

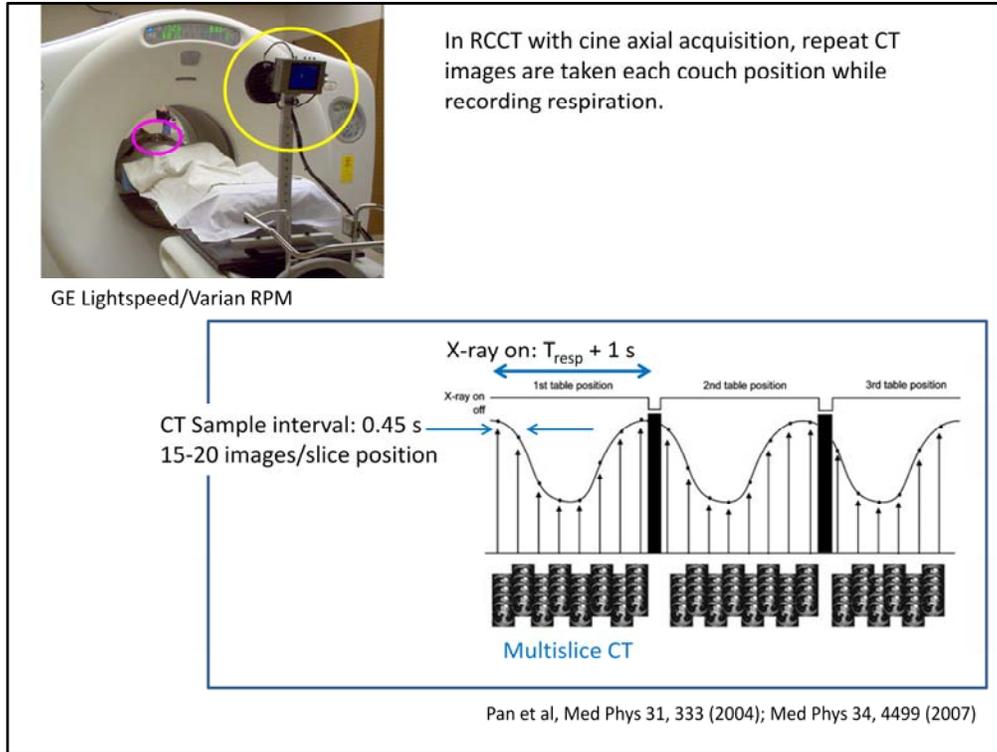
**Respiration-Correlated CT and Cone-Beam CT:  
Principles and Clinical Applications**

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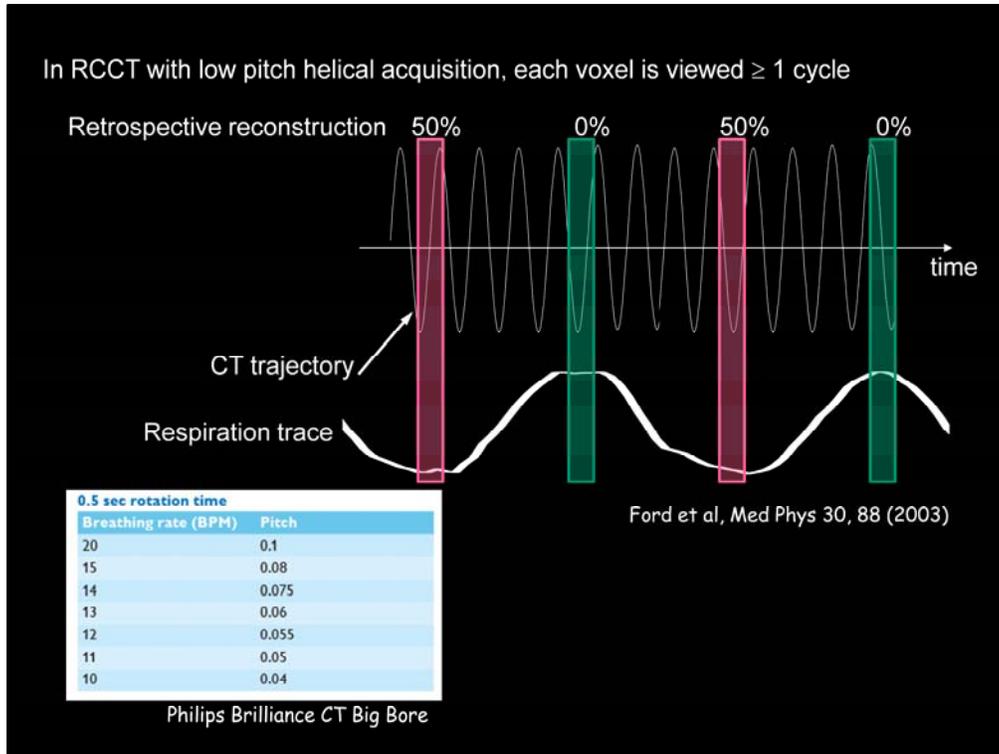
## Disclosure

