VMAT Treatment Planning

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Swedish Medical Center

- Founded in 1910 by Dr. Nils Johanson and a group of Seattle's leading Swedish-born businessmen.
- We treat 225 radiation oncology patients each day.

Acknowledgments

- Vivek Mehta
- Daliang Cao
- Min Rao
- Fan Chen
- Kevin Brown
- Rajinder Dhada
- Ke Sheng

Disclaimer

- Our IMAT work is sponsored in part through a grant from Elekta.

Objectives

1) To provide an overview of VMAT capable treatment planning systems.
2) To review VMAT planning techniques and tools for creating optimal VMAT plans
3) To examine the quality of plans that can be obtained using VMAT

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VMAT Treatment Planning

First Generation IMAT 2000-2007

- Treatment plans were developed using forward planning or simple beam shaping based on the patient's anatomy.
- The dose rate was constant as the gantry rotated around the patient.

Next Generation IMAT 2008-

- Treatment plans with full inverse planning.
- The dose rate varies as the gantry rotates around the patient.

IMAT Inverse Planning Solutions

- Varian → Eclipse RapidArc
- Philips → Pinnacle SmartArc
- Elekta → ERGO++
- Elekta → Monaco VMAT
- Nucletron → Oncentra MasterPlan VMAT
- Siemens/Prowess → Prowess Panther

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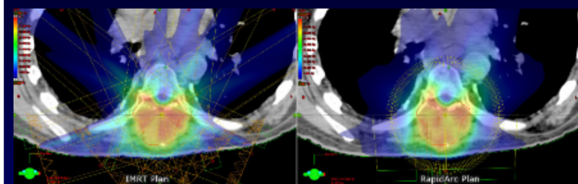
Varian Eclipse



- Planning is performed using Direct Aperture Optimization.
- Typical plan uses 1 arc with 177 control points.
- For some cases, multiple arcs are use to improve the plan quality or provide adequate coverage of large targets.

Direct aperture optimization: A turnkey solution for step-and-shoot IMRT

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(Received 26 September 2001; accepted for publication 12 March 2002; published 13 May 2002)

IMRT treatment plans for step-and-shoot delivery have traditionally been produced through the optimization of intensity distributions (or maps) for each beam angle. The optimization step is followed by the application of a leaf-sequencing algorithm that translates each intensity map into a set of deliverable aperture shapes. In this article, we introduce an automated planning system in which we bypass the traditional intensity optimization, and instead directly optimize the shapes and the weights of the apertures. We call this approach "direct aperture optimization." This technique allows the user to specify the maximum number of apertures per beam direction, and hence provides significant control over the complexity of the treatment delivery. This is possible because the machine dependent delivery constraints imposed by the MLC are enforced within the aperture optimization algorithm rather than in a separate leaf-sequencing step. The leaf settings and the aperture intensities are optimized simultaneously using a simulated annealing algorithm. We have tested direct aperture optimization on a variety of patient cases using the EGS4/BEAM Monte Carlo package for our dose calculation engine. The results demonstrate that direct aperture optimization can produce highly conformal step-and-shoot treatment plans using only three to five apertures per beam direction. As compared with traditional optimization strategies, our studies demonstrate that direct aperture optimization can result in a significant reduction in both the number of beam segments and the number of monitor units. Direct aperture optimization therefore produces highly efficient treatment deliveries that maintain the full dosimetric benefits of IMRT. [DOI: 10.1118/1.1477415]

Key words: IMRT, inverse treatment planning, optimization, intensity modulation

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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
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DAO for IMAT

- The key feature of DAO is that all of the delivery constraints are included directly into the IMAT optimization.
- The optimizer starts by matching the shapes to the BEV of the target.
- Throughout the optimization the MLC leaf position are optimized but they are never allowed to violate the delivery constraints.

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DAO Optimization

- A simulated annealing algorithm is used to optimize the MLC leaf positions and aperture weights.
- After each change in an MLC leaf position, the algorithm checks to see if any of the delivery constraints are violated. If so, the change is rejected.
- Otherwise, the change is accepted based on the rules of simulated annealing.

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Volumetric modulated arc therapy: IMRT in a single gantry arc

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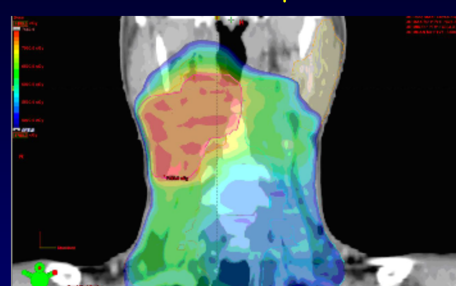
(Received 25 June 2007; revised 21 September 2007; accepted for publication 5 November 2007; published 26 December 2007)

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

Eclipse VMAT

- In Otto's paper, he used DAO to produced IMAT plans.
- Key innovations:
  1. Focused on a single arc approach with more control points in the single arc. Termed "VMAT".
  2. Progressive sampling was used to improve the speed of the algorithm.
- This is the approach utilized in Eclipse

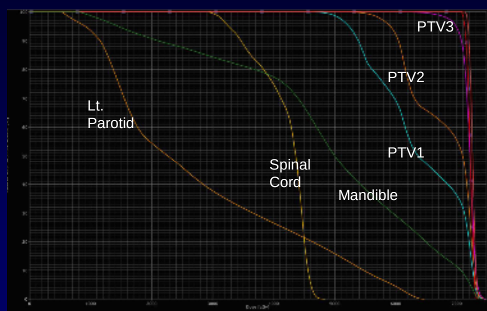
Varian Eclipse



- Composite dose for H&N patient treated at UMMS.
- Initial = 50.4 Gy, SFB1 = 9Gy, SFB2=10.8Gy

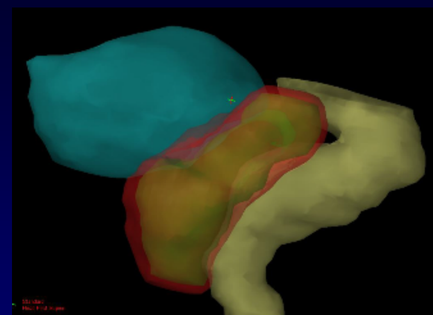
Courtesy of Warren D'Souza

Varian Eclipse



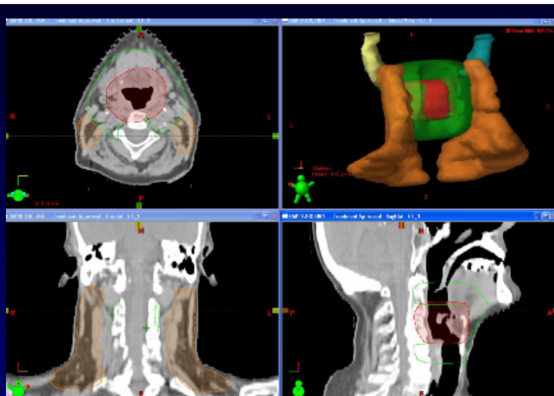
- Initial plan and SFB1 used 2 arcs, SFB2 used 1 arc
- Delivery time = 1.5 minutes per arc

Courtesy of Warren D'Souza



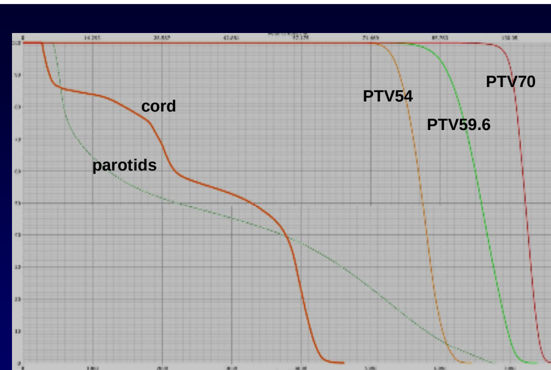
- Prostate and seminal vesicles plotted with 97% iso-cloud.
- 1 arc, 652 MUs, 1.7 minute delivery

Courtesy of Shirley Small



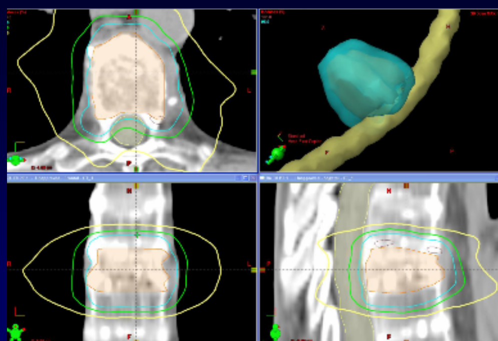
- H&N prescription levels of 54, 59.6, and 70 Gy

Courtesy of Shirley Small



- 1 arc, treatment time ≈ 2 minutes

Courtesy of Shirley Small



- Spine SBRT, 2 arcs, 4 minute delivery
- 95, 80, 50% isodose lines

Courtesy of Shirley Small

Elekta VMAT

- Anatomy based inverse planning is available (Ergo++).
- Full inverse planning solution is under development (Monaco)

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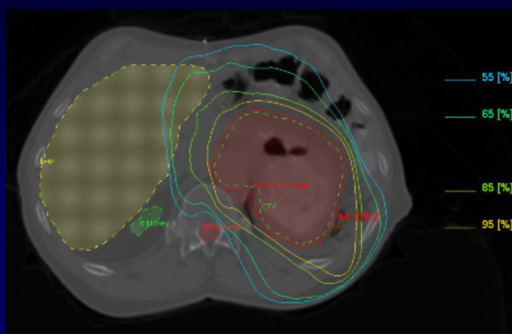
Ergo++ (1)

- Ergo++ is a treatment planning system developed by 3DLine, a company based in Milan Italy.
- Ergo++ was originally designed for planning dynamic arcs delivered using the 3DLine mMLC.
- 3DLine was acquired by Elekta in 2007.

