# Non-Coplanar Rotational Therapy

*w/ High Efficient Unflattened Beams*

TECHNOLOGY DEVELOPMENT AND SYSTEMS INTEGRATION

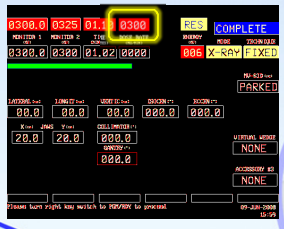
**Hansen Chen, M.S.**
**NewYork-Presbyterian Hospital, NY**

TDSI

## *Speed* of an Unflattened High Dose Rate Beam

**6 MV Flat Beam**

For 300 MU/Min Dose Rate
100 MU Beam On Time = **20 Sec**

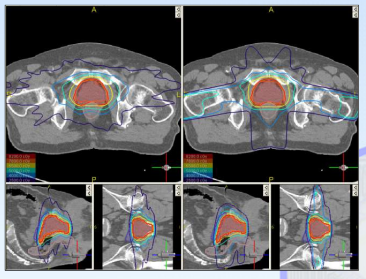



**7 MV Unflattened Beam**

For 2000 MU/Min Dose Rate
100 MU Beam On Time = **3 Sec**




## Rotational Therapy (VMAT) Helps the Speed



Comparison between
Static IMRT and VMAT

- Static IMRT (FF)
  414 MU, 7 beams,
  ~5 seg/beam
  Tx Time ~5 min
- VMAT (FFF)
  515 MU, 9~29 MU/OP,
  Min Gantry Speed 2
  deg/sec,
  Tx Time ~ 2 min

*Slide courtesy of Ali Bani-Hashemi*

## Published Beam-on-Time Comparison

Phys. Med. Biol. **56** (2011) 1931–1946 doi:10.1088/0031-9155/56/7/002

**Rotational IMRT delivery using a digital linear accelerator in very high dose rate 'burst mode'**

**Bill J Salter[1], Vikren Sarkar[1], Brian Wang[1], Himanshu Shukla[2], Martin Szegedi[1] and Prema Rassiah-Szegedi[1]**

[1] Department of Radiation Oncology, University of Utah, Salt Lake City, UT, USA
[2] Oncology Care Systems Group, Siemens Medical Solutions (USA), 4040 Nelson Avenue, Concord, CA, USA

E-mail: bill.salter@hci.utah.edu

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Modulated Arcs (MA)
Conformal Arcs (CA)
Segment-Weighted Conformal Arcs (SWCA)
Static Gantry IMRT (SG-IMRT)
3D Conformal (3DCRT)

**Table 5.** A comparison of the delivery times for the plans created for the different sites investigated in this work. The delivery times for arc plans are compared to a static gantry IMRT (SG-IMRT) and 3D conformal (3DCRT) plan developed using the same planning criteria as the arc plans.

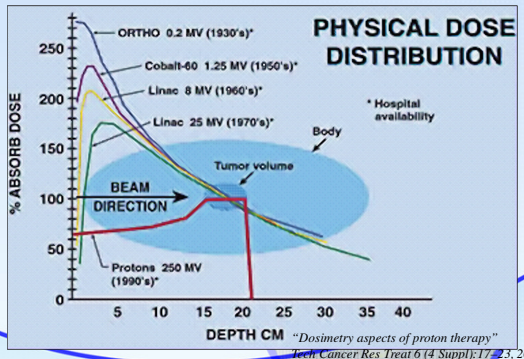
| Site | Modality | Rx dose (Gy) | Delivery time |
|---|---|---|---|
| Cavernous sinus | CA | 15.0 | 2 min 51 s |
| | SWCA | 15.0 | 2 min 59 s |
| | MA | 15.0 | 4 min 17 s |
| | SG-IMRT | 15.0 | 8 min 37 s |
| | 3D-CRT | 15.0 | 3 min 52 s |
| | CA | 20.0 | 3 min 25 s |
| | SWCA | 20.0 | 3 min 20 s |
| Lung | MA | 20.0 | 4 min 42 s |
| | SG-IMRT | 20.0 | 9 min 46 s |
| | 3D-CRT | 20.0 | 3 min 55 s |
| | CA | 1.8 | 2 min 08 s |
| | SWCA | 1.8 | 1 min 56 s |
| Prostate | MA | 1.8 | 2 min 35 s |
| | SG-IMRT | 1.8 | 4 min 10 s |
| | 3D-CRT | 1.8 | 2 min 11 s |
| | CA | 2.5 | 1 min 45 s |
| | SWCA | 2.5 | 1 min 55 s |
| Prostate | MA | 2.5 | 2 min 31 s |
| | SG-IMRT | 2.5 | 4 min 20 s |
| | 3D-CRT | 2.5 | 2 min 19 s |
| | CA | 12.0 | 2 min 06 s |
| | SWCA | 12.0 | 2 min 12 s |
| Liver | MA | 12.0 | 3 min 09 s |
| | SG-IMRT | 12.0 | 4 min 57 s |
| | 3D-CRT | 12.0 | 2 min 20 s |
| | CA | 6.0 | 1 min 48 s |
| | SWCA | 6.0 | 2 min 05 s |
| Spine RPC phantom | MA | 6.0 | 3 min 10 s |
| | SG-IMRT | 6.0 | 6 min 49 s |
| | 3D-CRT | 6.0 | 1 min 16 s |
| | CA | 6.6 | 2 min 31 s |
| | SWCA | 6.6 | 2 min 18 s |
| H&N RPC phantom | MA | 6.6 | 3 min 15 s |
| | SG-IMRT | 6.6 | 9 min 17 s |
| | 3D-CRT | 6.6 | 3 min 09 s |



