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Helical Tomotherapy Research in London, Ontario
Objectives of this presentation

• To define tomotherapy
• To review the history of its development
• To review our experience with early tomotherapy installations in London, Ontario
• To review the unique features of helical tomotherapy from patient perspective
• To discuss the past, present and future of tomotherapy-related research at LRCP
Helical Tomotherapy: quick overview
What is Tomotherapy?

- Radiation delivery “by-slice”
  - Fan of pencil beams
- Pencil beam “shutter”
  - Binary multi-leaf collimator (MLC)
- Sculpted dose distributions
- CT image guidance

The promise
- Precision
- Versatility
- Fewer treatment complications
- Better tumour control by increasing the dose prescribed
Rotational Therapy
Components of Helical Tomotherapy

Helical Scanning using couch movement and continuous gantry rotation
Components of Helical Tomotherapy

- Lower dose due to
  - Lower linac pulse rate
  - Lower energy (3.5MV)

Ring detector at exit side

TLDs in Rando
Tomotherapy

- “arc” type dose distribution
- excellent avoidance of normal tissues
- Dose “conforms” to target
- “Hit the tumor and miss the patient”
- Online cross sectional (MVCT) imaging for positioning and organ motion correction
Computer Simulation

Pencil Beams Exposure

Dose Painting

“Snapshot” of rotating, modulated fan beam on left and cumulative dose to prostate on right
Tomotherapy: Historical perspectives
Evolution of Radiotherapy

Time

Fixed SSD RT
Isocentric RT
Conformal RT
IMRT
Adaptive RT

Tumour Margin Size

better set-up
better targeting
better dose homogeneity
less patient variability

Computer planning
3D planning
inverse planning
4D planning
Tomotherapy: A new concept for the delivery of dynamic conformal radiotherapy

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Tomotherapy is a combination of radiation therapy with a linear accelerator, or linac, and a gantry-like CT scanner. The gantry rotates with the patient, and multiple independent leaves in the collimator are moved in any of three ways: (1) changing the gantry angle, (2) changing the leaf-trough, or (3) changing the leaf-trough as a whole. The resulting conformal radiation delivery is very different from traditional treatment delivery times. The linac, CT scanner, and megavoltage detector all contribute to a unique treatment unit design. Such a treatment unit requires unique treatment planning, and verification of treatment delivery are evaluated and validated.
1998  First formal exchange of letters and visits
12/2000  Clinical Collaboration Agreement with TTI
3/2002  Planning system (software) at LRCP
1/2003  Installation of HiArt 1 at LRCP
3/2003  First MVCT of phantom
7/2003  Commissioning/acceptance
9/2003  Decision to upgrade to “HiArt 2”
4/2004  Installation “HiArt 2”
9/2004  First Ontario patient treated
Tomotherapy at LRCP
London Regional Cancer Program

- 3500 new RT patients/year
- 16 RO, 10 physicists, 7 dosimetrists, >60 RTs
- 8 linacs, 3 brachy units, 1 superficial, 1 tomotherapy unit
- Partner institutions
  - Lawson Health Research Institute
  - University of Western Ontario
  - Robarts Research Institute
Tomotherapy in London

The “guts”!

LINAC

Waveguide

Magnetron

CT detector (hidden)
Tomotherapy in London: A typical day

- 7:30 warm-up, output check
- 9:00 physics QA, engineering PMI
- 10:00 MVCT slot
- 11:00 to 3:00 treatment
- after 3:00 Patient QA, physics research, database maintenance
Tomotherapy patient flow

1. Planning CT scan
2. Create outlines
3. Definition of constraints for inverse planning
4. Acceptance of the plan
5. Creation of QA procedures
6. QA measurements
7. First session: MVCT only
8. Treatment
Planning CT scan
Create outlines
Definition of constraints for inverse planning
Acceptance of the plan
Creation of QA procedures
QA measurements
First session: MVCT only
Treatment
Treatment Plan:
Characterized by some 60,000 numbers indicating the leaf opening time as a function of gantry rotation.
A helical tomotherapy treatment is characterized by some 60,000 MLC leaf opening times organised as an “open leaf sinogram”
Three ways to guide the optimisation:
1. Precedence, 2. Importance, 3. Dose penalty
Inverse planning for a resected large medullary carcinoma of the thyroid with microscopic residual disease.
Prostate Plan

Lung Plan

Brain Plan

London Health Sciences Centre
London Regional Cancer Program

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HT Planning: Target conformality, organ at risk avoidance
Planning CT scan
Create outlines
Definition of constraints for inverse planning
Acceptance of the plan
Creation of QA procedures
QA measurements
First session: MVCT only
Treatment
QA and dosimetry requirements

- No universally agreed QA schedule
- Helical delivery relatively forgiving:
  - arc type delivery
  - pitch factor <1
- Calibration according to TG51 or IAEA TRS398 not possible
QA and dosimetry

- Output determined in multiple rotations - similar to CTDI
- Critical for QA:
  - couch movement
  - output constancy
  - MVCT spatial accuracy
- MVCT detector is a most useful tool
Verify Plan on “Cheese” Phantom