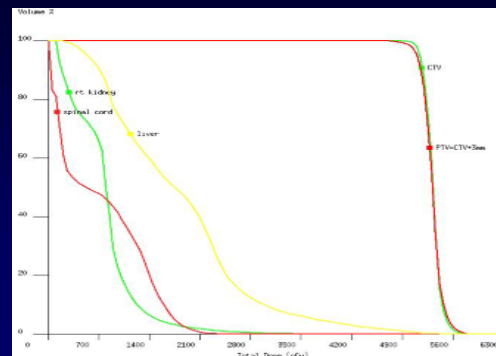
Ergo++ (2)

- Elekta modified Ergo++ to provide VMAT planning capabilities.
- For VMAT, Ergo++ designs the beam shapes based simply on the patient's anatomy.
- The beam weights within a given arc are then optimized.

Ergo++ - Pancreas



Ergo++ - Pancreas



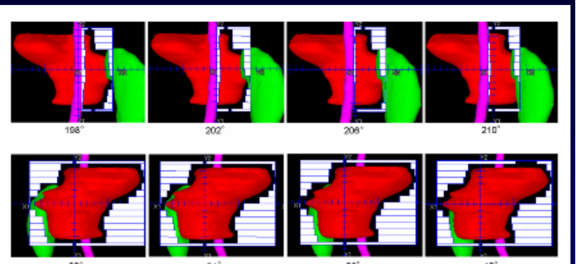


Fig. 5 MLC shapes of eight beam angles within the arc of the anatomy-based VMAT plan for a pancreas case (Case 3). Red: PTV, Green: Rt kidney, Purple: spinal cord.

Anatomy Based Inverse Planning

Plan Quality

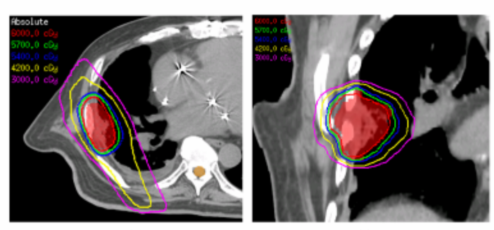


Fig. 3 Isodose plot for anatomy-based VMAT plan for a lung cancer patient. (A) Axial slice. (B) Coronal slice

Anatomy Based Inverse Planning
Plan Quality

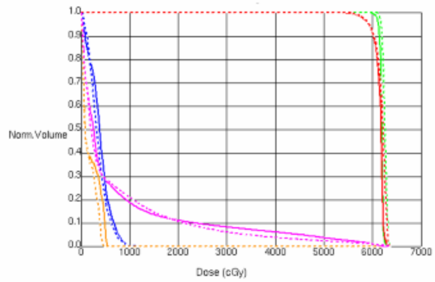


Fig. 4 DVH comparison for a lung case (Case 2). Solid lines = Anatomy-based VMAT. Dashed lines = Aperture-based VMAT. Green: GTV, red: PTV, purple: total lung volume, blue: heart, orange: spinal cord.

Anatomy Based Inverse Planning
Plan Quality

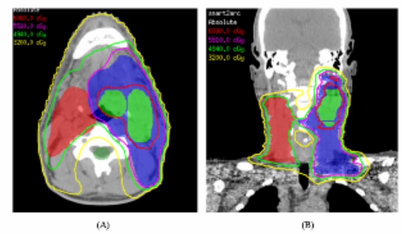


Fig. 12 Isodose plot for aperture-based VMAT plan for a HN cancer patient (Case 6). (A) Axial slice. (B) Coronal slice

Anatomy Based Inverse Planning
Plan Quality

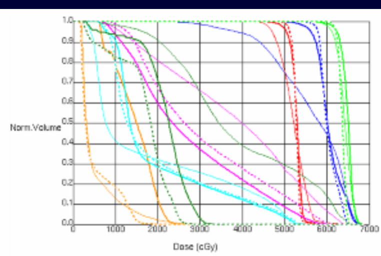


Fig. 13 DVH comparison for a HN case (Case 6). Thin solid lines = Anatomy-based VMAT. Thick solid lines = Fluence-based VMAT. Dashed lines = Aperture-based VMAT. Green: PTV1, Blue: PTV2, Red: PTV3, Dark green: spinal cord, Orange: Brain stem, Purple: Lt parotid, Sky-blue: Rt parotid.

Ergo++

- As an anatomy based solution, Ergo++ is not as sophisticated as a full inverse planning tool such as found in Eclipse.
- It can, however, match the plan quality of fixed field IMRT for convex target shapes.

The use of anatomy based inverse planning for IMAT:

0% 1. Directly optimizes the MLC leaf positions
0% 2. Provides plan quality consistently better than fixed field IMRT.
0% 3. Should provide high quality dose distributions for convex targets.
0% 4. Requires progressive sampling
0% 5. Utilizes a sweeping window delivery technique.

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Answer:

- Anatomy based inverse planning should provide high quality dose distributions for convex targets.

Monaco VMAT

Monaco Background (1)

- Markus Alber, a researcher at the University of Tübingen developed a treatment planning system called Hyperion.
- Two key feature of Hyperion are: (1) Monte Carlo based dose calculation and (2) Biology based IMRT optimization.
- Computerized Medical Systems (CMS) licensed the Hyperion system and created a commercial version called Monaco.

Monaco Background (2)

- Monaco 1.0 was released July 2007 as an IMRT-only planning system.
- In 2008, Elekta acquired CMS and began work to put a VMAT inverse planning solution into Monaco.
- Beta versions of the VMAT solution shipped in spring of 2010.

Monaco VMAT Algorithm

- First optimized fluence maps are produced at a series of discrete beam angles.
- These optimized fluence are then converted into deliverable VMAT arcs.

Monaco – Sweeping Window

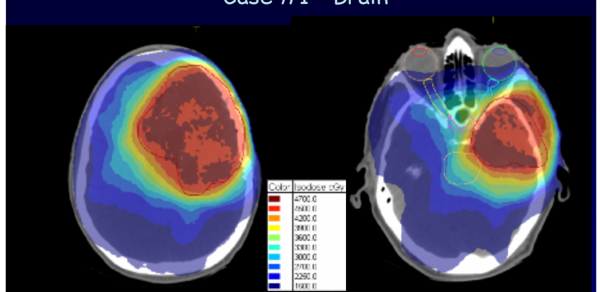
- Monaco produces plans using a "sweeping leaf sequencer" where the leaves move unidirectionally across the field.
- The leaf movement continues to alternate between sectors of the arc.

Sweeping-window arc therapy: an implementation of rotational IMRT with automatic beam-weight calculation

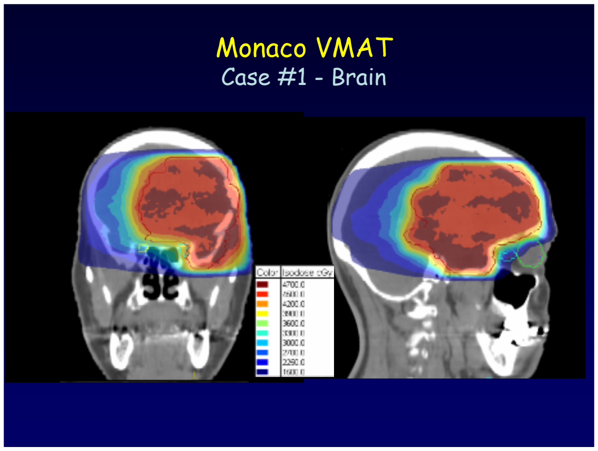
C Cameron 2005 *Phys. Med. Biol.* **50** 4317-4336 doi: 10.1088/0031-9155/50/18/006 Help