## Then What?



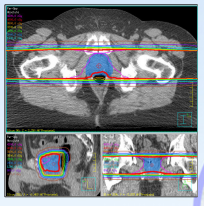
## Don't Worry, this is NOT Proton Symposium



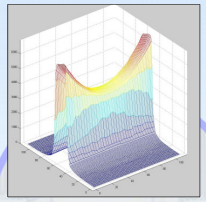

*"Dosimetry aspects of proton therapy"*
*Tech Cancer Res Treat 6 (4 Suppl):17-23, 2007*

## But We Don't Usually Use Single Photon Beam

Bi-Lateral Beams



Coronal Plane Dose





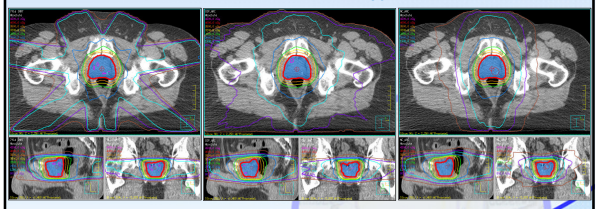
## Typical Photon Dose Distribution

Prostate SBRT Case
Prescribed Dose of 4000 cGy w/ 800 cGy / Fraction

7 Field Static IMRT

VMAT (Rotational Therapy)

Non-Coplanar Rotational with Unflattened Beams



3 Non-Coplanar Arcs w/ Couch 0, +30 and -30 Degrees

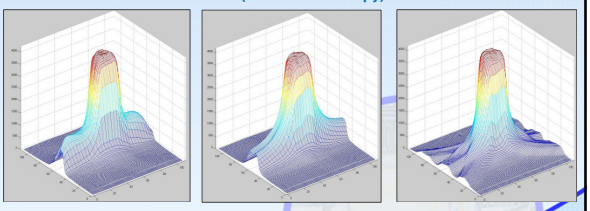


## Sampling the Isocenter Planar Dose

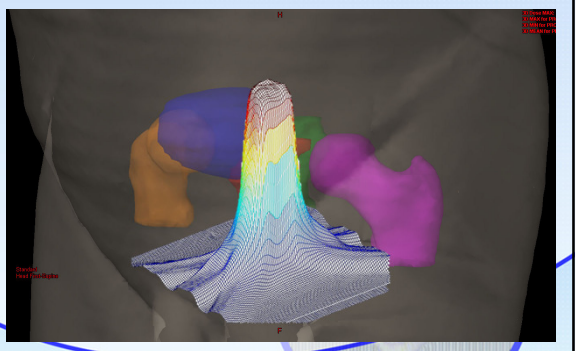
7 Field Static IMRT

VMAT (Rotational Therapy)