- Planning CT scan
- Create outlines
- Definition of constraints for inverse planning
- Acceptance of the plan
- Creation of QA procedures
- QA measurements
- First session: MVCT only
- Treatment
Quality assurance measurements with “cheese” phantom
Reverse view through bore of the HT unit with localization lasers
Planning CT scan
Create outlines
Definition of constraints for inverse planning
Acceptance of the plan
Creation of QA procedures
QA measurements
First session: MVCT only
Treatment
“Patient’s eye view”
“Patient’s eye view”

Reverse view through bore

In room CCTV to monitor patient
Tomotherapy team at the treatment console
Planning CT scan
Create outlines
Definition of constraints for inverse planning
Acceptance of the plan
Creation of QA procedures
QA measurements
First session: MVCT only
Treatment

Treatment verification

Simulator film, DRR
Port film, EPID

planning
Planning CT scan
Create outlines
Definition of constraints for inverse planning
Acceptance of the plan
Creation of QA procedures
QA measurements
First session: MVCT only
Treatment
Image registration for treatment: lung cancer
Image registration for treatment: prostate cancer
Image registration: abdominal wall tumor
(planning contours aligned with MVCT image)
$$R = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}$$

Setup corrections based on MVCT from 09/2004 to 10/2005

- Prostate
- H & N
  - Brain
- Spine
- Abdomen
  - Rib
- Thorax
- Breast
Treatment

- Planning CT scan
- Create outlines
- Definition of constraints for inverse planning
- Acceptance of the plan
- Creation of QA procedures
- QA measurements
- First session: MVCT only

“Snapshot” of rotating, modulated fan beam on left and cumulative dose to prostate on right
The adaptive radiotherapy loop

1. Patient data acquisition
2. Treatment plan optimization
3. Pre-treatment verification
4. Adjustment (if required)
5. Assessment of delivery
6. Verification

TREATMENT
Treatment verification and adaptation

- MVCT detector dataset which can be compared with ‘planned’ treatment delivery sinogram to derive differences in dose delivery.
Most simple adaptation

- The delivery start at an angle equal to the roll offset
# 1: Female, 67 years old, Adenocarcinoma of the right upper lung, non-small-cell lung cancer, stage III

Diagnostic scan

Simulation

Day 26

Day 33
Plan 1

Lt lung: $<D> = 4.7$ Gy

Rt lung: $V = 2.1$ l

Plan 2

Lt lung: $<D> = 3.2$ Gy

Rt lung: $V = 1.7$ l

Plan 3

Lt lung: $<D> = 5.6$ Gy

Rt lung: $V = 2.1$ l
Male, 84 years old, Bulky non-small-cell lung cancer, stage III
Gross tumour volume (GTV) regression from contours on MVCT images

-1.65%/day
-5.1%/day
-0.5%/day
Tomotherapy Research At LRCP
HT Research Interests at LRCP

- Dosimetry
  - small fields (A McNiven)
  - gel dosimetry (K Jordan)
  - in vivo dosimetry with film (S Yartsev)
- Treatment modification
  - asymmetric fan beams (A Gladwish)
  - lung motion (B Kim)
  - dose patching (C Lewis)
- MVCT (G Hajdok)
- HT/IMAT Modeling (E Wong)
- Clinical trials (G Bauman)
- RT/patient processes (B Warr)
Dose patching

- Suggested by Rock Mackie for prostate seed implants with sub-optimal postimplant plan
- Use 1.5 times prescription isodose (1.5 x 144Gy) as critical organ
- Use 0.5 times prescription isodose (72Gy) as target
- MVCT ensures accurate localisation
...not only for brachytherapy but also for complementing external beam (eg top up of cribiform plate for craniospinal treatment)
MVCT

- Detectors
- Clinical utility
- CT numbers

![Graph showing MVCT numbers vs. electron density with data points for MVCT in phantom, MVCT in air, and kVCT 130kV.]

![Images of MVCT scans with labels for hip replacements and gold seed markers.]

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HT and Tumour Motion

- Problem:
  - Tumour moving in and out of fan beam
  - Dose inside tumour will be different from planned!!!

1Kubo et al 2000 Med Phys 27 346-353
Proposed Solution: MRG-HT

**Multi-pass Respiratory Gated Helical Tomotherapy**

- Target position vs. time curve with respect to couch
- Duty cycle = “beam ON” time per respiratory period ($T_r$) / $T_r$
- “beam ON”: deliver planned projections
- “beam OFF”: projections blocked by closing all 64 binary leaves
Leaf Opening Sinogram

51 projections / 360°, 7° / projection

Original Leaf Sinogram

Beam Projection

Leaf Number

blue - fully closed
red - fully open

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Proposed Solution: MRG-HT

**Multi-pass Respiratory Gated Helical Tomotherapy**

- Target position vs. time curve with respect to couch
- Duty cycle = “beam ON” time per respiratory period ($T_r$) / $T_r$
- “beam ON”: deliver planned projections
- “beam OFF”: projections blocked by closing all 64 binary leaves
- Multiple passes required to fill in “blocked” beam projections
Proposed Solution: MRG-HT

