Routine clinical application of 4D Time-of-Flight PET/CT

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Integrated PET/CT imaging with the use of 18F FDG is a widely established imaging technique with major indications in oncology for staging, re-staging and monitoring response to therapy. FDG-PET/CT is also used in radiation oncology for target volume delineation and treatment strategy, taking full advantage of the state-of-the-art technology. PET biological information being integrated with the anatomical information provided by CT may accurately characterize the tumor tissue to be treated. However, an important source of image degradation in both CT and PET is represented by organ movement, mainly due to cardiac and respiratory motion. This affects image quality and quantitative accuracy for diagnostic purposes as well as the ability to define accurate target volumes in radiation oncology.[1] Philips has developed a comprehensive respiratory correlated imaging package (Pulmonary Toolkit) for both PET and CT to address the needs for both diagnostic and radiation therapy.

In diagnostic PET/CT studies respiratory gating is used to better localize abnormalities near the borders between organs such as lung and liver, as well as for the detection of very small lesions that are "blurred" into the background activity by respiratory motion. The aim of 4D PET/CT techniques is, in fact, to produce "motion free" and well-matched PET and CT images corresponding to specific phases of the patient's respiratory cycle.

As high resolution, conformal radiation therapy becomes standard in the industry, the demand for more accurate tumor localization and contour definition will increase. A contour is defined either by a CT simulation scan or PET/CT simulation scan using both PET and CT data. Since radiation therapy delivery can be respiratory gated, both CT and PET acquisitions need to be gated in the same way for more accurate therapy planning.

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Respiratory correlated imaging system

Philips Pulmonary Toolkit provides a pulmonary gating application to help facilitate high-quality imaging of respiratory motion. Image acquisition can be conducted using one of two devices.

Figure 1

Philips Bellows with Medspira's Interactive Breath Hold Control System (IBC) (Fig 1) formerly Mayo Clinic Respiratory Feedback System

This system consists of a deformable belt that when placed across the patient's chest/abdomen measures abdomen circumference. It generates a breathing signal corresponding to the expansion and contraction of the abdomen. The breathing signal is fed to the PET/CT system and to the Medspira IBC System. The Medspira device provides a simple bar graph that corresponds to the respiratory cycle and includes several remote displays so both the operator and the patient can observe the respiratory function.

Figure 2

RPM™ Respiratory Gating System (Fig 2)

This system uses an infrared camera that follows a positional reflective marker placed on the patient's chest (made especially by Varian for Radiation Therapy purposes). The sensor type used for respiratory monitoring and gating is the RPM™Respiratory Gating System which controls image acquisition with a trigger signal. The imaging device responds to the trigger and starts or stops the image acquisition. Philips Pulmonary Toolkit includes interface to Varian RPM gating system.

PET/CT acquisition and processing

The success of 4D PET/CT technique is based on product features and patient preparation specifically regarding the ability to regulate patient breathing. Before clinical data acquisition, the patient needs to be coached to relax in order to breathe at a consistent rate. Once this is accomplished a specific imaging protocol can be executed. Typically, CT data is acquired first followed by PET acquisition. Both CT and PET can be performed either as prospective or retrospective scans.

Prospective gating

The scanner collects images at only one phase of the patient's respiratory cycle. The prospective scan creates a single volumetric image collected at a specific respiratory segment. The phase to be measured is determined by the user prior to beginning the acquisition.

Retrospective gating

The scanner acquires data continuously during all phases of the breathing cycle. The data are retrospectively assigned to a respiratory cycle phase and hence to the corresponding image in the respiratory cycle. This requires a large set of raw data that may be edited and reprocessed and could possibly result in many phases.

A default 4D pulmonary gated (retrospective study with multi-phase reconstruction) acquisition consists of a surview, a retrospective pulmonary CT scan, and a retrospective pulmonary PET scan. This protocol is the most flexible and can be applied to both diagnostic and radiation therapy applications.

The following table describes the different protocol choices with their benefits and limitations.

