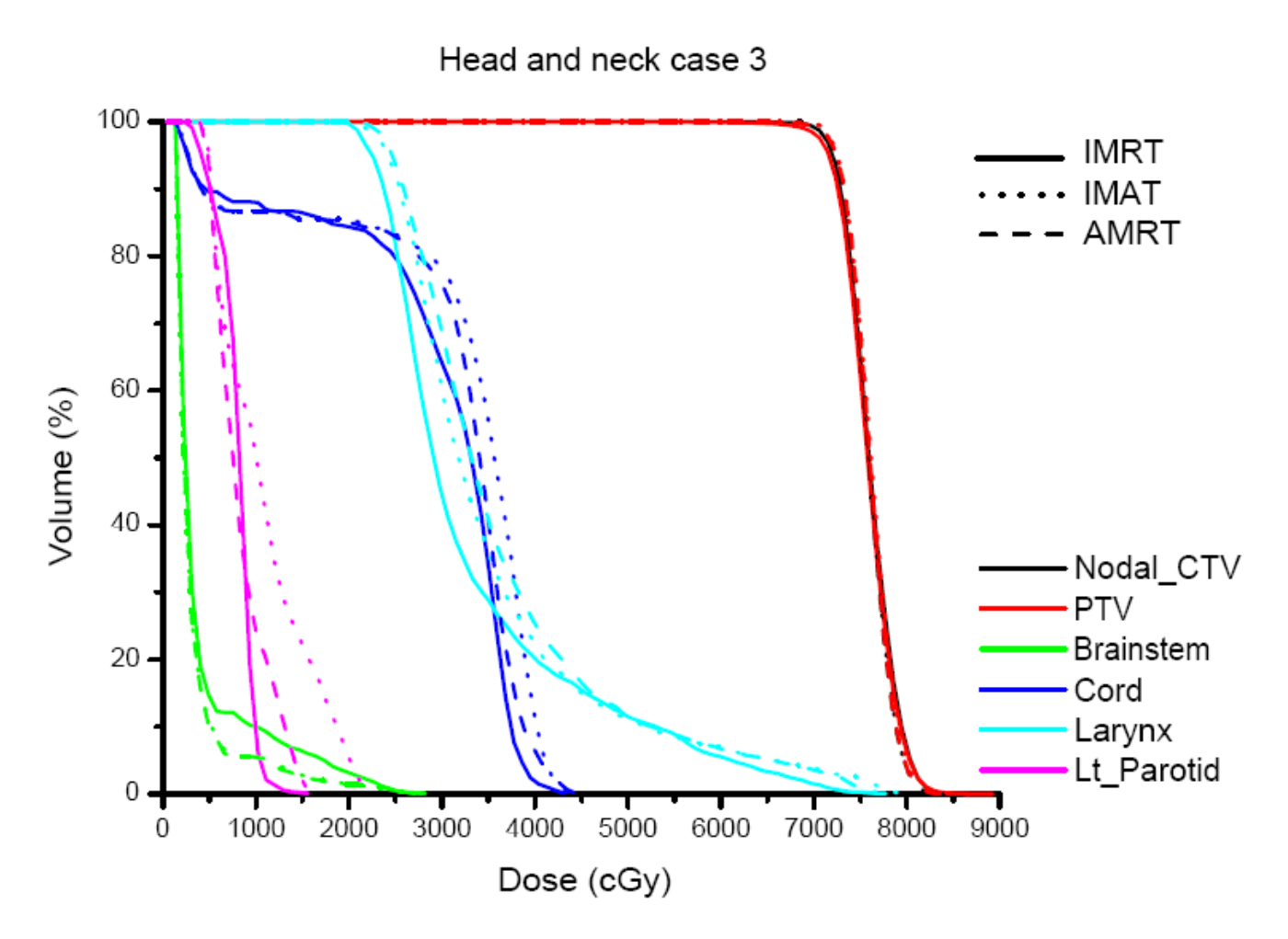
Results – H&N 2



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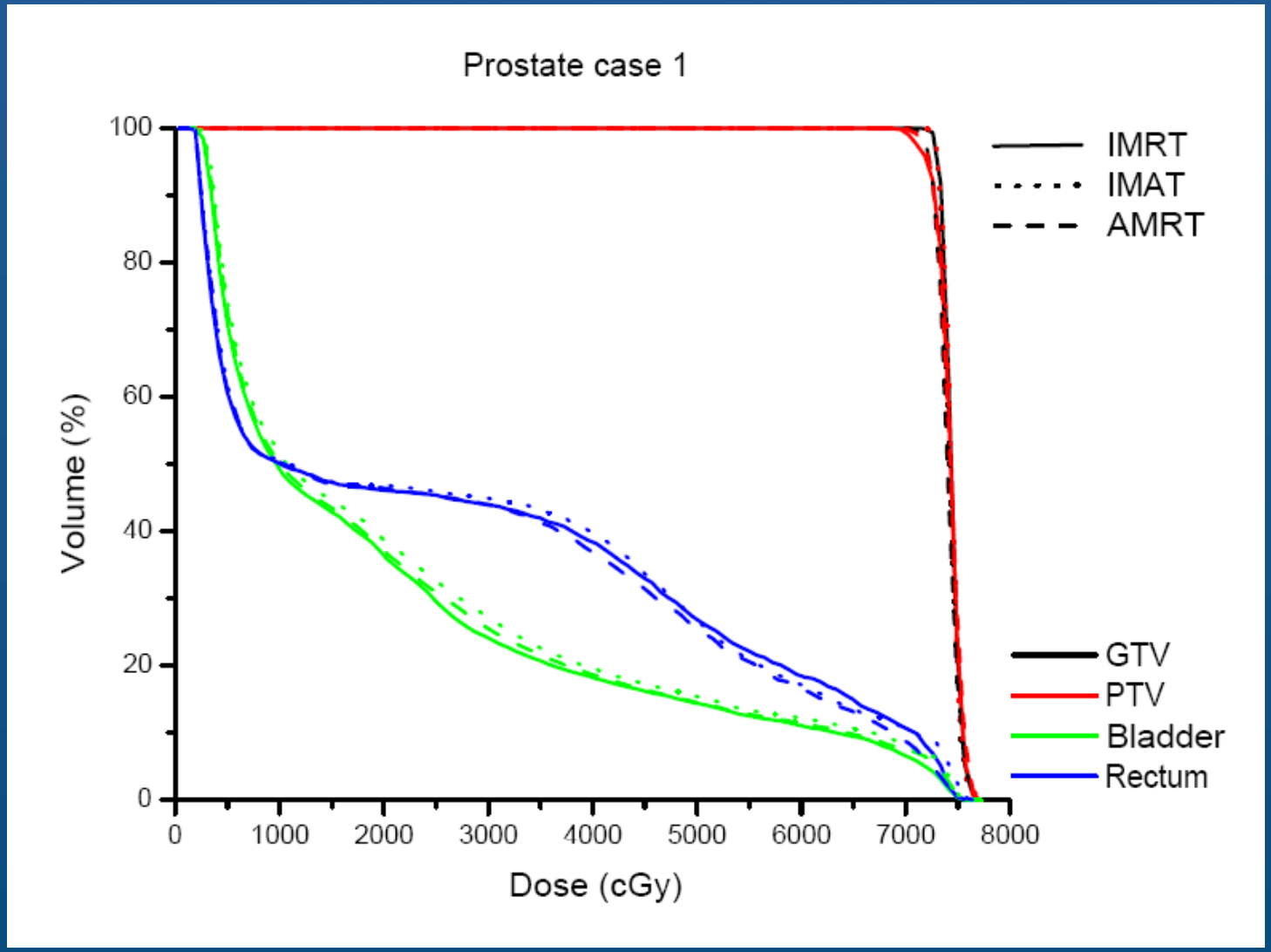
Results - Prostate