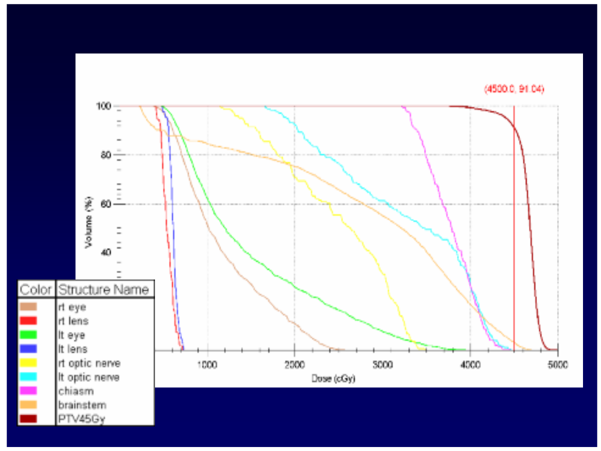
Monaco VMAT

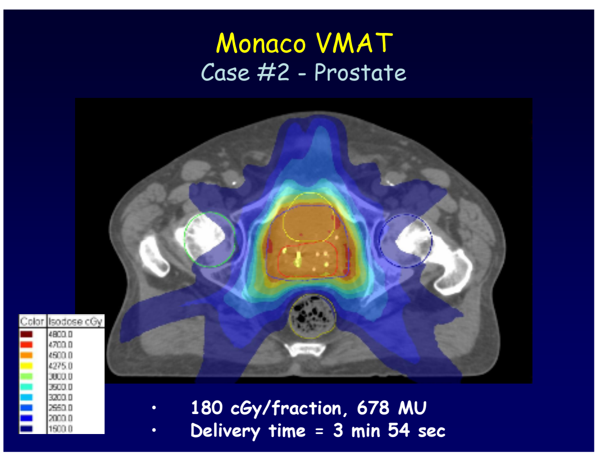
Case #1 - Brain

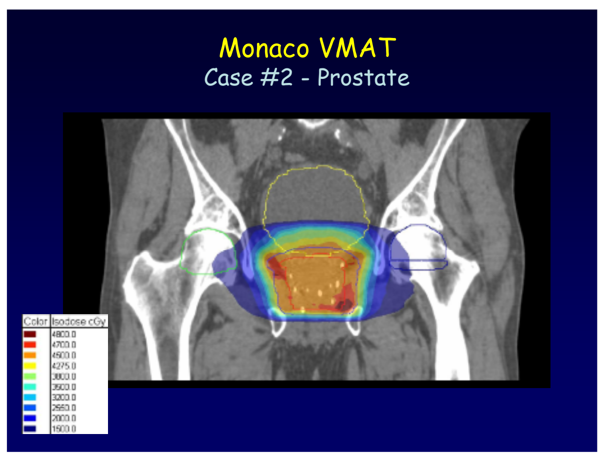


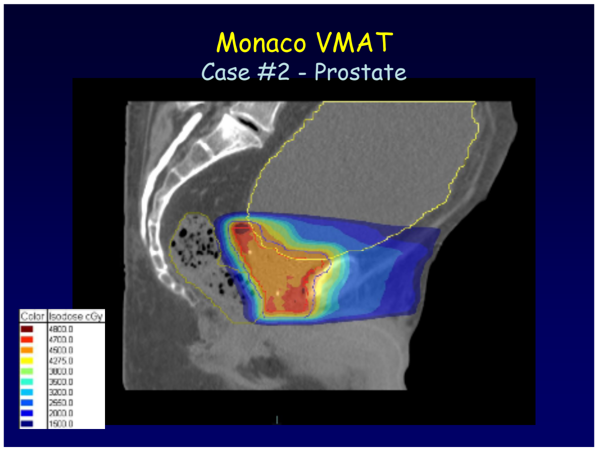
- 180 cGy/fraction, 320 MU
- Delivery time = 4 min. 40 sec.

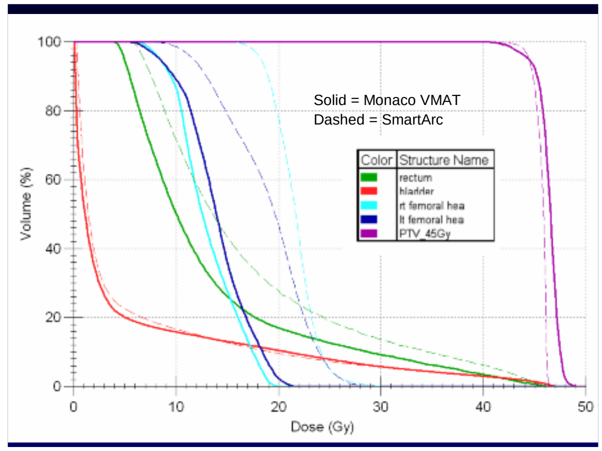

Monaco VMAT
Case #1 - Brain
Color
Isodose cGy
4700.0
4200.0
3600.0
3000.0
2250.0

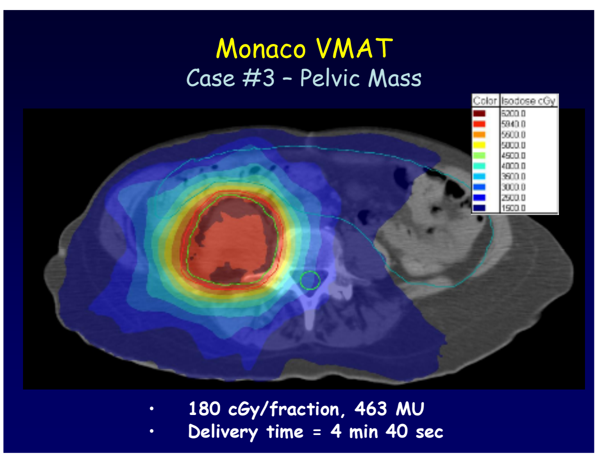

(4500.0, 91.04)
100
80
60
40
Volume (%)
1000
2000
3000
4000
5000
Dose (cGy)
Color
Structure Name
rt eye
rt lens
lt eye
lt lens
rt optic nerve
lt optic nerve
chiasm
brainstem
PTV45Gy

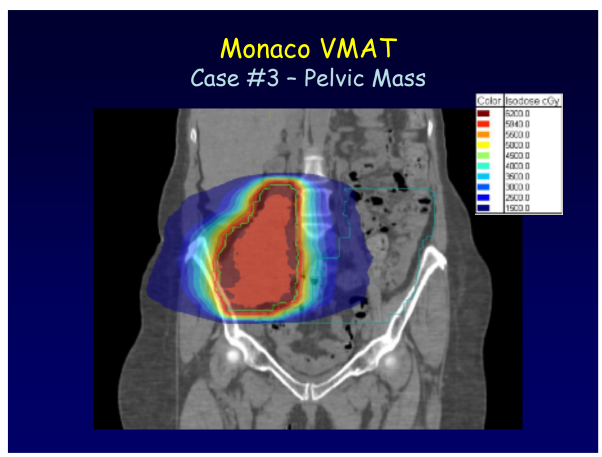

Monaco VMAT
Case #2 - Prostate
Color
Isodose cGy
4800.0
4700.0
4500.0
4275.0
3200.0
2550.0
2000.0
1500.0
180 cGy/fraction, 678 MU
Delivery time = 3 min 54 sec


Monaco VMAT
Case #2 - Prostate
Color
Isodose cGy
4800.0
4700.0
4500.0
4275.0
3200.0
2550.0
2000.0
1500.0


Monaco VMAT
Case #2 - Prostate
Color
Isodose cGy

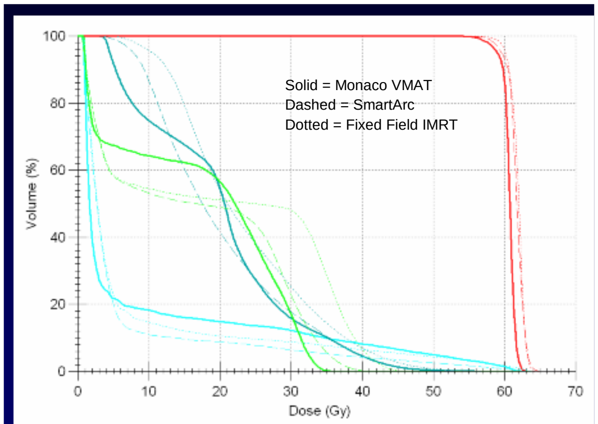

Solid = Monaco VMAT
Dashed = SmartArc
Color
Structure Name
rectum
bladder
rt femoral hea
lt femoral hea
PTV_45Gy
Volume (%)
Dose (Gy)
100
80
60
40
20
0
0
10
20
30
40
50


Monaco VMAT
Case #3 – Pelvic Mass
Color
Isodose cGy
• 180 cGy/fraction, 463 MU
• Delivery time = 4 min 40 sec

