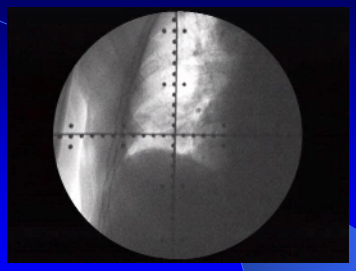
Respiratory-phase correlated imaging, treatment planning and delivery

Clinical Implementation



Department of Radiation Physics
AAPM Annual Meeting
Anaheim, CA USA 2009

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Disclosures

- None

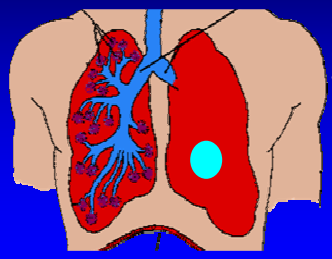
Session Objectives

- Understand the different respiratory phase correlated treatment planning and delivery approaches
- Compare the benefits and pitfalls of each of the above approaches
- Develop and establish respiratory correlated imaging, treatment planning and delivery appropriate to the available equipment

Reports ICRU 50 and 62: Prescribing, Recording and Reporting Photon Beam Therapy

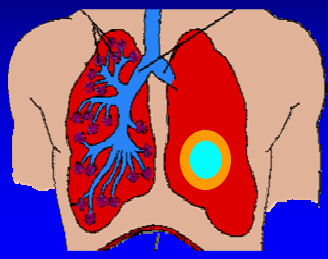
- Definitions
  - GTV – Gross Tumor Volume
  - CTV – Clinical Target Volume
  - ITV – Internal Target Volume
  - PTV – Planning Target Volume

GTV- Gross Tumor Volume



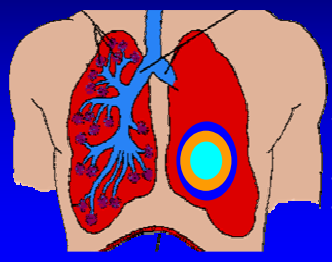
gross demonstrable extent and location of the malignant growth, i.e. visible disease

CTV- Clinical Target Volume



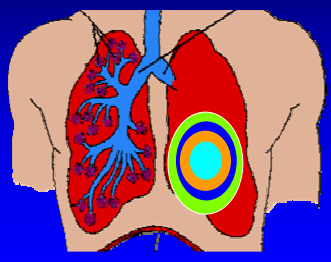
contains the GTV and/or subclinical disease that must be eliminated

ITV- Internal Target Volume



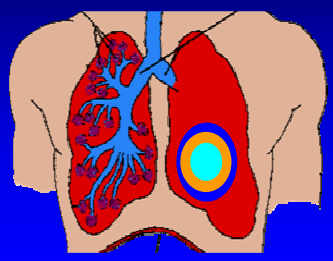
the CTV with a margin (termed the *internal margin*) added for expected physiologic movements and variations in size, shape and position of the CTV during therapy

PTV- Planning Target Volume



the ITV with a margin (termed the *set-up margin*) which accounts for uncertainties in patient positioning and alignment of the beams during treatment planning and through all treatment sessions

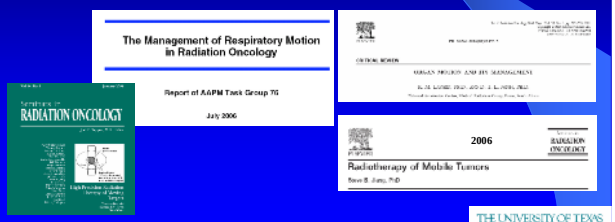
ITV- Internal Target Volume



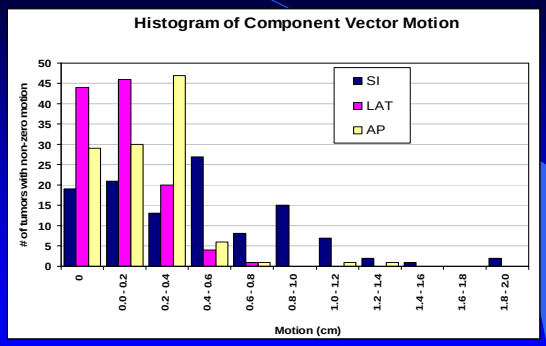
can be adapted based on respiratory motion information from respiratory correlated imaging

How much do thoracic tumors move ?

