Dependence of total-lung DVH upon respiratory phase-specific lung volume

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Outline of presentation

- Overview of lung-DVH guidelines
- Motivation for current study: DVH vs. lung volume
- Materials and methods
- Results and discussion
- Conclusions and future work

Overview of lung-DVH guidelines

- Cumulative lung DVH used to determine likelihood of respiratory complications following thoracic radiation
- In practice, specific ordinate values on the cumulative lung-DVH curve (e.g. V_{20}, V_{10}) are used to evaluate the quality of a radiotherapy treatment plan
- Lung DVH guidelines have been suggested, based on results from retrospective studies

V_{20} and respiratory complication

- M. V. Graham *et al*., IJROBP 45 (1999) pp. 323-329:
  - Among 99 NSCLC patients in study, 20% observed with Grade 2 pneumonitis 24 months after radiation
  - For patients with V_{20} > 40%: incidence = 36%
  - However:
    - patients not stratified according to concurrent chemotherapy or prior lung function
    - Lung DVH evaluated without subtracting PTV from lung

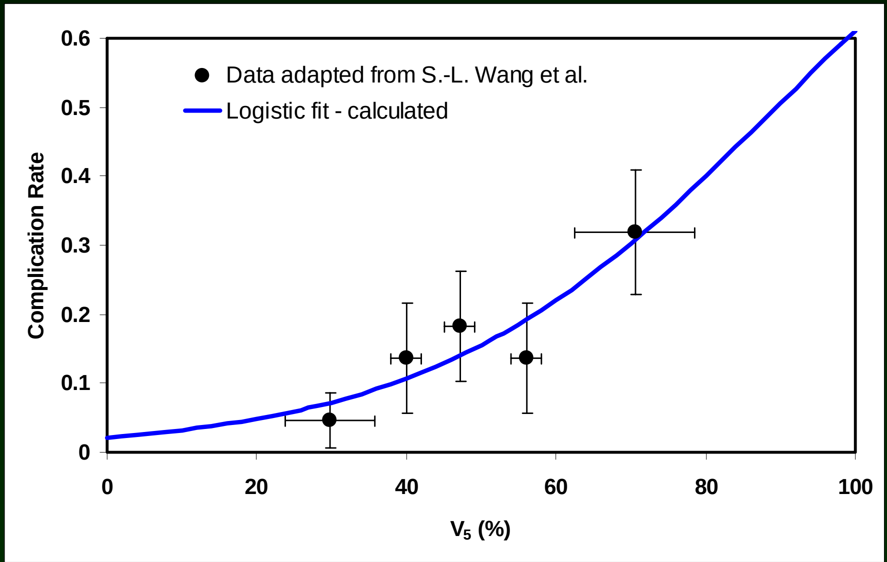
V_{10}, V_{20}, and respiratory complication

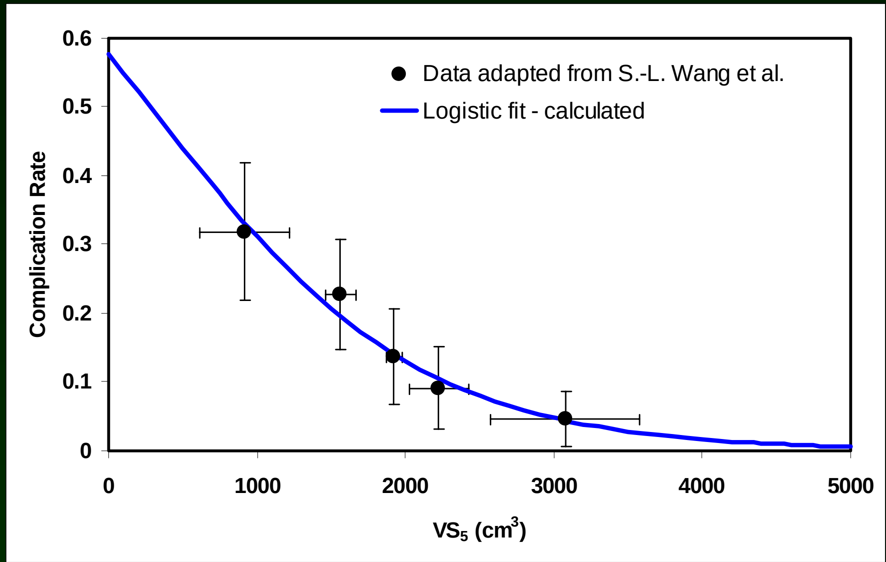
- H. K. Lee *et al*., IJROBP 57 (2003) pp. 1317-1322:
  - 61 esophageal patients receiving concurrent chemo/RT (45 Gy median dose), followed by surgery
  - Considered total-lung DVH; CTV, PTV not expanded into lung
  - 11/61 (18%) with pulmonary complications
  - For $V_{10} \geq 40\%$: 35% occurrence (vs. 8% for $V_{10} < 40\%$)
  - For $V_{20} \geq 20\%$: 32% occurrence vs. 10% (however, apparent increase not considered statistically significant: $p=0.079$)
  - Pulmonary complications not correlated with surgical procedure or site, induction vs. concurrent chemo, or smoking history