Non-Coplanar Rotational with Unflattened Beams



## Isn't This What We Are Fighting For?





## But How?



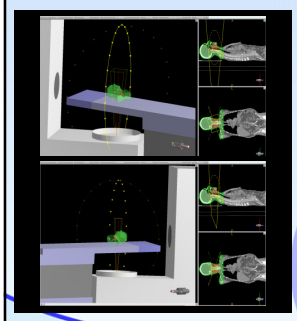
## Machines Deliver Non-Coplanar Beams

| C-Shape Linac | GammaKnife | CyberKnife | Vero |
|---|---|---|---|
|  |  |  |  |
| Rotational: Yes<br>Tx Time… | Rotational: No<br>Tx Time… | Rotational: No<br>Tx Time… | Rotational: Yes<br>Tx Time… |

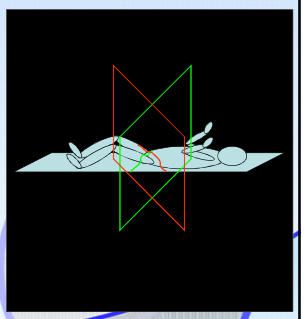
***And don't forget how high dose rate unflattened beam can help…***

## C-Shape Linac Non-Coplanar VMAT

**Head and Neck Case**



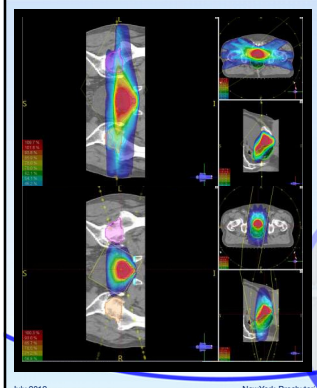
**Prostate Case**



*Slide courtesy of Ali Bani-Hashemi*



## Prostate with 2 Non-Coplanar Arcs

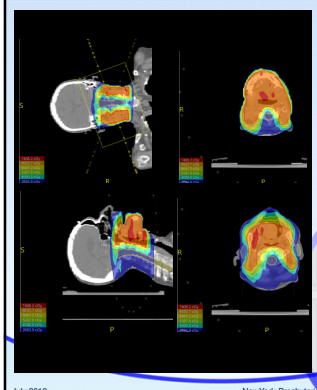


- Dose Spreading to Avoid Femoral Heads
- 11 MV Unflattened Beams
- Table at +/- 15°
- Rx Dose: 200 cGy per Fraction
- Total of 320 MU per Fraction, 350° Arcs
- Gantry Speed ~2°/sec
- Tx Delivery Time ~ 3 min

*Slide courtesy of Ali Bani-Hashemi*



## H&N with 2 Non-Coplanar Arcs



- Dose Spreading to Avoid Parotid Glands
- 7 MV Unflattened Beams
- Table at +/- 20°
- Rx Dose: 200 cGy per Fraction
- Total of 462 MU per Fraction
- Gantry Speed ~2.5°/sec
- Tx Delivery Time ~ 4 min

*Slide courtesy of Ali Bani-Hashemi*

## C-Shape Linac Potential Collision Issue

- **Patient Safety**
- **Time Efficiency**

| | | | | |
|---|---|---|---|---|
| SBRT #1 | Static IMRT FF | 800cGy x 5fx | 1371 mu | 5min beam on (coplanar) |
| SBRT #2 | Static IMRT FF | 1000cGy x 5fx | 2684 mu | 17min beam on (non-coplanar) |



## Searching for Non-Collision Sub-Arcs

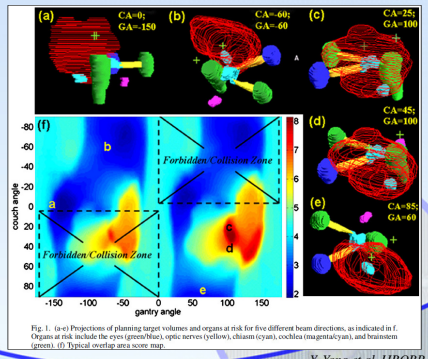


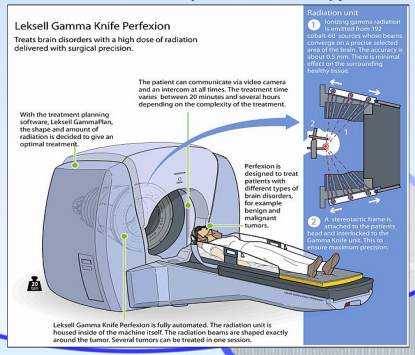

Fig. 1. (a-e) Projections of planning target volumes and organs at risk for five different beam directions, as indicated in f. Organs at risk include the eyes (green/blue), optic nerves (yellow), chiasm (cyan), cochlea (magenta/cyan), and brainstem (green). (f) Typical overlap area score map.

