4DCT Acquisition and Artifacts

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Tenet

- “Precise knowledge and control of the 4D dose distribution is essential for a favorable therapeutic outcome.”
- 4D imaging is a key component toward this goal.

Temporal Aliasing- 3D Helical Scans 2002

moving balls movie 30 sec.wmv

doublet after moviemaker.wmv

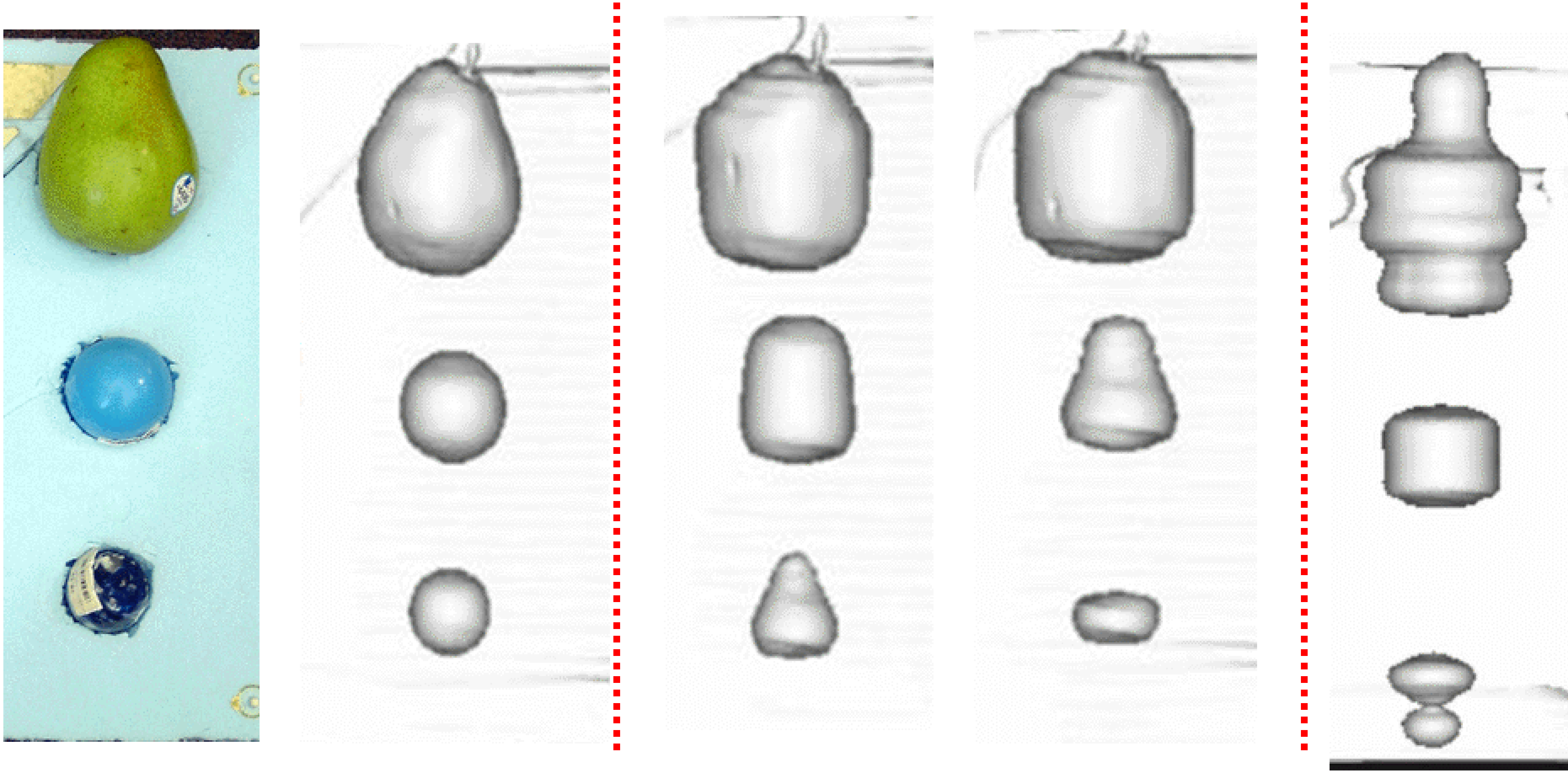
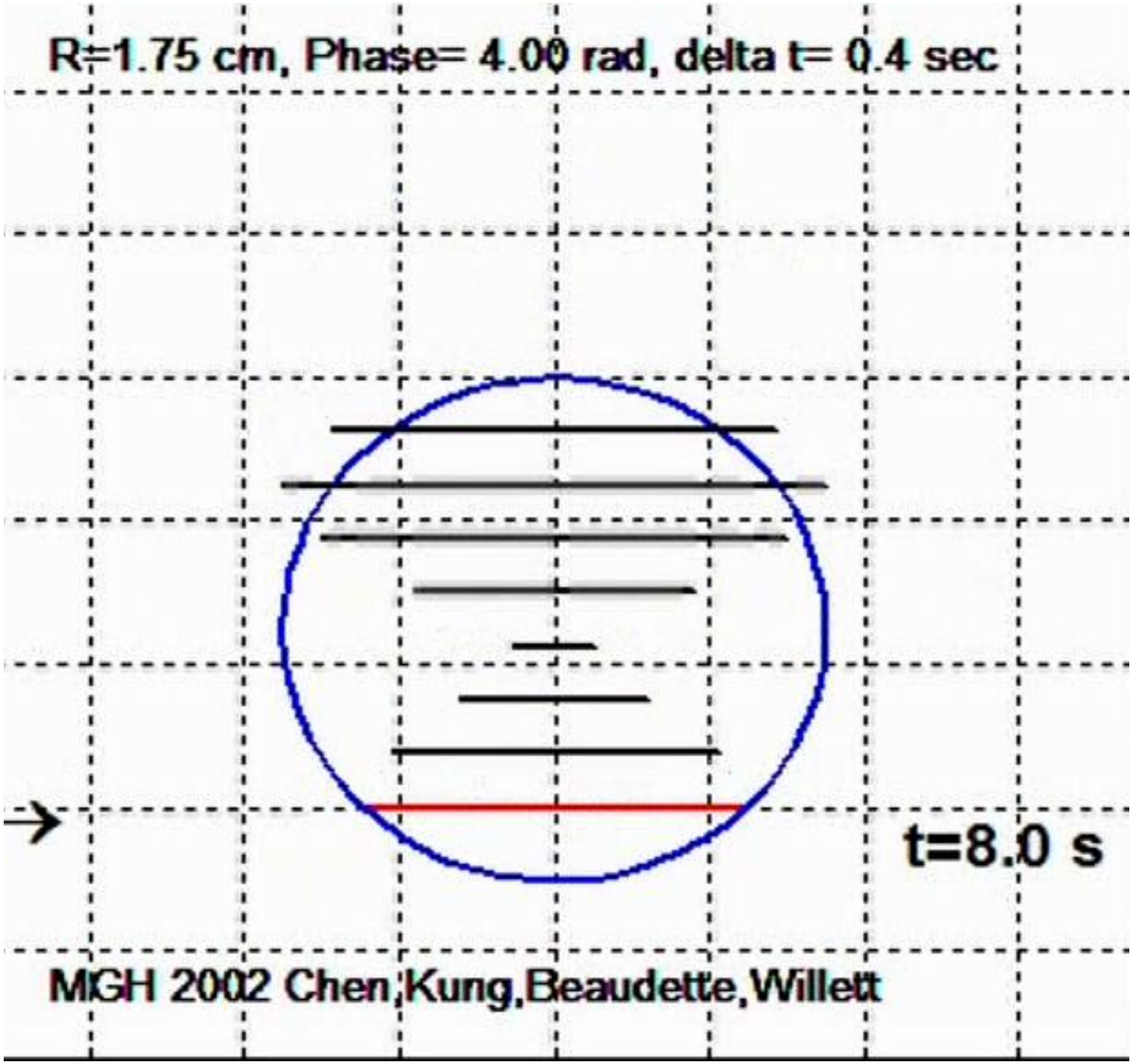


