A location dependent strategy for treating lung tumors with the CyberKnife® System

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The CyberKnife® System

- Initially developed to treat exclusively intracranial lesions
- X-Band linear accelerator mounted on a 6 joint robot
- 2 diagnostic X-Ray sources + 2 ASi image detectors
- Collimation:
  - 12 fixed collimators
  - IRIS (5 to 60mm apertures)
  - MLC (10 x 12 cm)
The CyberKnife® System evolution

6D Skull Tracking:

• Major versatility compared to other technology:
• No rigid fixation needed (frame)
• Compensation of accurate beam delivery ensured by the imaging system
• Realized by the fast registration of the live images with pre-processed DRRs derived from the planning CT scans
• Beam delivery accuracy < 1mm
As a neurosurgical tool, CyberKnife was then adapted to treat spine lesions.

A fiducial detection and tracking algorithm was developed.

Spine treatments performed by tracking Lorentz stainless screws implanted into the spinal processes.

Fiducial tracking of the spine lesions was abandoned in favor of Xsight Spine™ tracking.
The CyberKnife® System evolution

Fiducial tracking is performed for "slow-moving" tumors
A large variety of fiducial types can be used
The CyberKnife® System evolution

Xsight Spine™:

- Identifies unique bony structures
- Enables registration of non-rigid skeletal anatomy
- Estimates local displacements in bony features
- Hierarchical mesh tracking
The CyberKnife® System evolution

Xsight™ Spine tracking of lumbar spine
Moving tumors: the next challenge

Major Challenge: *Motion Compensation*
Synchrony® Respiratory Tracking

Synchrony®:
Synchrony® Respiratory Tracking

- Optical markers on chest or abdomen used as real time surrogate signal of tumor motion
- Optical signal is read by a ceiling mounted infrared stereoscopic camera
- X-ray images are taken at different phases of the breathing cycle and fiducial position is recorded
- A correlation model is established between the fiducial position and the real time signal from the optical markers
Synchrony® Respiratory Tracking
Before the treatment delivery, a correlation model between the optical markers and the tumor position is constructed using the camera and multiple orthogonal x-rays.

Model is updated continuously during treatment by further x-ray imaging.

During delivery, the tumor position is tracked using the live camera signal and the correlation model.

The robot is moved in real-time to maintain alignment with the tumor.
Synchrony® Respiratory Tracking

• Synchrony® is applicable to treating any lesion that moves due to patient’s breathing: lung, liver, breast, kidney, abdominal LNs

• Accuracy of the beam delivery in phantom < 1.5mm

• CTV to PTV margins are usually on the order of 3 to 5mm, and are dependent on the amplitude of the tumor excursion, its location and the breathing “fitness” of the patient

• A more consistent breathing pattern results in a more accurate correlation model and therefore more precise beam delivery

• Cons: fiducial placement is a major challenge (lung, pancreas)
Synchrony®: learned lessons

- Tumor’s silhouettes appeared clearly visible on the live images in approximately 50% of the lung cases treated.
- Could the real tumor projection be tracked instead of the fiducials?
**Xsight® & Lung Optimized Tracking**

**Xsight® Lung:**

- 2D tumor contour is generated in each DRR projection
- Window created from tumor contour & surrounding background. It is used as a matching block in tumor registration

Images courtesy of Paul Meskell
Xsight® & Lung Optimized Tracking

Matching window

Search window

Similarity Measure

Maximum similarity

Courtesy of Paul Meskell
**Xsight® & Lung Optimized Tracking**

**Xsight® Lung (2 View):**

- Fiducial-less lung tumor tracking
- Tumor is visible on both X-ray projections
- Works well for tumor’s diameter > 15mm
- Targeting accuracy as low as 1.5mm
- PTV margin as in Synchrony®
Xsight® & Lung Optimized Tracking

LOT Tracking (1 View):