V_5, VS_5, and respiratory complication

- S.-L. Wang *et al*., IJROBP 64 (2006) pp. 692-699:
  - 110 esophageal patients considered
    - Neoadjuvant chemo/RT (41.4 to 50.4 Gy) followed by surgery
    - Includes those analyzed within H. K. Lee et al.
  - 18/110 (16%) with postoperative pulmonary complications
  - From univariate analyses, increased incidence seen for:
    - Increased V_5
    - Reduced VS_5 (VS_5 = absolute lung volume receiving < 5 Gy)
    - Female patients (45% vs. 19%)
(likely related to smaller total lung volume, thus smaller VS_5)

V_5, VS_5, and respiratory complication





- Figure 2 from S.-L. Wang *et al*.:
  - Increasing V_5 found to correlate with increasing incidence of pulmonary complications
  - This has motivated attention to V_5 at MDACC (aim to keep it below 60%)

- Figure 4 from S.-L. Wang *et al*.:
  - Multivariate model: VS_5 the only significant independent predictive factor for post-op pulmonary complication
  - Ensuring adequate lung volume unexposed to radiation may effectively reduce incidence of respiratory complications

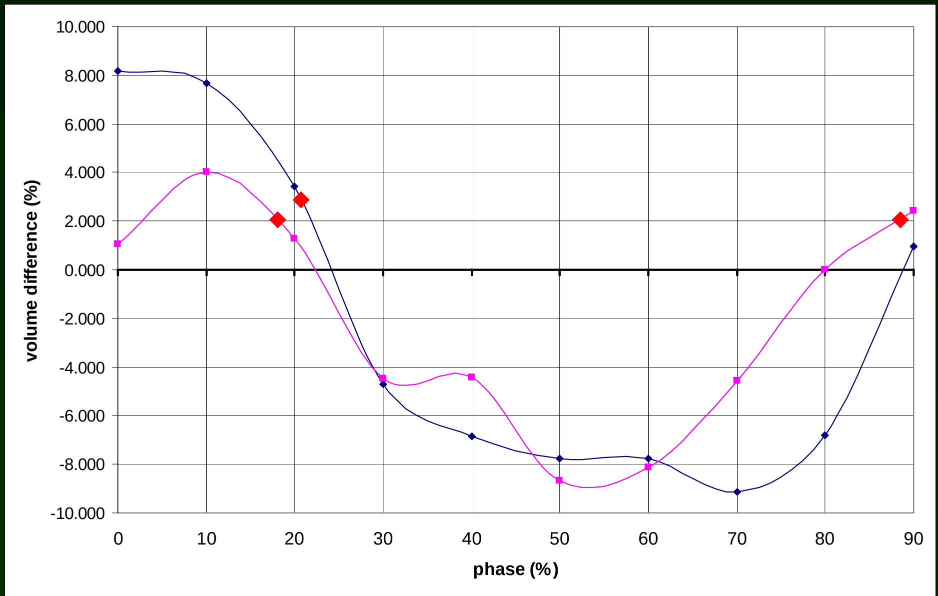
Respiratory-correlated lung volume and lung DVH

- Apparent lung volume appears critical in evaluating likelihood of respiratory complication
  - Especially given the correlation with VS_5
  - V_{20}, V_{10}, V_5 expected to change with lung volume as well
- However: the above lung-DVH criteria were determined from treatment plans using the apparent lung volume from CT scans acquired during free-breathing ("3D-CT")
  - Does the resulting DVH characterize the actual total-lung dose distribution over the course of treatment?

Respiratory-correlated lung volume from 4D-CT

- Study presented by C. Stepaniak *et al*., AAPM 2005:
  - Use 4D-CT to correlate apparent lung volume with respiratory phase
  - Determine the phase within which the apparent CT lung volume is most consistent with the 3D-CT lung volume
    - CT data for that phase may be used to generate the treatment plan (negating the need for separate 3D-CT scan)
    - Current DVH guidelines should be applicable for that phase
  - Determine the extent to which lung volume can vary over the course of a respiratory cycle
    - Lung-volume variation may correspond to lung-DVH variation