Prospective vs retrospective scanning

Protocols	Benefits	Limitations
Prospective CT	Lower radiation dose due to single phase acquisition Faster data interpretation with single volume (less information to review)	Single phase only acquisition Interpretation limited to specific phase Impossible to evaluate tumor motion
Prospective PET	Faster data interpretation with single volume (less information to review)	Single phase only acquisition Interpretation limited to specific phase Impossible to evaluate tumor motion
Retrospective CT	Data available for entire breathing cycle Flexibility to re-select a different phase Review breathing motion in cine mode	Increased radiation dose Increased interpretation complexity and time due to review of multiple phases Longer reconstruction times
Retrospective PET	Data available for entire breathing cycle Flexibility to re-select a different phase Review breathing motion in cine mode	Increased interpretation complexity and time due to review of multiple phases Longer reconstruction times

The example below represents a typical respiratory waveform. The blue tags highlight the start of inspiration phase while the bottom of the curves represents expiration phase. Peak to peak demonstrates one breathing cycle.

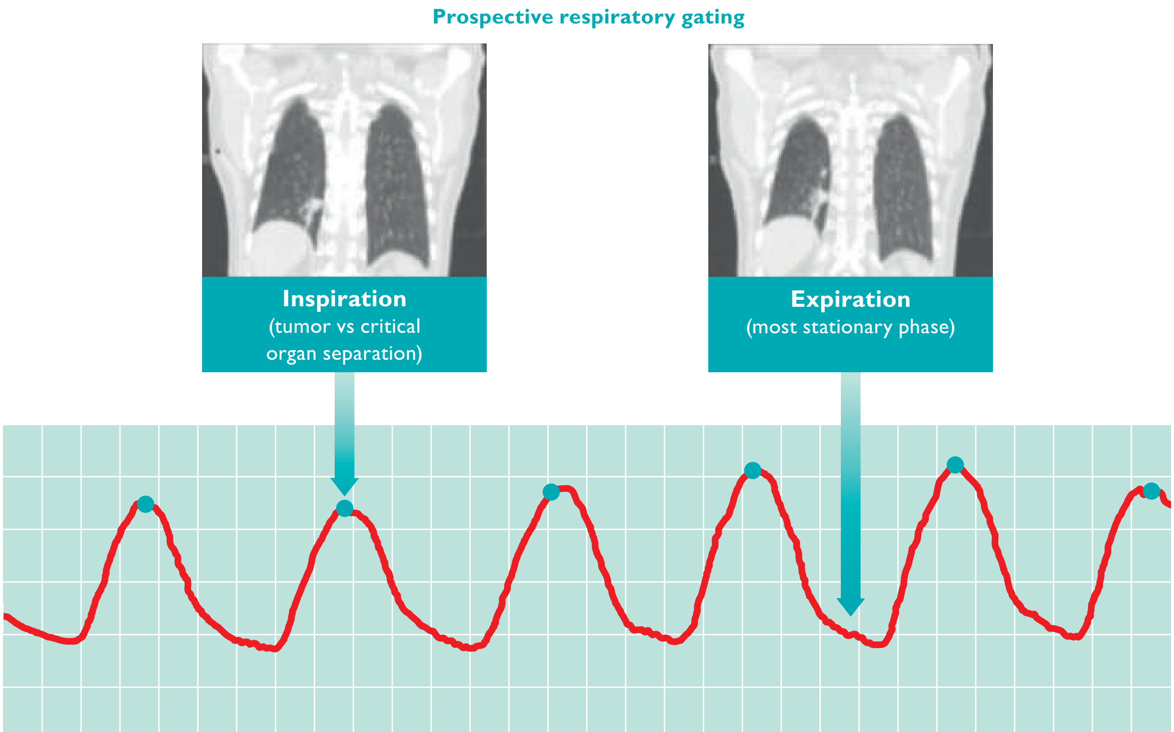


Figure 3 Example of 2 prospective CT scans. Image on the left represents end inspiration phase of respiratory cycle. This image is synchronized with respiratory waveform (above). Arrow points to the specific phase. Image on the right represents end expiration phase of respiratory cycle. This image is synchronized with respiratory waveform (above). Arrow points to the specific phase.