*Y. Yang et al. IJROBP Vol. 80 No. 4*



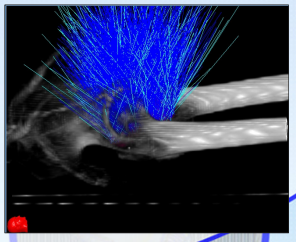
## GammaKnife Non-Coplanar Beams

**GammaKnife Provides 39° Non-coplanar Conical Therapy**



## CyberKnife

**CyberKnife Provides Anterior Non-Coplanar Beams**





## Mitsubishi Vero

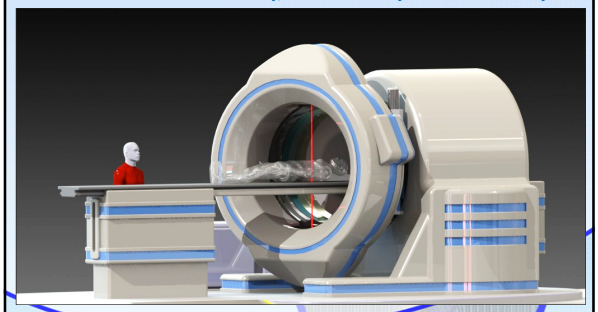

O-ring: Rotate $360^0$
Skew $\pm 60^0$



## ArcKnife

## A New Design of Non-Coplanar Rotational Linac

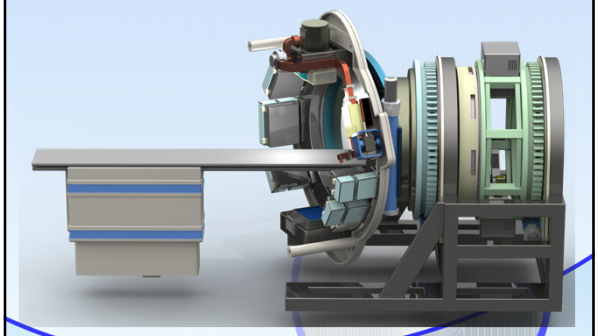
Joined efforts from Columbia University, Cornell University and NewYork-Presbyterian



*Slide courtesy of John Cheeseborough*



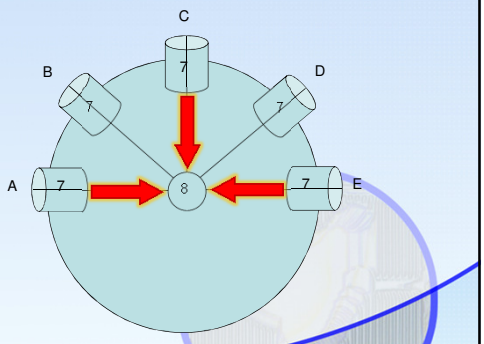
## Beam Directed by Two Rotational Rings