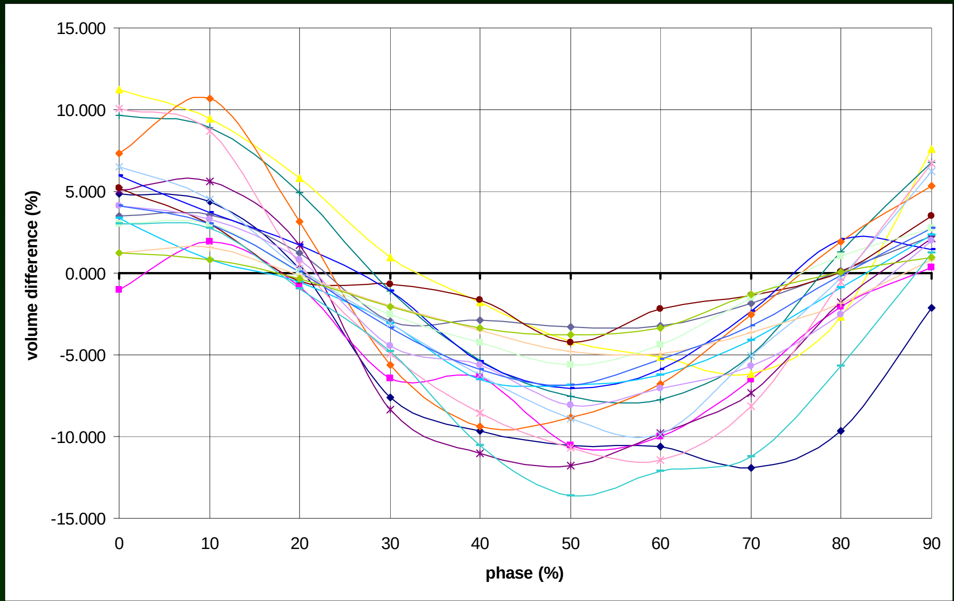
Results from C. Stepaniak *et al*., AAPM 2005



Individual-phase lung volume minus 3D-CT lung volume, data for two patients

- "Ave-IP": for each voxel, determine average CT number among all respiratory-phase images, and assign that average CT number to that voxel
- Apparent lung volume from Ave-IP (red diamonds) differs from apparent 3D-CT lung volume by 3%, at most
- 20% phase (mid-exhalation) and 80% phase (mid-inhalation): lung volume corresponds best to apparent Ave-IP lung volume

Results from C. Stepaniak *et al.*, AAPM 2005



Individual-phase lung volume minus Ave-IP lung volume, data for 18 patients

- 20%-phase, 80%-phase lung volumes correspond best to apparent Ave-IP lung volume
  - 20% phase: lung-volume difference 1.0±1.9%
  - 80% phase: –1.2±2.8%
- Motivated choice to use 20%-phase CT image set to develop the clinical treatment plan, for FMLH patients having undergone 4D-CT simulation

Objectives of the current study

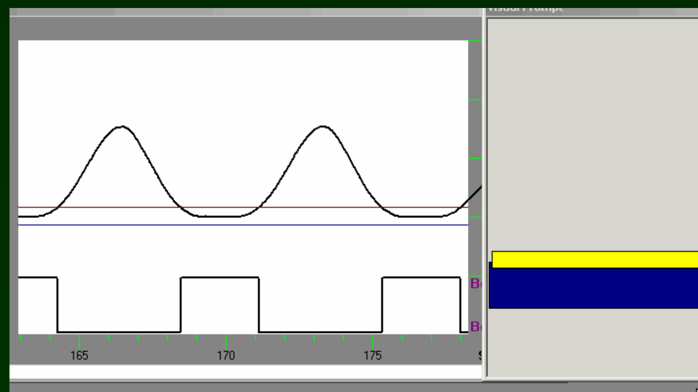
- Evaluate variation of total-lung DVH at distinct respiratory phases
  - If beams' paths remain entirely with lung during respiration, then may expect decrease in lung volume during exhalation → increase in DVH at low doses
  - Departures from the above: may indicate more-complex motion of lung relative to beam geometry
  - Increased density of lung during exhalation → increased attenuation of x-ray beams → reduced dose deposition interior to lung → reduced DVH at higher doses