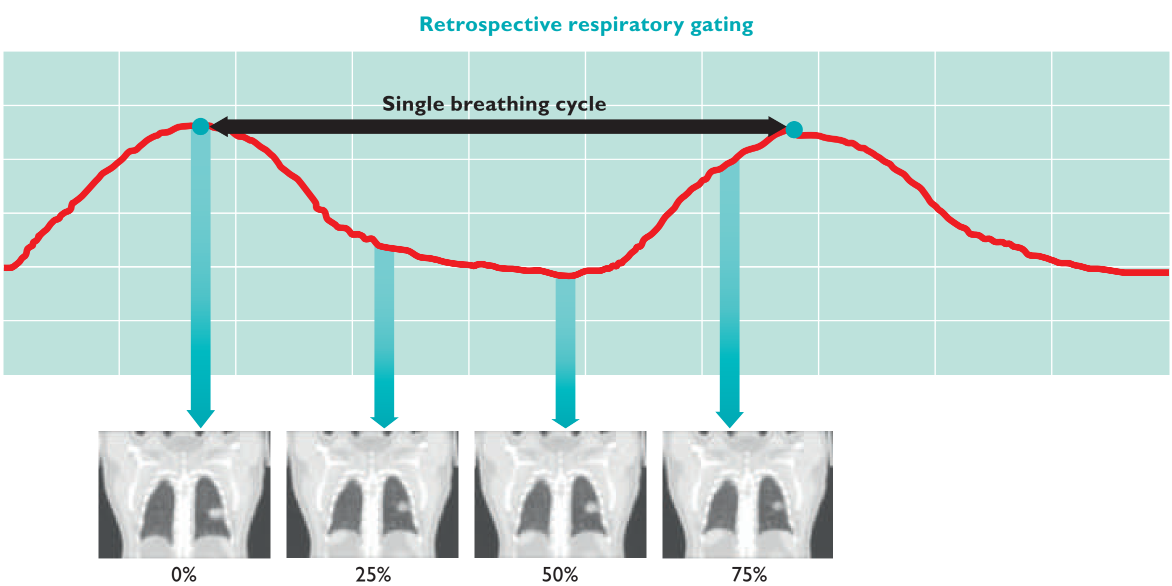


Figure 4 Example of 4 phases of respiratory cycle with retrospective CT data collection. Images represent 0%, 25%, 50%, 75% phase for one breathing cycle on respiratory waveform. This image is synchronized with respiratory waveform (above). Arrow points to the specific phase.

PET/CT clinical use

The following table summarizes a variety of clinical applications of respiratory correlated imaging. System flexibility allows creation of many different protocols. The most typical ones are presented in the table.

	Clinical benefits	Typical protocol	Example

Nuclear Medicine/ Radiology (Diagnostic PET/CT)	• Reduce respiratory motion artifacts during CT attenuation correction scan to improve the accuracy of PET attenuation correction
	  • Oncology
	  • Cardiology
	• Improve small lesion detectability
	• Improve small lesion localization
	• Improve accuracy of SUV
		Retrospective CT
		Prospective PET
		(End-Expiration)
			
			PET gated image fused with CT. PET image contrast enhanced compared to ungated (see below).

Radiation Oncology (Therapy Simulation PET/CT)	• Understand the range of tumor motion • Freeze motion in a specific phase • Determine tumor boundaries more accurately • Characterize tumor	Retrospective CT Ungated PET or Retrospective CT Retrospective PET	 Ungated PET shows tumor motion range. Contrast may be lower compared to gating.  CT gated fused with PET gated. Tumor motion can be viewed.
Interventional Radiology	In the CT interventional setting, a breath hold monitoring and feedback system allows visualization of mobile target lesions throughout CT guided biopsies of the lung and upper abdomen	Breath hold CT	 CT only image. Motion frozen in specific phase of respiration.