- Couch reset
- Treatment must start at a different phase of tumour motion to “fill in” different beam projections.
Proposed Solution: MRG-HT

- Previously delivered beam projections are not delivered to avoid duplicate beam projections.
Materials and Method: Experiment

- Film (7.3 cm x 16.9 cm) inside a sinusoidally moving insert (representing lung tumour)
- Original HT plans were modified according to duty cycle to produce a set of MRG-HT plans.
Results: Film Experiment

% Dose Profiles for $T_g = 10$ s, $T_r = 4$ s ($\alpha = 2.5$), $A = 0.25$ cm

- **Stationary**
- **50% gating**
Tomotherapy planning studies

• A. Brain
  • 12 patients from data set previously studied in Italy
  • different modalities

• B. Lung
  • 15 patients - large PTVs
  • evaluation of plans

• C. Prostate
  • 10 patients, 5 sets of margins
  • PMB 48 (2003) 1933-1943
Brain planning results

- Comparison with published results of multiple modalities
- Tomotherapy resulted in better target uniformity - this includes a comparison with proton radiotherapy!
- The integral brain dose and dose to critical structures (brain stem, optic chiasm) was higher than for protons but comparable to IMRT and conformal photon irradiation
- Rad Oncol. 2005 Jan;74(1):49-52
- Radiother Oncol. 2006 Aug 3
Neurinoma

Radiother Oncol. 2006 Aug
Helical Tomotherapy for Treatment of Brain Metastases

Hypothesis:

• Helical tomotherapy to deliver whole brain radiotherapy with synchronous boost to individual brain metastases to BED comparable to RS

• Using linear quadratic formulism and $\alpha/\beta = 3$ for late effects and $\alpha/\beta = 10$ for tumor/early effects: 30Gy/10 fractions + SIB 60Gy/10 fractions to mets
Rationale for SIB

Logistical advantages
- no separate SRS procedure
- easy to treat multiple mets
- non-invasive MVCT localization

Advantages of fractionation (4 R’s)
- Normal tissue: repair
- Tumor tissue: reoxygenation/reassortment

Dosimetric advantages
- boost incorporated into WB component
N=5 planning cases: successful escalation to 60 Gy
Lung planning studies

Aim: always get the target dose correct - compromises with normal structures
Comparison with IMRT

IMRT planning approach
- 9 fields; uni; 18MV
- 7 fields; adj; 6 and 18MV
- 7 fields; uni; 18MV
- 7 fields; uni; 6 and 18MV
- 6 fields; adj; 18MV
- 10 fields; con; 6 and 18MV
- 7 fields; adj; 6 and 18MV
- 7 fields; uni; 18MV
- 7 fields; uni; 18MV
- 6 fields; adj; 18MV
- 5 fields; adj; 6 and 18MV
- 7 fields; uni; 18MV
- 7 fields; uni; 18MV
- 8 fields; adj; 18MV
- 6 fields; adj; 6 and 18MV

Uni = uniform spacing of beams
Results of Tomotherapy planning for prostate cancer

• With margins of 7mm or below around the prostate it is always possible to fulfil RTOG P-0126 tolerance criteria for 82Gy delivery to target
• Large bladder volume and overlap between rectum and PTV is a predictor for dosimetric outcome
• In practice, imaging is likely to be the most important feature
Who benefits most? And from what?

- Different treatment techniques are available – how to choose?
- Radiother Oncol. 2006 Jul 31

In many cases the image guidance will be the most important feature of Helical Tomotherapy.

Evolution of radiotherapy

- Fixed SSD RT
- Isocentric RT
- Conformal RT
- IMRT
- Adaptive RT

- better set-up
- better targeting
- better dose homogeneity
- less patient variability

Planning comparison for 10 prostate cancer patients.
Clinical trials: examples of patients

- Palliative treatment of vertebral and para-aortic metastases from prostate cancer

- Radical treatment of a chondrosarcoma of the base of skull

- Synchronous whole brain radiotherapy and stereotactic boost to brain metastasis
Phase I Clinical Trial: opened 08/05
• 30Gy 10 fractions with SIB to mets:
  • 35/10 3/3
  • 45/10 3/3 (6)
  • 50/10 3/3
  • 55/10 pending
  • 60/10 pending
RT/Process Research topics

• How reliable is the automatic registration?
• Who will make/verify that the decision is correct
• What action levels should be applied
• Do we need additional training (eg cross sectional anatomy)?
Summary

• Tomotherapy has been a strong example of:
  • Translational Research
  • Multidisciplinary Research

• Our research has resulted in:
  • Peer-reviewed publications (30% of non-Madison literature)
  • International presentations (e.g. Saudi Arabia to Korea)
  • Leverage for peer-reviewed grants (> $1.5M)
  • Research collaboration with industry
  • Retention and recruitment of highly qualified staff
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