Photo **Static** **Moving / HS mode** **HQ**

Early simulation of helical scan of moving sphere



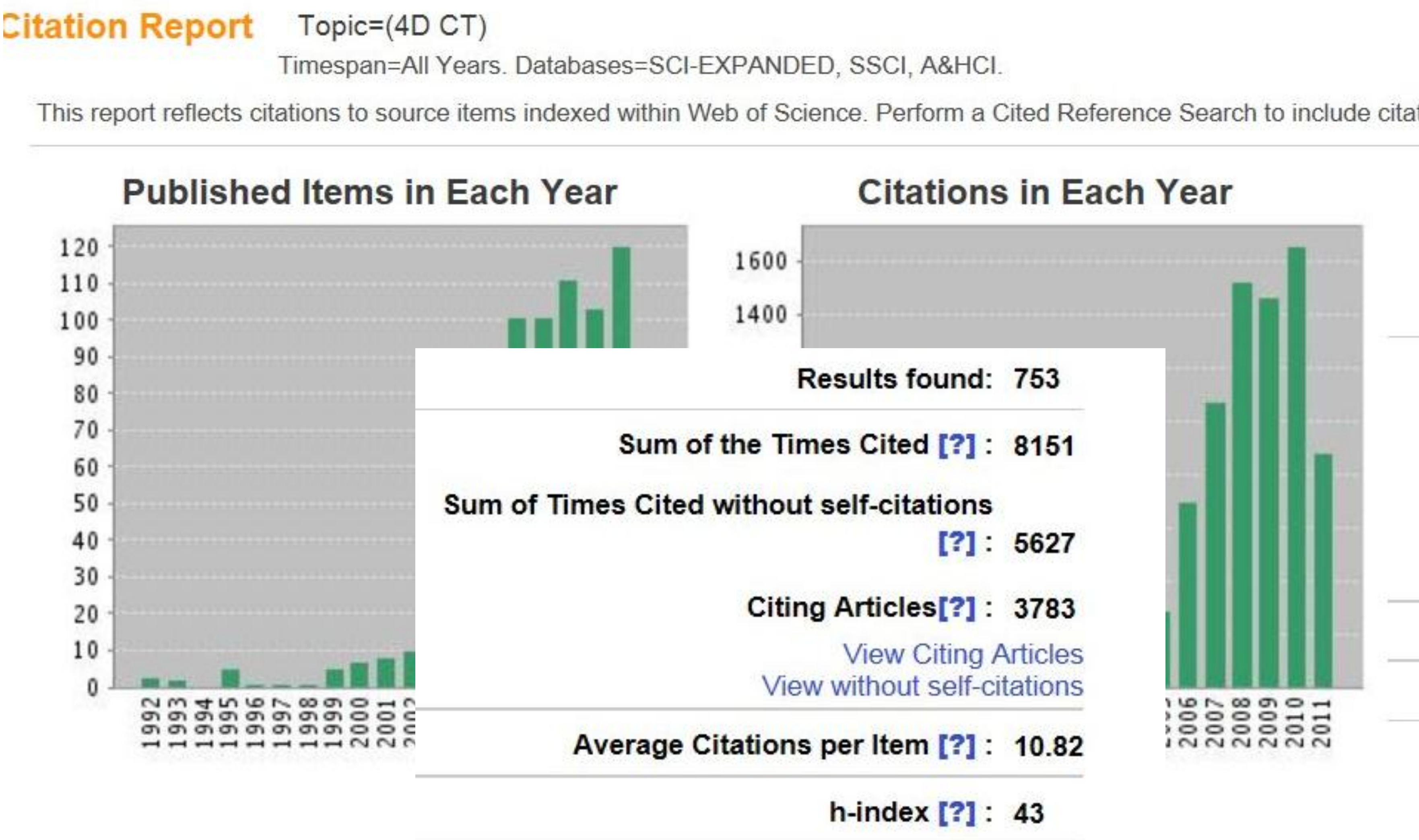
Ideal Imaging of Moving Targets

- Expectations
  - Coherent volumetric / temporal images to:
    - Characterize organ motion / over multiple cycles
    - Provide data for treatment planning (aperture,etc)
    - Provide data for adaptive therapy
    - QA metric to determine “suitability” of 4D scan for planning
  - Minimal artifacts
  - Performed serially
  - Software that digests and extracts clinically relevant motion parameters

4D CT Scanning Early Studies

- Proof of Principle
  - EC Ford et al MSKCC. Jan 2003 Med Phys
  - S Vedam,et al VCU Jan 2003 PMB
  - D Low et al MIR. June 2003 Med Phys
  - M van Herk, et al NKI: Respiration-correlated CT of lung cancer patients. ESTRO Prague 2003
- Commercial approach – at MGH
  - GE / Varian September 2002
  - Rietzel, MGH 2003 / 2004

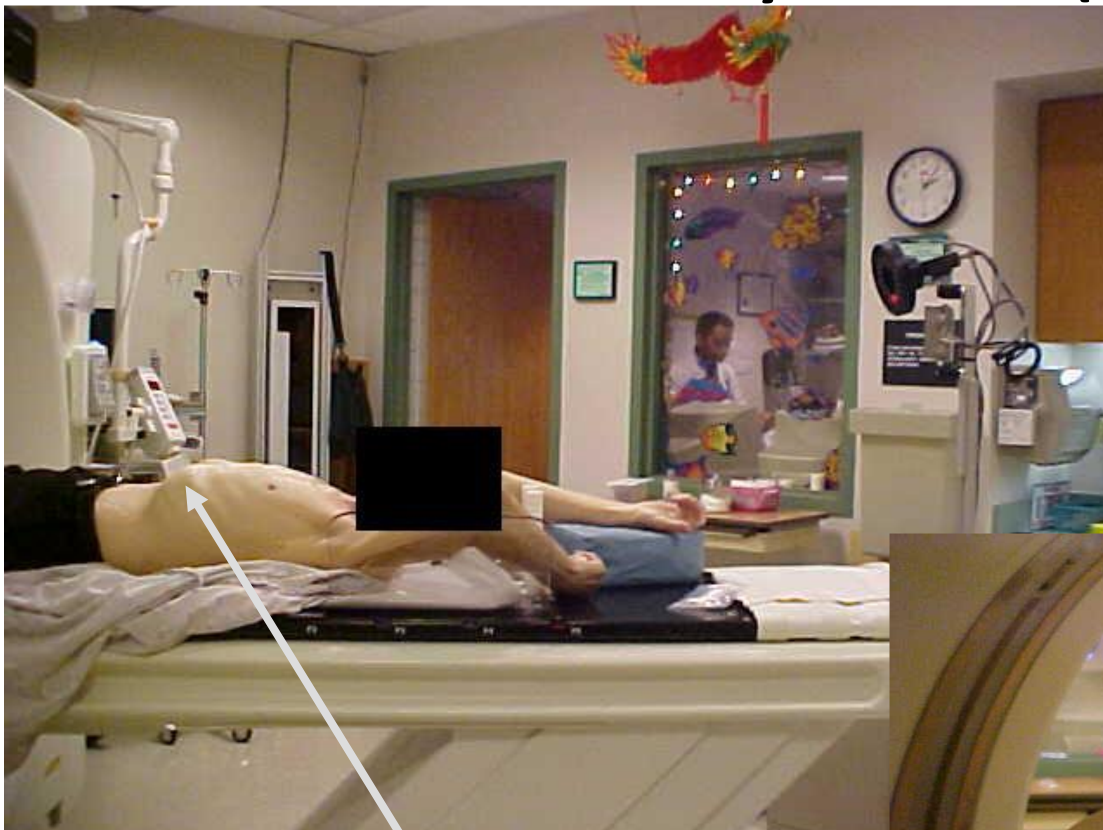
Enter 4DCT


Citation Report
Topic=(4D CT)
Timespan=All Years. Databases=SCI-EXPANDED, SSCI, A&HCI.
This report reflects citations to source items indexed within Web of Science. Perform a Cited Reference Search to include citati
Published Items in Each Year
Citations in Each Year
Results found: 753
Sum of the Times Cited [?] : 8151
Sum of Times Cited without self-citations [?] : 5627
Citing Articles[?] : 3783
View Citing Articles
View without self-citations
Average Citations per Item [?] : 10.82
h-index [?] : 43

Many 4DCT resources on Web

- Do a Google search on 4DCT / RCCT
- AAPM Virtual Library
- Vendor specific information
- Outline of this talk:
- Brief overview of the acquisition technology and reconstruction
- Perspective on selected topics and remaining issues

Commercial System (cine)

