

Quality Assurance of Helical Tomotherapy Machines

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Most of what is being said in this talk can be found in:

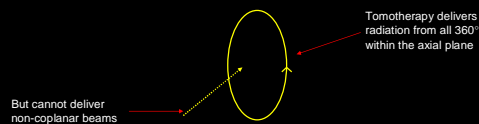


What is Helical Tomotherapy ?

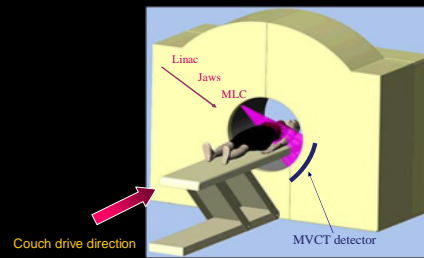
- Tomotherapy is slow rotational IMRT.
- Compared to conventional linac-based IMRT it has one possible advantage and one disadvantage.

Advantage – delivers radiation from all 360° of the axial plane in a helical fashion.

Disadvantage – delivery is exclusively coplanar; currently noncoplanar fields cannot be delivered.



Schematic view of the of a Helical Tomotherapy Machine



'Serial' and 'Helical' Tomotherapy

Serial Tomotherapy

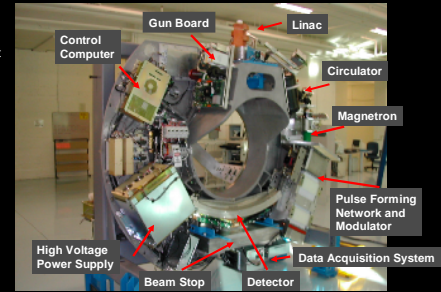
- Therapy analogue of the Serial CT Scanner.
- Delivers treatment slice-by-slice using a conventional medical linear accelerator.
- Uses a binary MLC to modulate beam intensity.
- Requires accurate couch 'indexing' between slices to avoid matchline problems.

Helical Tomotherapy

- Therapy analogue of the Helical CT Scanner.
- Delivers treatment in a helical fashion thus limiting matchline problems.
- Requires a completely re-engineered delivery system.
- Pre-treatment MVCT image guidance.
- In the future: Treatment adaptation based on post treatment dosimetry of fractions delivered up to that point.

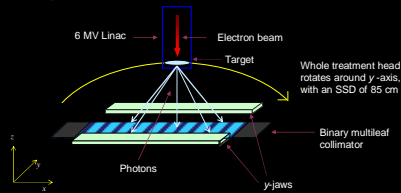
Actual Design of the HI-ART II Helical Tomotherapy Unit

Adapted from: Mackie et al. Helical Tomotherapy. "Intensity Modulated Radiation Therapy: The State of the Art." eds. J. Palta & TR. Mackie, Med. Phys. Pub. 2003 247-284.



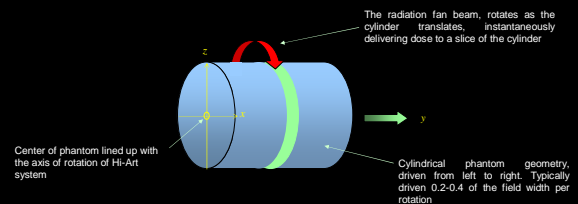
How does Helical Tomotherapy work ?

A short 6 MV linac is collimated by jaws and a binary multileaf collimator. The treatment head rotates on a gantry in the x/z plane while a patient is continuously translated through the bore of the machine in the y -direction – the therapy analogue of spiral CT.



How does Helical Tomotherapy work ?

Beam is collimated to a fan beam. The jaw width is held constant (typically 1 or 2.5 cm) for the entire treatment delivery. Laterally the beam is modulated using a binary MLC, which consists of 64 leaves each of width .625 cm for a total possible beam length at isocenter of 40 cm. The modulation changes as the gantry rotates, individual modulation patterns being defined over 7° rotational intervals (51 projections).