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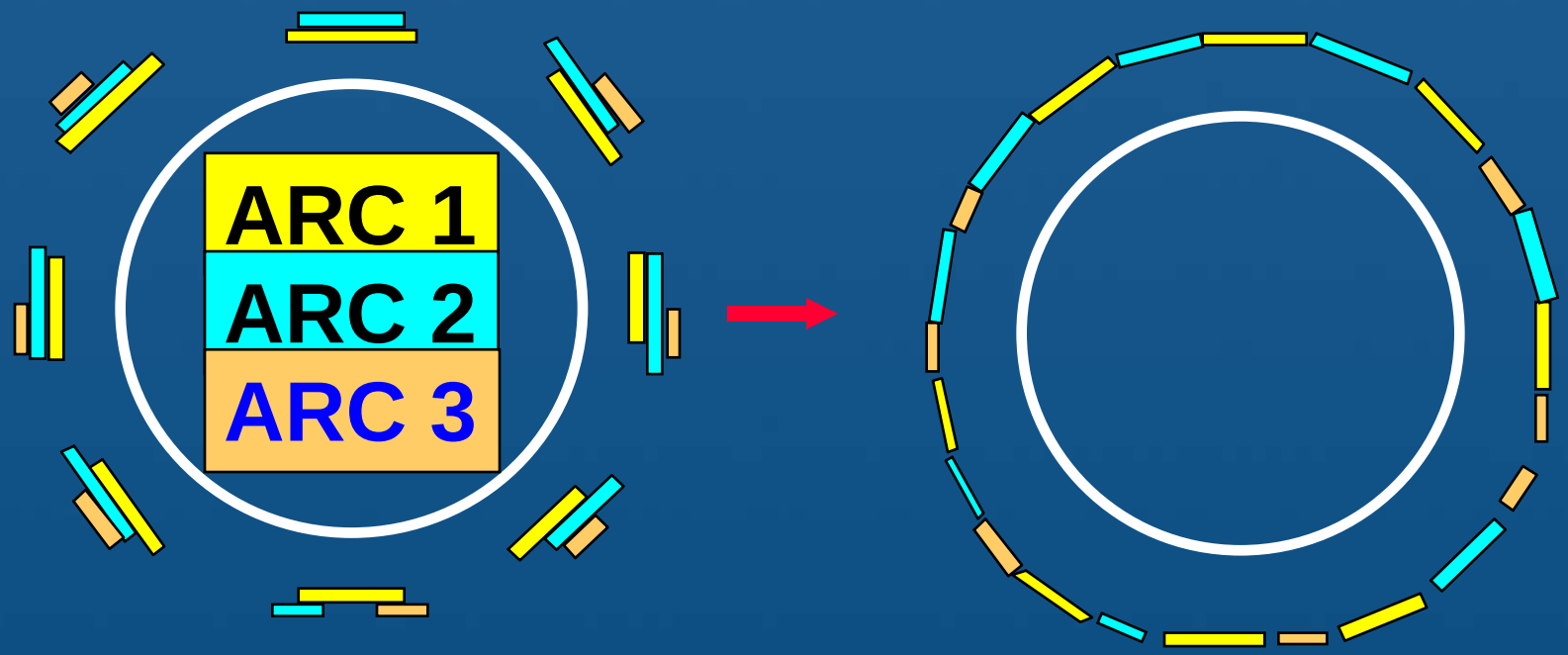
Compare IMAT and IMRT for 10 Cases

- Multiple arc IMAT wins every time
- Single arc IMAT performs better than 7-field IMRT in most of the cases

Multi-arc to Single arc



Tang et al, Int. J Rad Onc. Biol Phys, 2007

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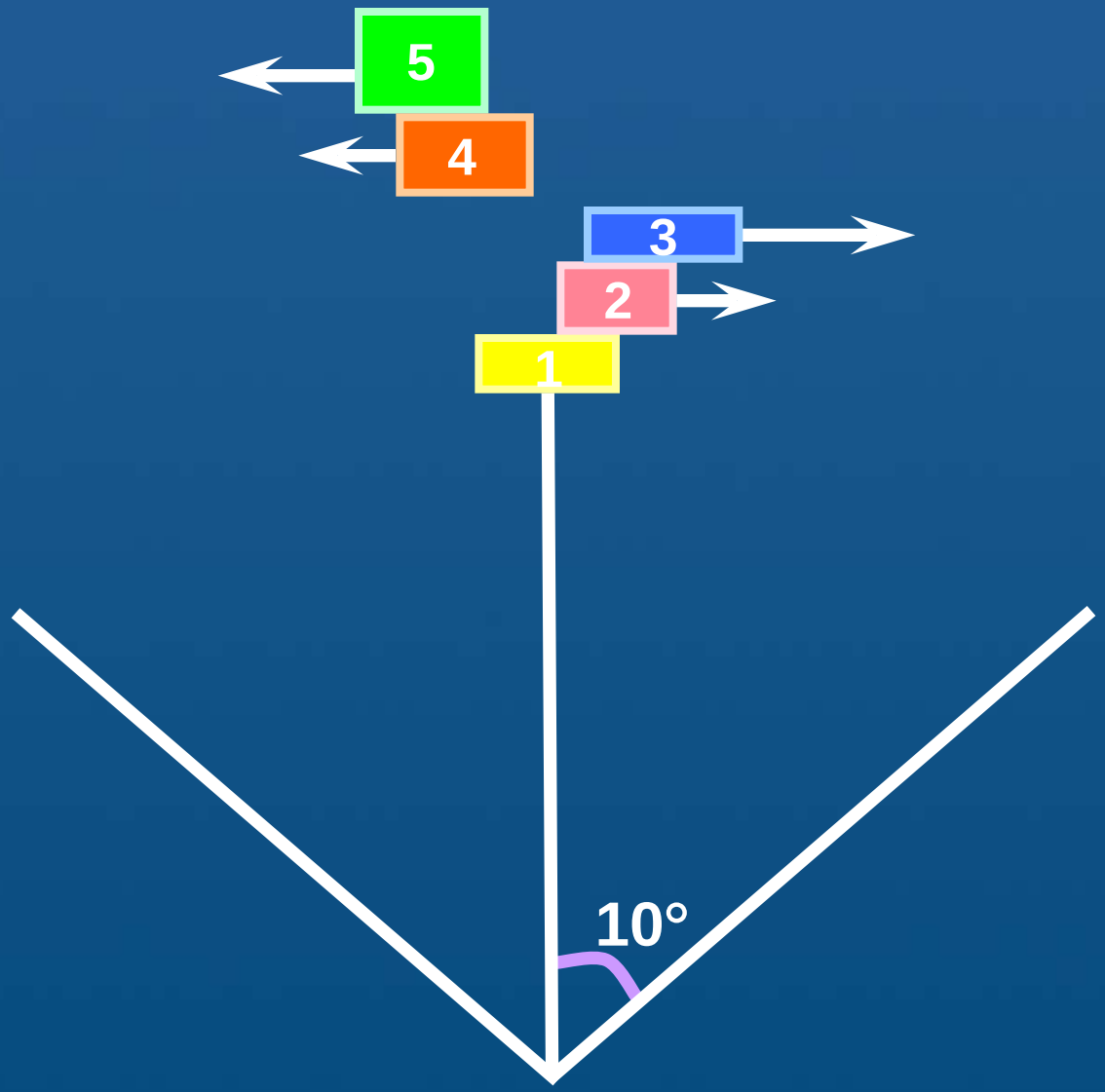
Converting multiple arcs to a single arc …



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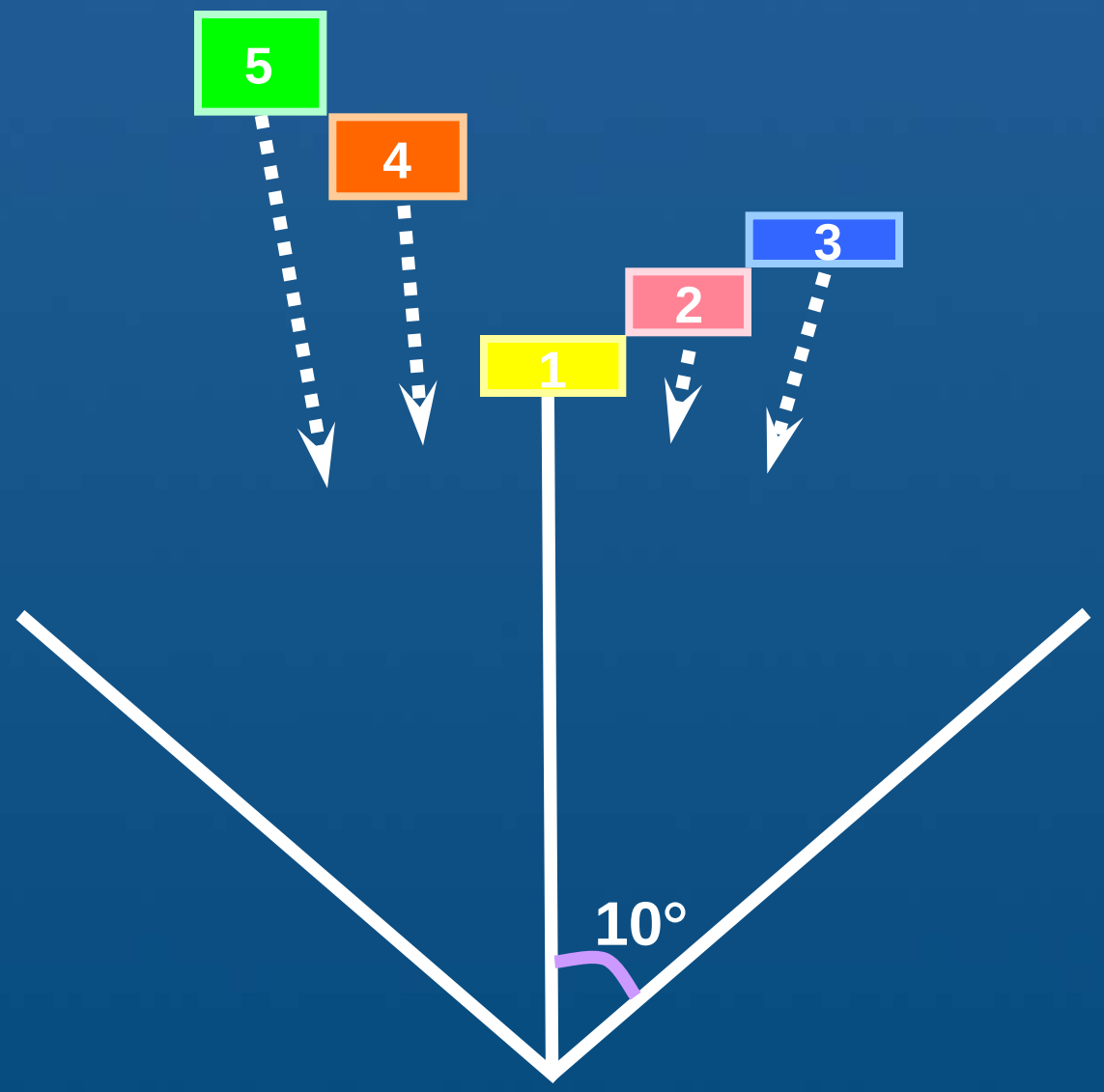
Converting multiple arcs to a single arc …