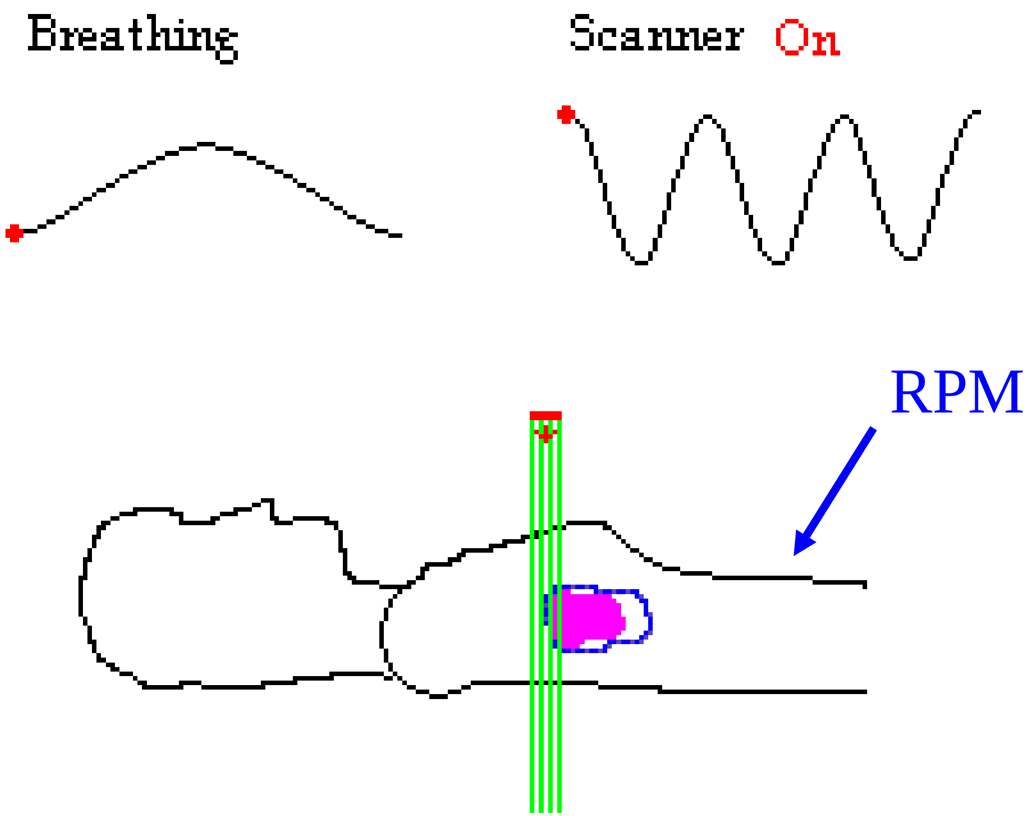


marker block with
IR-reflecting dots

Other surrogates: belt or lung tidal volume monitor

Schematic – 4D CT Acquisition

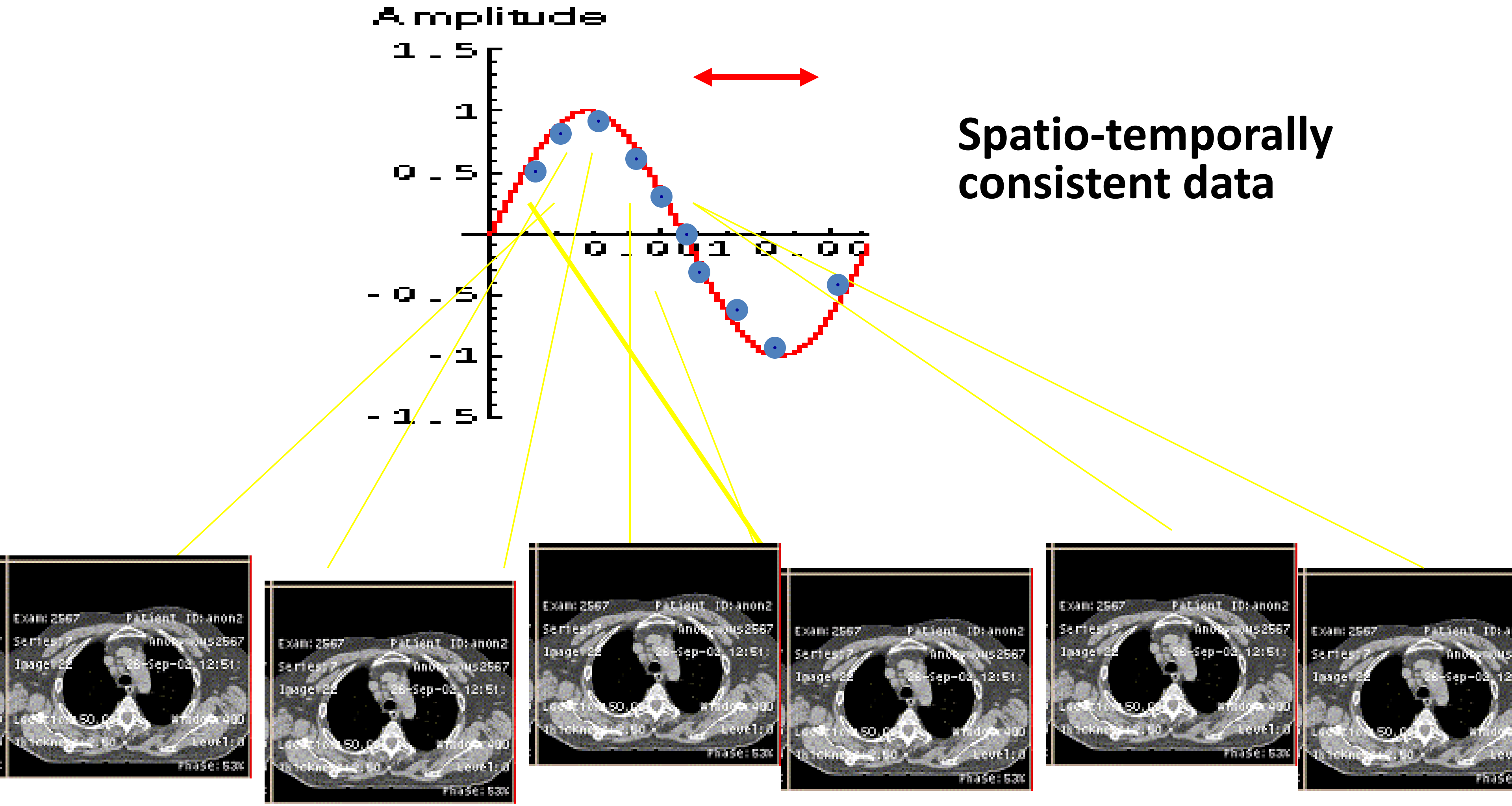
Scan in cine mode /breathing lightly



Record respiratory motion with Varian RPM

Input: ~1500 slices of data

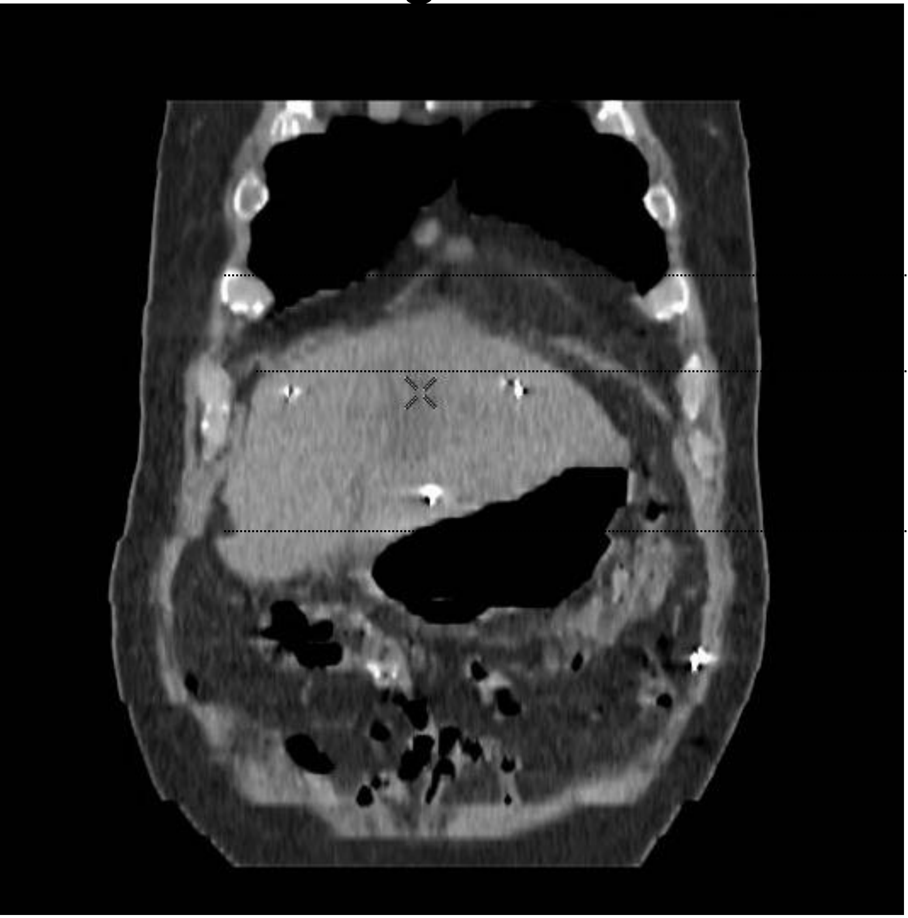
Output: 4D CT – 10 volumetric scans over ~4 sec respiratory cycle