Data: Hampton University Proton Therapy Institute (GEMINI TF Big Bore) using CIRS Dynamic Thorax Phantom

Clinical value

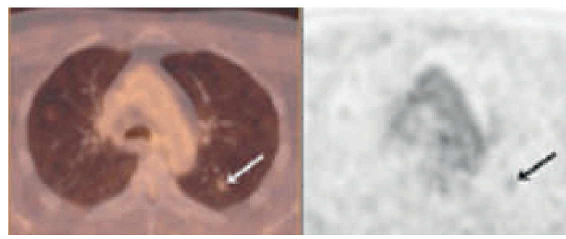
In the following section of this paper several examples of clinical and clinical research work published by Philips users will be summarized.

1. Improve accuracy of SUV

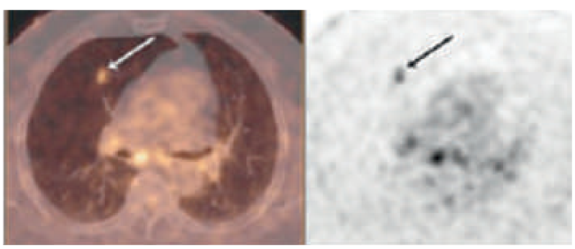
Impact of respiratory gating on the metabolic activity of pulmonary lesions in FDG PET/CT: Initial experience

Moinuddin A, Tran I, and Osman M. St. Louis University Division of Nuclear Medicine, St. Louis, MO

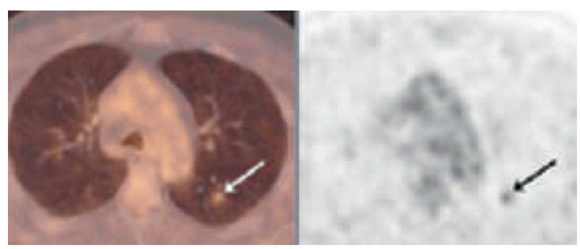
Ungated



Ungated



Respiratory gated



Respiratory gated

St. Louis University evaluated the impact of respiratory gating on PET/CT volume definition and SUV quantification for small pulmonary lesions due to breathing motion.

In 24 patients lesions mean SUVmax of the lesions in the whole-body ungated image was 2.85 in comparison to meanSUVmax of 3.49 after respiratory gating. Mean size of the lesions in whole-body ungated image was 1.33 cm and 1.31 cm after respiratory gating.

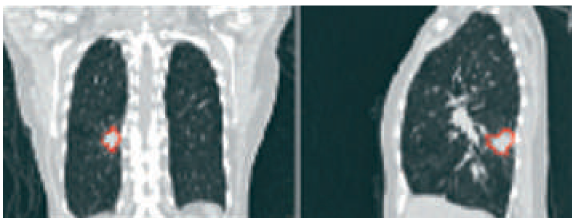
Conclusion

In pulmonary lesions ≥1 cm, respiratory gating changed the SUV max by 22.5% but had no impact on lesion size.

2. Minimize respiratory motion artifacts during CT

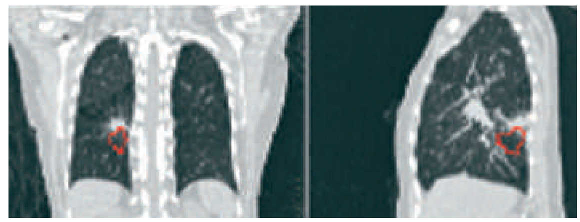
Respiratory-correlated multislice CT for radiation therapy planning: imaging and visualization methods
Klahr P, Subramanian P, and Yanof JH. Philips Medical Systems, Cleveland, OH. MEDICAMUNDI 49/3 2005/11