Memorial Sloan Kettering has a research agreement with Varian Medical Systems

Respiration-Correlated CT: Principles Of Operation



There are two methods of RCCT acquisition in widespread clinical use: cine axial and helical. In RCCT with cine axial acquisition, repeat CT images are taken each couch position while recording respiration. An example is shown of a GE multislice CT scanner in combination with the Varian RPM system for monitoring respiration, specifically, abdominal displacement by means of an infrared reflecting block placed on the patient. The data sufficiency condition is such that, acquisition at each couch position is normally 1 s longer than the average breath cycle. The time interval between successive CT images is typically 0.45 s or less, yielding 15 to 20 images per slice location. This is a trade-off between a sufficient number of samples for retrospective sorting and limiting the imaging dose. A 0.5 s gantry rotation yields the highest temporal resolution CT images. In cine-based RCCT, the axial CT slices are reconstructed first, then retrospectively sorted into typically 10 bins across the respiratory cycle, most commonly according to the phase of the respiration trace.

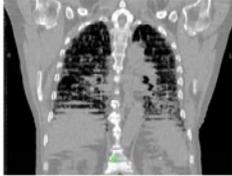


The alternative approach uses helical CT acquisition with low pitch and gantry rotation chosen such that each voxel in the patient is viewed by the CT detectors for at least 1 cycle, again while recording respiration. In helical RCCT, CT slices are retrospectively reconstructed, using the sinogram data at the desired respiration phase, e.g. those at end inspiration are selected at the 0% phase, and approximate end expiration at the 50% phase. The requirement that the couch moves slowly enough such that each voxel is viewed at least one cycle determines a maximum pitch which is breathing rate dependent, as shown in the table for the Philips Brilliance CT Big Bore.

RCCT: Advantages and Limitations

Advantages: 1) Reduced motion-induced distortions, 2) visualization of motion in 3-D, mapped from several cycles into one.

Standard helical CT



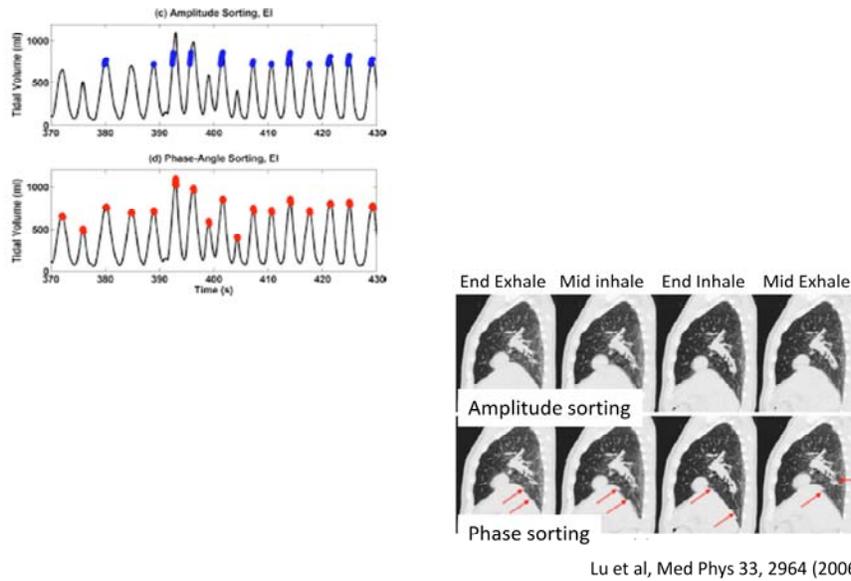
Helical RCCT



Keall et al, PMB 49, 2053 (2004)