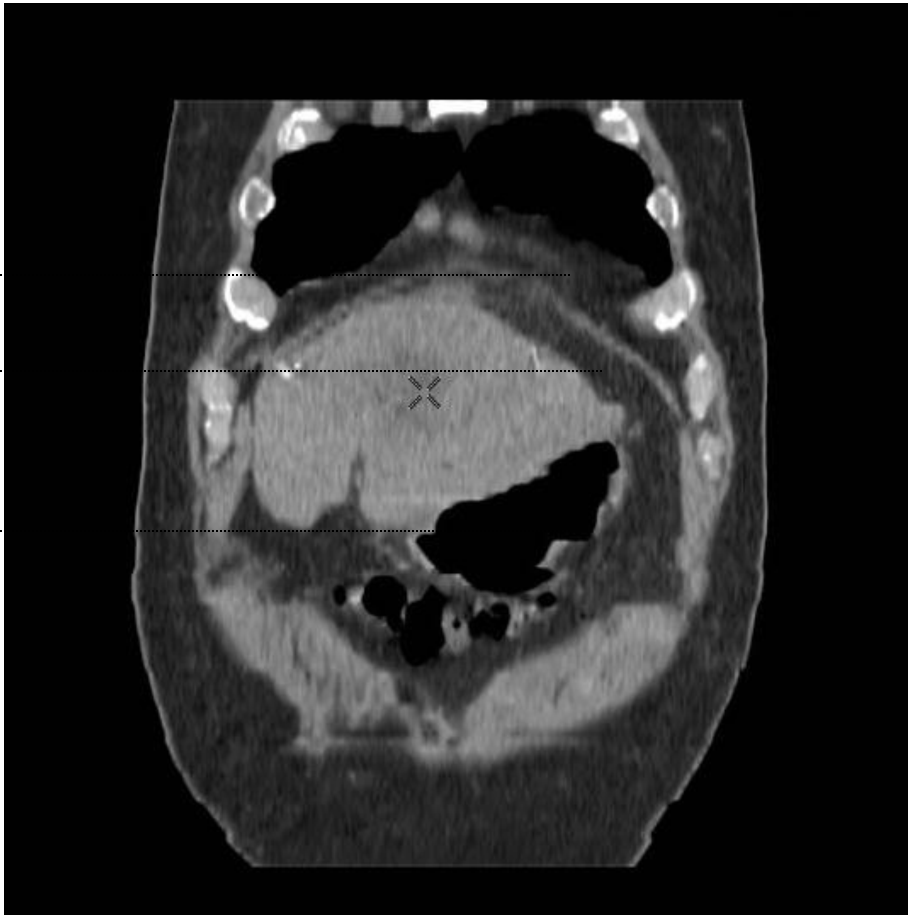
Spatio-temporally consistent data

Anon 5619

Ungated



Gated 40-60%

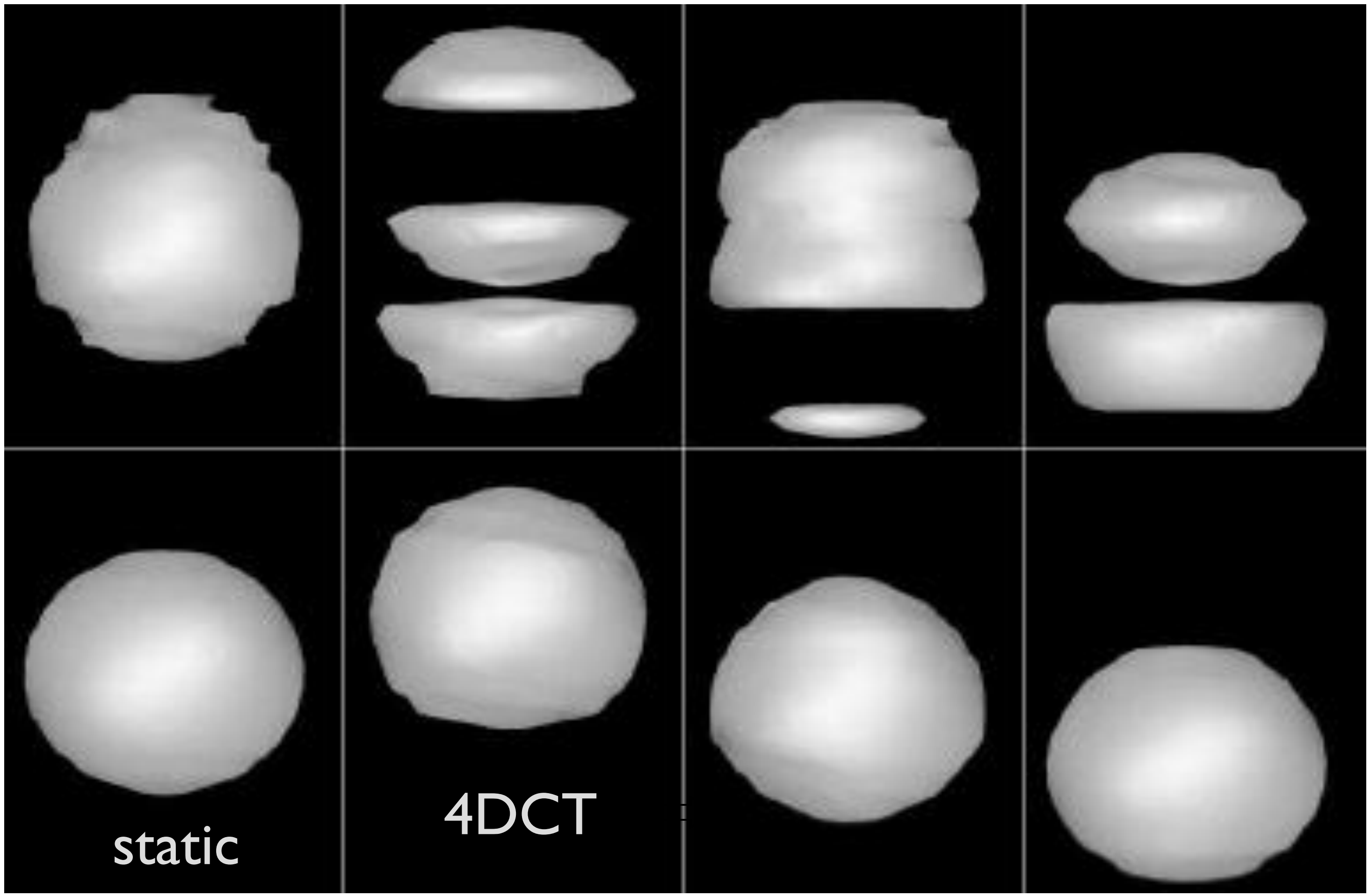


Caveat: Loop!

4D: accurate shape / trajectory

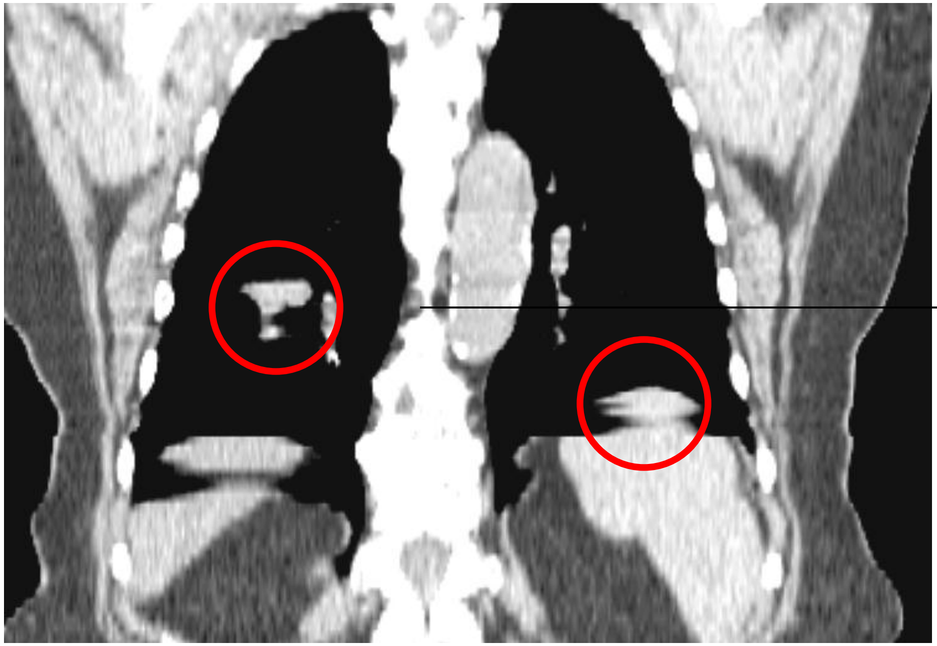
Moving Helical

static 4D

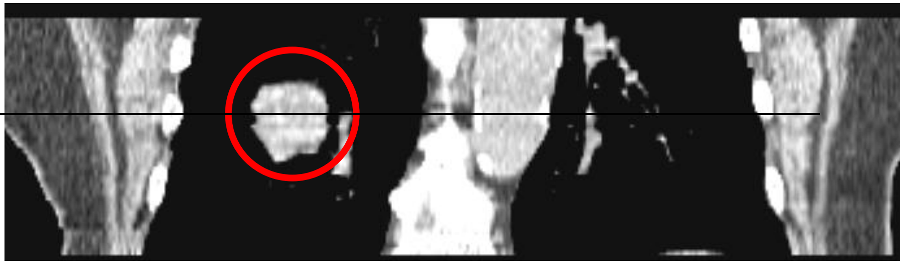


Rietzel et al

4D can reduce shape artifacts



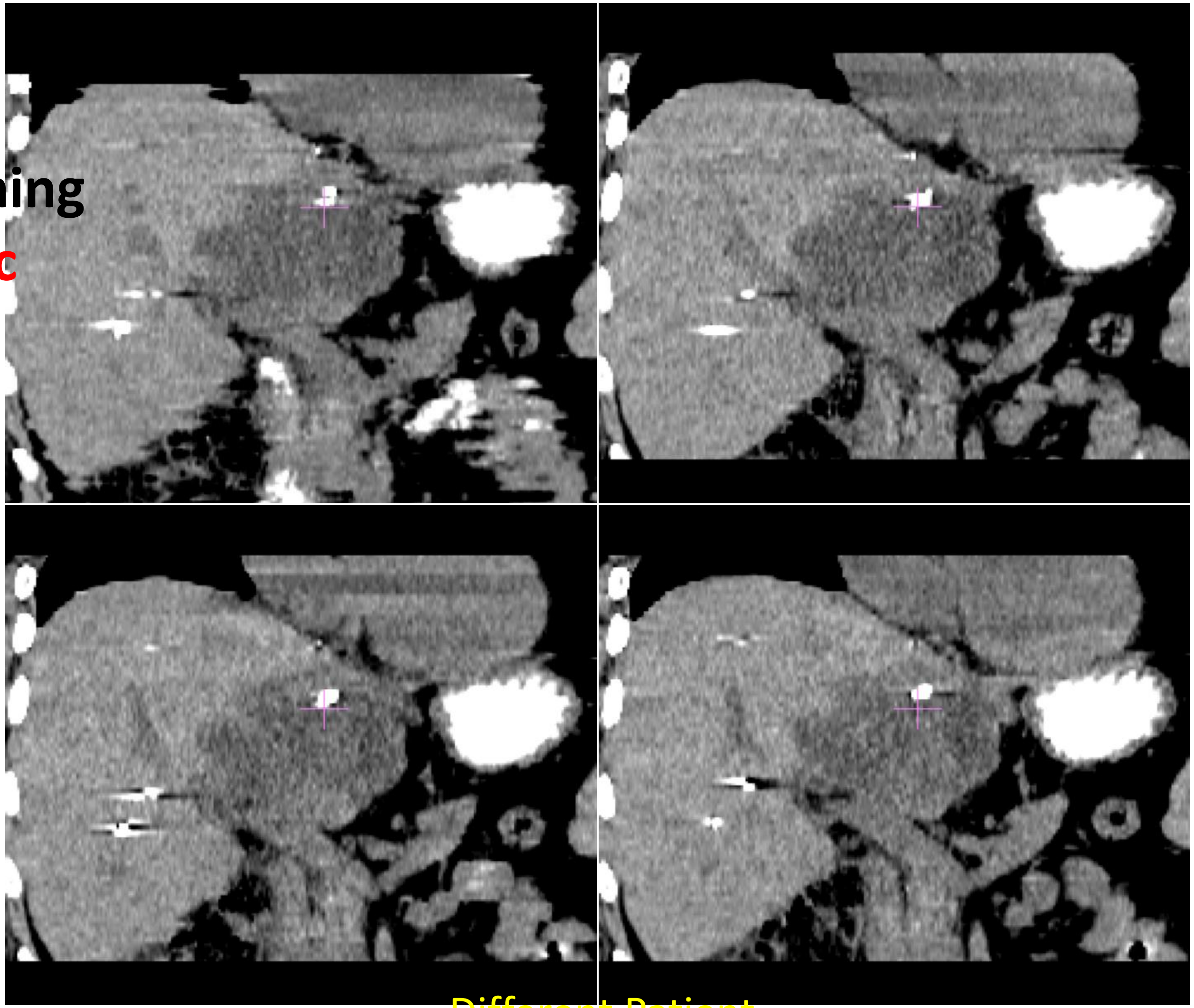
helical light breathing scan



4DCT dataset

Liver Volume – missing 200 cc

Light Breathing
Liver: -200cc



4D CT
0%

4D CT Liver volumes are ~equal

4D CT
20%

4D CT
40%

YL Chen et al
ASTRO 2004

Different Patient

4D Scanning Artifacts

How common are artifacts in 4DCT?