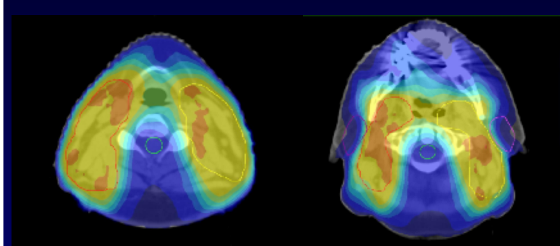

Monaco VMAT
Case #3 – Pelvic Mass
Color
Isodose cGy

Monaco VMAT
Case #3 – Pelvic Mass

- Pelvis: 180cGy/fx (5940), 463MU
- Delivery time = 4min 40sec

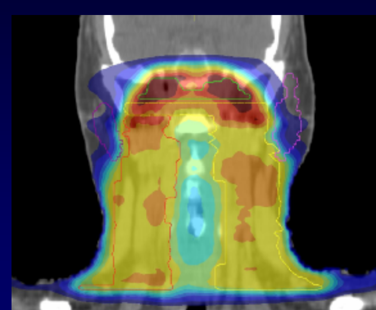


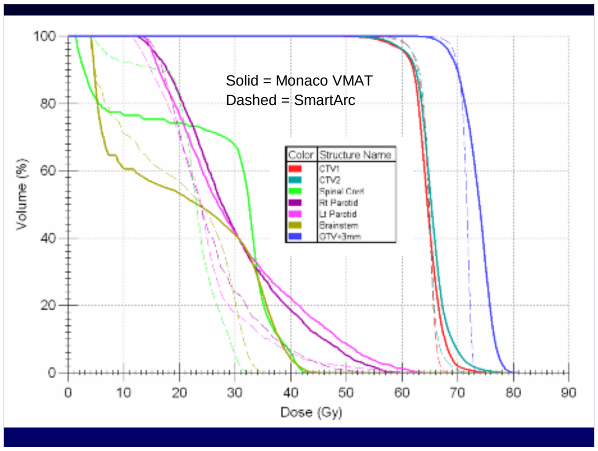
Monaco VMAT
Case #4 – H&N



- 200 cGy/fraction, 847 MU
- Deliver time = 12 min 44 sec

Monaco VMAT
Case #4 – H&N





Monaco - Summary

- Monaco will serve as Elekta's VMAT planning solution.
- Monaco VMAT is in Beta testing.
- Initial results are promising, but it is unclear if Monaco VMAT works well for the most complex cases.

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Philips Pinnacle³ SmartArc

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Philips Pinnacle - SmartArc

- SmartArc is an extension of the DMPO planning functionality in Pinnacle.
- The SmartArc planning tools were developed by RaySearch (Stockholm).

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SmartArc Features

- Works with VMAT-capable Varian and Elekta linacs
- Plans can be created with constant or variable dose rates
- Single or multiple arcs covering 90 to 360°
- Dose objectives can be changed during optimization
- Coplanar or non-coplanar plans

Courtesy Kevin Reynolds

SmartArc Planning Steps

1. Add a dynamic arc beam
2. Specify couch, collimator, and beam angles
3. Specify dose objectives
4. Specify SmartArc optimization parameters
5. Optimize
6. Compute final convolution dose

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Courtesy Kevin Reynolds

SmartArc Optimization (1)

1. Beams are generated at the start and the stop angles and at 24° increments from the start angle.
2. A fluence map optimization is performed.
3. The fluence maps are sequenced and filtered so that there are only 2 control points per initial beam angle.

Courtesy of Philips Medical

SmartArc Optimization (2)

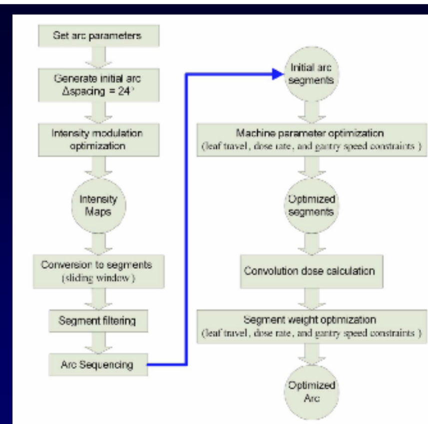
4. These control points are distributed to adjacent gantry angles and additional control points are added to achieve the desired final gantry spacing.
5. All control points are processed to comply with the motion constraints of VMAT.

Courtesy of Philips Medical

SmartArc Optimization (3)

6. The DMPO algorithm is applied with an aperture based optimization that takes into account all of the VMAT delivery constraints.
7. The jaws are conformed to the segments based on the characteristics of the linac.

Courtesy of Philips Medical



Courtesy of Philips Medical

SmartArc Plan Quality

- An alpha version of the SmartArc module was installed in our clinic in February 2009.
- For a series of cases, the accuracy of the predicted dose was verified using the IBA MatriXX 2D ion chamber array inserted in a MULTICube Phantom.

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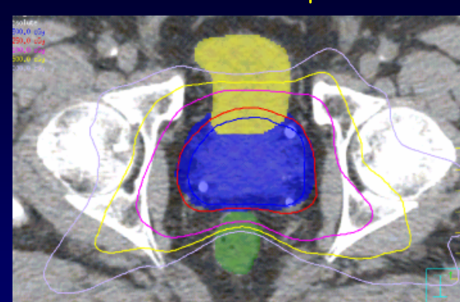
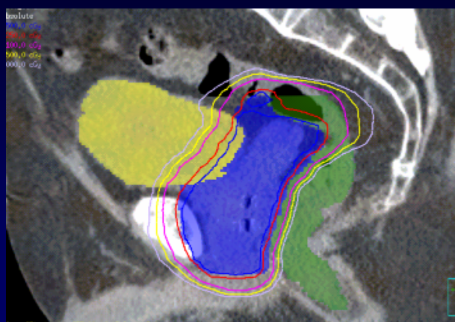
Prostate Example

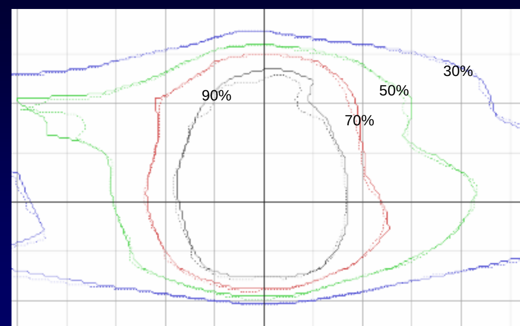


- 1 arc, 180 cGy/fraction
- 480 monitor units, 1.75 minutes

Prostate Example



Prostate Verification



case	Treatment site	# of Arcs	MU	Daily Dose (Gy)	Delivery time (sec)	QA passing rate (%)
1	H&N	2	640	1.8	265	98.6
2	H&N	2	683	2.0	313	96.0
3	H&N	3	545	2.0	317	99.6
4	H&N	3	560	2.0	390	99.8
5	Lung	1	904	4.0	140	99.0
6	Lung	1	595	3.0	124	98.6
7	Prostate	1	481	1.8	105	99.9
8	Prostate	1	600	2.6	129	98.6
9	Prostate	1	526	2.6	112	99.1

Clinical Implementation of SmartArc

- After extensive testing and validation, we began using SmartArc clinically in June 2009 under an IRB protocol.
- We began using it more frequently after the official release of Pinnacle 9.0.

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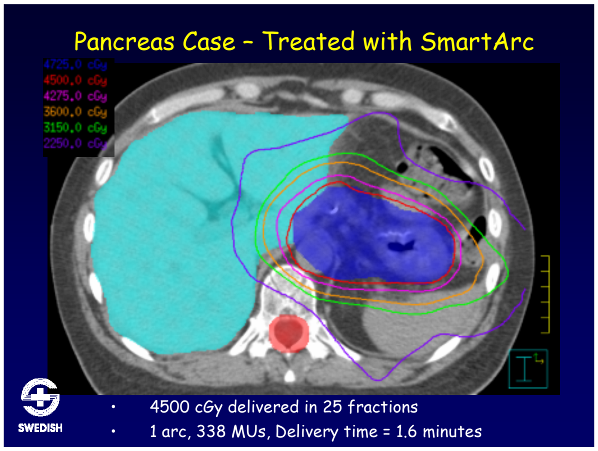
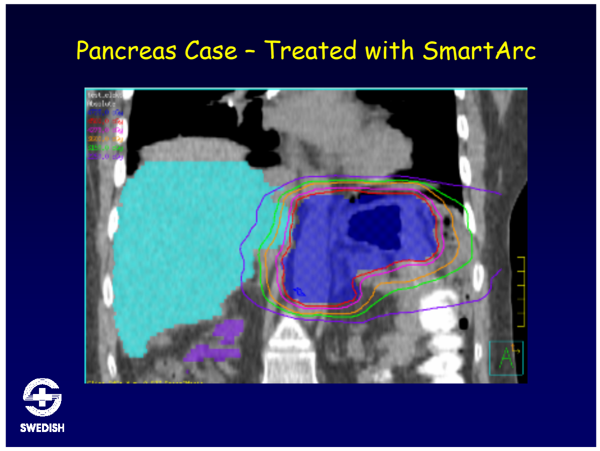

Pancreas Case – Treated with SmartArc
4725.0 cGy
4500.0 cGy
4275.0 cGy
3600.0 cGy
3150.0 cGy
2250.0 cGy
SWEDISH
• 4500 cGy delivered in 25 fractions
• 1 arc, 338 MUs, Delivery time = 1.6 minutes