Factors impacting on dose-distributions delivered by a helical Tomotherapy machine

- Generally, the total dose delivered to an anatomical point within a patient is the time-integral of the dose-rate at that point.
- Therefore, for helical Tomotherapy, the total dose depends on factors relating to

- A. System Geometry
- B. Static Beam Dosimetry
- C. System Dynamics
- D. System Synchrony

A. System Geometry

Geometric checks are not very different from those for ordinary Linacs. Some of the slightly more novel facets of machine geometry that need testing are:

- field centering in the y-direction – beams should not diverge out of the rotational plane of the gantry;
- collimator twist – jaws should be aligned with the gantry plane;
- MLC twist – leaves should run perpendicular to the gantry plane;
- MLC centring and alignment – the central leaves 32 and 33 should project to either side of the isocenter, and TG artefacts induced in the radiation beam cone by sequentially opening neighbouring leaves should be roughly symmetric about the field center.

A. System Geometry

Other fairly conventional geometric checks include:

- Isocenter constancy with gantry rotation;
- Gantry angle accuracy;
- Jaw opening width (to ensure that superior and inferior target borders are accurate);
- Laser setup, checking that lasers point to the 'virtual isocenter' and are correctly aligned with the machine axes;
- Couch top horizontal levelling;
- Couch drive distance accuracy along the y- and vertical z- axes;
- Couch drive direction accuracy, checking that y-axis translations are perpendicular to the gantry plane and that z-axis translations are unaccompanied by movement laterally.

B. Static Beam Dosimetry

Static beam factors which directly impact on delivered dose are

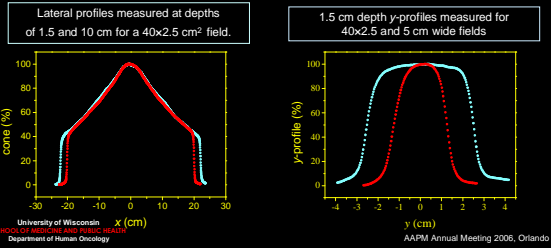
1. Output (dose-rate)
2. Output versus field-size
3. Depth-dose
4. Lateral off-axis ratio ('cone')
5. Off-axis y-direction profile
6. Output ramp-up time

Output and depth-dose are very similar to conventional Linac concepts (except that output is based on a dose-rate system). Other parameters are a little different.

B. Static Beam Dosimetry – Beam Profiles

Laterally (in the x/z-plane), the unmodulated beam is peaked, reflecting the absence of a flattening filter (plots at depths of 1.5 and 10 cm are shown).

In the y-direction, profiles (plotted for 2.5 and 5 cm widths) are similar to those of small fields delivered using conventional linacs.



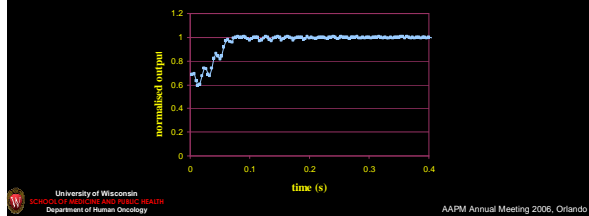
B. Static Beam Dosimetry – Output variation with Field-size

Output varies with field-size because of changes in:

- i. Head scatter – very limited (because beam profile is peaked in direction of largest field variation (x/z-plane) and the equivalent square varies little for a given jaw opening) therefore, to a good approximation can be taken as constant for a chosen jaw setting;
- ii. Phantom scatter – well modelled by the planning system;
- iii. Primary fluence per leaf-opening – tongue-and-groove effect (TG) of the MLC leads to a variation in total fluence-per-leaf-opening with the number of adjacent open leaves. The planning system accounts for this effect using TG correction factors measured for each leaf.