- Several studies have looked at respiratory motion of thoracic and abdominal tumors
- Some good references:



MDACC: Distribution of Tumor Motion



From Balter/MDACC

Determination of demonstrable tumor motion extent

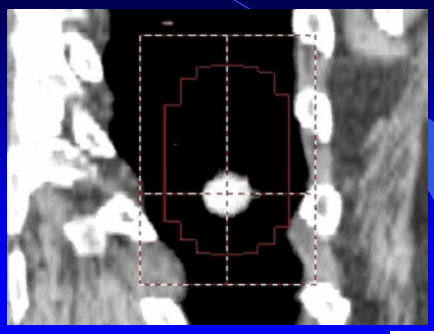
Accounting for tumor motion

- Past:
  - Accommodation: Surround CTV with generic margin to allow for tumor motion
- Current:
  - Accommodation: Customized treatment margins and techniques for each patient based on respiratory correlated imaging
  - Gating: Gate the treatment over a limited number of phases of the respiratory cycle
  - Breath-hold: Eliminate motion by immobilizing the tumor
  - Tracking: Beam follows the motion of the tumor throughout respiratory cycle

How can we obtain demonstrable tumor motion extent ?

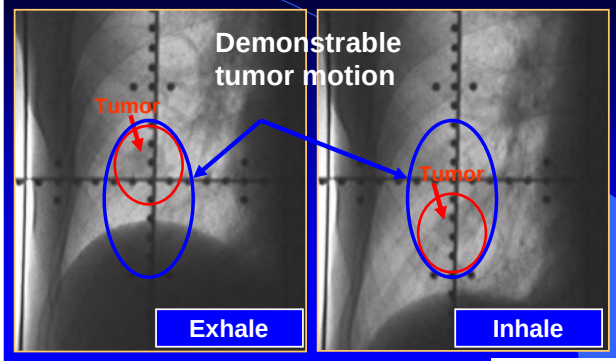
- Accommodation
  - Breath hold CT at respiratory extrema (peak inhale and peak exhale)
  - Respiratory extremes from 4D CT
  - All resp. phases from 4D CT
  - Max IP, Min IP, Avg CT
- Breath hold
- Gating
  - Prospectively triggered axial CT
  - Retrospectively sorted cine/spiral CT
- Tracking
  - All resp. phases from 4D CT

Accommodation



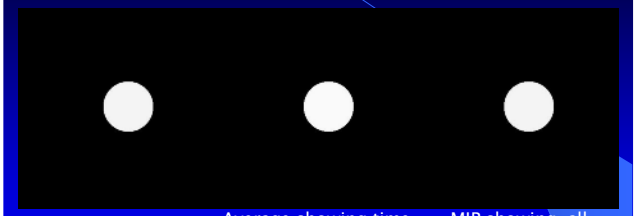
From Keall/Stanford

Inhale & exhale breath hold



From Keall/Stanford

Abstractions of 4D Data: The average dataset and the maximum intensity projection (MIP) dataset.



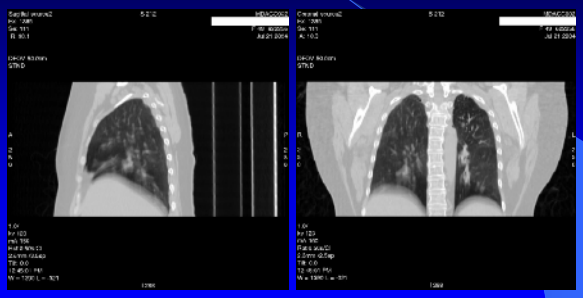
Moving tumor

Average showing time averaging of the moving tumor

MIP showing all voxels occupied by the tumor over the respiratory cycle

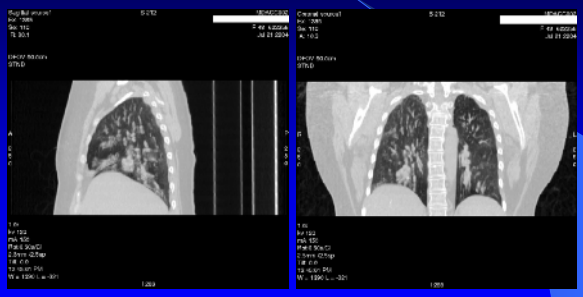
Average Image

Each voxel is given a value equal to the numeric average of the values for that voxel over all respiratory phases (equivalent to a slow CT)