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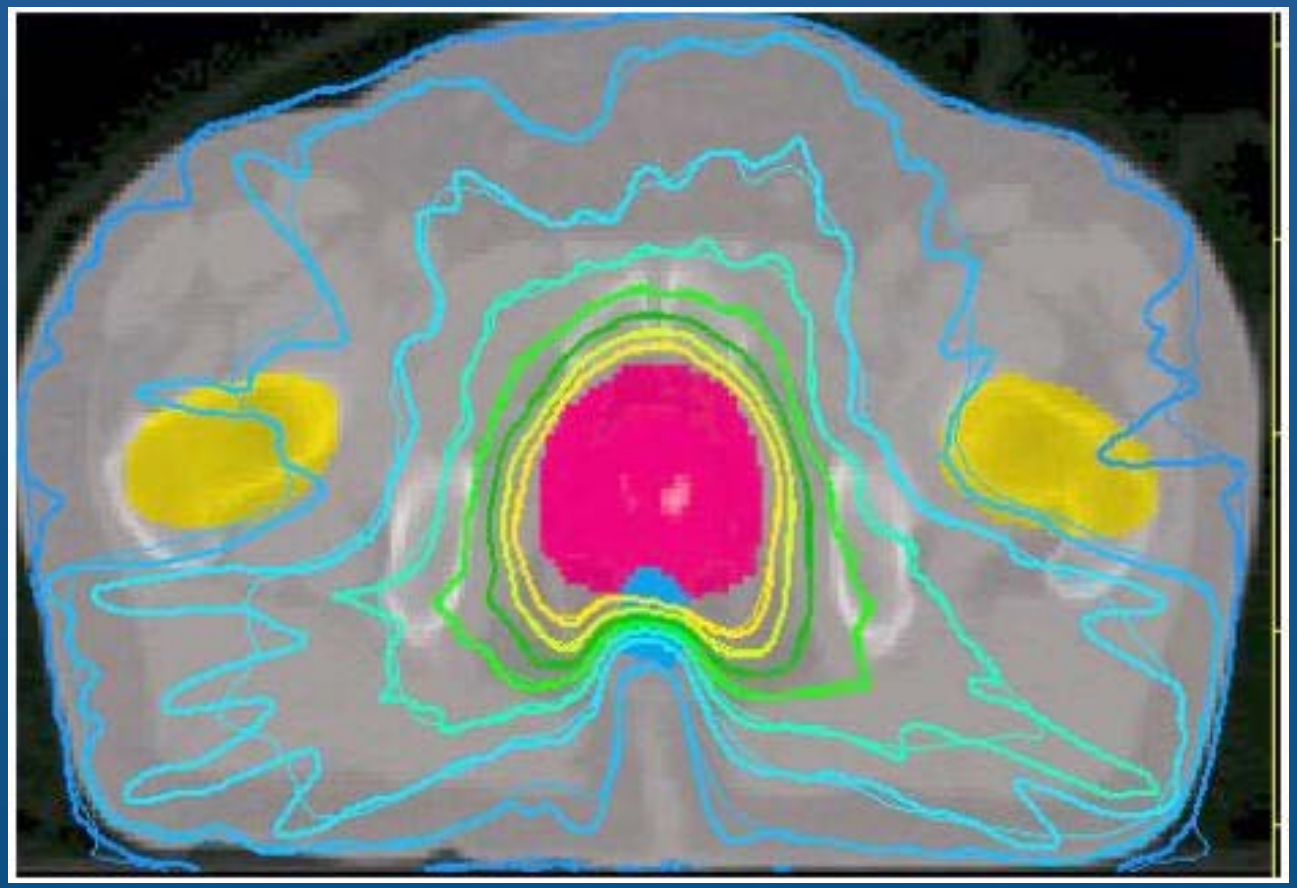
Stacked -> Spaced



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

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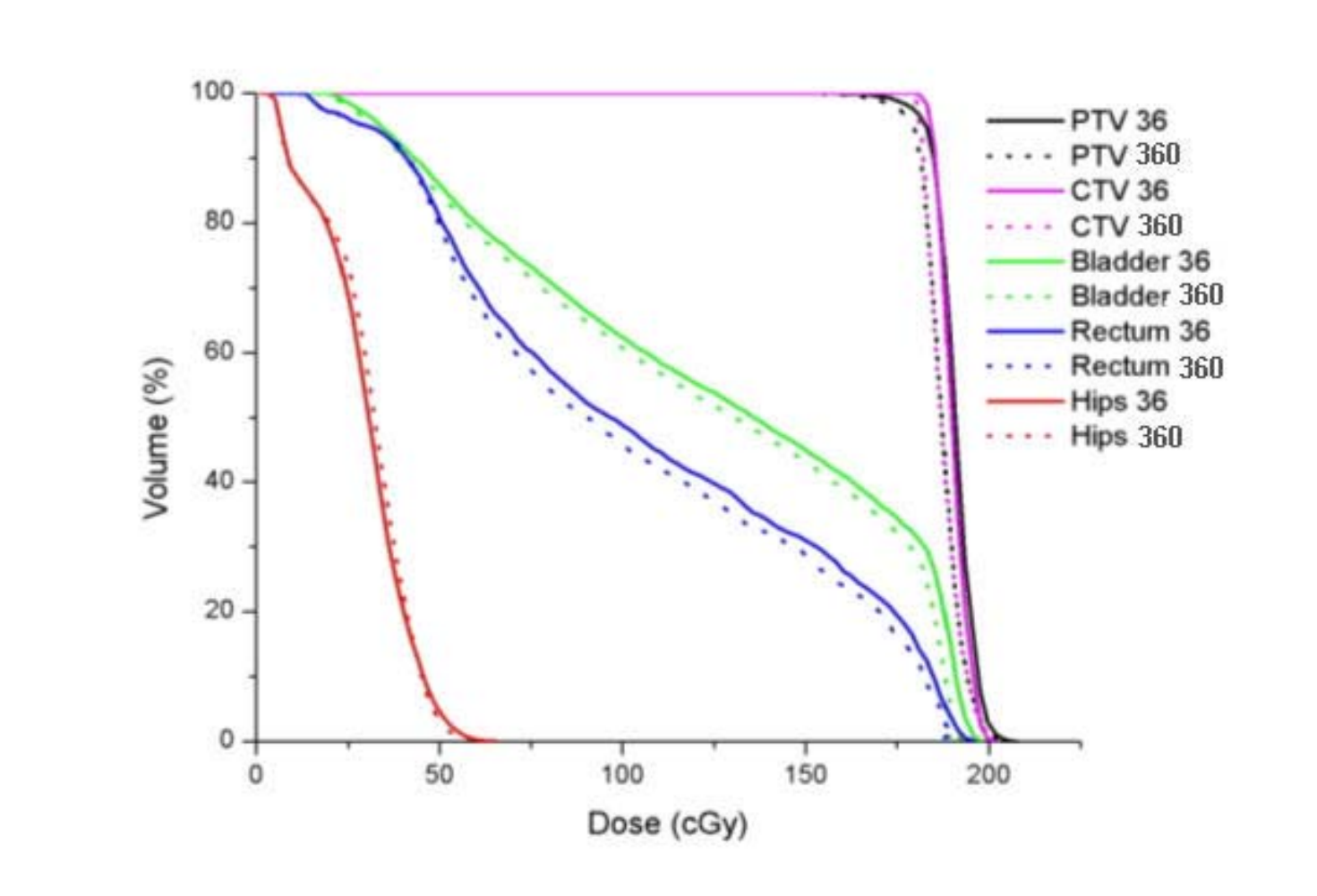
Stack v.s. Spaced DVH