Objectives of the current study

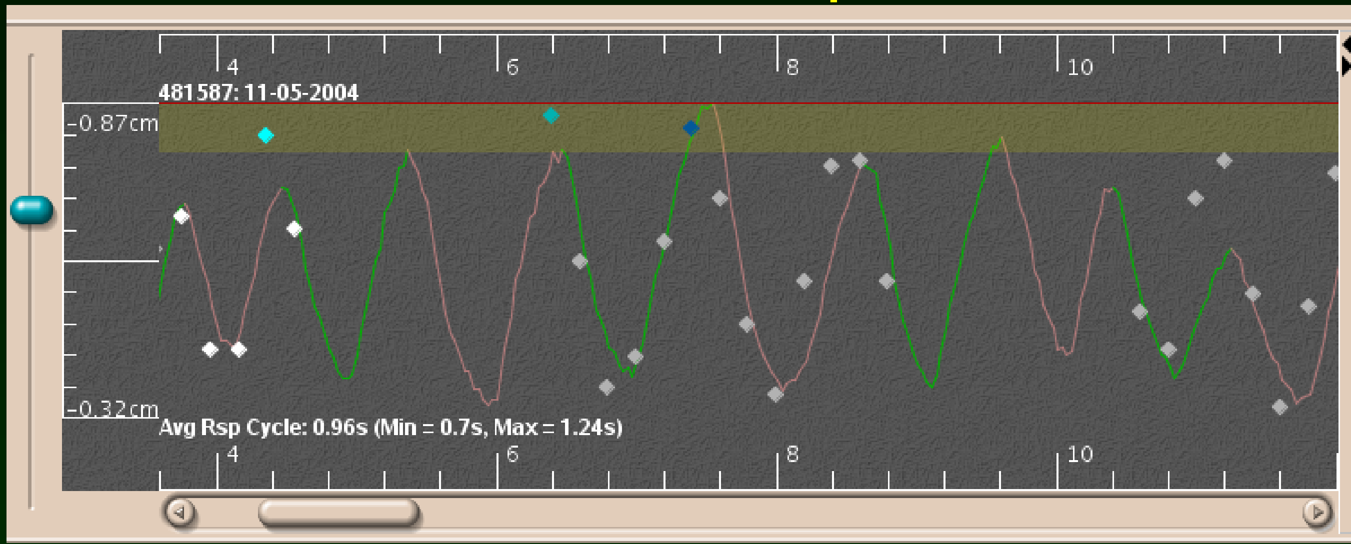
- Assess impact of DVH variations upon lung-DVH guidelines for routine thoracic radiotherapy, prospective gated treatments
  - Are DVH differences, from phase to phase, on the order of several percent? (for some treatment plans, criteria such as “$V_{20} < 20\%$” may be challenging to meet)
  - End-inhalation, end-exhalation gated treatment: might the “true” DVH be significantly different from the apparent DVH associated with 3D-CT lung volume?

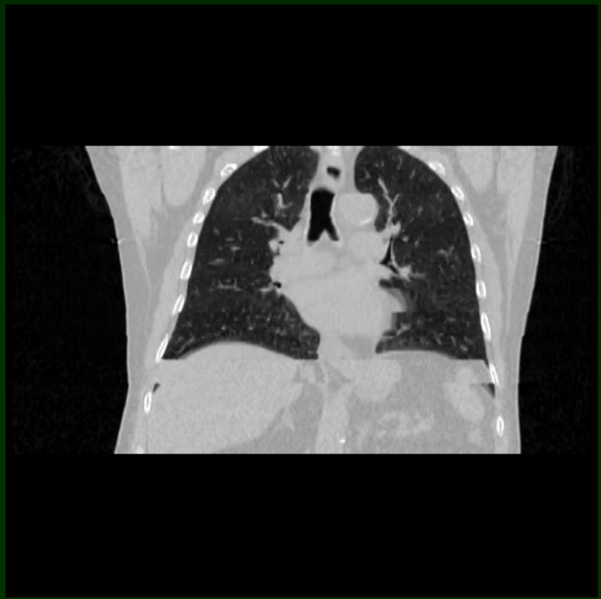
4D-CT data acquisition

- 4D-CT hardware:
  - GE LightSpeed 4-slice CT scanner:
    - Axial scans (increment couch, acquire CT data)
    - Cine-CT mode: at each couch position, x-ray tube rotates at least 10 times around patient, acquiring axial CT image during each rotation
  - Varian Real-time Position Management (RPM) system:
    - Monitors abdominal AP displacement – correlated with respiratory phase/lung volume