B. Static Beam Dosimetry – Output ramp-up time

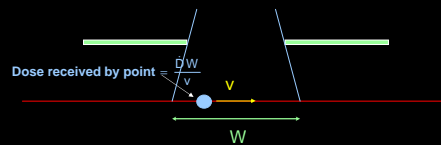
After the Linac is loaded with RF it takes a while for the dose-per-pulse to reach a stable value. This is not a problem for monitor-unit based Linacs, but might create difficulties for a Hi-Art machine. In fact all leaves are closed for the first 10 seconds of any delivery to allow the beam to stabilize. Thus it is important that the beam stabilizes within that time-frame; this can easily be checked by graphing the signal from one of the Hi-Art head ion chambers.



C. System Dynamics

In addition to static beam dosimetry, the dose at the center of the target region is directly proportional to three other factors:

1. field (jaw)-width in the y-direction;
2. reciprocal of couch velocity;
3. 'actual' fraction of time for which leaves are open.

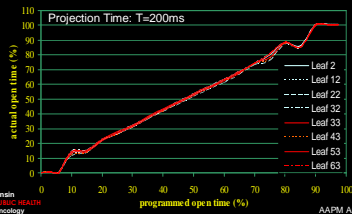


C. System Dynamics – Leaf Latency

The 'actual' fraction of time for which leaves are open is not quite equal to the programmed open time (because of the ~ 20 ms for which the leaves are moving in or out). This is corrected for by 'latency' correction factors, measured for each leaf and given by

$$f \times \text{Output for time } T \text{ with leaves constantly open}$$

Output for time T with leaves programmed open a fraction f of the time

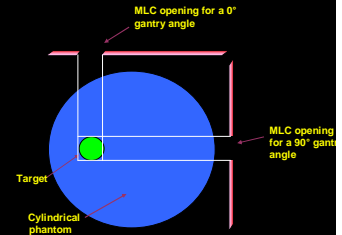


D. System Synchrony

For dose-distributions to be correctly delivered, then in addition to accurate static beam dosimetry and dynamics, various system components need to be correctly synchronized with gantry angle:

1. leaf opening;
2. linac pulsing;
3. couch drive.

The need for leaf opening and gantry angle to be properly synchronized is illustrated here for an offset target. Without adequate synchrony, incorrect regions will be irradiated.



D. System Synchrony – Leaf opening and Linac pulsing

- Both leaf opening and Linac pulsing are explicitly synchronized with gantry angle through an optical 'tick fence'.
- The fence generates a signal every fraction of a rotation of the gantry. That signal controls the timing of Linac pulsing and the opening and closing of the MLC leaves.
- Synchronizing Linac pulsing with gantry rotation removes the possibility of an unbalanced gantry (whose velocity would vary with angle) generating an erroneous variation of dose with angle.

D. System Synchrony – Couch Drive

- The couch is currently driven independently of the gantry, so synchrony is achieved by ensuring that both gantry and couch velocities are properly calibrated and matched.
- The Tomotherapy planning system can accurately calculate the peripheral spiralling of the dose and a small 'thread artefact' within the high dose volume, which are both generated by the helical delivery. Without active synchronization, the planned shape of these effects will be a little distorted by any variation of gantry velocity over the course of a rotation.
- More seriously, an N% mismatch in average velocities would currently lead to
 - an N% error in the length of the irradiated high-dose volume;
 - an N% error in the dose delivered to the high-dose volume.
 Ultimately, the couch and gantry will be synchronized via the tick fence.