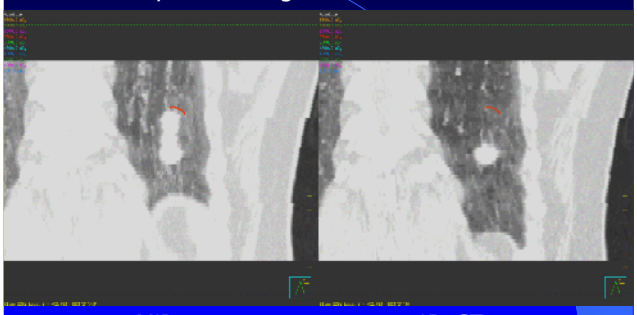
MIP Image (Maximum Intensity Projection)

Each voxel is given a value equal to the maximum of the values for that voxel over all respiratory phases



Maximum Intensity Projection (MIP): Clinical exam

The range of tumor motion, the ITV, can be estimated by contouring on the MIP



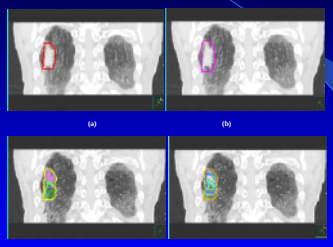
MIP 4D-CT

Maximum Intensity Projection
MIP – Stage I

Trust but verify

MIP

MIP modified



2 Phases

All Phases

Figure 1. Demonstrable respiratory tumor motion determination for stage I lung tumor based on contouring on (a) Maximum intensity projection (MIP) (b) modified MIP (c) 2 extreme phases and (d) all phases of a 4D CT data set. MIP based contours, as shown in panels (a) and (b), are as they appear on the MIP data set. GTV contours drawn on individual phases, as shown in panels (c) and (d) are registered to the peak exhalation phase of the 4D CT data set.

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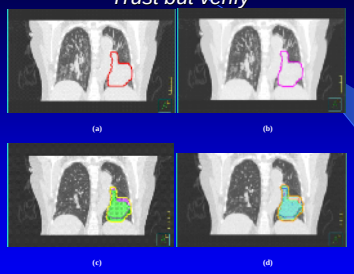
Maximum Intensity Projection
MIP – Stage III

Trust but verify

MIP

MIP modified



2 Phases

All Phases

Figure 1. Demonstrable respiratory tumor motion determination for stage III lung tumor based on contouring on (a) Maximum intensity projection (MIP) (b) modified MIP (c) 2 extreme phases and (d) all phases of a 4D CT data set. MIP based contours, as shown in panels (a) and (b), are as they appear on the MIP data set. GTV contours drawn on individual phases, as shown in panels (c) and (d) are registered to the peak exhalation phase of the 4D CT data set.

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Problems with MIP and Average

- Do not easily distinguish tumor for anatomy that crosses path with tumor
  - Is not useful near the diaphragm
  - Is not useful for esophagus
- Does not allow customization of CTV expansion with motion
  - The relationship between the GTV and boundaries (i.e. chest wall) changes with respiration.