4D-CT data acquisition

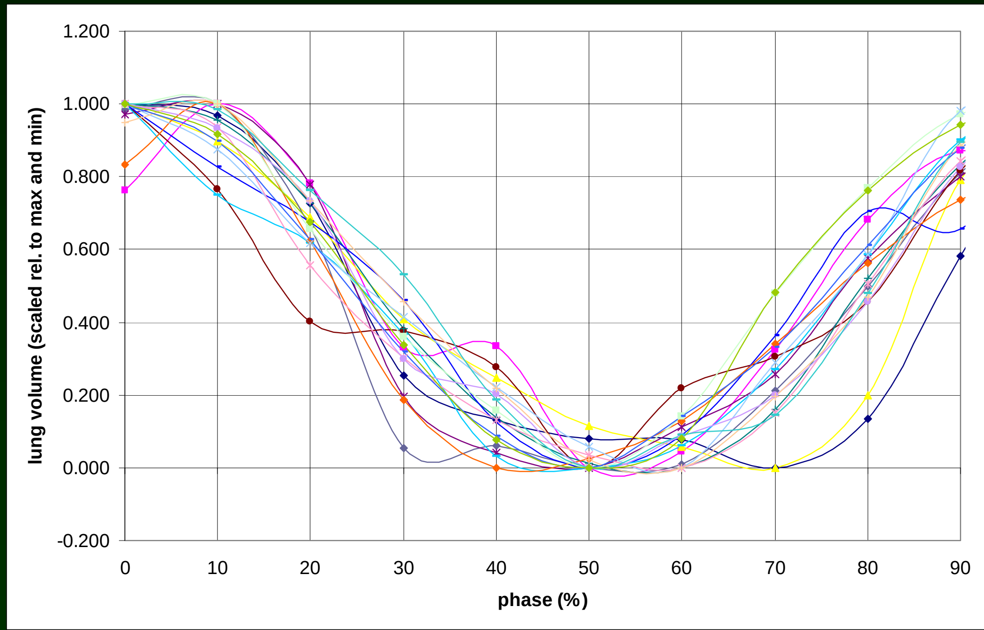




- GE Advantage Workstation:
  - Associates "time-stamp" of each cine-CT image with RPM trace
  - At each couch position, for each cine-CT image, enables association with specific respiratory phase
  - Images associated with one of ten phases in respiratory cycle: 0%, 10%, 20%, … 90%

4D-CT image sets used in analysis

- Respiratory phase images used in treatment planning:
  - 0% phase
    - Peak inhalation, by definition
  - 50% phase
    - Peak exhalation, on average
    - Peak exhalation typically arises between 40% and 60% phases
  - 20% phase
    - Mid-exhalation
    - Most consistent with apparent 3D-CT lung volume
    - Routinely used to develop “clinical plan” for patient treatment