PHYSICS CONTRIBUTION

RETROSPECTIVE ANALYSIS OF ARTIFACTS IN FOUR-DIMENSIONAL CT IMAGES OF 50 ABDOMINAL AND THORACIC RADIOTHERAPY PATIENTS

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Purpose: To quantify the type, frequency, and magnitude of artifacts in four-dimensional (4D) CT images acquired using a multislice cine method.
Methods and Materials: Fifty consecutive patients who underwent 4D-CT scanning and radiotherapy for thoracic or abdominal cancers were included in this study. All the 4D-CT scans were performed on the GE multislice PET/CT scanner with the Varian Real-time Position Management system in cine mode. The GE Advantage 4D software was used to create 4D-CT data sets. The artifacts were then visually and quantitatively analyzed. We performed statistical analyses to evaluate the relationships between patient- or breathing-pattern-related parameters and the occurrence as well as magnitude of artifacts.
Results: It was found that 45 of 50 patients (90%) had at least one artifact (other than blurring) with a mean magnitude of 11.6 mm (range, 4.4–56.0 mm) in the diaphragm or heart. We also observed at least one artifact in 6 of 20 lung or mediastinal tumors (30%). Statistical analysis revealed that there were significant differences between several breathing-pattern-related parameters, including abdominal displacement ($p < 0.01$), for the subgroups of patients with and without artifacts. The magnitude of an artifact was found to be significantly but weakly correlated with the abdominal displacement difference between two adjacent couch positions ($R = 0.34$, $p < 0.01$).
Conclusions: This study has identified that the frequency and magnitude of artifacts in 4D-CT is alarmingly high. Significant improvement is needed in 4D-CT imaging.

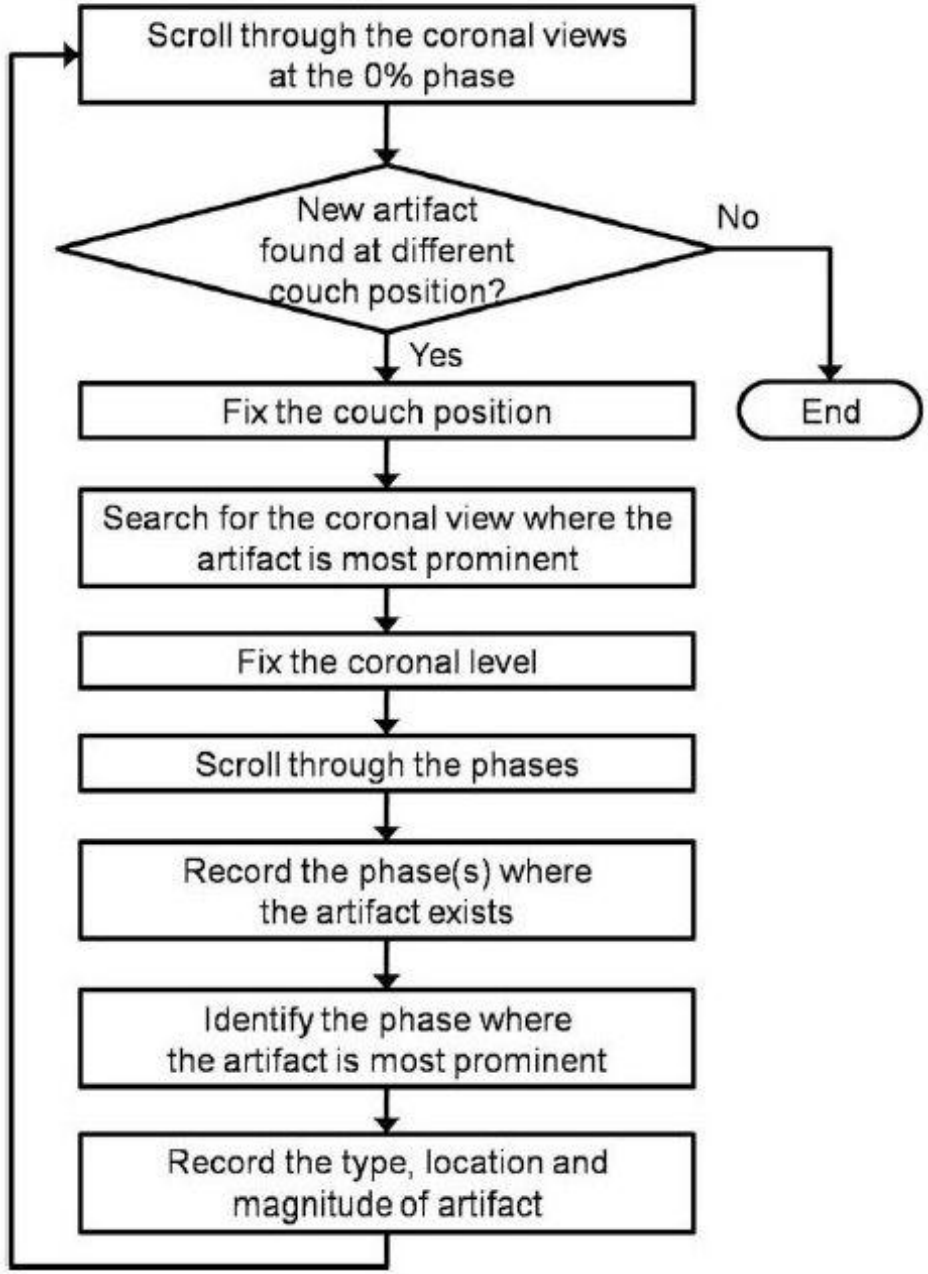

Fig. 1. A flow diagram of the method to analyze the artifact in the four-dimensional CT image.

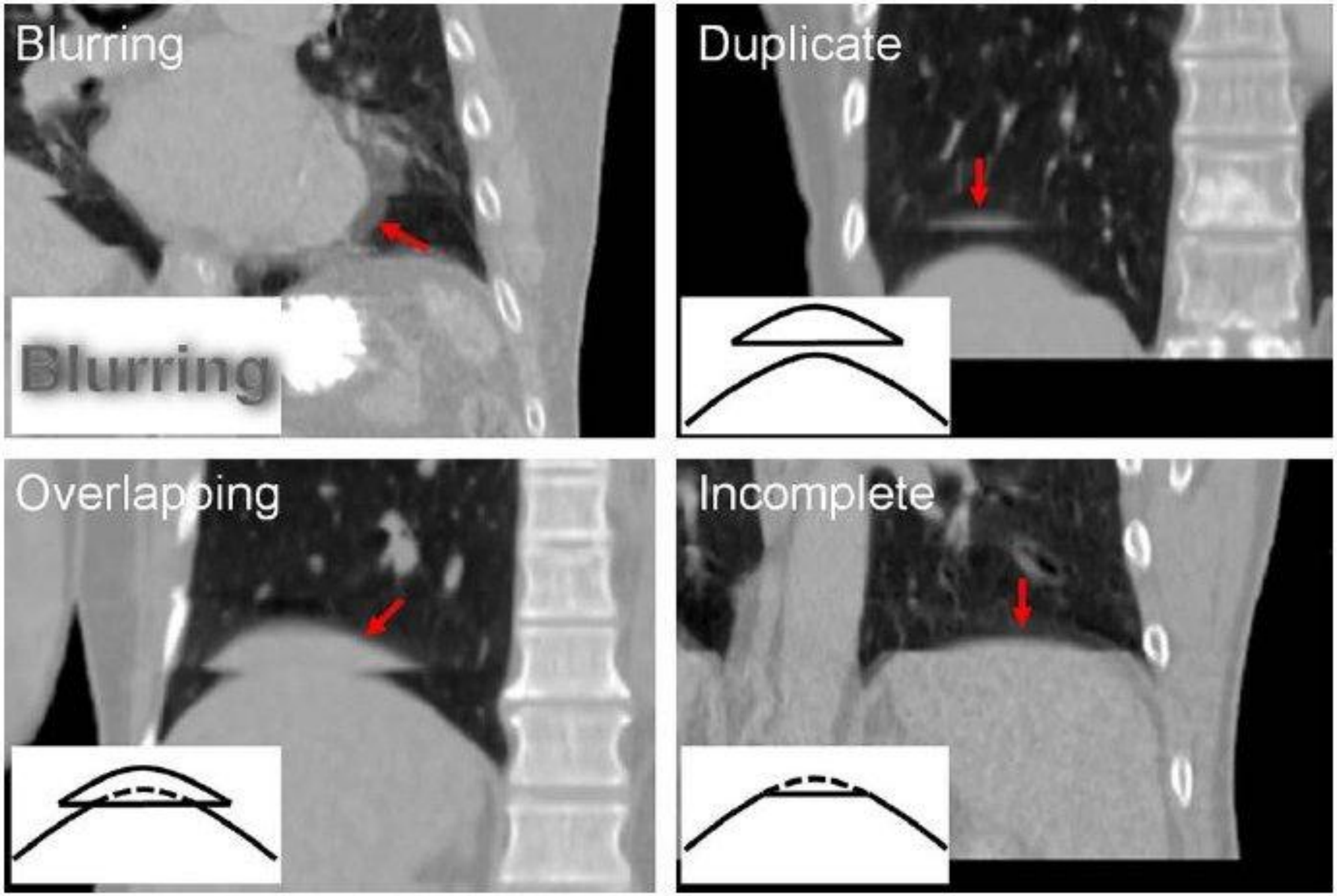

Fig. 2. Example four-dimensional CT images with schematic diagrams for the four types of artifacts: blurring, duplicate structure, overlapping structure, and incomplete structure. Corresponding artifacts are indicated by arrows in respective images. Note that other artifacts can also be observed in these images.