Pancreas Case – Treated with SmartArc
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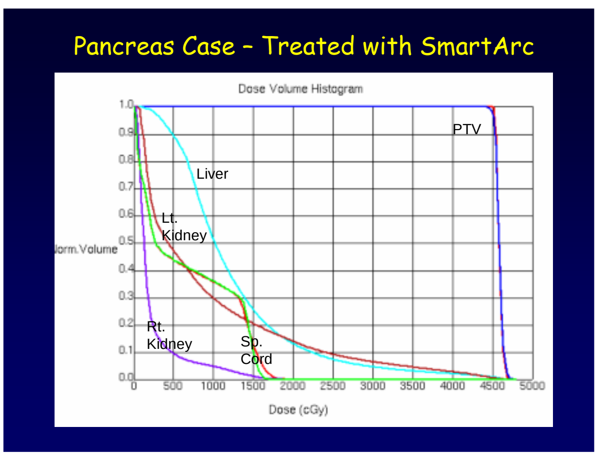
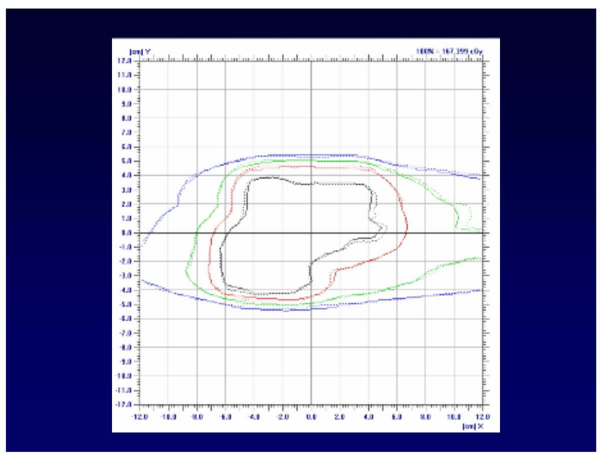
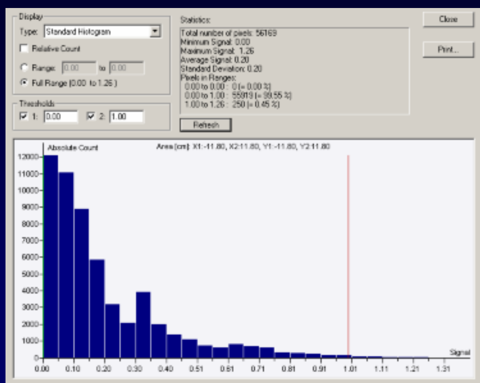
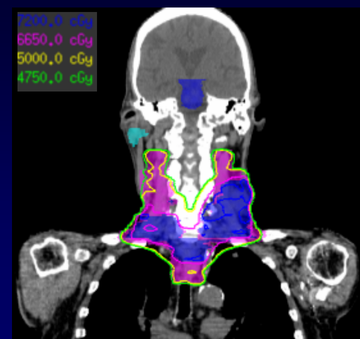

Pancreas Case – Treated with SmartArc
Dose Volume Histogram
PTV
Liver
Lt. Kidney
Rt. Kidney
Sp. Cord
Norm.Volume
Dose (cGy)



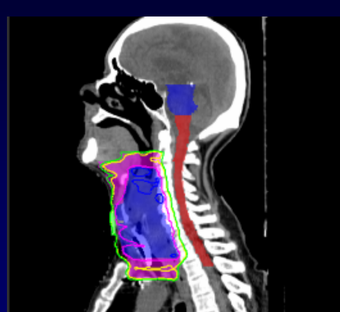


H&N – Treated with SmartArc

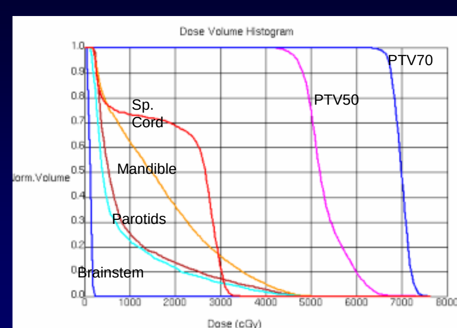


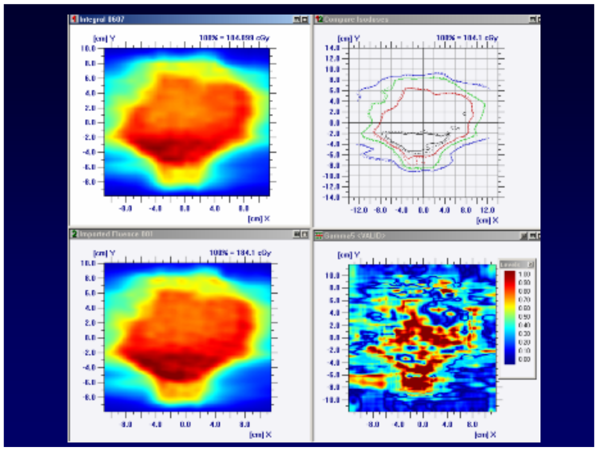
- 2 arc H&N delivery

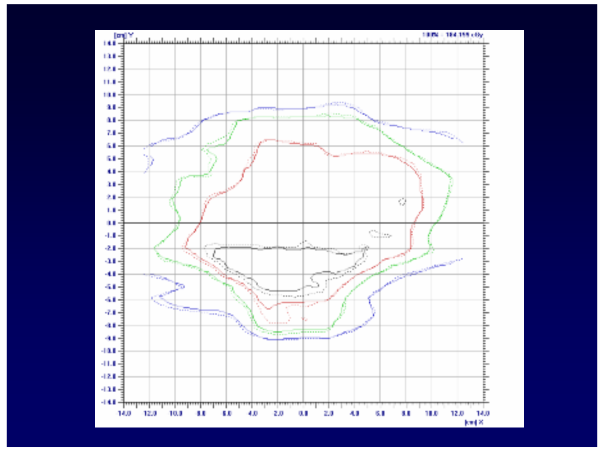
H&N – Treated with SmartArc



H&N – Treated with SmartArc







Summary of SmartArc Clinical Cases

- 30 patients treated covering a variety of treatment sites including lung, head-and-neck, liver, pancreas, esophagus, brain, and chest wall.
- 1 arc used in 19 cases
- 2 arcs used in 11 cases.
- Average delivery time: 1 arc cases = 1.9 minutes, 2 arc cases = 3.9 minutes.

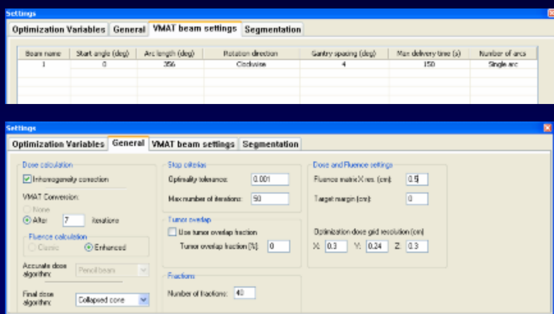
SWEDISH

Nucletron – Oncentra VMAT

- The Oncentra VMAT module was developed by RaySearch Laboratories, a software development company located in Stockholm.
- RaySearch also developed the SmartArc module for Pinnacle.
- The underlying VMAT planning engine is the same.

SWEDISH

Nucletron – Oncentra VMAT

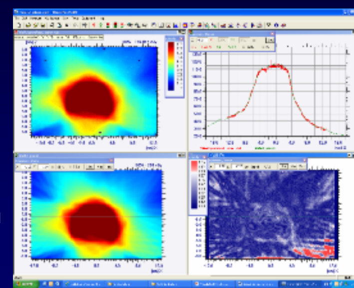


Prostate Verification

1-arc VMAT γ(3%,1mm)

planned

measured

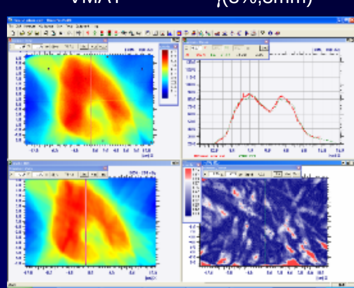


H&N Verification

VMAT γ(3%,3mm)

planned

measured



Nucletron – Oncentra VMAT

- Oncentra VMAT was released in December 2009.
- 14 sites have been installed in Europe (non are clinical).
- No sites in the U.S. at this time.

SWEDISH

Siemens/Prowess CBT

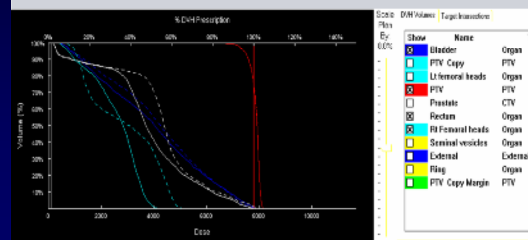
- Prowess' Direct Aperture Optimization algorithm is used to develop VMAT plans for delivery on Siemens linacs.