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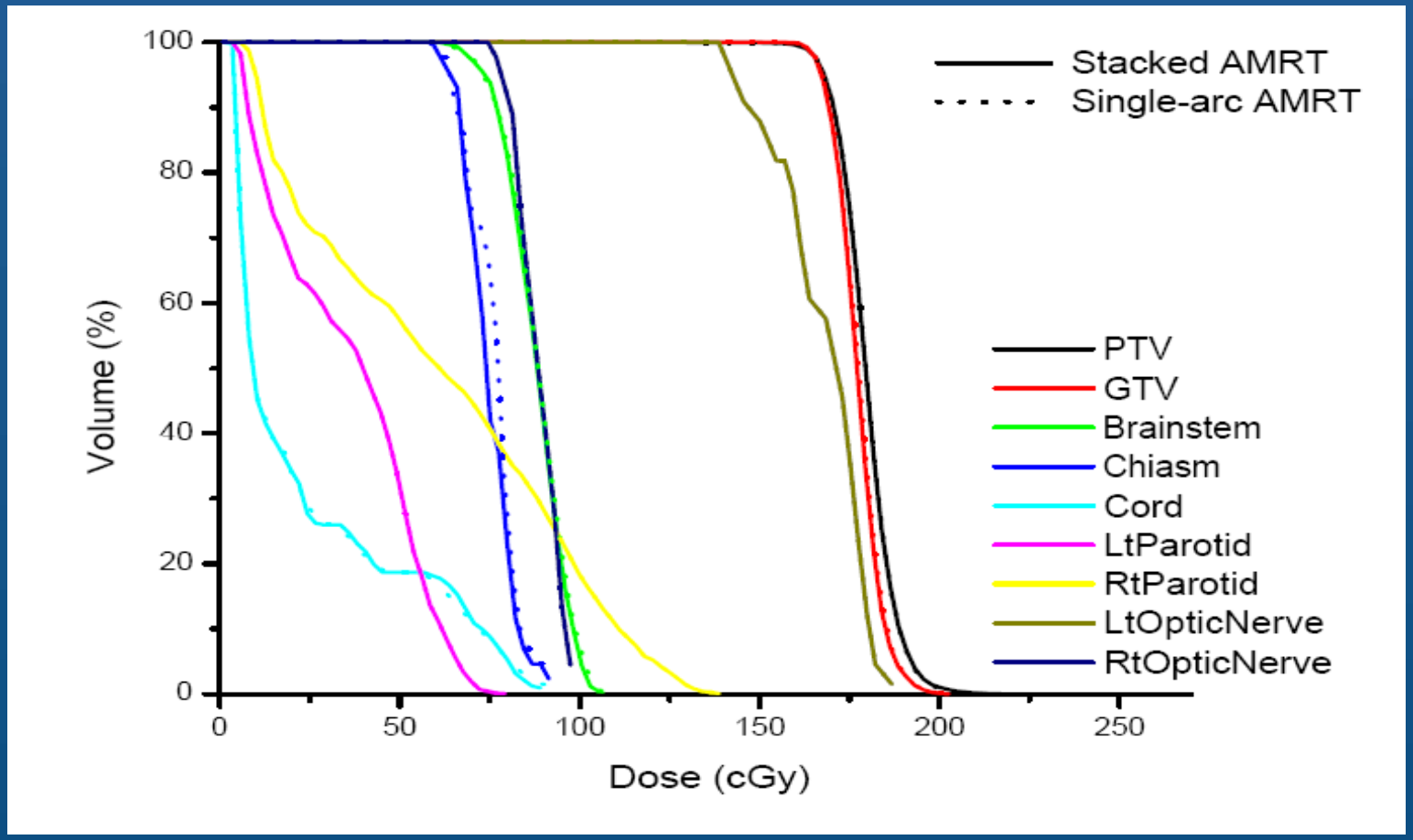
Stacked v.s. Spaced



Same number of apertures, same plan quality

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Observation:

Rotational IMRT is insensitive to small angular errors

Understanding Single Arc

- By using 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.

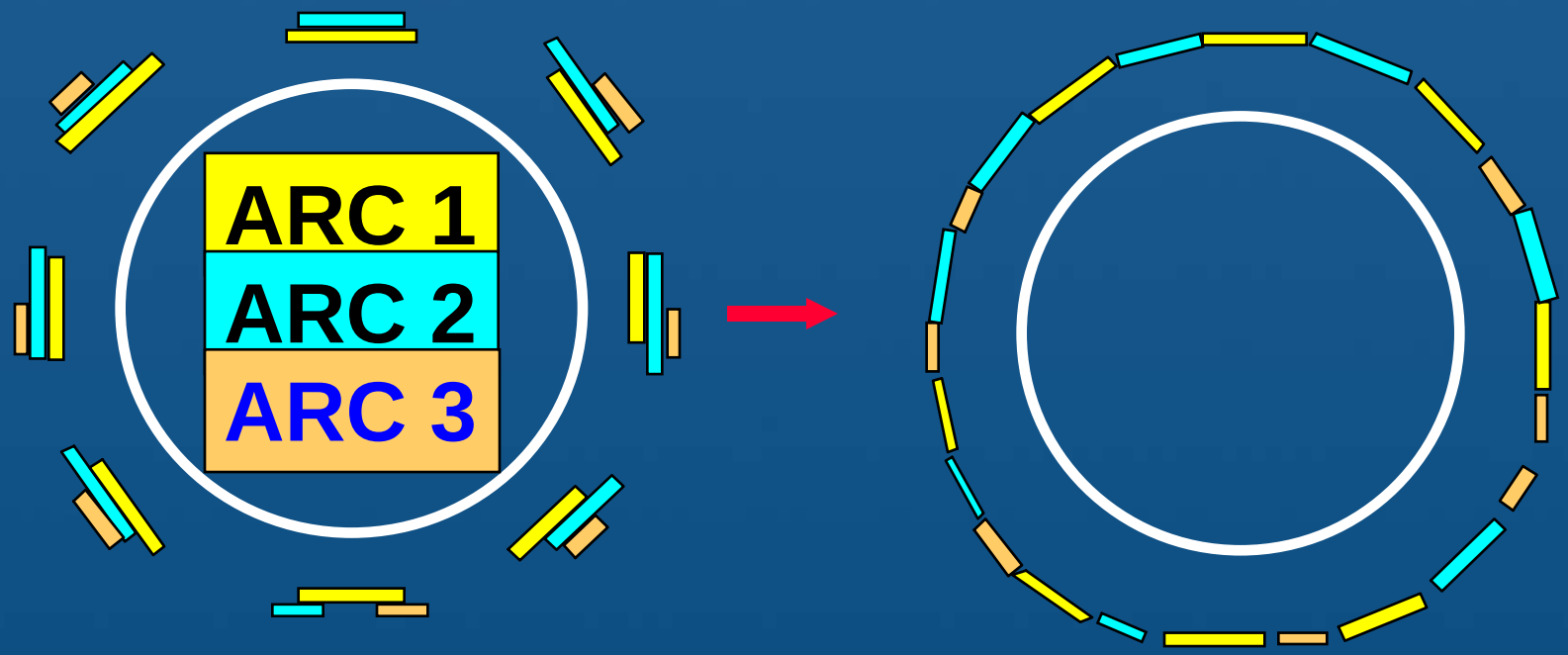
so,

Is it the same as 36 beam IMRT?

In principle: Yes.

In practice: No quite.

This picture ignored deliverability!



Tang et al, Int. J Rad Onc. Biol Phys, 2007

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.

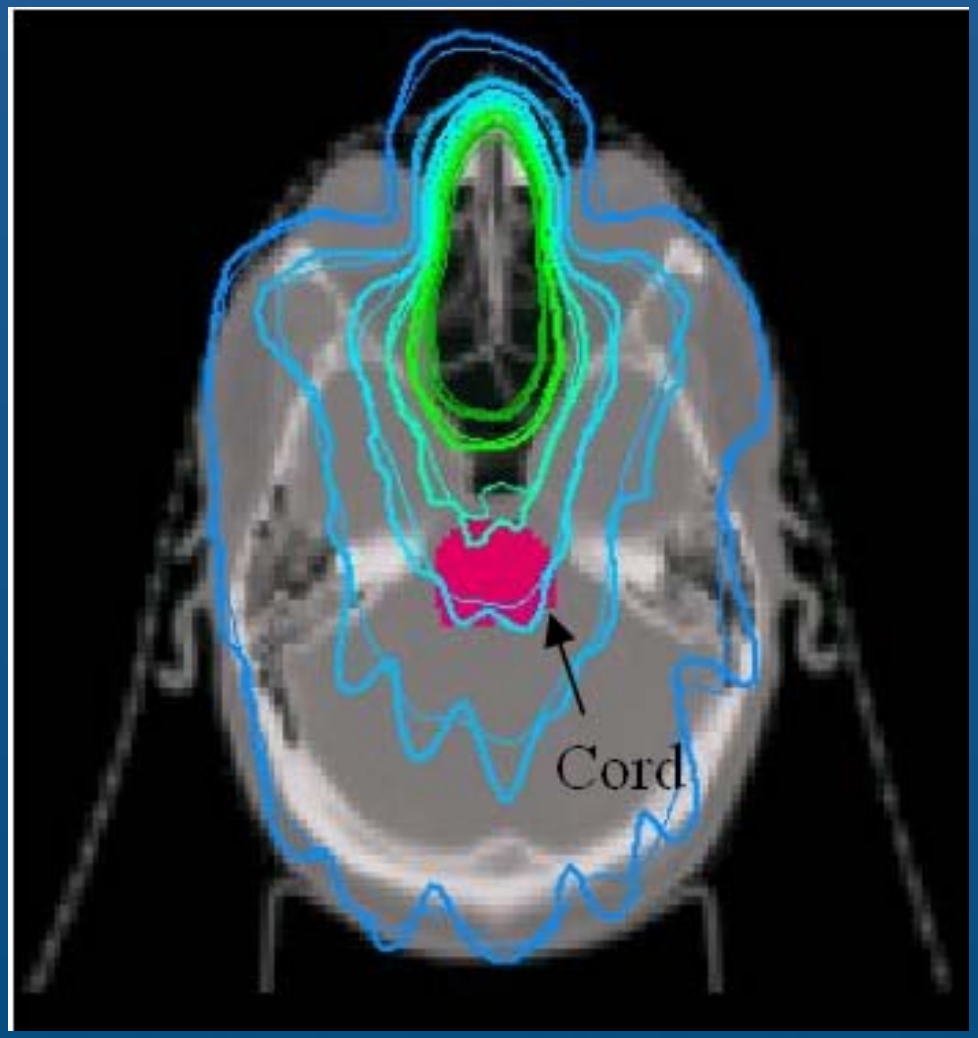
What if I have a fast MLC and fast dose rate variation?