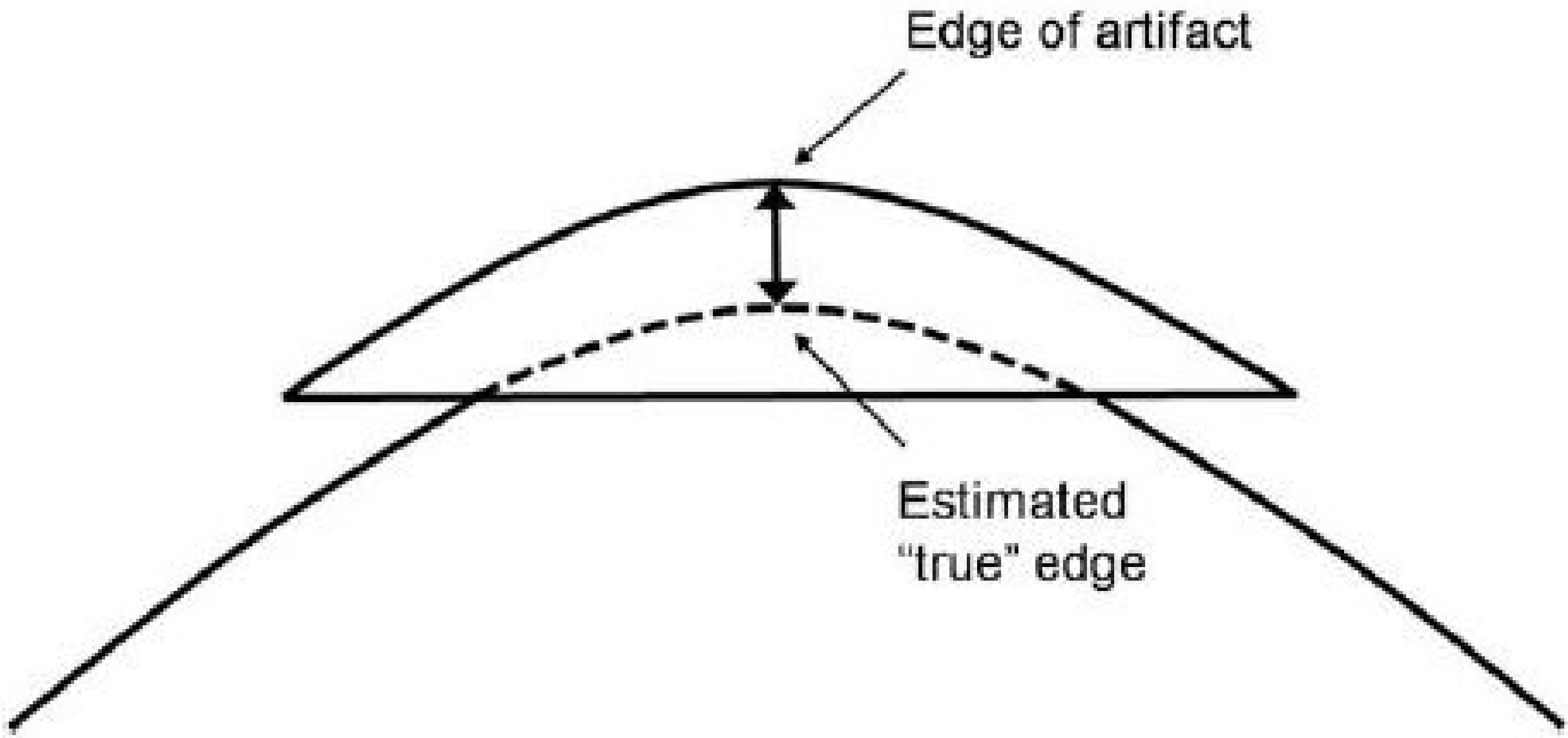

Fig. 3. A schematic diagram of the method to measure the artifact magnitude for the overlapping structure. The ''true'' edge was visually estimated by the observer. The distance in the superior-inferior direction between the edge of the artifact and the ''true'' edge of the organ was then measured. Duplicate and incomplete structure artifacts were also measured by the same method.

How common are 4D artifacts?

- Examine retrospectively 50 patients with lung or abdominal tumors
- 90% of scans have at least one artifact
- (But this does not mean 90% of scans are not useful)

What factors influence artifacts?

Variations in tumor size and position due to irregular breathing in 4D-CT: A simulation study

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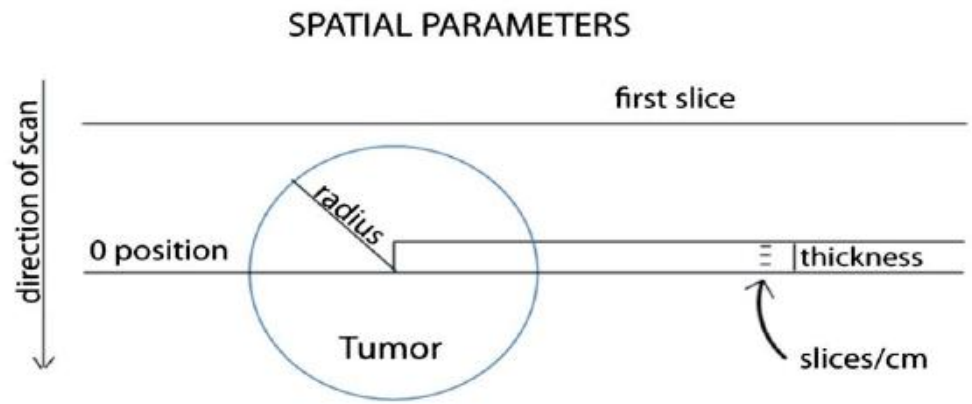

(b)

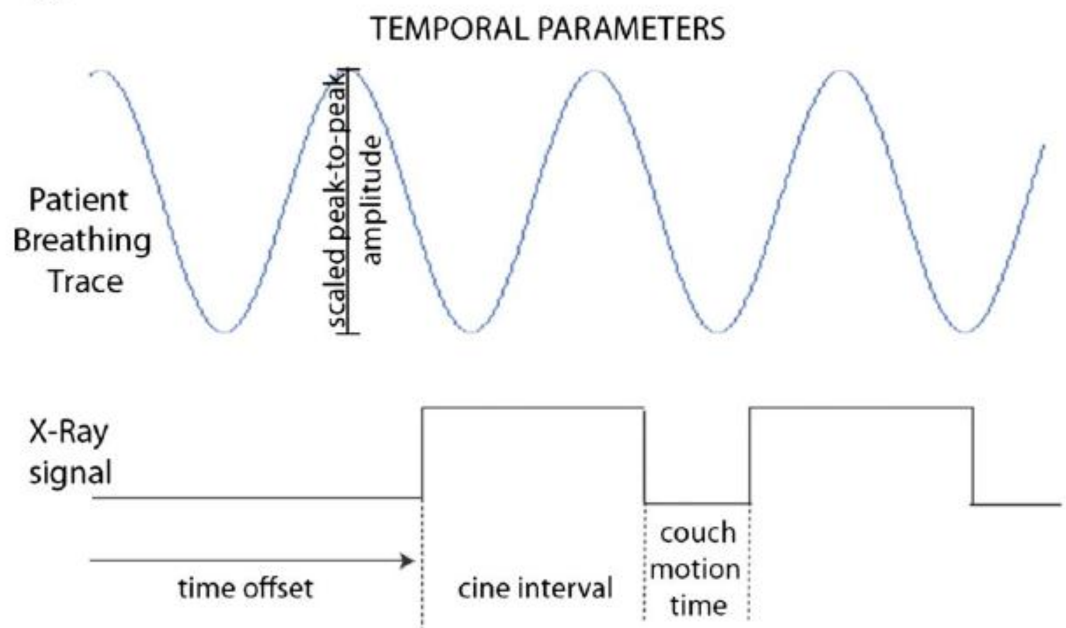

FIG. 1. *(a) Spatial and (b) temporal parameters of virtual 4D-CT scanner.* Note: A patient breathing trace does not follow a sine wave exactly.

TABLE I. *Changeable parameters in virtual 4D-CT scanner*. The values used to test the data are shown in the second column. However, other values can also be set for the various parameters. The results found in slice thickness can be calculated by multiplying thickness of the slab times the number of slices in each centimeter.

Parameters	Values tested
Slice thickness	0.25 cm
Slices per rotation	4
Tumor motion	{1, 2, 3} cm
Time before first image capture (offset)	3.3 s
Radius of the spherical tumor	{2, 4} cm
In-plane pixel size	0.1 cm
Cine interval (x-ray beam is on)	6 s
Couch motion time (x-ray beam is off)	1.5 s
Number of couch positions	25
Gantry rotation time (in seconds)	0.8 s
Number of scanner acquisitions per couch position	12

COM of 155 different patient RPM traces

TABLE III. *Average of center of mass positions measured over all phases* $n=155$. The mean position is slightly negative due to the longer duration of inhalation. The standard deviation of the mean position increases as the tumor motion increases and the inhale position has greater variability than the exhale position.

			Exhale		Inhale	
Radius (cm)	Motion (cm)	Mean position (cm)	Mean position (cm)	Mean standard deviation (cm)	Mean position (cm)	Mean standard deviation (cm)
2	**1**	-0.027 ± 0.066	0.28	0.084	-0.47	0.15
	2	-0.049 ± 0.13	0.56	0.17	-0.94	0.3
	3	-0.064 ± 0.19	0.86	0.24	-1.4	0.46
4	**1**	-0.020 ± 0.059	0.29	0.078	-0.47	0.15
	2	-0.035 ± 0.11	0.58	0.15	-0.93	0.29
	3	-0.047 ± 0.17	0.87	0.23	-1.39	0.43

Factors that influence artifacts

- Size of tumor (not explicitly location)
- Motion trajectory / amplitude variations / baseline drift
- Shape
- Scanner parameters
- Sorting by amplitude or phase

Example of 4DCT simulator output

- test6f.mp4
- phase.mp4
- pureamplitude.mp4
- Conclusions of Sarkar paper: Irregular breathing during 4D-CT simulation causes systematic errors in volume and center of mass measurements. These errors are small but depend on the tumor size, motion amplitude, and degree of breathing irregularity.