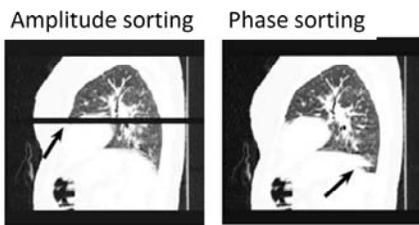
The advantages of RCCT are twofold: first, it reduces respiratory motion-induced distortions of the anatomy; second, it provides 3-D visualization of motion across one breath cycle. The standard helical CT example illustrates the motion-induced distortions that may occur. It is important to keep in mind that in RCCT, retrospective sorting maps CT slices from several cycles into one, thus it assumes that breath cycles are repeatable. This assumption is violated to some degree by practically all patients, leading to artifacts such as those shown here.

Limitations: Distortions in phase-sorted RCCT caused by amplitude changes in breathing

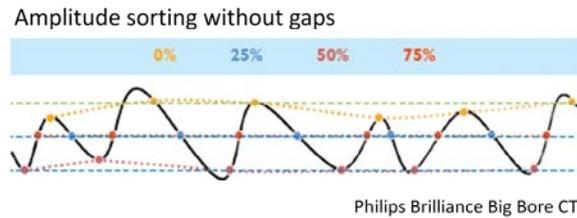


The distortions that one sees in phase-sorted RCCT are caused in many (but not all) cases by changes in breathing amplitude. This is illustrated by the lower plot of tidal volume vs time at left: phase sorting at end expiration selects the points marked in red. There is large variation in tidal volume between points, leading to artifacts in the image at end expiration and elsewhere in the cycle (lower row of images). The same problem occurs for phase sorting using abdominal displacement (RPM), because internal motion correlates with external respiratory motion. Amplitude sorting reduces the variation in selected points on the respiration trace (blue points in upper plot), and reduces image artifacts (upper row of images).

Limitation of strict amplitude sorting: missing CT data (gaps)

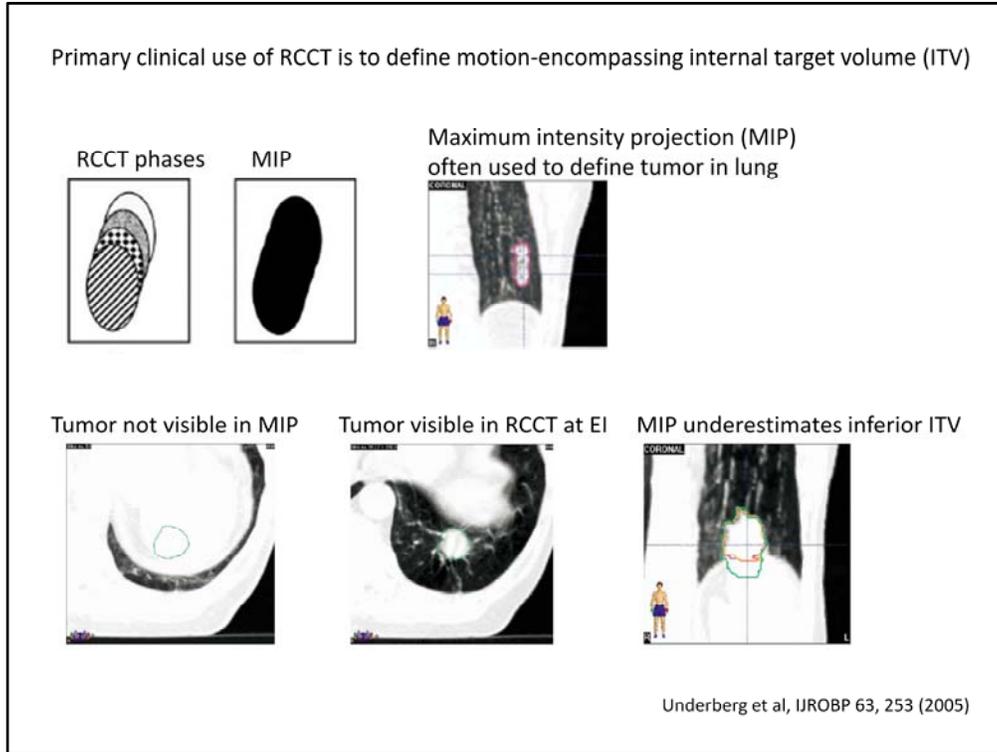


Abdelnour et al, PMB 52, 3515 (2007)