*Slide courtesy of John Cheeseborough*

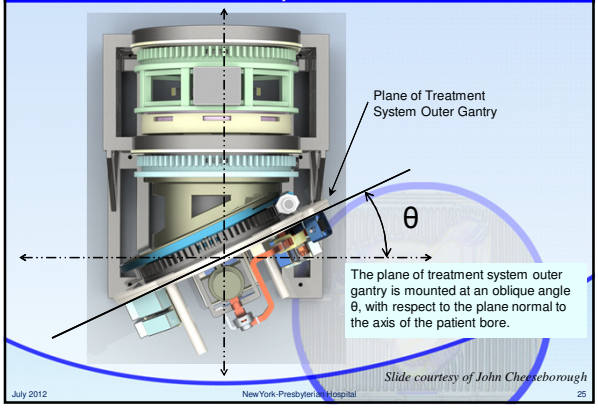


## Double-Ring Mechanism Front View




*Slide courtesy of John Cheeseborough*

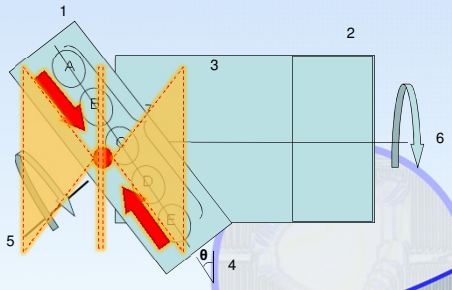
## View From Top of the Machine




*Slide courtesy of John Cheeseborough*



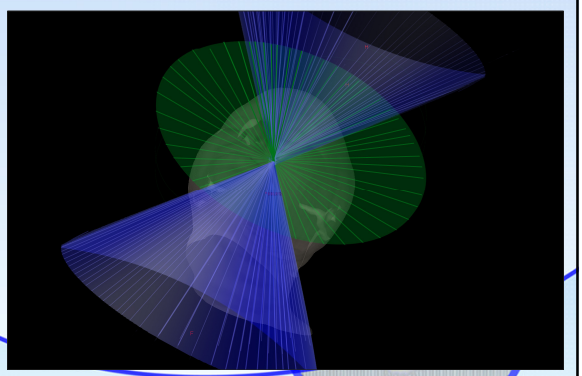
## Double-Ring Mechanism Top View



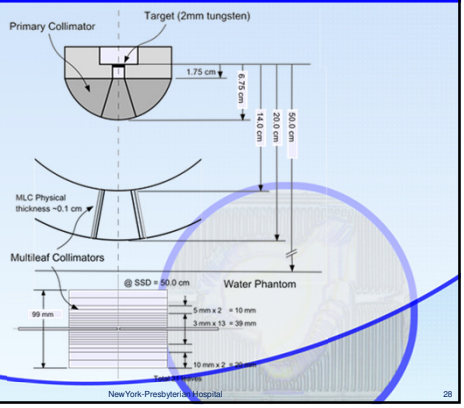

*Slide courtesy of John Cheeseborough*



## Conical Non-Coplanar Rotational Beams

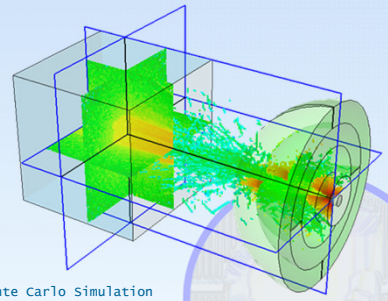


## Preliminary Machine Geometry






## Monte Carlo Beam Data Simulation



**FLUKA**[1] Monte Carlo Simulation

-Ver.: 2008.3c.0

-Displayed by SimpleGeo/DaVis3D

[1]*The MC code is developed by INFN and CERN*



## Taking Advantage of Unflattened Beam

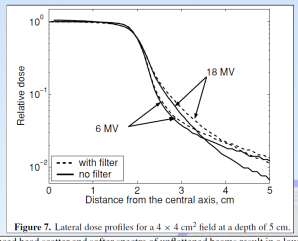
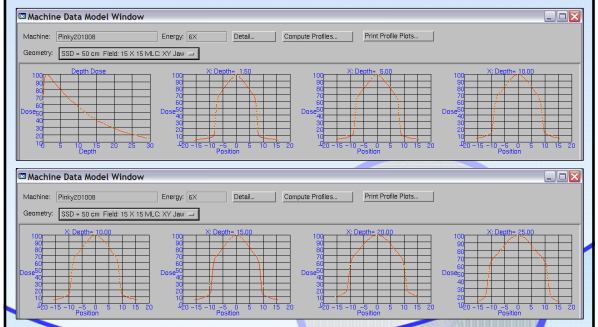



**Figure 7.** Lateral dose profiles for a 4 × 4 cm$^2$ field at a depth of 5 cm.

Reduced head scatter and softer spectra of unflattened beams result in a lower out-of-field dose. Measured flattened and unflattened beam profiles for a small field size (4 × 4 cm$^2$) at a depth of 5 cm are shown in figure 7. For this comparison, the flat profile is normalized to 1 on the central axis, and the nonflat profile is normalized so that the two profiles intersect at the off-axis distance equal to 80% of the field size. The dose at 4 cm off-axis distance is lower in unflattened beams by 15% (6 MV) and 43% (18 MV). Farther away from the field the dose tends to decrease faster with increasing distance than in flattened beams. There is less reduction in larger fields. Faster lateral dose fall-off outside the treatment field will result in lower doses to normal tissues. The main reason for the faster fall-off is that the flattening filter elevates relative fluence of primary photons propagating off-axis.