From Balter/MDACC

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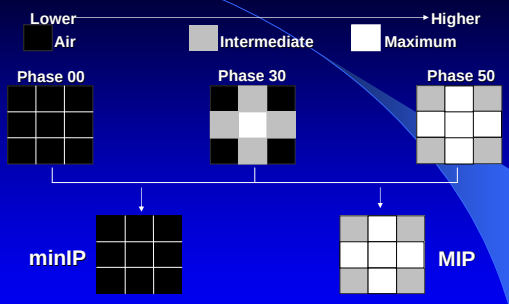
Intensity Projection



Intermediate values may be under-represented in both minIP and MIP

From Beddar/MDACC

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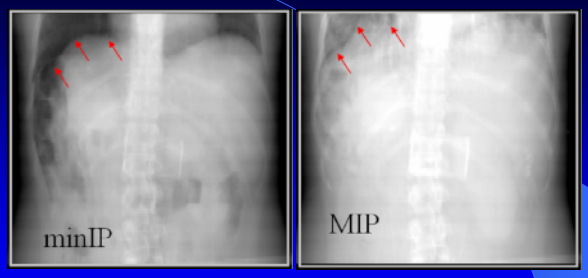
Use of Intensity Projection

- For Lung: use maximum intensity projection (MIP) to delineate tumors
  - image contrast: air – to – tissue
- Abdomen: GI physicians contour over 10 sets of images
  - cannot use MIP for the liver
    - Maximum value is for liver, not tumor
    - Tumor volume would be underestimated
  - image contrast: tissue – to – tissue
- Use of other projection schemes currently under investigation

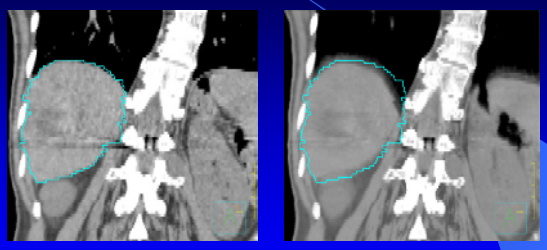
minIP vs. MIP



MIP: highest CT # selected
minIP: lowest CT # selected
Loss of liver/tumor volume at lung/liver interface

Ave-CT vs. Free-Breathing

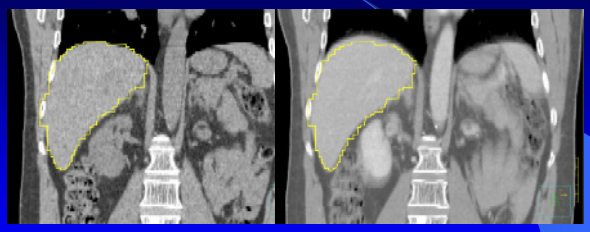
Free-Breathing **Average-CT**



FB and Ave-CT borders differ

Ave-CT vs. Free-Breathing

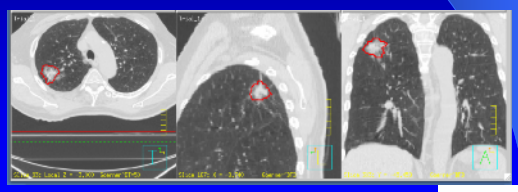
Free-Breathing **Average-CT**



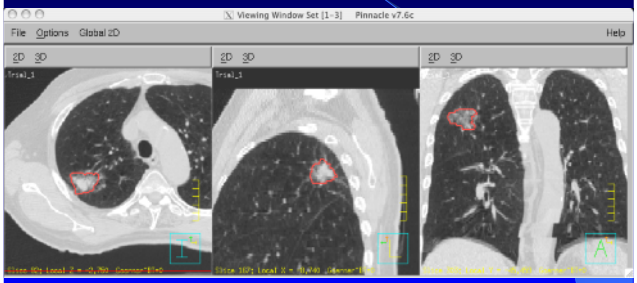
Ave-CT liver volume larger

Propagation of GTV

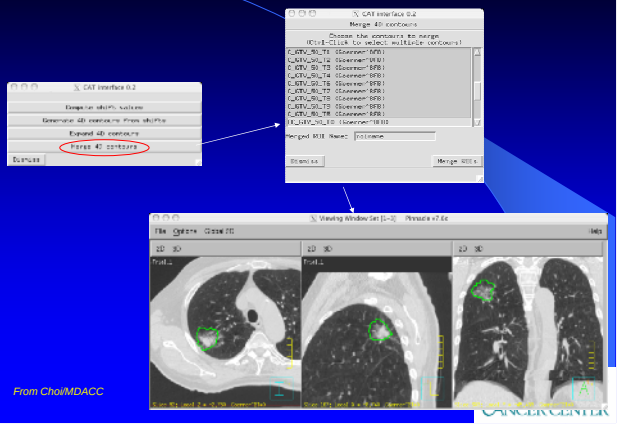
- If GTV TVs is contoured on a reference phase it can be translated and rotated to match the GTV on the other phases in a rigid manner.