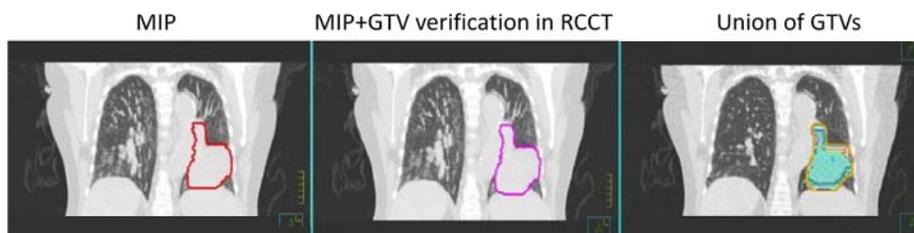
A limitation of amplitude sorting is that the respiration trace may not intersect the selected amplitude at all cycles, leading to missing slice data and hence gaps in the 3-D images (left). The amplitude sorting algorithm in Philips Brilliance CT illustrates a possible way to address this problem at right: when the identical amplitude is not always available because the patient breathed shallowly on some cycles, the algorithm chooses the nearest available amplitude (dashed orange line).

RCCT: Clinical Application



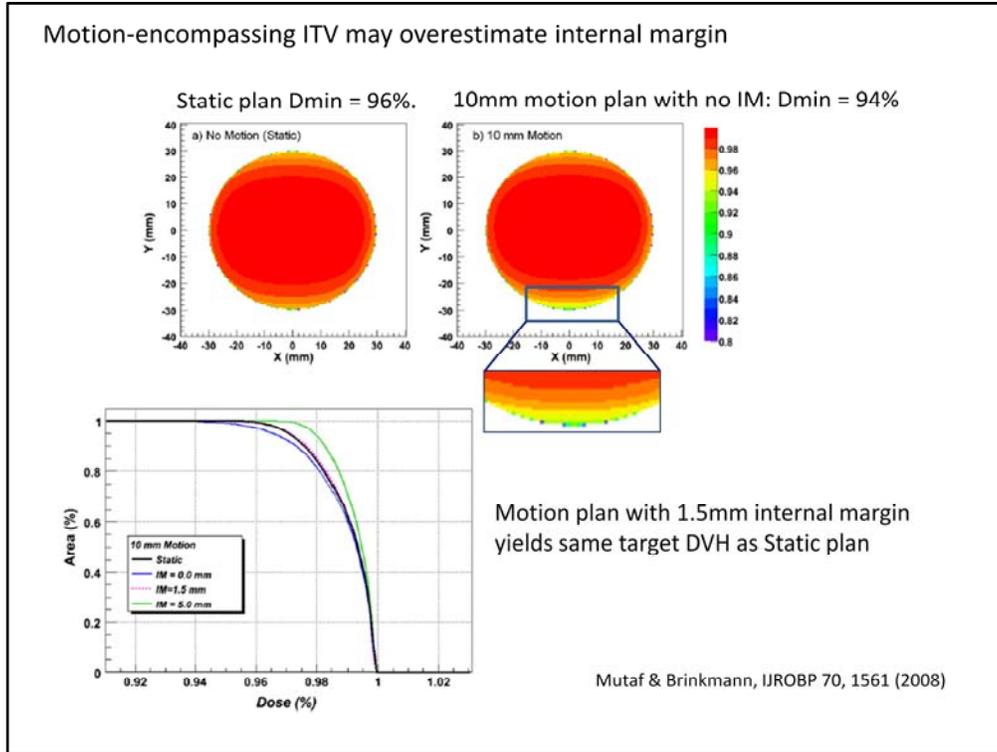
A primary clinical use of RCCT is to define motion-encompassing internal target volume (ITV). Maximum intensity projection (MIP) often used to define tumor in lung. An MIP image is computed by choosing, for each voxel location, the maximum CT number from the RCCT image set. This usually works well to identify a tumor surrounded by low-density lung tissue. But MIP may underestimate lung tumor ITV when the tumor is attached to tissue of similar density, such as diaphragm, mediastinum, or chest wall. Lower row of images show an example of tumor adjacent to diaphragm. At left, the tumor is not visible in maximum intensity projection image because of overlap with diaphragm. Middle: Tumor (outlined in green) is visible in the RCCT at end inspiration. Right: MIP image underestimates the inferior extent of the ITV (orange) compared to an encompassing volume derived from the individual RCCT images (green).