Figure 5a



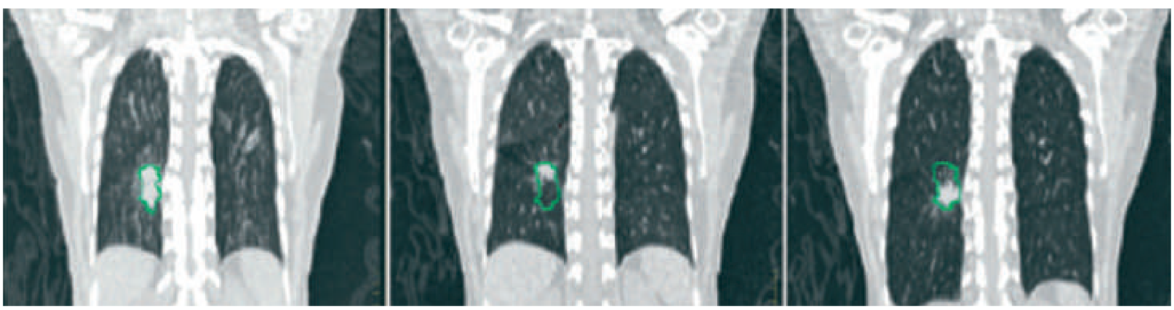
MPR views with the tumor contoured for maximum inspiration

Figure 5b



The images for maximum expiration show the movement of the tumor

Figure 6



Coronal multiphase maximum intensity projection (mMIP)

Single phase MPR at maximum expiration

Single phase MPR at maximum inspiration

Figure 5a shows coronal (left) and sagittal (right) views for maximum inspiration. Figure 5b shows coronal (left) and sagittal (right) views for maximum expiration phases. The tumor has been segmented and the resulting contours can be viewed in any respiratory phase to quantify tumor motion and its effect on the treatment plan. To illustrate this, Figure 5a shows tumor contours for the maximum inhalation phase and Figure 5b shows the same contours mapped to the maximum expiration phase.

In addition to the cine view, a single (composite) view can be generated which shows the tumor's entire range of movement (Figure 6). This multiphasic maximum intensity projection (mMIP) can be used to plan the geometric aspects of the radiation therapy treatment. Image volumes from each phase of the respiratory cycle are spatially projected to create a multiphasic set of MPR images. This set is then temporally projected by selecting the maximum voxel over each phase, computationally similar to the traditional spatial MIP of an image volume. Lung tumors usually have enhanced conspicuity in mMIP since they are generally surrounded by very low density lung tissue. Furthermore, as shown in Figure 6, the mMIP can be used to segment the tumor's excursion for planning blocks, multileaf collimation and other aspects of the radiation therapy plan.

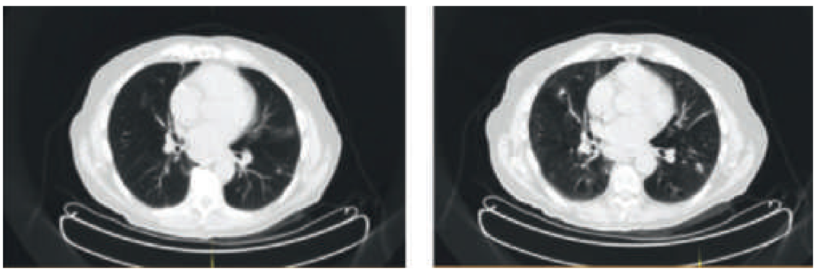
Conclusion

New visualization methods have been developed for radiation therapy planning with respiratory gated, multiphase CT data sets system which facilitates the visualization of respiratory movement, helps to identify patients with minimal tumor movement, and reduces the tumor margins needed to keep the tumor in the treatment beam. Furthermore, respiratory gated images are less prone to respiratory motion artifacts.

3. Improve small lesion detectability

Respiratory synchronization to improve the detection of small pulmonary nodules on PET/CT

Benard F,[1] Turcotte E,[1] Scheuermann J,[2] Saffer J,[2] Karp J,[2] and Divgi C.[2]
[1] Nuclear Medicine and Radiobiology, Universite de Sherbrooke, Sherbrooke, Quebec, Canada
[2] Radiology, University of Pennsylvania, Philadelphia, PA



Ungated   Respiratory gated

maximal SUV 1.55   maximal SUV 3.48

The groups from Sherbrooke and University of Pennsylvania performed a study to assess the clinical implementation of PET and CT respiratory gating and its impact on lung nodule detection and quantification.