*O Vassiliev et al., PMB 51 (2006) 1907-1917*

## Pinnacle Tx Plan Beam Modeling





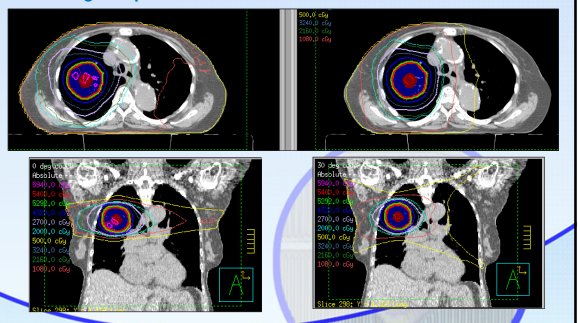

## Lung Cancer Case Study

- Prescription: 18 Gray for 3 Fractions
- Lung Volume: 2844.7 $cm^3$
- Tumor Volume:
  - Pt 1: PTV ~ 36.42 $cm^3$ (1cm GTV, ±1cm ITV, +0.5cm PTV)
  - Pt 2: PTV ~ 114.65 $cm^3$ (3cm GTV, ±1cm ITV, +0.5cm PTV)
  - Pt 3: PTV ~ 268.1 $cm^3$ (5cm GTV, ±1cm ITV, +0.5cm PTV)
- Plans to be Compared:
  - Static Field IMRT (FF)
  - Coplanar VMAT (FF)
  - Non-Coplanar VMAT (FFF)



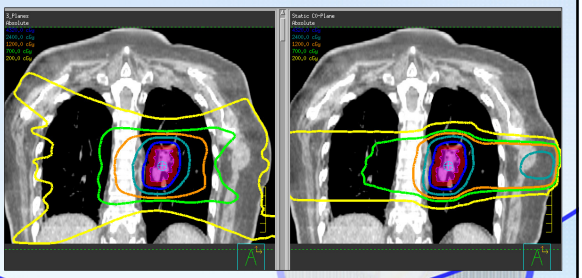
## Tx Plan Comparison

**Single Coplanar VMAT** **Multiple Non-Coplanar VMAT**



## Butterfly Shaped Isodose Distribution

**Multiple Non-Coplanar VMAT (FFF)** **Static Coplanar IMRT (FF)**





## Plan Quality Quantitative Evaluation

- **RTOG CI** = PV/TV, where PV is the prescription volume, and TV is the target volume (=1 is a perfect plan)
- **Paddick CI** = $(TVPV)^2/(TV \times PV)$, where PV is the prescription volume, TVPV is the target volume within the prescribed isodose surface, and TV is the target volume ($\leq$ 1, closer to unity is better)
- **Paddick GI** = PV50%/PV, where PV50% is 50% of the prescription volume isodose line, and PV is the prescription volume (lower is better)



## Plan Quality Comparison Table

**PTV = 36.4 $cm^3$**

| | IMRT | Coplanar VMAT | Non-Coplanar VMAT |
|---|---|---|---|
| $TV_{PV}$ | 33.99 | 33.54 | 33.55 |
| RTOG CI | 1.00 | 0.99 | 0.97 |
| CI | 0.87 | 0.86 | 0.88 |
| GI | 5.65 | 5.43 | 4.36 |

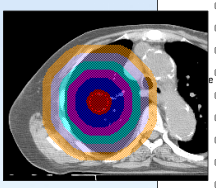
**PTV = 114.7 $cm^3$**

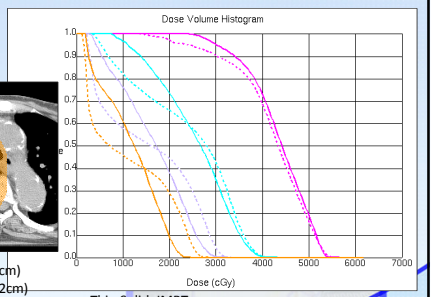
| | Coplanar VMAT | Non-Coplanar VMAT |
|---|---|---|
| $TV_{PV}$ | 108.86 | 108.45 |
| RTOG CI | 0.98 | 0.97 |
| CI | 0.92 | 0.93 |
| GI | 4.65 | 4.09 |