Examples of phase / amplitude sorting (simulation – C Spier/J Wolfgang)

Amplitude sorted

Phase sorted

Does an aperture (gating window) from 4DCT encompass the target for more than 1 cycle?)

Effects of breathing variation on gating window internal target volume in respiratory gated radiation therapy[a)]

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Cai Study

- Goal – compare ITV(gw) aperture generated by 4DCT methods to ground truth.
- Phantom study and study on 18 patients
- Methods: Ground truth is cine MRI; apply same resorting algorithms as used in clinic and compare apertures from "4DCT"
- Findings: Apertures over 5 minutes differ by a significant amount (area, axes of ITV)
- Geometry changes over 5 min

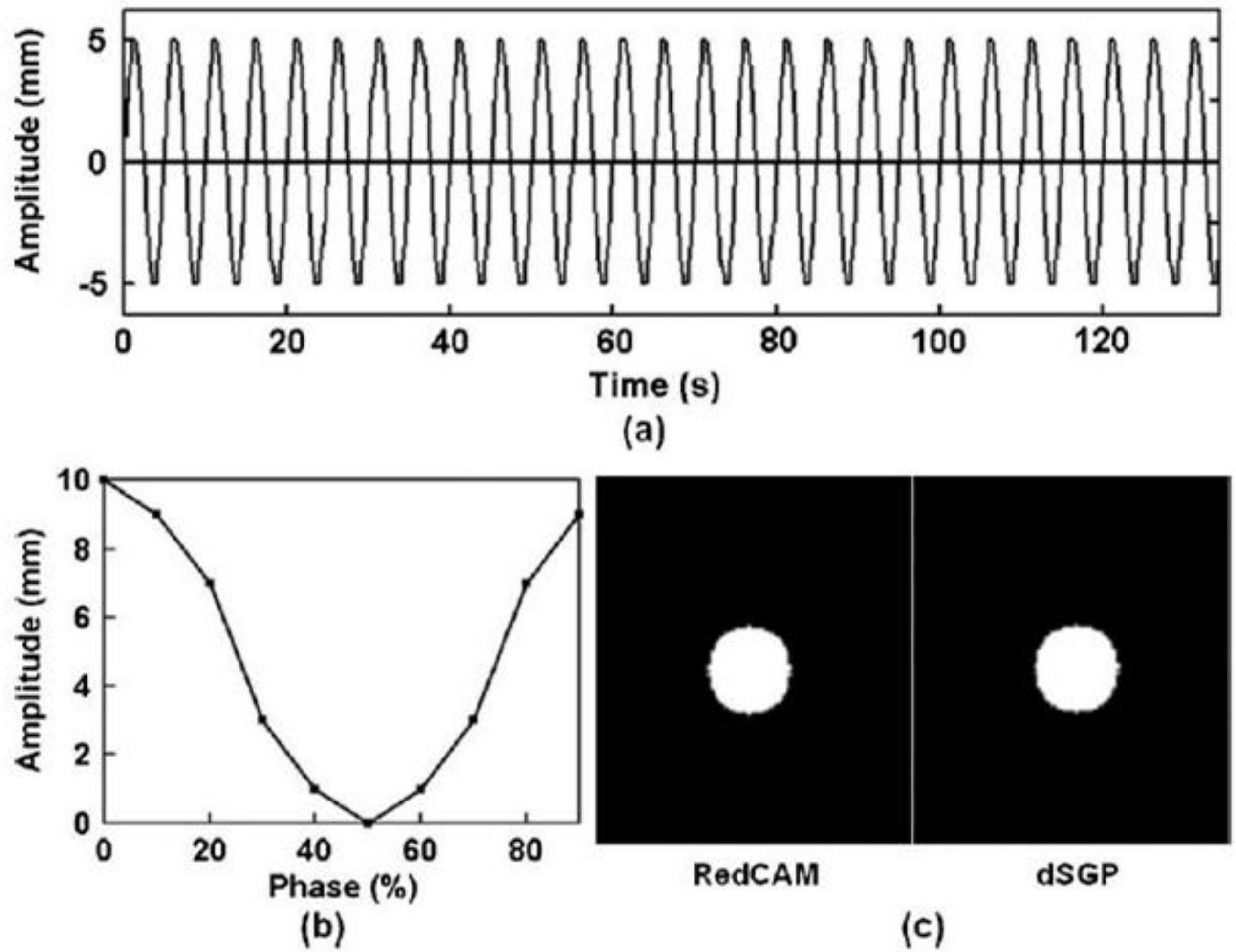
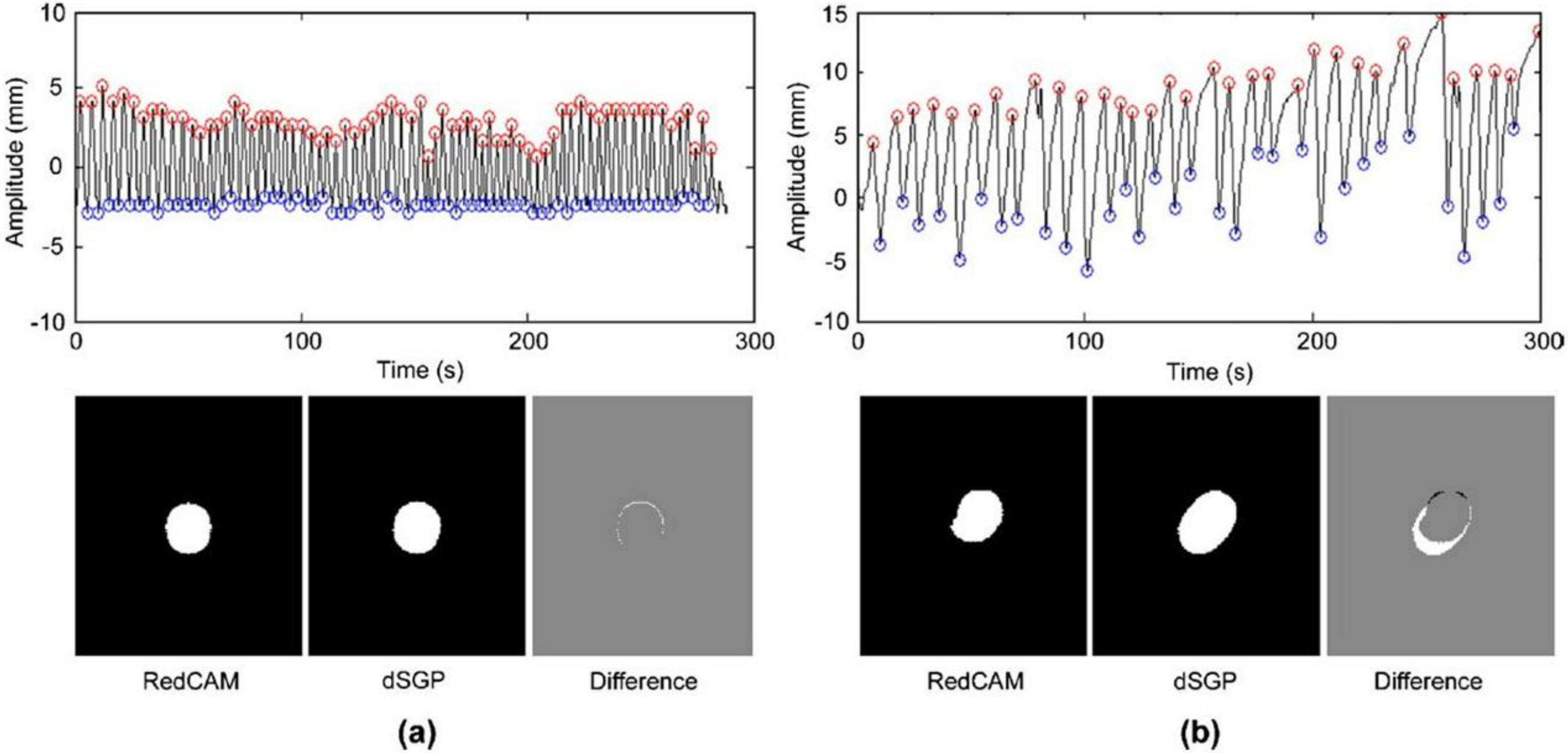
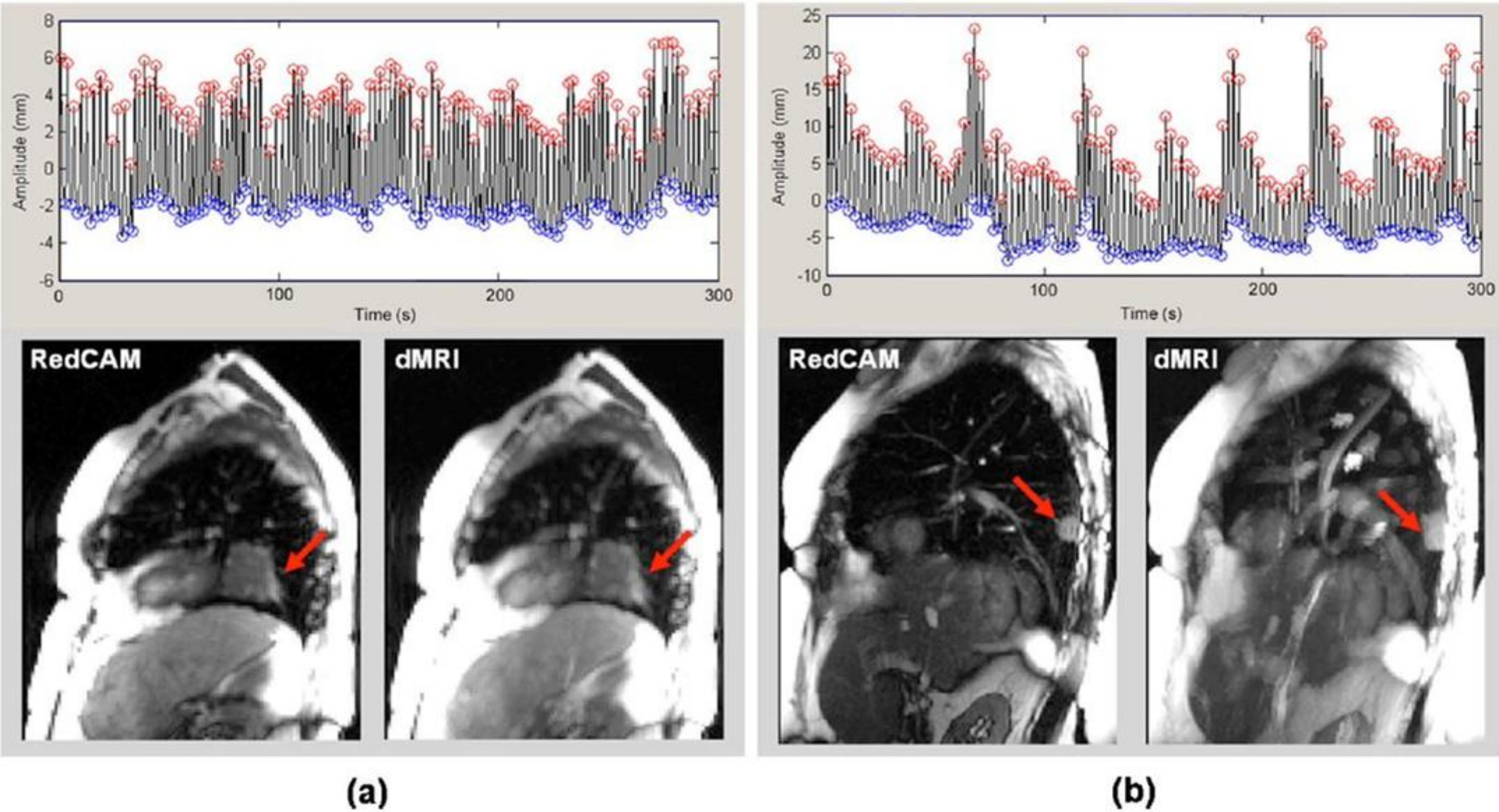