SWEDISH

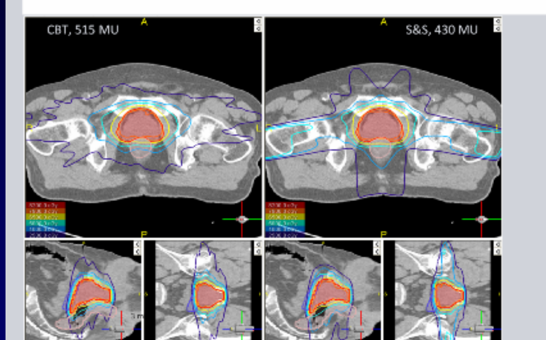
SIEMENS

Prostate IMRT (S&S and CBT) – MCW case 6/2009

- Step&Shoot IMRT (DAO) (dashed), and CBT (solid)
- S&S : 430 MU, 5 beams, 5 segments/beam
- CBT : 515 MU, 9 -29 MU/OP, nominal gantry speed ~2 deg/s



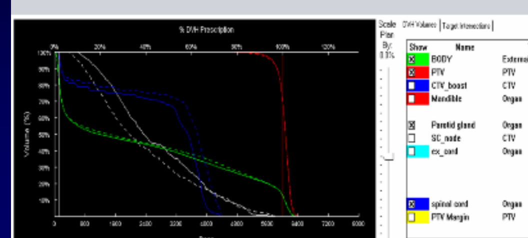
SIEMENS

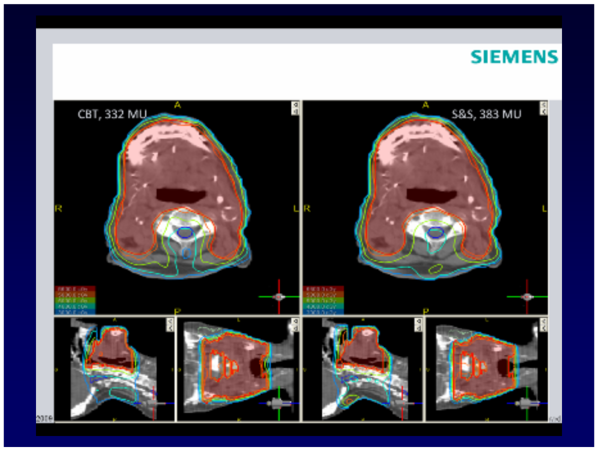


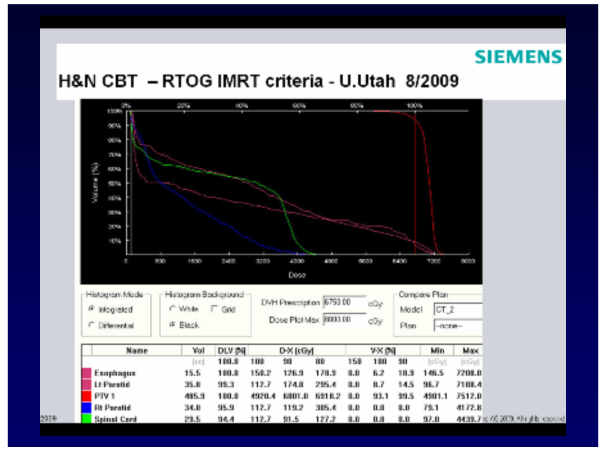
SIEMENS

Prowess H&N IMRT (S&S and CBT) – MCW case 6/2009

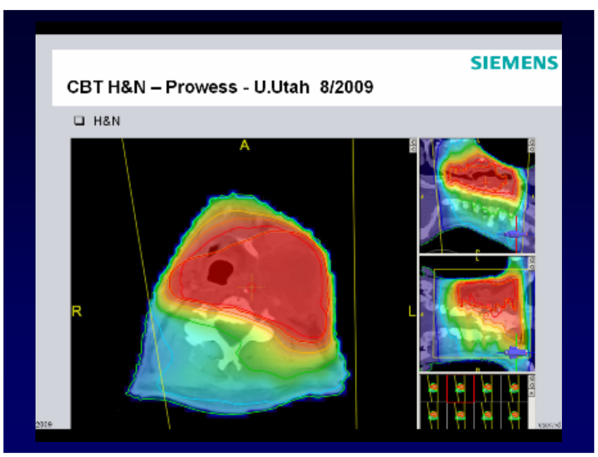
- Step&Shoot IMRT (DAO) (dashed), and CBT (solid)
- S&S : 383 MU, 7 beams, 5 segments/beam
- CBT : 332 MU, 3-15 MU/OP, nominal gantry speed ~1.5 deg/s

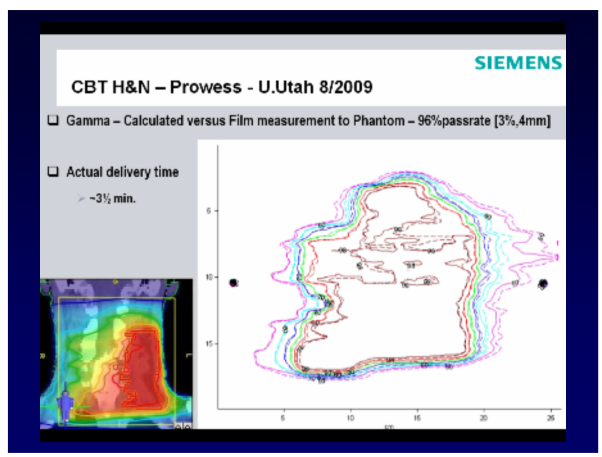






Name	Vol	DLV [%]	D-X [cGy]			V-X [%]			Min	Max
	[cc]	100.0	100	90	80	150	100	90	[cGy]	[cGy]
Esophagus	15.5	100.0	150.2	126.9	178.9	0.0	6.2	18.9	146.5	7208.0
Lt Parotid	35.8	99.3	112.7	174.8	295.4	0.0	8.7	14.5	96.7	7188.4
PTV 1	485.9	100.0	4920.4	6801.0	6918.2	0.0	93.1	99.5	4901.1	7512.0
Rt Parotid	34.0	95.9	112.7	119.2	305.4	0.0	0.0	0.0	79.1	4172.8
Spinal Cord	29.5	94.4	112.7	91.5	127.2	0.0	0.0	0.0	97.0	4439.7





Commercial Solutions - Summary

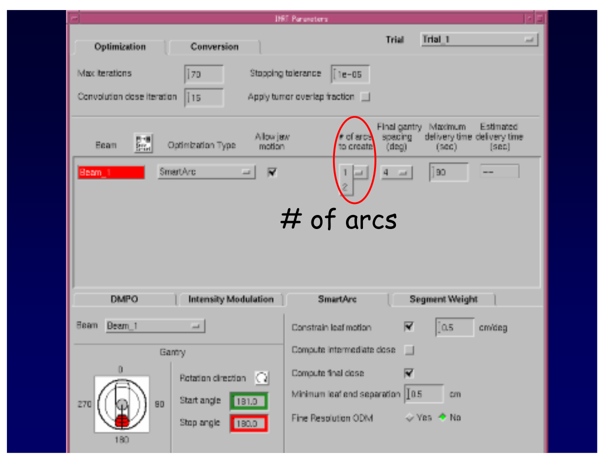
- The availability of fully dynamic rotational IMRT delivery capabilities of conventional linacs has allowed us to fully realize the capabilities of IMAT.
- This has also been made possible through the availability of the first robust commercial inverse planning solution for IMAT.

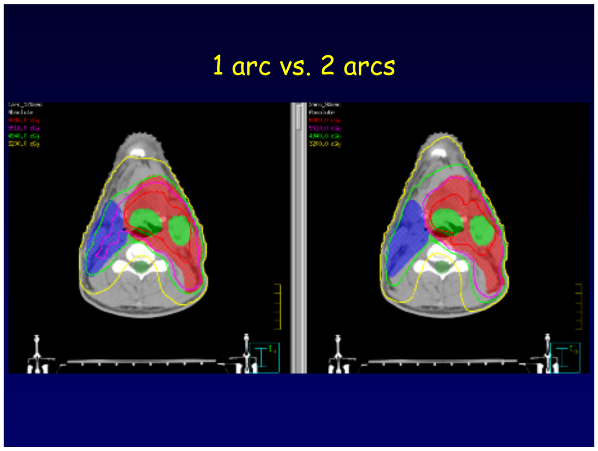
VMAT Planning – Key Questions

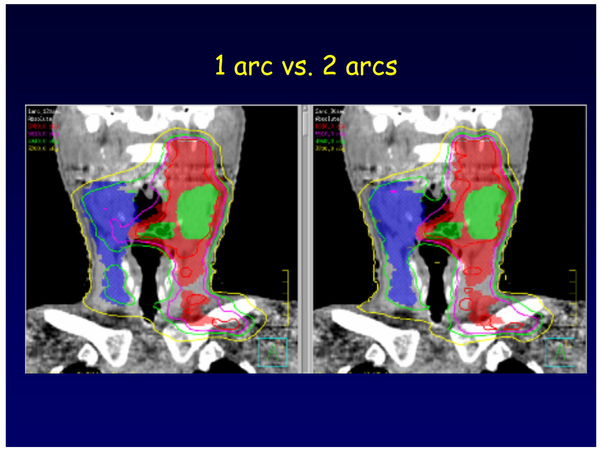
- Single arc vs. Multi-arc delivery
- Coplanar vs. Noncoplanar

Single vs. Multi Arc

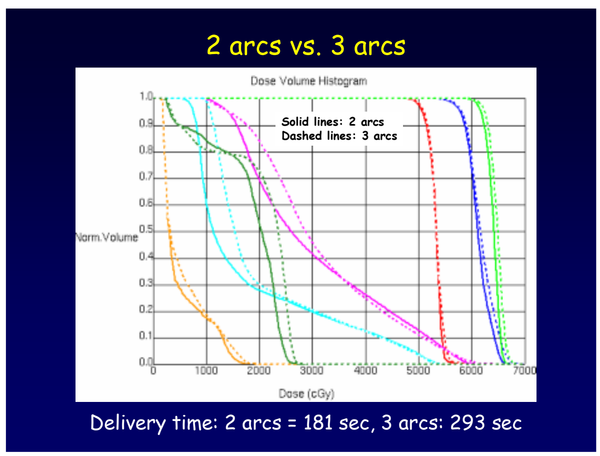
- Increasing the number of arcs provides additional flexibility in shaping the dose distribution.
- The key questions are which cases benefit from the use of multiple arcs and what number of arcs should be used.