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 appear 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

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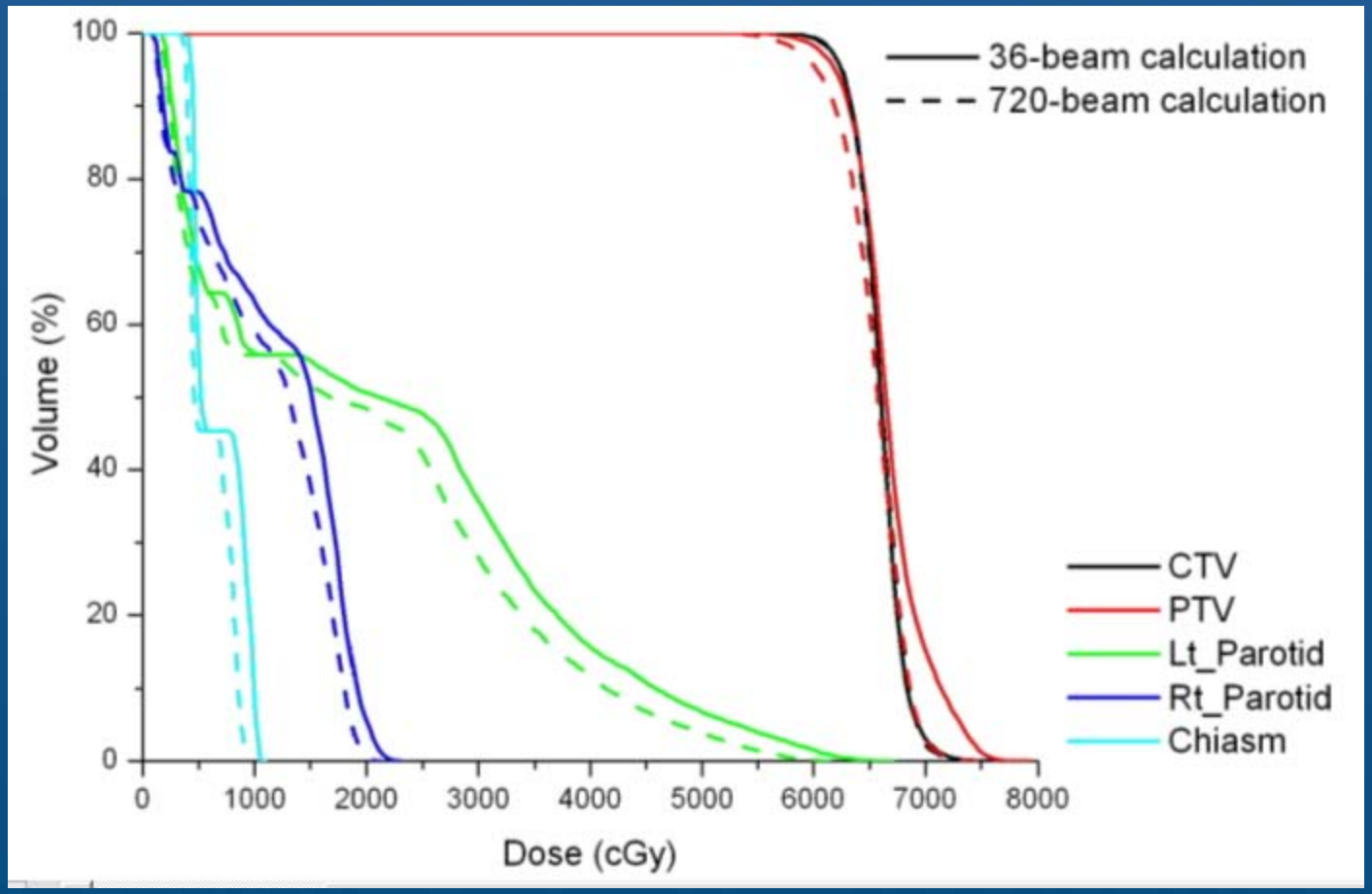
Some Cases – noticeable Differences



Plan B

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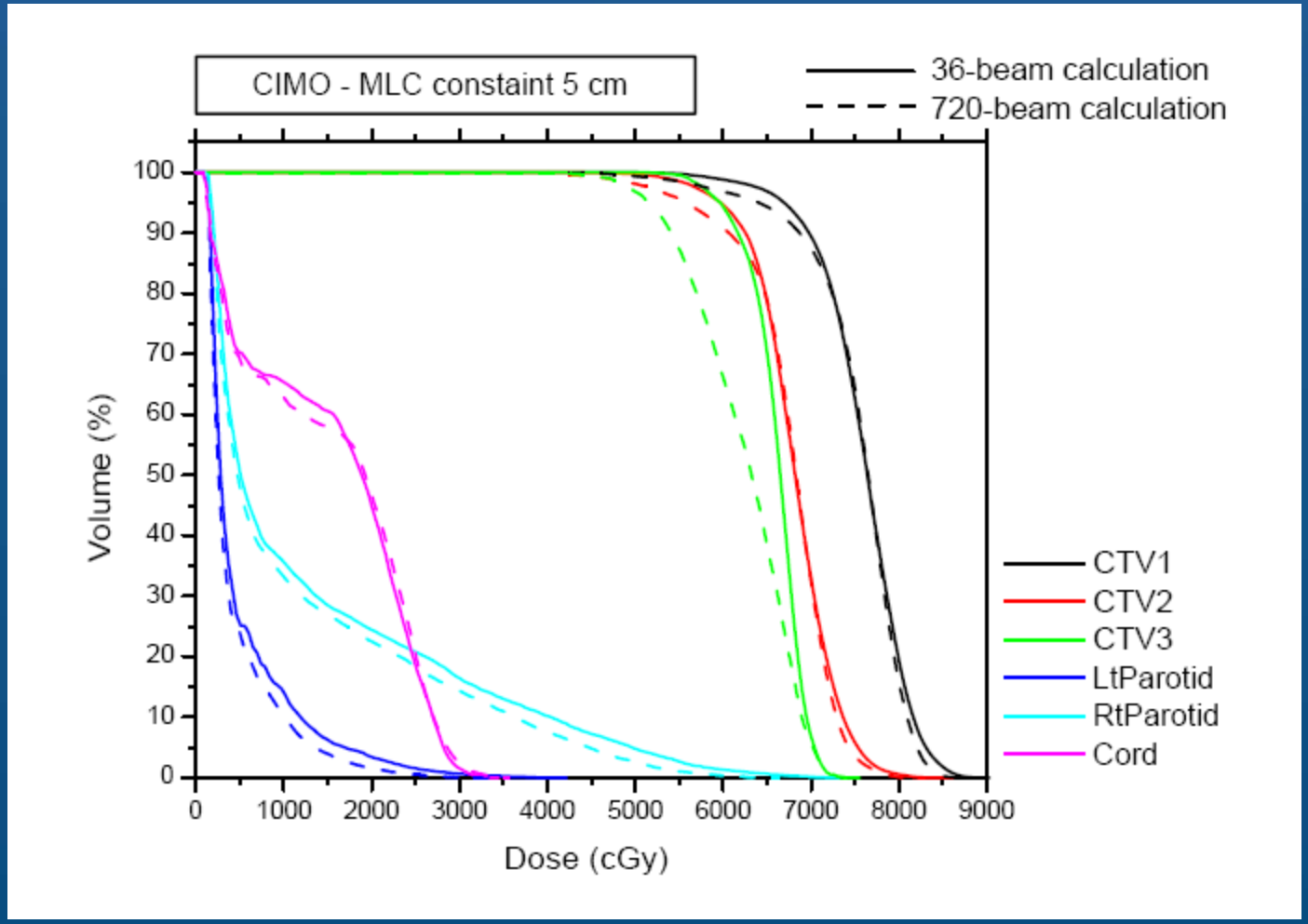
Some Cases – Large Differences