Relevancy of AAPM TG40

- Same Meaning
- New Meaning
- Not Relevant

Adapted from Kyoungkeun Jeong, Yonsei University, Korea

Frequency	Procedure
Daily	Input output consistency
	Lesionless iserts
	Reference measurements
Monthly	X-ray output consistency
	Backup monitor consistency
	X-ray central axis fluency parameter (FDD, TAR) consistency
	X-ray beam fluency consistency
	Isotax field symmetry
	Scatter/monitor field dependence
	Scatter/monitor angle indicators
	Monitor position
	Fluency position
	Field size indicators
Scatter/monitor field size	
Annual	Treatment couch position indicators
	Scatter/monitor field size
	Field size dependency
	Energy output calibration consistency
	Field size dependency of x-ray output consistency
	Central axis parameter consistency (FDD, TAR)
	Scatter/monitor consistency
	Transmission factor consistency for all treatment accessories
	Monitor transmission factor consistency
	Monitor chamber fluency
X-ray output consistency vs gantry angle	
Off-axis factor consistency vs gantry angle	
Scatter/monitor	
Scatter/monitor consistency	
Scatter/monitor consistency	
Consistency of scatter/monitor, scatter area with scatterer	
Consistency of scatter/monitor and monitorer consistency	
Table top map	
Source level of error	

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UW Quality Assurance Schedule

Frequency	Procedure
Daily	Check consistency of input/output
	Check consistency of input/output
	Check consistency of input/output
	Check consistency of input/output
	Check consistency of input/output
	Check consistency of input/output
	Check consistency of input/output
	Check consistency of input/output
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	Check consistency of input/output
Monthly	Check consistency of input/output
	Check consistency of input/output
	Check consistency of input/output
	Check consistency of input/output
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	Check consistency of input/output
	Check consistency of input/output
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Annual	Check consistency of input/output
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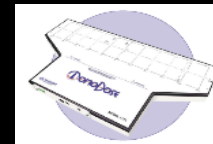
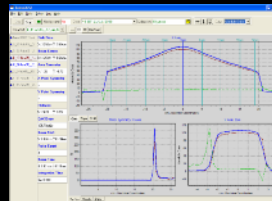
E. Daily Quality Assurance Checks



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E. TomoDose™



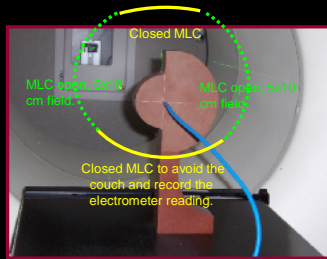
- Diode array designed by Sun Nuclear for tomotherapy QA
- Many users have incorporated it into the daily, monthly and annual QA

223 0.8mm x 0.8mm solid state detectors
Y Axis – 1 profile, 53 cm, 5mm spacing
X Axis – 9 Profiles, 9.8cm, 4mm and 8mm spacing

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E. Quick Daily QA Check Dose in Phantom at Two Depths



Courtesy of Hazim Jaradat, University of Wisconsin

E. TomoElectrometer™

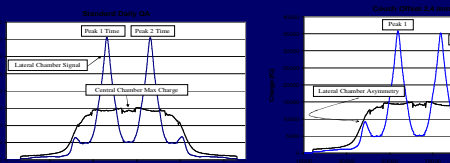


- 8 Channel electrometer
- 100 Hz sampling rate
- Field width can be measured with topographic procedure
- Tim Holmes, at St. Agnes created more comprehensive daily and monthly QA procedures using charge profiles from the "Tomo-trometer" and multiple ion chambers.



Kindly provided by T.R. Mackie

E. St. Agnes Dynamic Daily



- Cheese Phantom with 2 A1SL ion chambers at 0.5cm from the center and 14 cm (last hole) anterior.
- MVCT procedure prior to treatment procedure
- Treatment Procedure: 5cm FW, couch speed 1mm/s for 100s.
- Charge profiles as a function of time are analyzed.