**PTV = 268.1 $cm^3$**

| | Coplanar VMAT | Non-Coplanar VMAT |
|---|---|---|
| $TV_{PV}$ | 255.69 | 255.32 |
| RTOG CI | 1.33 | 1.12 |
| CI | 0.60 | 0.71 |
| GI | 3.71 | 3.59 |

## Using DCR to Evaluate Dose Fall-Off





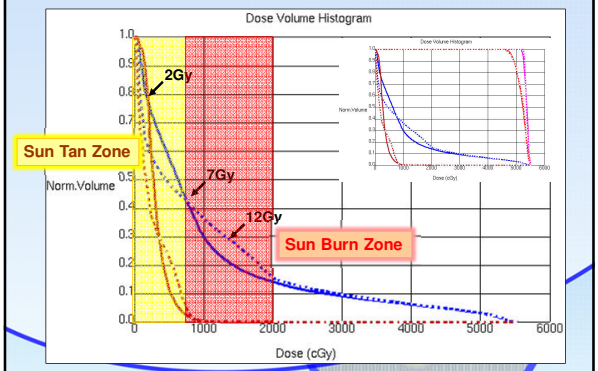

- Purple: dcr1 (PTV+1cm)
- Skyblue: dcr2 (PTV+2cm)
- Lavender: dcr3 (PTV+3cm)
- Orange: dcr4 (PTV+4cm)

DCR (Dose Constrain Rings)

- Thin Solid: IMRT
- Medium Dashed: Coplanar VMAT
- Medium Solid: Non-Coplanar VMAT



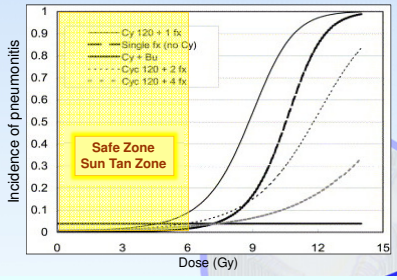
## Lung Dose Volume Histogram






## Biological Lung Irradiation Response

**Dose response of interstitial pneumonitis after whole lung irradiation for TBI**




Dose response functions are shown for 1, 2, and 4 fractions combined with 120 mg/kg Cy given over 2 days. A single-dose dose response function without any Cy is shown, as well as the incidence of IP using Cy + Bu without XRT as the conditioning regimen.

Cy = cyclophosphamide; BU = busulfan;

*Sampath et al. IJROBP 2005, 63:876*

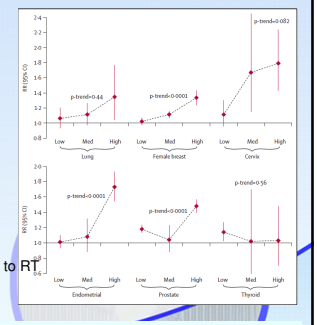
## Very Few 2nd Cancers Attributable to Radiotherapy in Adults

647,672 adult (≥20 y/o at diagnosis) cancer survivors in US SEER registries. Survived >5 years

Survivors of 15 types of cancers Over 30 years of follow-up

60,271 (9%) developed 2nd cancers

3,266 **(0.001%)** of them might be related to RT




*Amy Berrington de Gonzalez, Lancet Oncol 2011; 12: 353–60*



# Conclusion



## Non-Coplanar Rotational Therapy

- The rationale for unflattened beam – the Speed!
- The rotational VMAT delivery increase the speed even more
- For the time saved, we propose to do non-coplanar VMAT to gain more dose distribution advantage
- The non-coplanar rotational beam has reduced the mid dose volume with larger low dose spread
- Not every facility can afford the built-up cost for proton therapy, non-coplanar VMAT might provide an affordable solution as to the similar dose fall-off

## Non-Coplanar Rotational Therapy

- The non-coplanar techniques has been discussed
- The hurdles by using C-Shaped Linac for non-coplanar rotational delivery has ben discussed
- A new design for non-coplanar conical rotational Tx delivery technique – ArcKnife has been introduced
- The ArcKnife Tx plan evaluation and dose distribution has been presented
- Biological and clinical implication of sun tan zone (low dose bath) and sun burn zone (hot spot) for both NTCP and 2nd cancer incidence has been addressed



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