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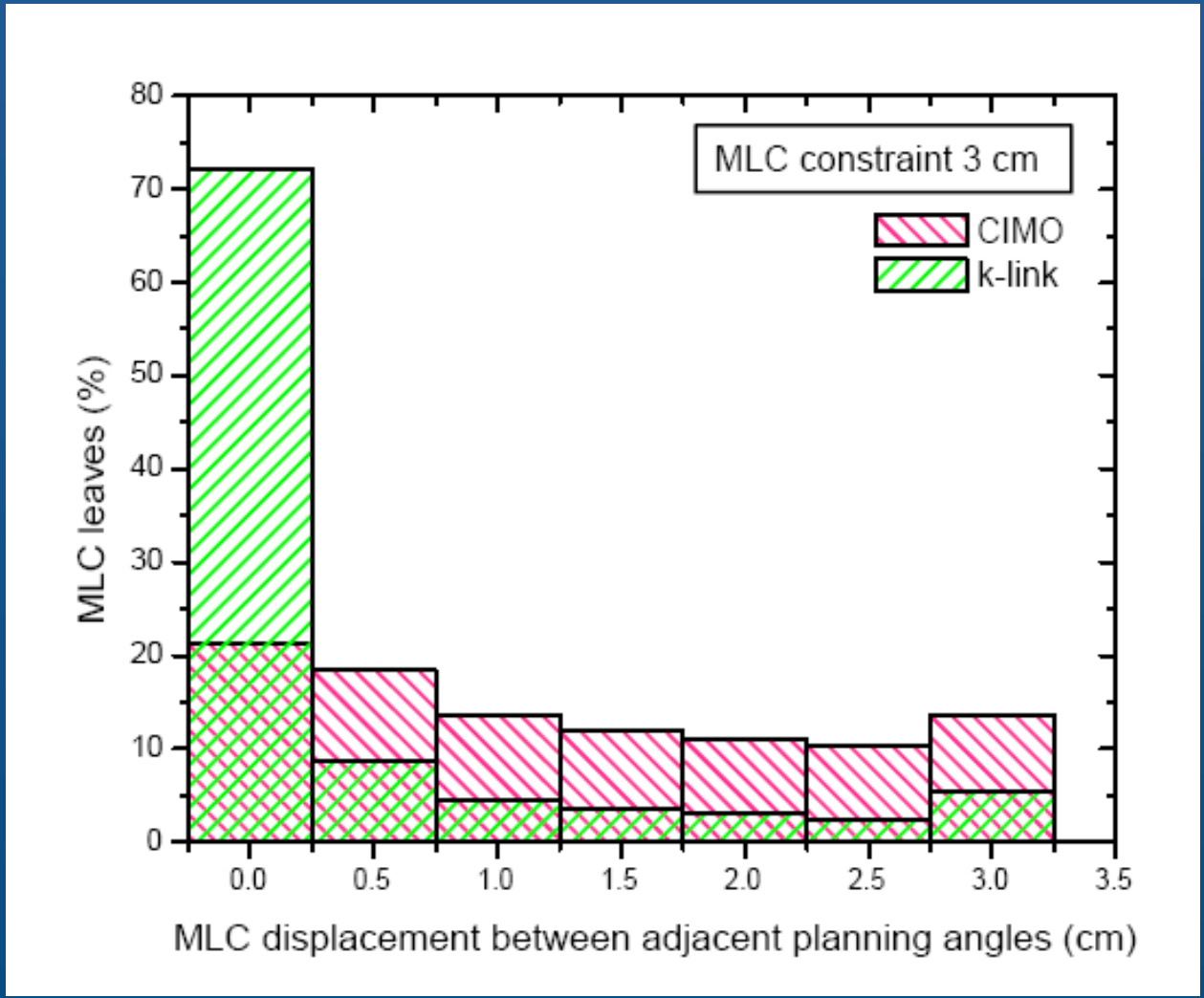
Reason 1: Too much MLC movement



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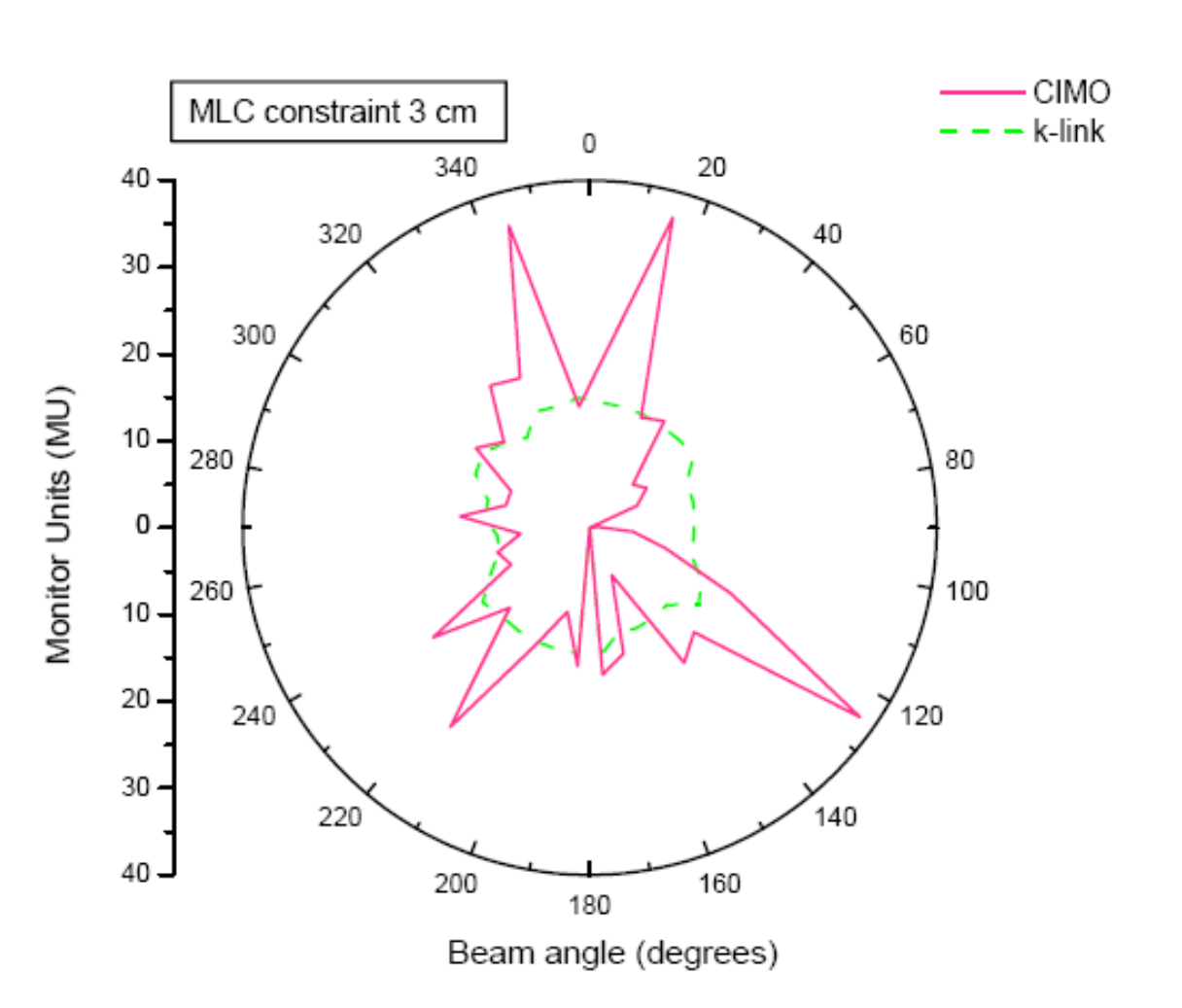
Reason 2: Too Much Dose Rate Variation



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No.2 Principle of IMAT

Large MLC motion and dose rate variation can cause:

$$\text{Delivered} \neq \text{Planned}$$

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

2. Compare RapidArc™ with Tomotherapy™

Double-blined, two institution study

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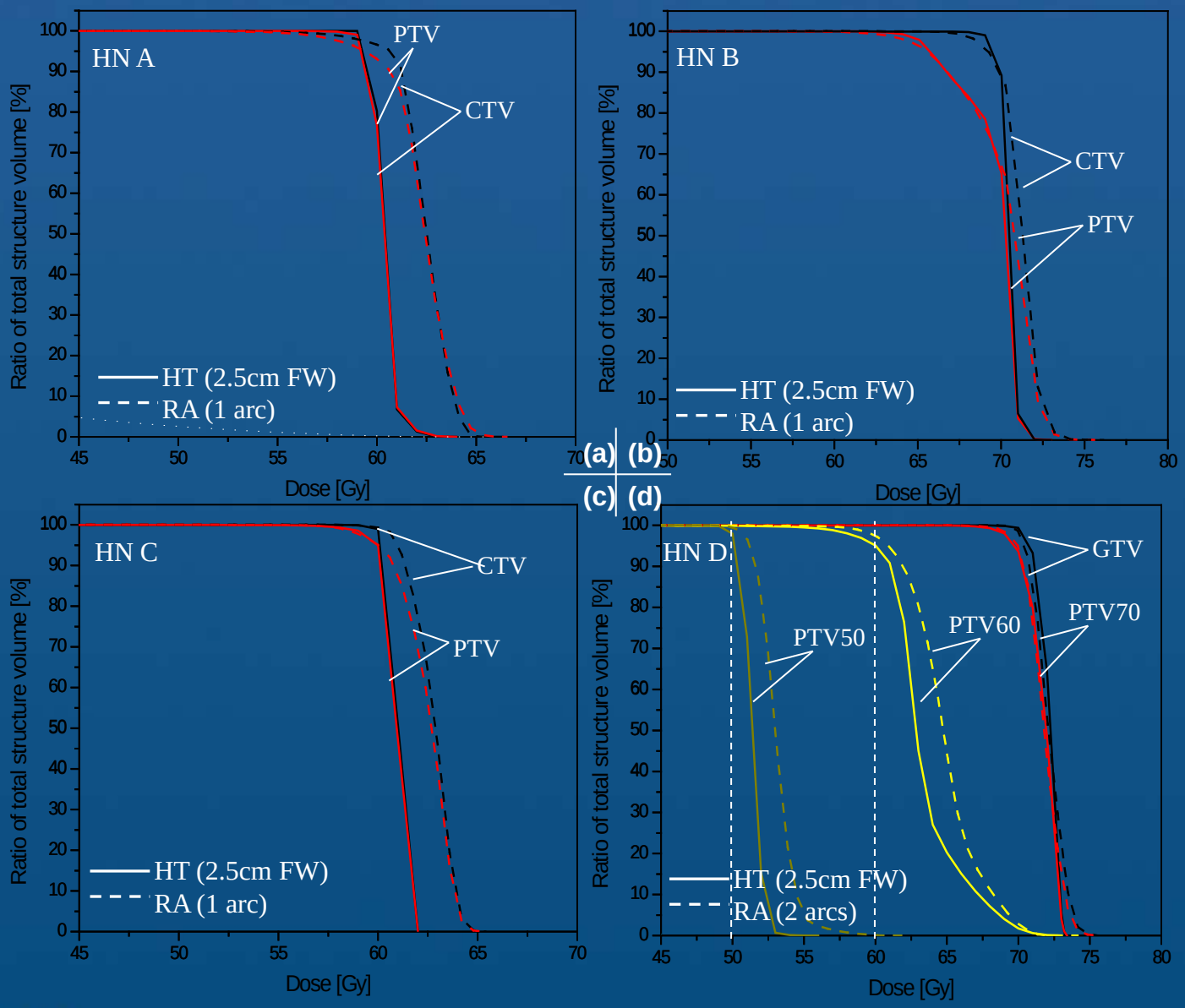
Patients		Targets	Volume (cc)	Prescriptions (Gy)	Fraction dose (Gy)
UMM	Brain A (SEQ)	GTV 1	736.7	46	2
		GTV 2	333.6	60	2
	Brain B	GTV	258.2	41.4	1.8
UWR	Brain C (SIB)	Whole brain, GTV55	1332.6, 3.64	30, 55	3.0, 5.5
	Brain D (SIB)	GTV36, GTV45	28.7, 10.7	36, 45	2.0, 2.5
UMM	HN A	PTV	196.0	59.4	1.8
	HN B (SEQ)	PTV 1	128.6	63	1.8
		PTV 2	260.0	70.2	1.8
UWR	HN C	PTV	165.2	60	2
	HN D (SIB)	PTV70, PTV60, PTV50	148.4, 654.1, 303.9	70, 60, 50	2.12, 1.8, 1.5
UMM	Prostate A	PTV 3 only	90.3	72	1.8
	Prostate B (SEQ)	PTV 1	1229.2	75.6	1.8
		PTV 2	156.8	30.6	1.8
		PTV 3	109.3	10.8	1.8
UWR	Prostate C	PTV	105.3	70	2.5
	Prostate D	PTV	94.4	65	2.5
UMM	Lung A	PTV	55.7	72	1.8
	Lung B	PTV	120.8	70.2	1.8
UWR	Lung C	PTV	246.1	30	2
	Lung D	PTV	349.1	45	1.5

SEQ: sequential boost; SIB: simultaneous in-field boost



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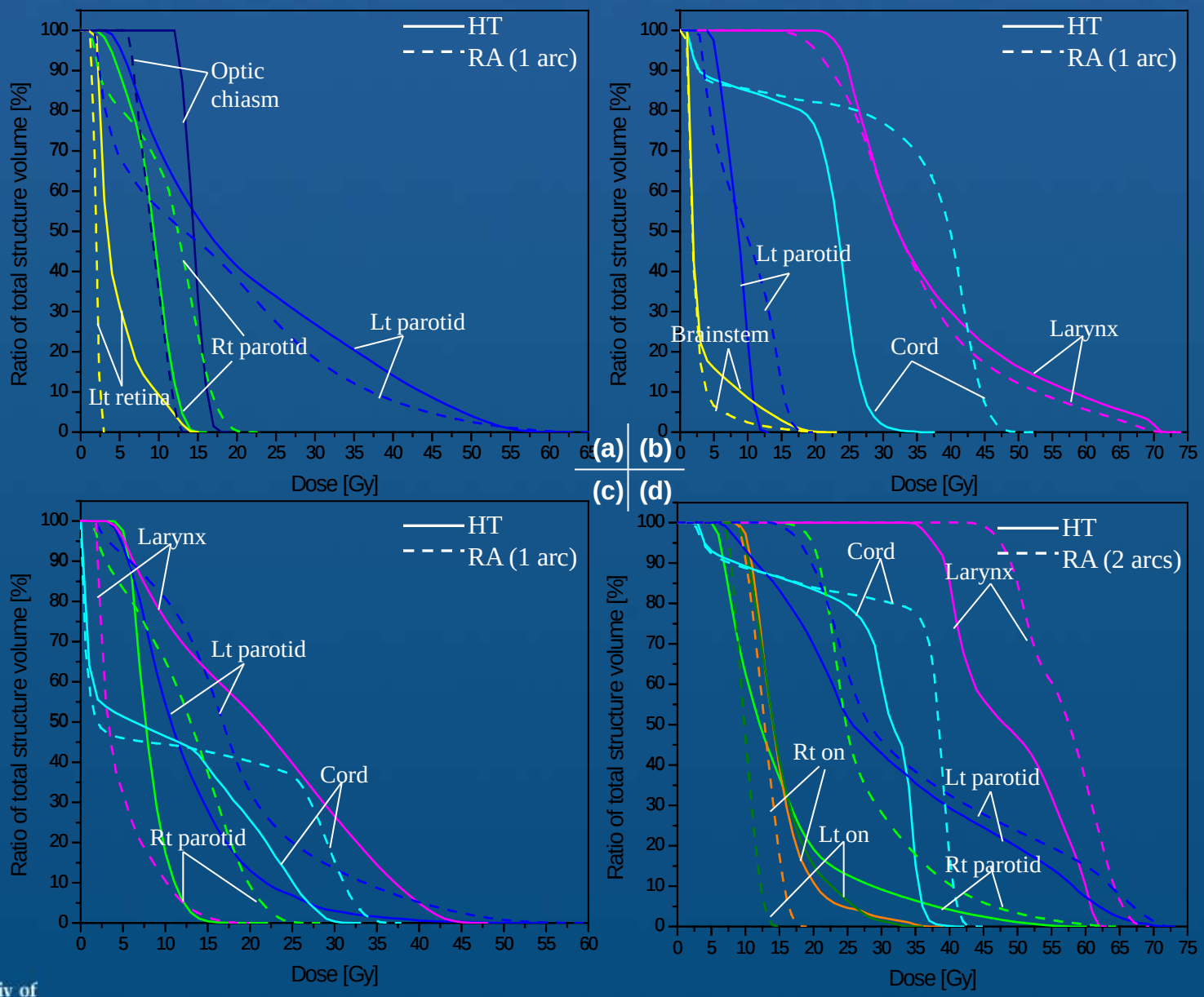