Retrospective gating was obtained in all cases over the lesion of interest. The respiratory signal was obtained from an extensible bellows installed around the patients' chest or abdomen and linked to the PET/CT scanner to send a trigger to the list mode acquisition at a predefined portion of the respiratory cycle.

Findings

In some cases, small lesions clearly seen on CT but negative on conventional PET images could be clearly resolved on the respiratory-synchronized PET images. Shape distortion on CT and PET/CT mismatch were also corrected with the use of respiratory synchronized CT data.

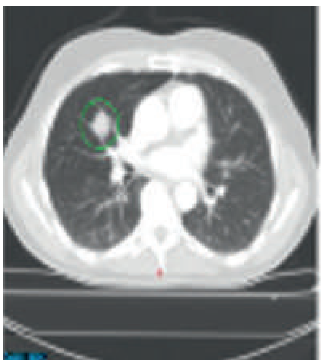
Conclusions

Respiratory synchronized PET and CT data acquisition can be practically implemented in a busy clinical setting. Smaller lesions were visually more conspicuous and striking SUVmax increases were noted in small lesions with significant blurring artifacts.

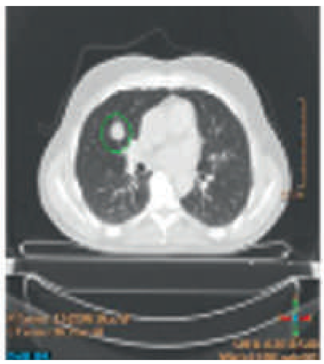
4. Patient motion management

Feasibility of a single breath hold PET/CT to avoid motion artifacts

Czyborra-Brinkmann J, Bruderkrankenhaus, St. Josef, Nuclear Medicine, Paderborn, Germany

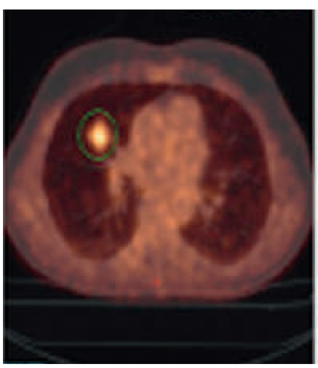


Whole body CT

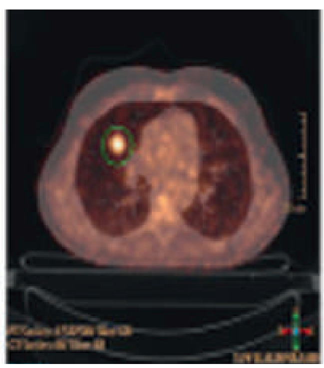


4D CT

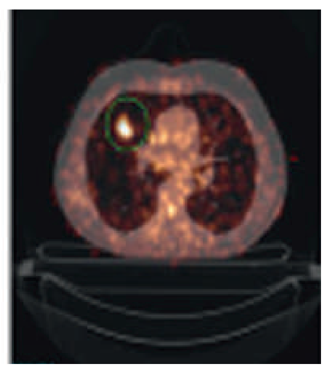
Breath hold CT



Whole body PET/CT



4D PET/CT



Breath hold PET/CT

The group from Paderborn demonstrated that it is possible to reduce motion artifacts caused by breathing through the use of ultra-fast PET acquisition and breath hold techniques.

Findings

An SUV comparison between the free-breathing group and the breath hold group was carried out. The image quality of the PET scan was excellent in the free-breathing group and tolerable in the breath hold group. The CT scan was of better quality in the breath hold group compared to the free-breathing group.

Conclusion

Ultra-fast PET scanning in deep inspiration is feasible and helps for better characterization by lessening motion artifacts. No tumors were overseen due to the short scanning time, therefore, it is feasible to add breath hold PET scans to the routine scanning protocols.

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