1 arc vs. 2 arcs


1 arc vs. 2 arcs


1 arc vs. 2 arcs
Dose Volume Histogram
Solid lines: 2 arcs
Dashed lines: 1 arc
Norm.Volume
Dose (cGy)
0 1000 2000 3000 4000 5000 6000 7000
Delivery time: 1 arc= 124 sec, 2 arcs = 181 sec


2 arcs vs. 3 arcs
Dose Volume Histogram
Solid lines: 2 arcs
Dashed lines: 3 arcs
Norm.Volume
Dose (cGy)
0 1000 2000 3000 4000 5000 6000 7000
Delivery time: 2 arcs = 181 sec, 3 arcs: 293 sec

What treatment site would most likely see a dosimetric benefit to increasing the # of VMAT arcs to more than 1?

0%	1. Lung
0%	2. Prostate
0%	3. Brain
0%	4. Pancreas
0%	5. Head & Neck

10

Answer:

- Due to the complex target volumes and the frequent use of multiple prescription levels head & neck cases are most likely to see significant dosimetric improvement when using more than 1 VMAT arc.

Coplanar vs. Noncoplanr VMAT

- An advantage of VMAT relative to tomotherapy is the availability of non-coplanar arcs.
- Initial VMAT work has focused almost exclusively on coplanar delivery…

SWEDISH

Planning Parameters

- 1 arc is sufficient for simple cases such as prostate, but 2 arcs are needed for more complex cases such as H&N.
- Coplanar versus non-coplanar…

SWEDISH

Dosimetric Comparison of IMAT with Conventional IMRT Delivery Techniques

SWEDISH

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

- With the latest advances in IMAT planning and delivery, we can now test if IMAT can serve as a true alternative to tomotherapy in terms of plan quality and delivery efficiency.

Published 2007

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0360-3016/07/$–see front matter

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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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. © 2007 Elsevier Inc.

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

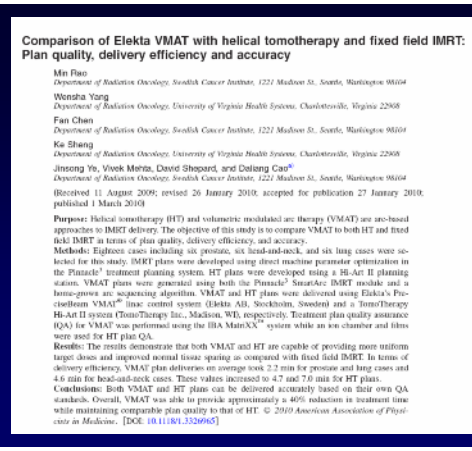
Arc Sequencer

- We developed an algorithm that can convert optimized fluence maps into deliverable IMAT plans.
- Using this algorithm we compared the plan quality for IMAT with that for helical tomotherapy.
- <u>At the time, however, no machine existed capable of delivering the plans.</u>

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.

SWEDISH



Comparison of Elekta VMAT with helical tomotherapy and fixed field IMRT: Plan quality, delivery efficiency and accuracy

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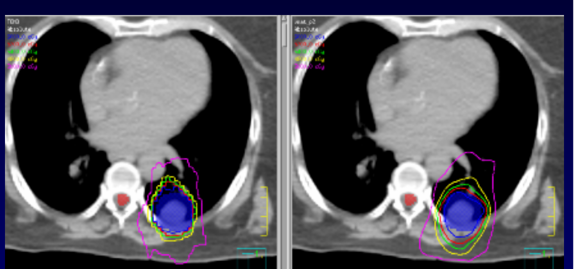
(Received 11 August 2009; revised 26 January 2010; accepted for publication 27 January 2010; published 1 March 2010)

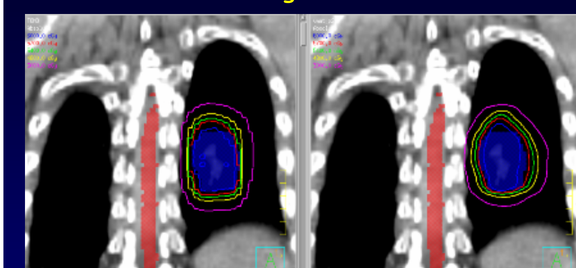
Purpose: Helical tomotherapy (HT) and volumetric modulated arc therapy (VMAT) are arc-based approaches to IMRT delivery. The objective of this study is to compare VMAT to both HT and fixed field IMRT in terms of plan quality, delivery efficiency, and accuracy.
Methods: Eighteen cases including six prostate, six head-and-neck, and six lung cases were selected for this study. IMRT plans were developed using direct machine parameter optimization in the Pinnacle[3] treatment planning system. HT plans were developed using a Hi-Art II planning station. VMAT plans were generated using both the Pinnacle[3] SmartArc IMRT module and a home-grown arc sequencing algorithm. VMAT and HT plans were delivered using Elekta's PreciseBeam VMAT[®] linac control system (Elekta AB, Stockholm, Sweden) and a TomoTherapy Hi-Art II system (TomoTherapy Inc., Madison, WI), respectively. Treatment plan quality assurance (QA) for VMAT was performed using the IBA MatriXX[TM] system while an ion chamber and films were used for HT plan QA.
Results: The results demonstrate that both VMAT and HT are capable of providing more uniform target doses and improved normal tissue sparing as compared with fixed field IMRT. In terms of delivery efficiency, VMAT plan deliveries on average took 2.2 min for prostate and lung cases and 4.6 min for head-and-neck cases. These values increased to 4.7 and 7.0 min for HT plans.
Conclusions: Both VMAT and HT plans can be delivered accurately based on their own QA standards. Overall, VMAT was able to provide approximately a 40% reduction in treatment time while maintaining comparable plan quality to that of HT. © *2010 American Association of Physicists in Medicine*. [DOI: 10.1118/1.3326965]

Lung Case



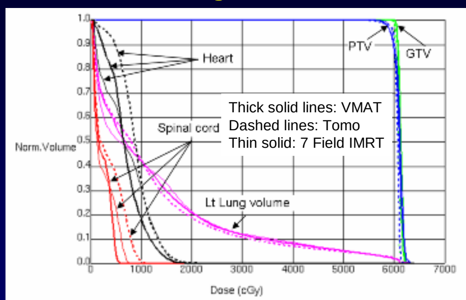
Helical Tomotherapy 1-arc VMAT

Lung Case



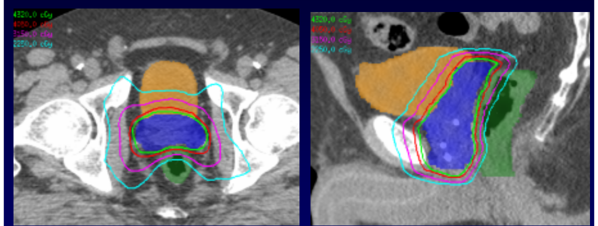
Helical Tomotherapy 1-arc VMAT

Lung Case

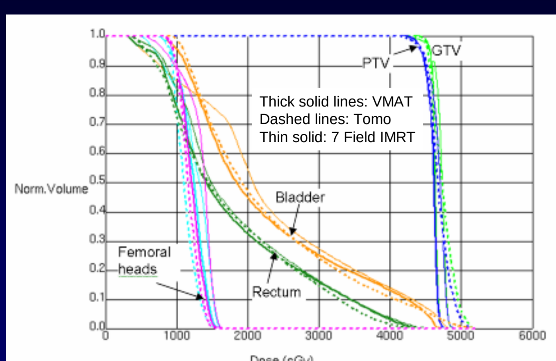


- Delivery time for VMAT plan was 2'04"
- Delivery time for the Tomotherapy plan was 5'44"
- Delivery time for fixed field IMRT was 7'26"