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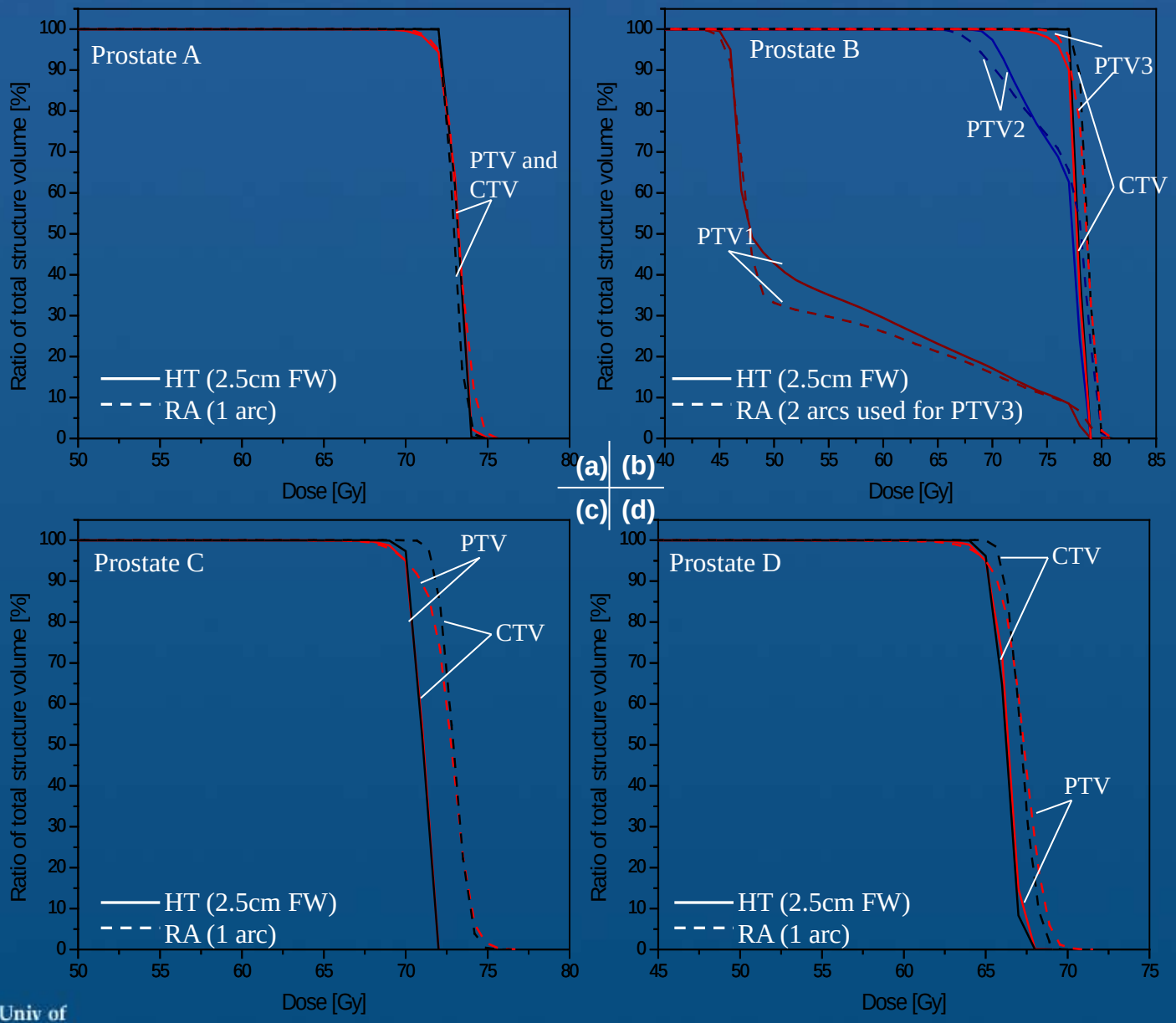

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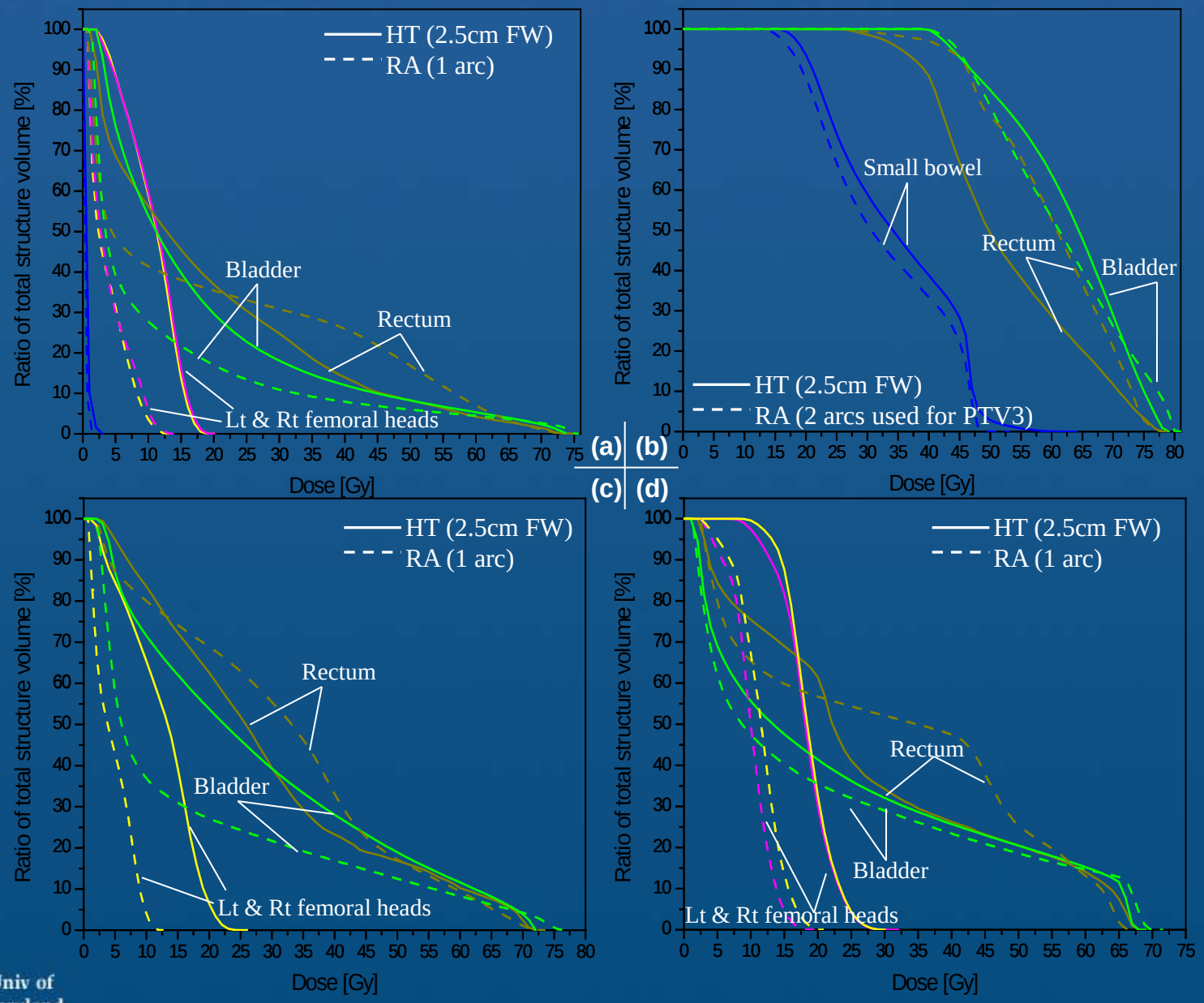

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MUs and Beam-on Time

	RA			HT	
Patient	Arcs	MU	BOT (min)	MU	BOT (min)
Brain A (SEQ)	1	177	0.57	4314	5.10
	2	515	1.23	3581	4.25
Brain B	2	296	1.17	3163	3.77
Brain C (SIB)	2	744	1.91	6820	7.95
Brain D (SIB)	1	441	1.26	3845	4.56
HN A	1	366	1.25	2674	3.22
HN B (SEQ)	1	287	1.23	5027	5.91
	1	418	1.24	4859	5.72
HN C	1	386	1.25	4008	4.74
HN D (SIB)	2	463	2.47	7877	9.16
Prostate A	1	584	1.28	2235	2.72
Prostate B (SEQ)	2	714	2.49	6018	7.03
	1	393	1.25	2725	3.28
	1	494	1.26	2420	2.93
Prostate C	1	744	1.38	5072	5.96
Prostate D	1	940	1.69	4514	5.32
Lung A	1	398	1.25	2851	3.42
Lung B	1	539	1.28	2718	3.27
Lung C	1	470	1.28	3321	3.96
Lung D	1	329	1.27	3579	4.26
Average over 16 cases		**485**	**1.40**	**4081**	**4.83**
Standard deviation		**185**	**0.44**	**1517**	**1.73**

No.3 Principle of IMAT

- For a given problem, there are preferred angles and locations to take advantage of the planning geometry.
- Intensity modulation within a field is one way, but not the only way, to achieve such angular and location preferences.

Question 1:

A key principle of IMAT is:

0% 1. The use of arcs reduces the integral dose delivered to the patient.

0% 2. Patient specific QA measurements are no longer required.

0% 3. Increasing the total number of shape changes results in improved plan quality.

0% 4. Aperture shapes should track the shape of the target during rotation

0% 5. Neutron dose to the patient is reduced as compared with fixed field IMRT.

Answer:

References:
Yu, CX: Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy. Phys. Med. Biol., 40: 1435-49, 1995

Question 2

In single arc IMAT delivery, intensity modulation is effectively achieved at the target level by all of the following *except*:

0% 1. By using large number (100+) of shape variations
0% 2. Delivery of overlapping shapes from each beam angle
0% 3. Varying the dose rate
0% 4. Dynamic motion of the MLC leaves

Answer:

Refrences:
G. Tang, M. Earl, S. Luan, S. Naqvi and C.X. Yu, “Converting multiple-arc Intensity-modulated Arc Therapy into a single arc for efficient delivery,” Int. J. Rad. Oncol. Biol. Phys 69(3,) Sup, S673 (2007)
Otto K 2008 Volumetric modulated arc therapy: IMRT in a single gantry arc. Med Phys. 35 310-317.

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10

Conclusion

- 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 strata) 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 fluctuation are allowed.
- Delivery is not less reliable than dynamic IMRT, but careful commissioning and regular QA is needed.