FIG. 2. Image phantom simulation using the sinusoidal trajectory. (a) The hypothesized sinusoidal trajectory. (b) Tumor motion trajectory determined from RedCAM. (c) Comparison of gating window ITAs from RedCAM and dSGP. Gating window of 30%–70% was used in generating these images.



REDCAM: dMRI -simulated 4DCT / dSGP –digital software phantom



Examples of patient study with (a) a relative stable breathing pattern and (b) a highly irregular breathing pattern. ITA_{GW} are indicated by the

Cai - Conclusions

- ITVgw can be underestimated by 4DCT due to breathing variations. An additional margin may be needed to account for this potential error in generating a PTVgw. Cautions need to be taken when generating ITVgw from 4DCT in respiratory gated radiation therapy, especially for small tumors <3 cm with a large motion range> 1 cm.
- *Geometry –surrogate for dose coverage; need 4D treatment planning to assess impact of geometric "miss".*

What are current approaches to ITV Target Delineation using 4DCT?

- Maximum Intensity Projection: generates a 3D bitmap that encompasses GTV over all phases
- Combine inhale / exhale GTVs – similar to MIP but uses only 2 phases that represent maximum GTV excursions
- Define GTV on single phase of 4D and propagate contours to all respiratory phases using deformable registration

Target Delineation cont’d

- Mid-ventilation scan with margins – estimates center position of target, with margins adequate (in principle) to cover motion excursion

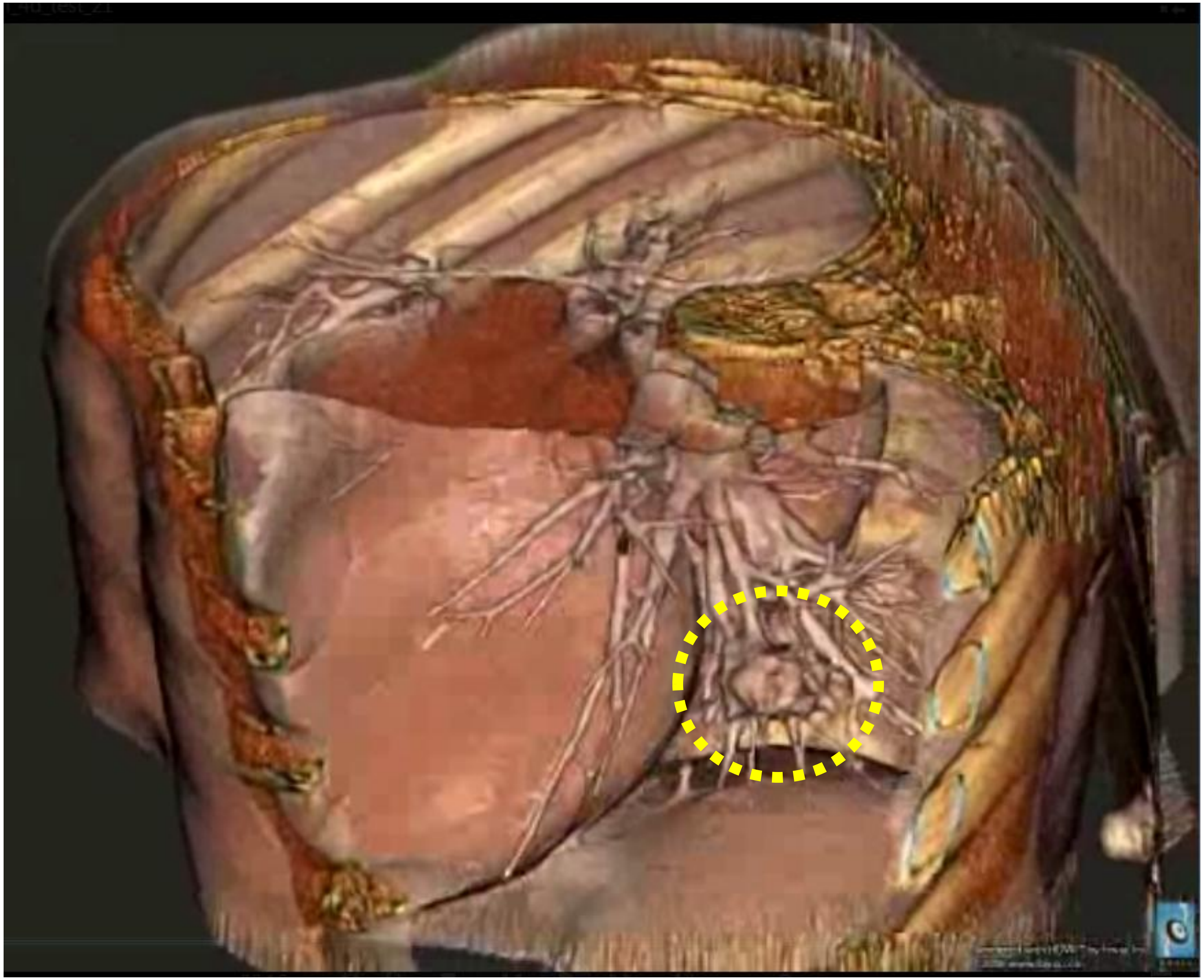
Another approach

- Average Intensity Image – generated by averaging HU of pixels traversed by GTV. Depending on threshold for contour definition, this **does not fully cover entire instances of GTV in time.**
- With statistical coverage of target. Margins added.
- Geometric / not dosimetric coverage

Visualization Challenge

- Assimilation and understanding of multiple 4D data sets
- Use 4D volume rendering
- st1mm_4d_test_21.wmv
- itv.wmv
- Pan12 LAO flythru.gif

Lung tumor imaged by 256 slice CT scanner



SAMS Questions
4DCT Methods and Artifacts

Excluding blurring, what percentage of 4DCT scans exhibit artifacts?

0%	1. 10%
0%	2. 30%
0%	3. 50%
0%	4. 70%
0%	5. 90%

10

Excluding blurring, what percentage of 4DCT scans exhibit artifacts?

1. 10%
2. 30%
3. 50%
4. 70%
5. 90%

Ans – 5. Ref: Yamamoto Int J Rad Onc Bio Phys

Vol 72, No. 4 pp 1250

Which parameter does not affect shape artifacts during 4DCT?

0%	1. Motion periodicity
0%	2. Tumor location
0%	3. Motion amplitude
0%	4. Scan speed
0%	5. Trajectory baseline shift

10

Which parameter does not directly affect shape artifacts during 4DCT?

1. Motion periodicity
2. Tumor location
3. Motion amplitude
4. Scan speed
5. Trajectory baseline drift

   – Answer: 2 . Sarkar et al: Med Phys Vol 37, No. 3 2010 p 1255-60

Which target definition method does not fully cover the GTV as imaged by 4DCT?

0%	1. Maximum Intensity Projection
0%	2. Average Intensity Projection
0%	3. Union of inhale and exhale targets
0%	4. One phase target propagated to other phases by DR; take union
0%	5. Mid-ventilation target with margin

10

Which target definition method does not fully cover the GTV as imaged by 4DCT?

1) Maximum-Intensity Projection
2) Average-Intensity Projection
3) Union of inhale and exhale targets
4) One phase target propagated to other phases by deformable registration; take union
5) Mid-ventilation image with margin

> (ANS = 2) AAPM Report 91: The Management of Respiratory Motion in Radiation Oncology. AAPM 2006

Summary

- 4DCT / RCCT is an advance
- Some artifacts, issues in sorting
- Provides substantially more data; new methods to assimilate data are needed.
- 4DCT refinements are still an active topic

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