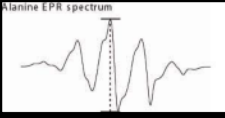

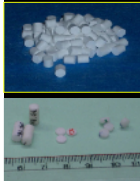
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E. Dosimetric Quality Assurance Tests



E. Alanine Dosimetry using Electron Paramagnetic Resonance (EPR) Spectroscopy

Project of Simon Duane, NPL and Stefaan Vynckier, Brussels

Alanine Properties

- Water equivalent
- 10 Gy exposure required
- Need 1 day to stabilize
- Read out with a spectrometer

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E. Summary of Data

Alanine data are averaged over 2-5 adjacent pellets



Machineream	UCL dosimeter	UCL / NPL alanine
Tomo / static 5 cm thick, 1.5 cm deep	A1SL	1.000
Tomo / static 5 cm thick, 5 cm deep	A1SL	1.002
SL25 / 6MV 10x10 cm, 5 cm deep	NE2571	1.002
SL25 / 6MV 10x10 cm, 5 cm deep	NE2571	1.001
Tomo / helical, 2.5 cm width, in target	A1SL	1.015
Tomo / helical, 2.5 cm width, in target	A1SL	1.012
Tomo / helical, 1.0 cm width, in target	A1SL	1.002
Tomo / helical, 1.0 cm width, in target	A1SL	1.005
Tomo / helical, 5 cm width, in target	A1SL	1.009
Tomo / helical, 5 cm width, in target	A1SL	1.011

From Stefaan Vynckier, St. Luc Hospital, Brussels

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E. Gortec IMRT Test Phantom


- Point 1: Isocenter
- Point 2: Spinal cord isocenter
- Point 3: Spinal cord cranial
- Point 4: PTV T R
- Point 5: PTV T R cranial
- Point 6: PTV N L
- Point 7: PTV N L caudal

Courtesy M. Tomsej, St. Luc, Brussels

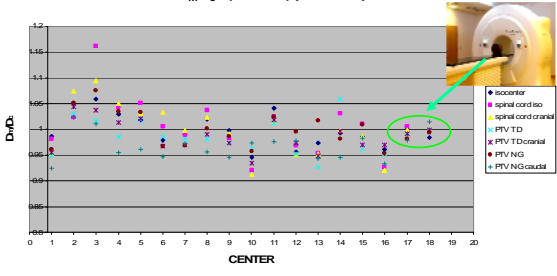
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E. Some Preliminary Audit Results



$D_{100}/D_{50} = f(\text{CENTER})$ per meas. pt



Legend:

- Isocenter
- spinal cord top
- spinal cord cranial
- PTV TD
- PTV TD cranial
- PTV NG
- PTV NG caudal

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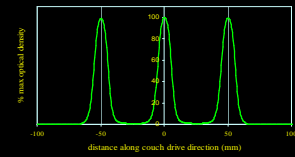
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E. Monthly and Annual Checks



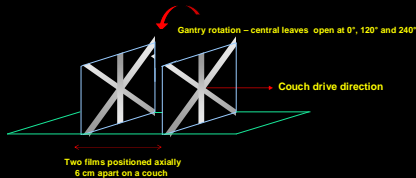
E. Radiographic test to determine couch y-translation and gantry synchrony

Couch y-translation and gantry synchrony is checked over the course of several rotations, by opening the leaves for segments of the 3rd, 8th and 13th of fifteen consecutive rotations, while driving the couch 1 cm per rotation, with a film taped to the couch-top. The spacing of the irradiated segments is checked to ensure that it is 5 cm (± 1 mm).



E. Radiographic test to determine MLC and gantry synchrony

To check MLC and gantry synchrony, two films are positioned axially 6 cm apart on the couch, separated by solid water slabs, and a treatment is delivered that irradiates narrow fields at 0°, 120° and 240° to the vertical. The gantry rotates 40 times while the couch is driven 10 cm, and so between irradiation of the first and second film the gantry rotates 24 times.