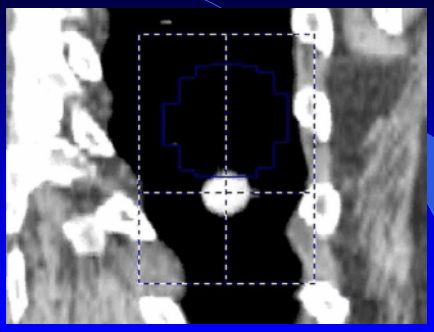
Rigid propagation gives us a GTV contour on each phase



The contours can be combined to form an iGTV or an ITV

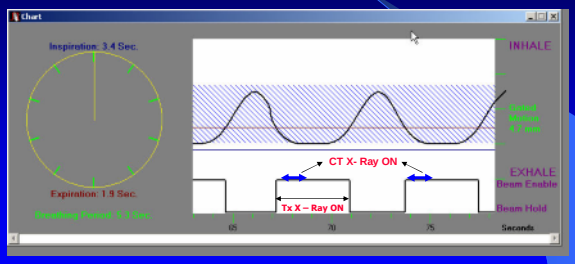


Respiratory gating



Prospectively triggered CT

Only turn the CT X-Ray ON when the respiratory position crosses a threshold/gate



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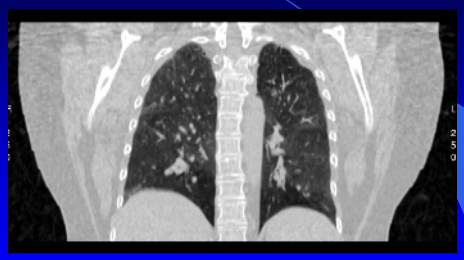
Retrospectively sorted cine/spiral CT

Residual motion



These images represent a 30% duty cycle around expiration, there is still residual motion

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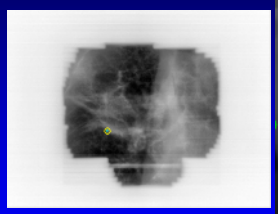
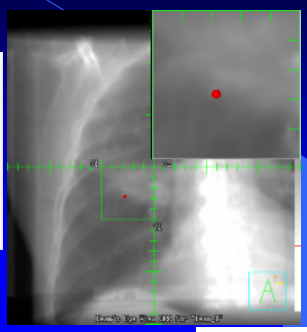
Gated motion can be significant



Max Sup-Inf Gated Motion = 1.5 cm



Max Sup-Inf 4DCT Motion (same day) = 2.1 cm

From Nelson/MDACC

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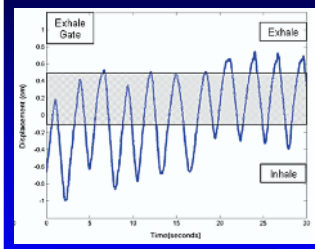
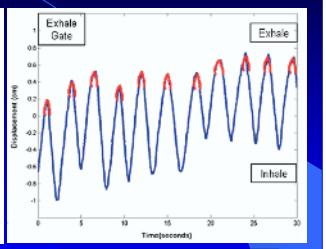
Baseline Drift



Displacement gating



Phase gating

From Keall/Stanford

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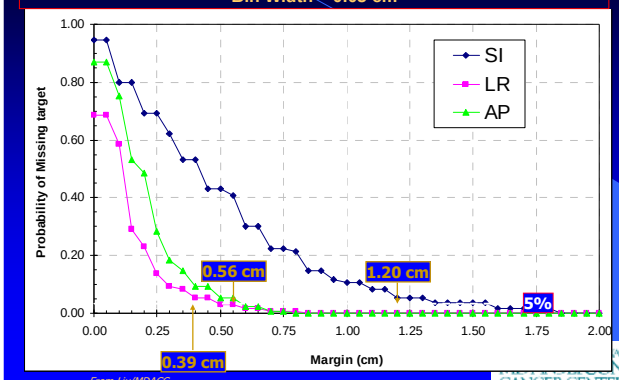
Margins …