Alternative approach to ITV definition is MIP followed by GTV verification at all phases.



(Ezhil 2009)

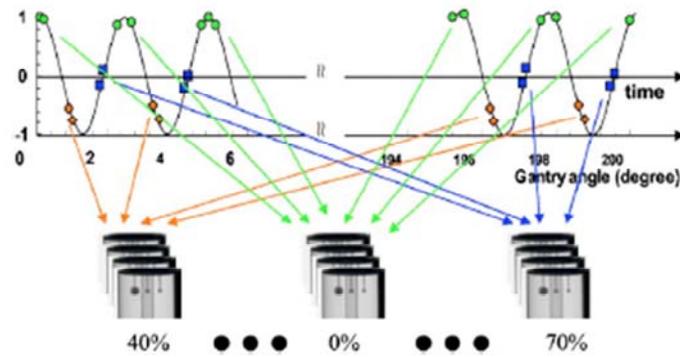
An alternative approach to ITV definition is MIP (left), overlaying the resultant ITV on all images in the RCCT set, and verifying that the GTV is contained on each of the images. Example is shown at center: the resultant ITV is consistent with the more laborious approach of drawing the GTV on each RCCT image, then computing the union of the GTVs.



It is worthwhile to note that a motion-encompassing ITV may overestimate the internal margin needed in terms of dose to target. Upper left figure is a 2D dose profile of a 3cm radius CTV with no respiratory motion. When 10mm peak-to-trough motion is introduced, a treatment plan with no internal margin yields a minimum dose to target of 94% of prescription, only slightly lower than that for the treatment plan of the static target (Dmin = 96%, see inset in upper right figure). Further, a motion plan with only a 1.5mm internal margin yields the target DVH as the static plan, whereas the target receives more dose than the static plan when the full range of motion ( $\pm 5$ mm) is used for the IM expansion.

Respiration-Correlated CBCT: Principles Of Operation

RC-CBCT uses slow gantry rotation (3-4 min over 200°) and retrospective sorting of projections according to an internal or external respiratory signal.

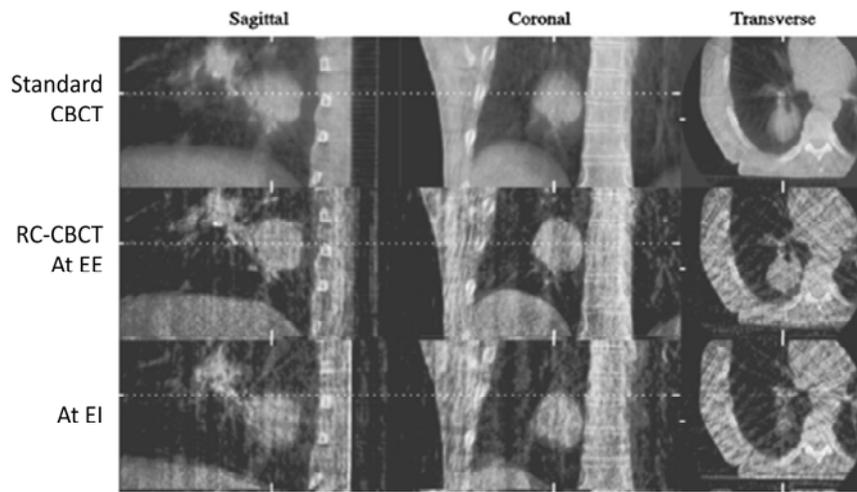


Lu et al, Med Phys 34, 3520 (2007)

RC-CBCT uses slow gantry rotation ( $\sim 3$  min over  $200^\circ$ ) and retrospective sorting of projections according to internal or external respiratory signal. Typical thoracic RC-CBCT scans with Elekta XVI 4.5 Symmetry take 3 minutes with 200 degree gantry rotation (Peng et al 2012). Figure illustrates the correlation of projection data and respiratory signal in the RC-CBCT (Lu et al 2007). The projections are sorted into different groups according to respiratory phase, and a set of projections are grouped for each 10% phase window. Only three phases 0%, 40%, and 70% are shown.