- Tumor visible on a single X-ray
- Involves the acquisition of an exhale and an inhale CT
- A patient simulation process is necessary to determine the final tracking method
- An internal (ITV) target volume is constructed in the planning
Xsight® & Lung Optimized Tracking

LOT Tracking (0 View):

- ITV
- Inhale
- Exhale

B Imaging panel
A Imaging panel
Xsight® & Lung Optimized Tracking

LOT 1 View A

Exhale DRR B

Exhale DRR A

Inhale DRR B

Inhale DRR A
Xsight® & Lung Optimized Tracking

LOT 1 View A

Exhale phase

Inhale phase
Location dependent strategy for Lung Tx

- Regardless of location, any Lung tumor can be treated with implanted fiducials and Synchrony® tracking.
- The CTV to PTV margin expansion is dependent on the location of the tumor.
- Range of motion varies*:
  - Lower Lung:
    - Sup-Inf = 1.5 – 14.0mm; Left-Right= 0.1 – 12.6mm; Ant-Post = 0.6 – 7.0mm
  - Middle Lung:
    - Sup-Inf = 0.7 – 7.4mm; Left-Right= 0.5 – 2.5mm; Ant-Post = 0.6 – 3.4mm
  - Upper Lung:
    - Sup-Inf = 0.2 – 8.1mm; Left-Right= 0.1 – 6.3mm; Ant-Post = 0.2 – 6.2mm

* S Dieterich and Y. Suh, Tumor Motion Ranges Due to Respiration and Respiratory Motion Characteristics, in *Robotic Radiosurgery – Treating Tumors that Move with Respiration*, Springer 2007, pp. 3-13
Challenges in treating fiducial implanted Lung tumors:

- Optimal placement of fiducials
  - At least 3 fiducials that would not overlap on the 45° projections
  - Fiducials placed at a minimum 2cm apart

- Estimation of the PTV margin expansion, especially when the fiducial centroid is off the tumor centroid and there is significant tumor rotation during the breathing cycle

- Pneumothorax
Location dependent strategy for Lung Tx

Goals of the strategy:

- Utilize at the maximum Xsight Lung® and LOT tracking
- Minimize the risk of Pneumothorax
- Develop a schema for optimal treatment based on the tumor size and location within the lung
  - Defined four lung regions characterized by their ability to be tracked with a specific modality
  - A cutoff value of 15mm diameter tumor is used in the selection between fiducial and non-fiducial tracking modes
Location dependent strategy for Lung Tx

A: Favorable for Xsight® Lung and LOT™ (spine alignment - angles)
B: Xsight® Lung, LOT™ 1View; transbronchialy placed fiducials
C: Less favorable Xsight® Lung, LOT™ 1View, but Chestwall fiducials
D: Percutaneously fiducials or LOT™ (0 View) if close to spine (A)
Location dependent strategy for Lung Tx

**Fiducials:** 3 or more fiducials are placed in the chestwall, in the vicinity of the tumor (preferably next to ribs to avoid excessive deformation)
Location dependent strategy for Lung Tx

Registration: 2 CT datasets are acquired: Exhale (planning) and Inhale
CT datasets are co-registered on fiducials in the LOT module
Location dependent strategy for Lung Tx

ITV and PTV: GTVs are outlined on both Exhale and Inhale phases. An ITV is constructed using the LOT module using a 0 View approach.
Location dependent strategy for Lung Tx

Treatment plan: Volumes are exported and then re-imported into regular planning. Treatment is performed using regular Synchrony® tracking.
Summary

Region

Preferred Tracking

- A
  - <1.5cm: LOT™ 0 View (4D CT)
  - >1.5cm: LOT™ Sim

- B
  - <1.5cm: LOT™ 0 View Transbronch Fiducials
  - >1.5cm: LOT™ Sim

- C
  - <1.5cm: Chest Wall Fiducials
  - >1.5cm: LOT™ Sim Post only
  - >3.0cm: Chest Wall Fiducials

- D
  - Percutaneous Fiducials
  - LOT™ 0 View
Thank you!