Margin for Respiratory Motion vs. Probability of Missing the Target
N = 130 (patients for whom full extent of motion could be determined)
Bin Width = 0.05 cm



From Liu/MDACC

Treatment planning guidelines

- The following components should be considered when designing CTV-PTV margins:
  - Motion artifacts in the CT scan
  - Respiration motion during delivery
  - Daily variations of respiration motion
  - Variations caused by the changing volumes of organs
  - Tumor growth and shrinkage
  - Treatment related anatomic changes- reductions in bronchiole obstructions and changes in atelectasis regions
  - Patient setup error: typical 3-mm (1σ)

UTMDACC Thoracic Service Treatment planning guidelines: Margins**

*** Without image guidance for patient setup*

Accommodation:	CTV = MIP mod-GTV + 8 mm margin PTV = CTV + 1 cm margin (7mm setup uncertainty + 3 mm motion variations)
Resp Gating:	CTV = GatedMIP mod-GTV + 8 mm margin PTV = CTV + 1.5 cm margin (7 mm setup uncertainty + 8 mm gating margin)
Extended Time CT:	PTV = CTV + 1.5 cm margin (7 mm setup uncertainty + 8 mm motion margin)

Courtesy Komaki/MDACC

UTMDACC Thoracic Service Treatment planning guidelines: Margins**

*** With daily kV imaging and weekly CBCT guidance for patient setup*

Accommodation:	CTV = MIP mod-GTV + 8 mm margin PTV = CTV + 0.5 cm margin (5 mm setup uncertainty)
Resp Gating:	CTV = GatedMIP mod-GTV + 8 mm margin PTV = CTV + 'x' cm margin (5 mm setup uncertainty + 'y' mm gating margin)

Courtesy Balter/MDACC

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Dose calculation on respiratory phase correlated CT datasets

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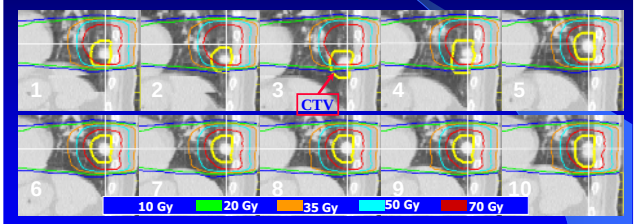
IMRT Plan Based on a Conventional CT Scan Applied to 10 Phases of Respiratory Cycle



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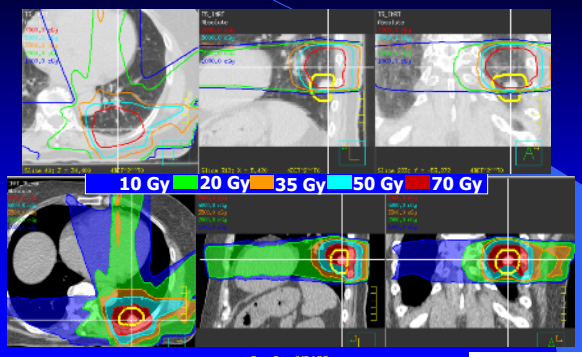
Respiratory Motion and its effect on dose – example planned on 3DCT evaluated on 4DCT



From Dong/MDACC

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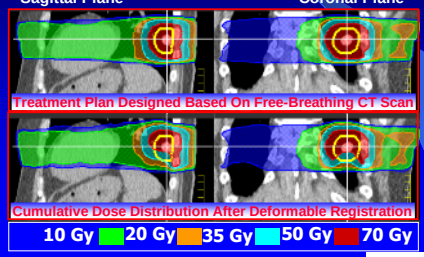
IMRT Plan Based on a Conventional CT Scan
Applied to 10 Phases of Respiratory Cycle

Sagittal Plane | Coronal Plane

Perception



Reality

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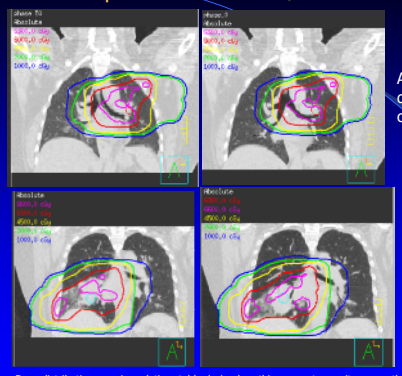
T50 Expiration | T0 Inspiration