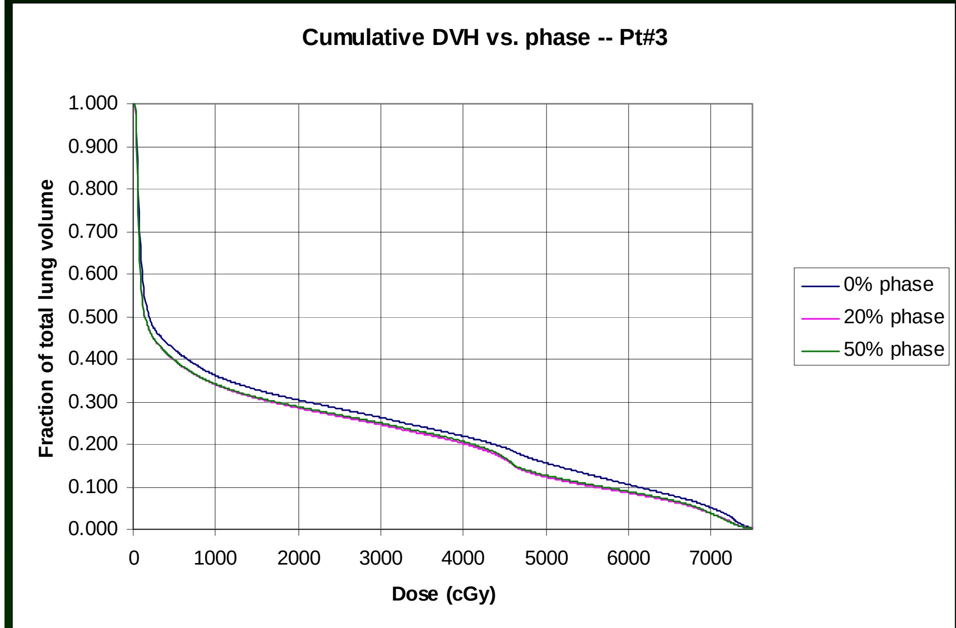


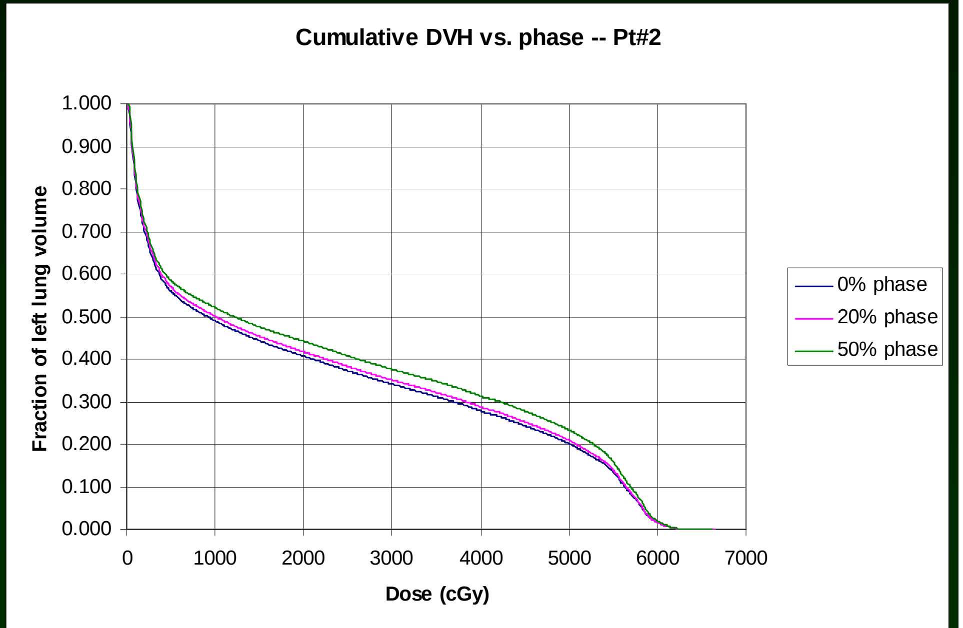
Adapted from data incorporated in
C. Stepaniak *et al*., AAPM 2005 – 18 patients

Treatment planning processes and DVH analyses

- Contouring:
  - For each image set: patient skin surface, right lung, left lung
  - ITV/PTV not transferred, subtracted from lung
- Beam design and dose calculation:
  - Transferred the following from the “clinical” plan to the other 4D-CT phase image sets:
    - Beam orientations (gantry/collimator angles, isocenter) and energies
    - Apertures (blocks/MLCs) and wedges
    - MU per beam
  - Heterogeneity corrections turned on
- Ten clinical cases considered
  - Both lateral and medial lung targets
  - Several NSCLC cases (prescribed 63 to 66 Gy)
  - Treatments to mediastinum
- Determine cumulative DVH for total lung
  - Compute V_{20}, V_{10}, V_5, VS_5

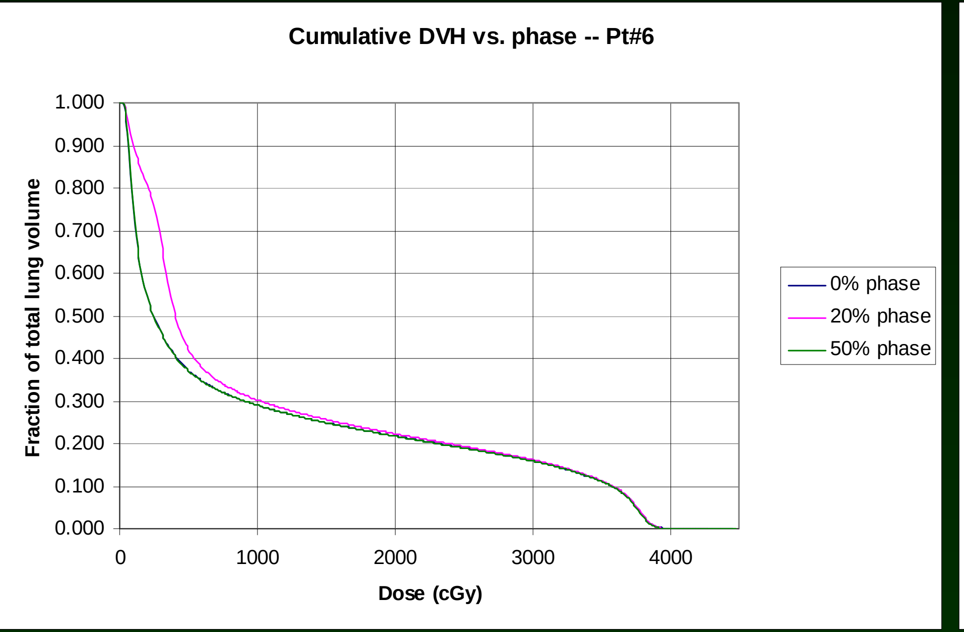
DVH analyses: NSCLC, lateral-lung targets