Respiration-Correlated CBCT: Advantages & Limitations

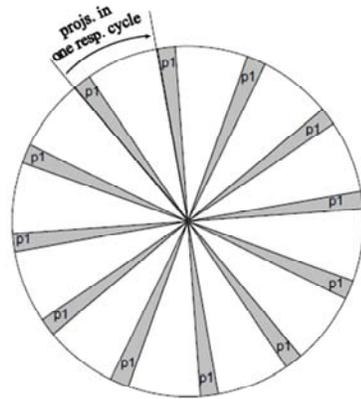
Advantages: Motion-induced blur is reduced, and motion extent can be measured.



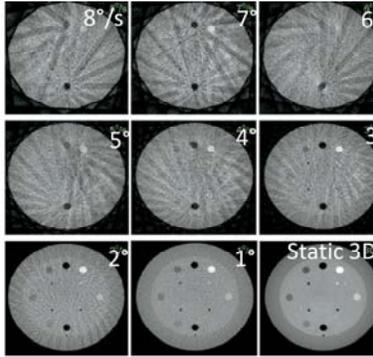
Sonke et al, Med Phys 32, 1176 (2005)

The advantages of RC-CBCT are that motion-induced blur is reduced, and motion extent can be measured. In standard CBCT (top row) tumor and diaphragm are blurred, whereas in the RC-CBCT image at end expiration (middle) and end expiration (bottom) soft tissue features are sharper. But the RC-CBCT images exhibit streaking artifacts, particularly apparent in the axial images.

Disadvantage: Limited number and nonuniform arrangement of projections per reconstructed phase bin cause streaking artifacts.