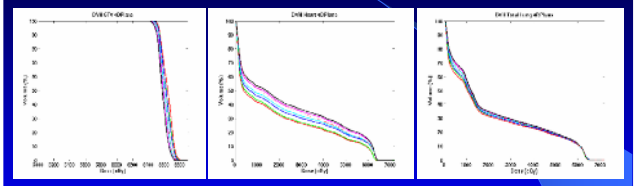
Away from diaphragm dose is stable/lung volume changes

Near diaphragm high dose region moves with diaphragm

- Dose distribution remains relative stable during breathing except were it crosses the diaphragm
- However, lung volume is increased from expiration to inspiration

From Balter/MDACC

DVH vs Respiratory Phase



GTV | Heart | Lung

The DVH is a function of respiratory phase, but is generally bounded by the Inspiration and Expiration DVH

From Liu H/MDACC

Changes in Dose Distribution and DVH vs Respiration

- Megavoltage photons are relatively insensitive to local density changes
- Large doses differences occur only when objects move in and out of the dose distribution
- Changes in lung DVH are mainly due to changes in lung volume with respiration
- Changes in other DVHs only occur when object move in and out of the high dose region

From Balter/MDACC

MDACC: Current Clinical Practice

How we estimate the dose based on 4D CT data

- We define the location of the ITV on the 4D data
- We calculate and display the dose on the average CT (Dose of DVH).
- We determine volumes on different datasets (Volume of DVH).
  - Lung: 0% and 50%
  - Heart: Average
  - Esophagus: Free Breathing
  - Cord: Free Breathing

From Balter/MDACC

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3D vs 4D dose calculation

- Calculate dose on a reference phase of the 4D CT data set
- Deform the data to obtain internal anatomy information for all other phases
- Recalculate dose on each individual phase
- Deform dose matrix according to volume deformation in each phase
- Accumulate dose on reference phase to get 4D dose distribution
- Is 3D calculation better than 4D ??
  - Currently under evaluation …

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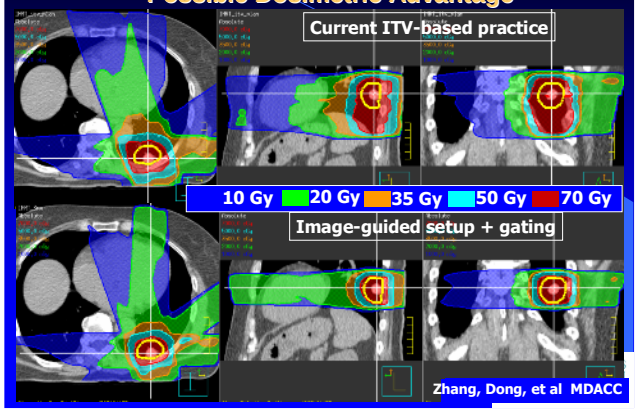
Image-Guided IMRT
Possible Dosimetric Advantage



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Take-home message

- Respiratory-induced tumor motion is significant and unpredictable
- Various methods have been developed to measure the extent of demonstrable tumor motion
- We are now able to rationally define target volumes that explicitly account for the effect of respiratory motion
- Respiratory correlated CT imaging will become the standard-of-care for mobile tumors

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Take-home message

- Average CT data set is an appropriate choice as the reference data set for dose calculations, although other choices exist
- For megavoltage photon treatments, changes in regional features as a result of respiratory motion do not affect dose distributions greatly
- For proton treatment planning, such changes could have a great bearing on the resultant dose distributions and therefore have to be explicitly addressed
- Respiratory correlated CT imaging will be a necessity whenever active management of respiratory motion during radiotherapy is required

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- Lei Dong, Ph.D. MDACC
- Helen Liu, Ph.D. MDACC
- Thoracic clinical physics group, MDACC
- Thoracic radiation oncology service, MDACC