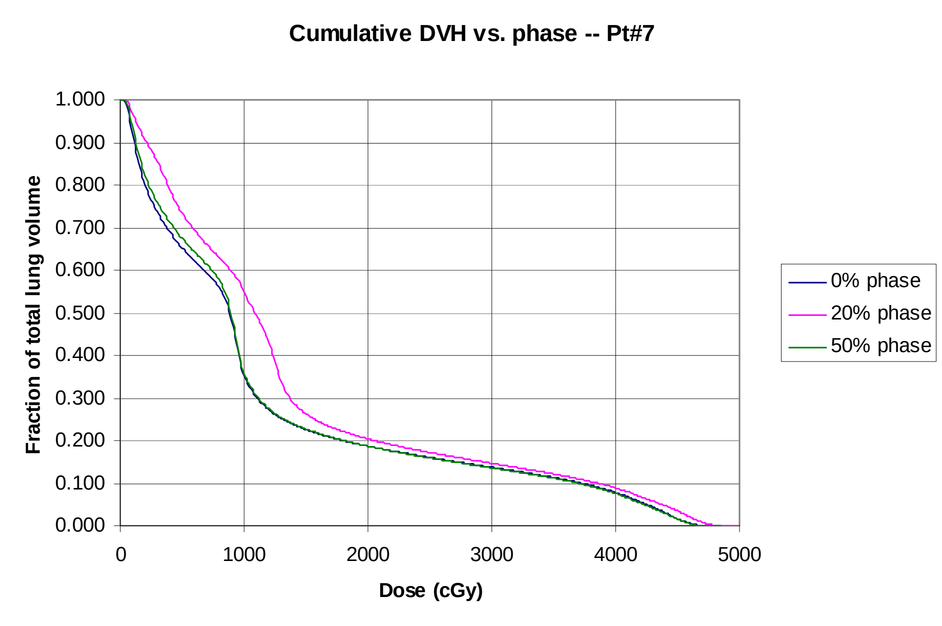




- As phase changes from 0% to 50%, V_{10} and V_{20} tend to change by 2 to 3 %
- Increase (or decrease) of DVH with respiratory phase is case-specific

DVH analyses: mediastinal targets





- Total-lung DVH may not increase or decrease monotonically with change in respiratory phase (end-inhalation to end-exhalation)
- Lung motion, in and out of treatment fields, as a function of respiratory phase, can be complex
- For one patient case presented: effect of respiratory phase upon V_{10} is substantial (~20%)

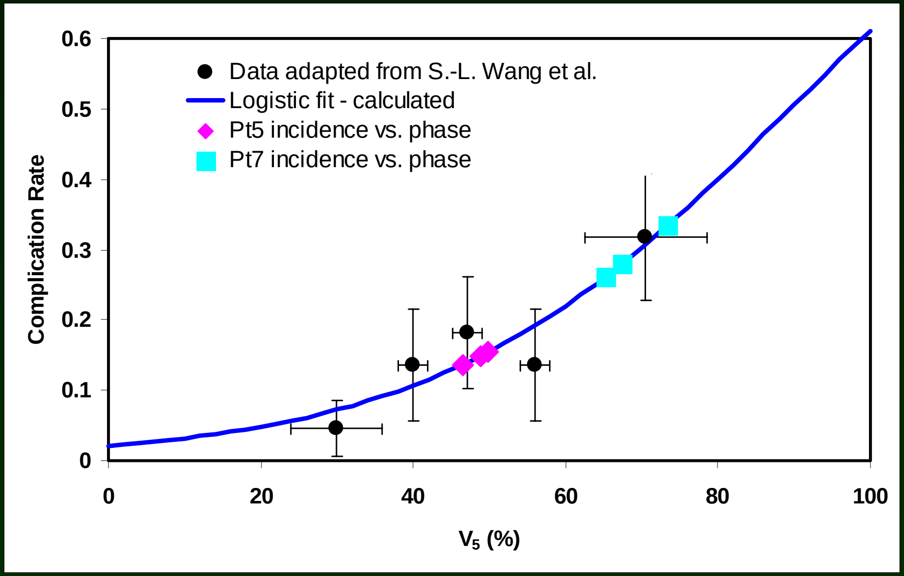
Variation in DVH: V_{20} and V_{10}

Patient Label	**V_{20} (%)**			**V_{20}**	**V_{10} (%)**			**V_{10}**
	phase 0	**phase 20**	**phase 50**	**spread**	**phase 0**	**phase 20**	**phase 50**	**spread**
Pt1 (lateral)	7%	6%	7%	1%	10%	9%	10%	1%
Pt2 (lateral)	41%	42%	44%	3%	49%	50%	52%	3%
Pt3 (lateral)	30%	29%	29%	2%	36%	34%	34%	2%
Pt4 (lateral)	17%	16%	16%	1%	24%	23%	23%	1%
Pt5 (lateral)	17%	18%	20%	2%	22%	24%	24%	2%
Pt6 (medial)	22%	22%	22%	1%	29%	30%	29%	1%
Pt7 (medial)	19%	20%	19%	2%	*35%*	*55%*	*36%*	*20%*
Pt8 (lateral)	27%	28%	29%	2%	42%	43%	46%	3%
Pt9 (lateral)	34%	35%	36%	1%	48%	48%	50%	2%
Pt10 (lateral)	19%	19%	19%	0%	25%	25%	25%	1%
μ spread, excl *outlier*				**2%**				**2%**
σ spread, excl *outlier*				**1%**				**1%**

- Change in V_{20}, V_{10}: typically by 2%, at most by 3%
- Not always monotonic increase with decreasing lung volume