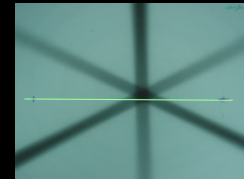
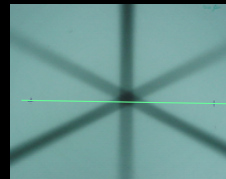


E. Radiographic test to determine MLC and gantry synchrony

The two films taken to test multileaf and gantry synchrony, showing the fields planned to lie at 0°, 120° and 240° to the horizontal (marked in red). The fields on both films lie within 1° of their planned angle.

+ 3 cm film

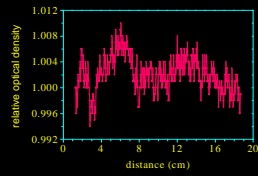
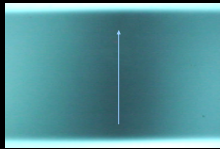
- 3 cm film



E. Radiographic test to determine couch drive speed uniformity

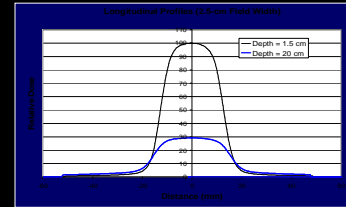
A film is irradiated using a static 40×1 cm² field, to test the effect on delivered dose of any nonuniformity of couch drive speed. Optical density drops off laterally as the cone decreases, but will be uniform along the direction of couch drive if the drive speed is constant.

Film driven 20 cm in this (y-)direction, in which the field width is 1 cm



E. St. Agnes Monthly

- Rectangular solid water centered at virtual isocenter and 85 cm SSD
- A1SL ion chamber at 1.5 cm depth
- 2nd chamber at 20 cm depth
- Couch moves 2mm per second
- Repeat for all 3 FWs



T. Holmes, J.P. Balog, "Helical Tomotherapy Dynamic Quality Assurance", in press.



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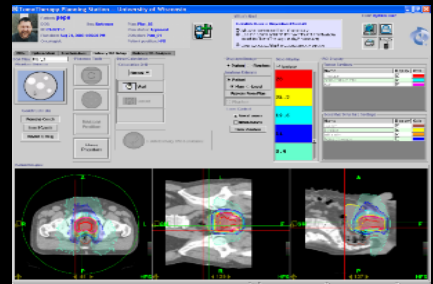
F. Patient Specific QA



F. Integrated Patient-Specific QA

On Planning Station apply patient plan to included Tomotherapy "Cheese" phantom

Adjust phantom position for best readings and calculate patients plan on phantom



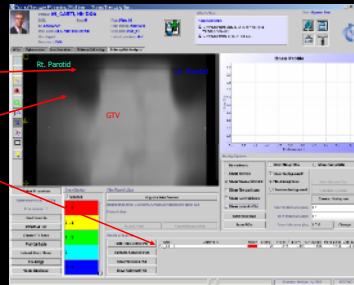
F. Plane and Point Measurements

Convert film to dose

Overlay patient contours

Evaluate profiles and point dose

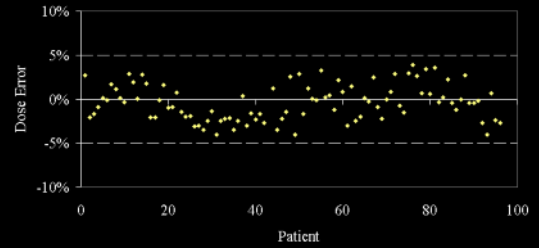
Analyze predicted vs. measured using Gamma map



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F. Patient Specific Ion Chamber Readings



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Summary:

- Over the course of the clinical implementation of the HiArt we and others have developed a quality assurance (QA) system that covers machine specific QA.
- The machine specific QA system is similar to that recommended for conventional linear accelerator QA by AAPM Task Group 40.
- However the Hi-Art design and operation differs from that of conventional medical linear accelerators.
- Therefore, the tomotherapy QA system contains also novel components, such as QA checks for synchrony of gantry rotation, couch translation, linac pulsing and the opening and closing of the leaves of the binary multileaf collimator.

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Thank you!



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