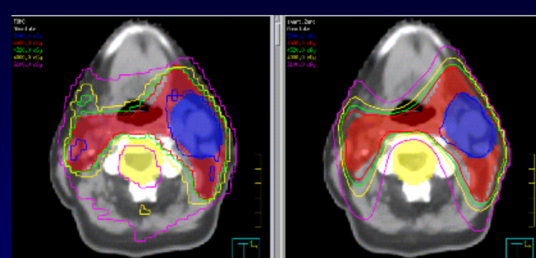
Prostate Case



SmartArc Plan



Head & Neck Case #1

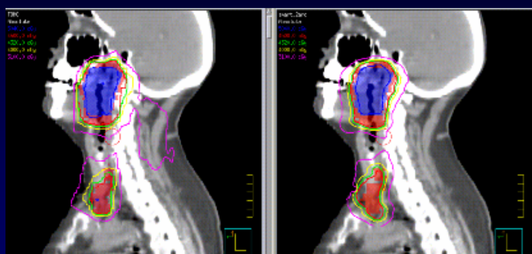


Helical Tomotherapy

2-arc VMAT

- Two targets with prescription levels of 5040 and 4500 cGy

Head & Neck Case #1

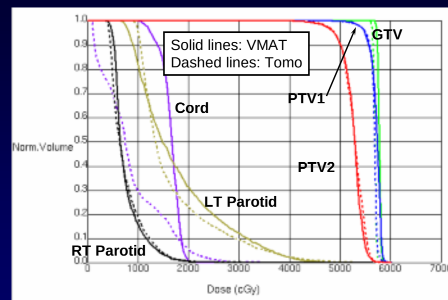


Helical Tomotherapy

2-arc VMAT

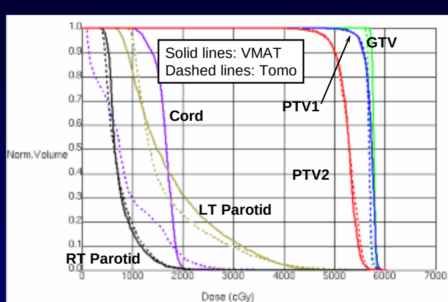
- Two targets with prescription levels of 5040 and 4500 cGy

Head & Neck Case #1



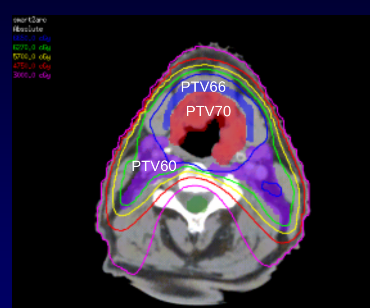
- Average V95: Tomotherapy = 98.4% and VMAT = 98.6%
- Max cord dose: Tomotherapy = 34.4 Gy and VMAT = 21.6 Gy
- Mean parotids dose: Tomotherapy = 12.1 GY and VMAT = 12.6 Gy.

Head & Neck Case #1



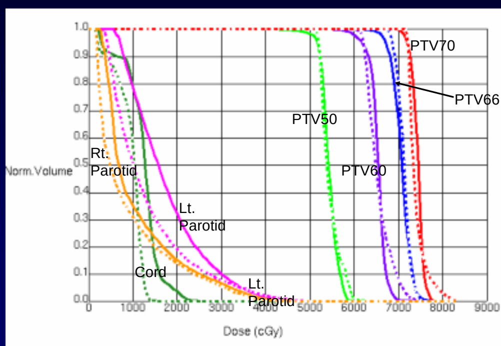
- Delivery time for VMAT plan was 4'25"
- Delivery time for the Helical Tomotherapy plan was 9'07"

H&N Example #2



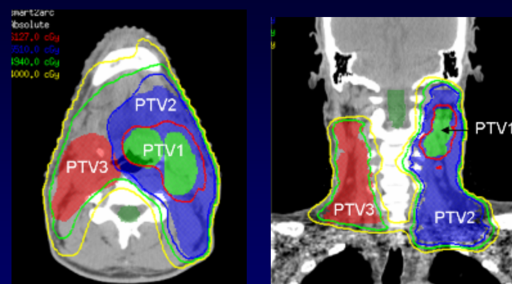
- 2 arcs, 512 monitor units
- Deliver time = 4 minutes 7 seconds

H&N Example #2

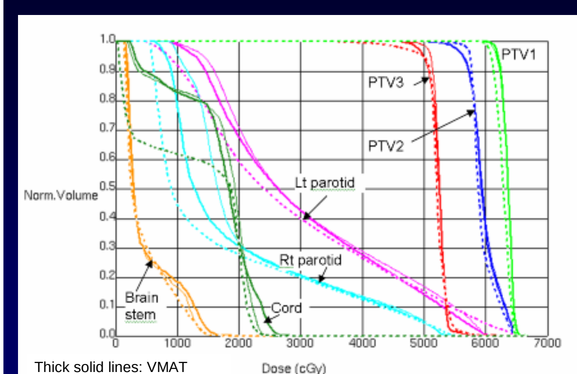


Solid = SmartArc Dashed = Tomotherapy

H&N Example #3



SmartArc Plan



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

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
$D_{20\%}/D_{presc}$ (%)	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: $D_{x\%}$ = minimal dose to n% of structure, D_{presc} = 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.

Future Developments

- With the current HiArt system, the jaw width and the couch speed are set to constant values for each plan.
- In 2011, Tomotherapy Inc. will offer a new option with dynamic jaw motion and dynamic couch motion.
- This should improve the efficiency of delivery and the quality of the plans.

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PHYSICS CONTRIBUTIONS

DYNAMIC JAWS AND DYNAMIC COUCH IN HELICAL TOMOTHERAPY

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Purpose: To investigate the next generation of helical tomotherapy delivery with dynamic jaw and dynamic couch movements.
Methods and Materials: The new technique of dynamic jaw and dynamic couch movements is described, and a comparative planning study is performed. Ten nasopharyngeal cancer patients with skull base infiltration were chosen for this comparison of longitudinal dose profiles using regular tomotherapy delivery, running-start-stop treatment, and dynamic jaw and dynamic couch delivery. A multifocal simultaneous integrated boost concept was used (70.4Gy to the primary tumor and involved lymph nodes; 57.4Gy to the bilateral cervical lymphatic drainage pathways, 32 fractions). Target coverage, conformity, homogeneity, sparing of organs at risk, integral dose, and radiation delivery time were evaluated.
Results: Mean parotid dose for all different deliveries was between 24.8 and 26.1Gy, without significant differences. The mean integral dose was lowered by 6.3% by using the dynamic technique, in comparison with a 2.5-cm-field width for regular delivery and 16.7% with 5-cm-field width for regular delivery. Dynamic jaw and couch movements reduced the calculated radiation time by 66% of the time required with regular 2.5-cm-field width delivery (199 sec vs. 595 sec, $p < 0.001$).
Conclusions: The current delivery mode of helical tomotherapy produces dose distributions with conformal avoidance of parotid glands, brain stem, and spinal cord. The new technology with dynamic jaw and couch movements improves the plan quality by reducing the dose penumbra and thereby reducing the integral dose. In addition, radiation time is reduced by 66% of the regular delivery time. © 2009 Elsevier Inc.

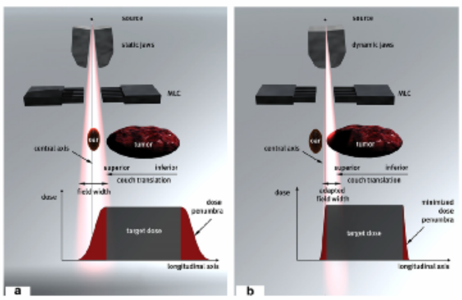

Fig. 1. Outline of jaw and fan beam characteristics of different delivery modes: (a) regular tomotherapy delivery causes a considerable dose penumbra above and below the target, whereas (b) RSS delivery with dynamic jaws reduces this dose exposure to healthy tissue. oar = organ at risk.

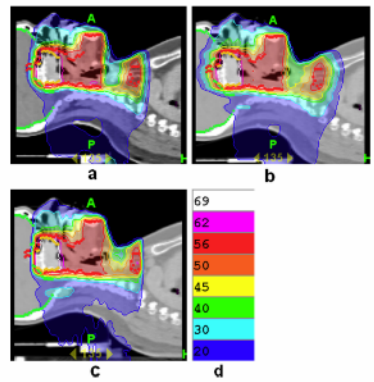

Fig. 3. (a–d) Dose distribution for one patient of regular delivery with 2.5-cm-field width (REG 2.5) and 5-cm-field width (REG 5) and DJDC delivery with 5 cm (DJDC 5), doses are shown in Gy.

Dynamic Jaws/Dynamic Couch

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

VMAT Planning - Summary

1. All major planning vendors now offer inverse planning solutions for VMAT with varying levels of robustness.
2. Initial work on VMAT has largely focused on single arc coplanar delivery. The advantages of using multiple arcs and non-coplanar beams are now being more fully explored.
3. With current technology, VMAT can provide similar plan quality as tomotherapy with a more efficient delivery.