Variation in DVH: V_5

Patient Label	V_5 (%)			V_5
	phase 0	phase 20	phase 50	spread
Pt1 (lateral)	13%	11%	13%	1%
Pt2 (lateral)	56%	57%	59%	3%
Pt3 (lateral)	42%	40%	40%	3%
Pt4 (lateral)	30%	28%	29%	2%
Pt5 (lateral)	46%	49%	50%	3%
Pt6 (medial)	37%	42%	37%	5%
Pt7 (medial)	65%	73%	67%	8%
Pt8 (lateral)	52%	53%	57%	4%
Pt9 (lateral)	66%	68%	70%	3%
Pt10 (lateral)	31%	30%	30%	1%
μ spread				**3%**
σ spread				**2%**

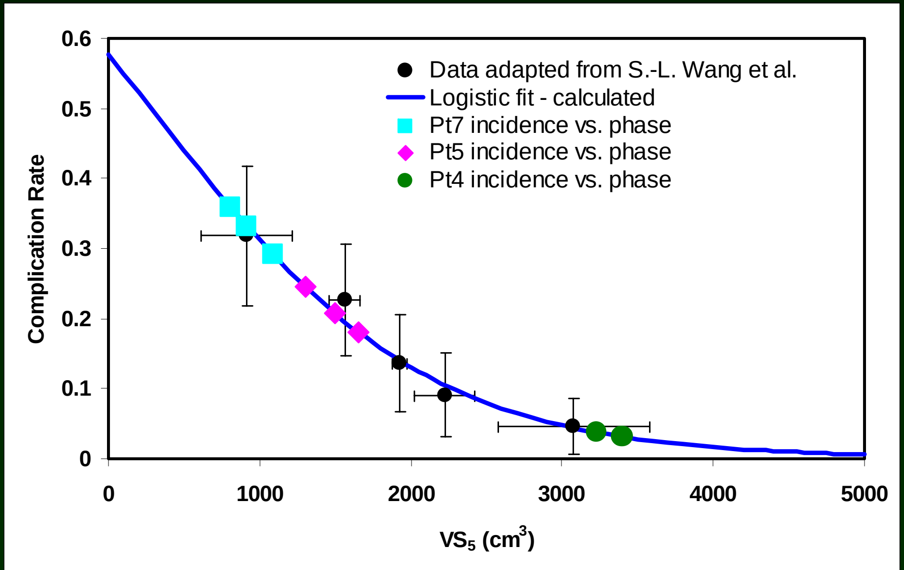


Adapted from S.-L. Wang et al., IJROBP 64 (2006) pp. 692-699

- Typical change in V_5 is approximately 3%; not necessarily monotonic with respiratory phase
- Increase in respiratory-complication likelihood: can be modest (~2%) or significant (~7%), depending on whether V_5 is higher or lower

Variation in DVH: VS_5

Patient Label	VS_5 (cm^3)			VS_5
	phase 0	phase 20	phase 50	spread
Pt1 (lateral)	4325	4318	4082	243
Pt2 (lateral)	1143	1080	909	234
Pt3 (lateral)	1750	1788	1556	232
Pt4 (lateral)	3394	3408	3227	181
Pt5 (lateral)	1650	1500	1305	345
Pt6 (medial)	1832	1899	1665	233
Pt7 (medial)	1087	808	915	279
Pt8 (lateral)	2156	2083	1744	413
Pt9 (lateral)	792	701	601	191
Pt10 (lateral)	2635	2513	2416	219
μ spread				**257**
σ spread				**72**



Adapted from S.-L. Wang et al., IJROBP 64 (2006) pp. 692-699

- Typical change in VS_5 is approximately 260 cm^3; not necessarily monotonic with respiratory phase
- If VS_5 is smaller, effect of lung volume upon VS_5 can be significant (~5% to 7% difference in respiratory-complication likelihood)

Conclusions

- Variations in total-lung DVH with respiratory phase:
  - 2% to 3% variations can be expected
  - Low-dose DVH variations can be substantial for some patients
  - Sufficient to warrant a re-assessment of existing DVH guidelines
- Trends in DVH variations may be patient-specific
- Current DVH criteria for V_{10} and V_{20} (based on 20%-phase CT) might not be applicable for gated treatments (at 0%- or 50%-phase)

Areas for future study

- Investigate the more-detailed aspects of the change in lung geometry with respiratory phase
  - expansion/contraction in AP/SI/RL directions
  - local variations in lung density
- Investigate effect, legitimacy of excluding PTV from total-lung DVH calculation
- Investigate lung-DVH differences, IMRT vs. 3DCRT
  - Might IMRT yield unacceptable V_5, VS_5?
- Is there an observed reduction/increase in post-RT respiratory complication following gating or breath-hold treatments, relative to free-breathing treatments?