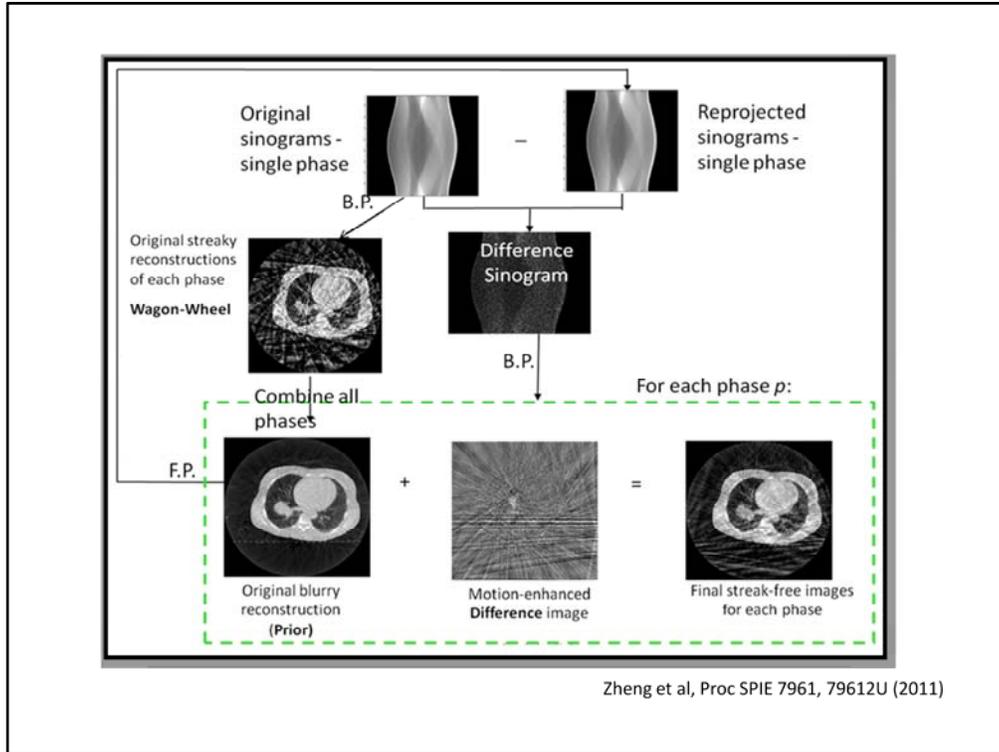


Phantom on motion platform



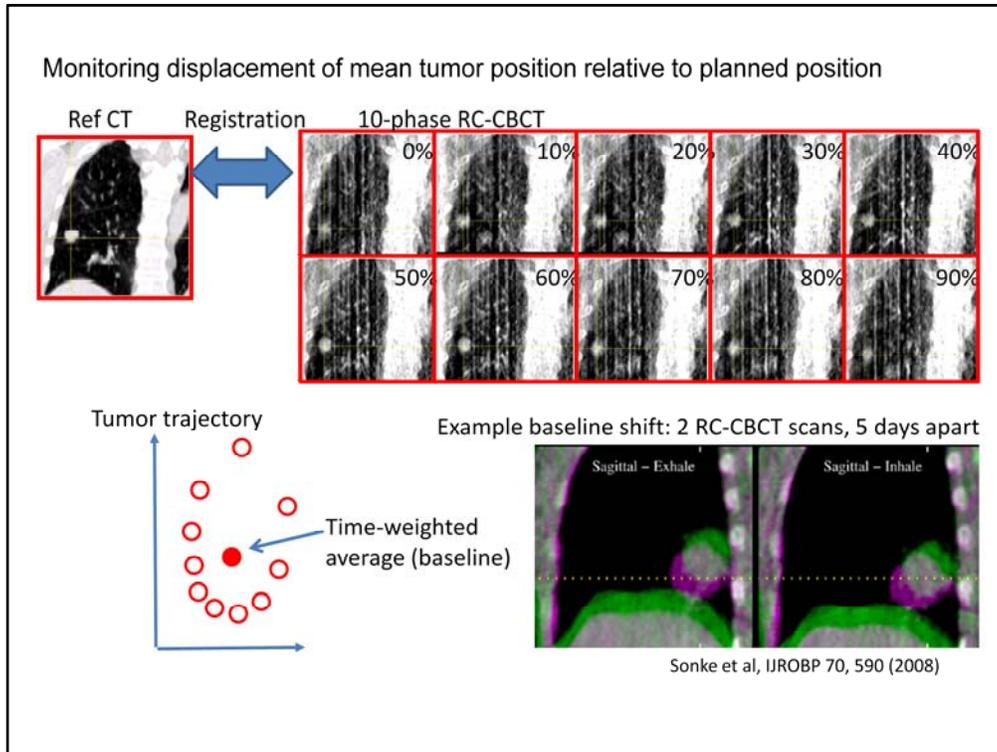
Li & Xing, IJROBP 67, 1211, 2007

Disadvantages of RC-CBCT are twofold: 1) the longer scan times (3 minutes or more) owing due the slower gantry rotation; 2) the limited number and nonuniform arrangement of projections per reconstructed phase bin cause streaking artifacts. Phase-sorted projections cluster in a “wagon wheel” arrangement (left), causing streaking artifacts with a similar appearance. Streaking artifacts diminish with slower gantry rotation (right), but at a cost of longer scanning times.



Varian has developed a fast 4D CBCT reconstruction based on the McKinnon-Bates algorithm. A prior image is reconstructed using all projections belonging to all phases. The prior is forward-projected and the resulting projections are subtracted from the original projections to create motion-enhanced difference images, one for each respiratory phase. These are added to the prior to create streak-reduced phase-correlated images. 4D CBCT is currently available offline in ARIA for evaluating motion, but is not available for online image guidance.

RC-CBCT: Clinical Application



In the Elekta system, RC-CBCT is commonly used to monitor the displacement of mean tumor position relative to the planned position. This is accomplished by registering each image in the RC-CBCT set to the reference CT by aligning the tumor in both images. This computes a trajectory of tumor positions, from which a time-weighted average position is computed, called a baseline. An example baseline shift between 2 RC-CBCT scans 5 days apart is shown at lower right. Left image shows the tumor position discrepancy at end expiration, right image at end inspiration.