MotionFree

Device-less digital respiratory gating technique, seamlessly integrated in PET imaging routine

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Introduction

Respiratory motion is one of the main factors significantly impacting PET/CT acquisition, as it typically takes several minutes in which breath holding is not an option. It negatively affects about half of all PET/CT procedures, not limited only to the thorax but also to the abdomen and pelvis areas. Since PET is a tomographic technique and uses coincidence photon detection events along a nearly straight line, movement of a source with positron decays will produce events which cover larger detector area, hence when these events are reconstructed into blurred and fainter images, associated with inaccurate localization of features of interest.

Motion artifacts degrade PET image quality and lead to reduction in lesion detectability. Quantitation accuracy is also impacted by respiratory motion artifacts, resulting in reduction in standard uptake value (SUV) and overestimation in lesion volume. These erroneous results are often hard to detect and may impact diagnosis, treatment planning and follow up.[1] [2] [3]

These artifacts can be eliminated by utilizing GE Healthcare's powerful respiratory motion management techniques: Q.Static,[4] 4D Gated and Q.Freeze.[5]

However, despite the importance of respiratory motion management, it is still not commonly used as part of standard clinical practice. This is because motion management techniques currently offered by the different vendors require external gating devices that are mostly based on pressure sensor or infrared camera with a tracking block.[6] The setup and interaction with these external devices are cumbersome and time consuming, making the entire process challenging and not as reliable as needed.

GE Healthcare's MotionFree is the first-ever digital respiratory gating solution that derives respiratory waveforms from PET coincidence data, without requiring an external gating device. It is available as part of protocol definition or prescription, allowing active monitoring of respiratory motion for every field of view (FOV) and every patient. It is fully and seamlessly integrated in the existing Q.Static acquisition protocol, and can be used in every PET/CT procedure. The user is no longer required to decide which FOVs and which patients should have motion correction applied. This is possible thanks to the fact that MotionFree automatically, during live acquisition, detects if a respiratory motion is affecting the current scan FOV and can modify the scan duration according to user preferences. If significant motion is detected, the feature performs quiescent phase-based Q.Static reconstruction.

Being a SW-only option, the feature addresses the challenges of an external gating device. It significantly reduces scan setup time[1] and optimizes overall scan time, and it applies motion correction only if there is significant respiratory motion in the current FOV. MotionFree can be applied prospectively as well as retrospectively on any previously acquired scan without respiratory information recorded from a device, making respiratory motion management accessible at any time for any data.

GE Healthcare has designed MotionFree to leverage the 4-dimensional information encompassed within the coincidence events to derive respiratory waveforms for the current FOV. This makes it superior to a respiratory signal measured at a fixed patient location with respect to the thorax using a device-based approach.

[1] Compared to a Q.Static acquisition with an external device.
[2] MotionFree is intended to be used for any PET static acquisition. It's current implementation does not support cardiac gating. Performance of MotionFree with Dynamic imaging will depend on acquisition time per phase, hence for short acquisition time, results may not be guaranteed. For 4D gated imaging, MotionFree does not support prospective 4D Gated acquisition. MotionFree should be applied first with Q.Static, and then Replay using 4D Gated mode.

GE Motion Management Techniques

GE Healthcare's vision has always aimed to incorporate respiratory motion correction by bringing advanced technologies to manage respiratory motion and reduce the impact on PET image quality with a minimal impact on clinical routine workflow. Among these technologies are Q.Static, 4D Gated and Q.Freeze.

Q.Static

Q.Static is an acquisition mode that is fully integrated into the clinical whole-body PET/CT protocol. It receives as an input the respiratory signal and isolates data when the motion-impacted area is in a low motion state. Respiratory trace analysis has shown that a majority of patients tend to spend more breathing time dwelling at an end-expiration quiescent period and breath to the same end-expiration location.[7] These results indicate that imaging at end-expiration could involve less motion while still retaining a large fraction of the PET data.

Based on these findings, Q.Static was designed to be a phase-based gating method that extracts a fraction of PET data from the end-expiration quiescent portions of patient breathing cycles, and forms a single motion-free PET image volume for physician review, with no involvements of additional data processing before or after the acquisition. A respiration curve with a quiescent period indicated can be seen in *Figure 1*. The conventional scanning method, referred to as 'static', uses the entire signal in each respiration cycle. Q.Static only extracts data during the quiescent period of the respiratory cycle.

The Q.Static quiescent period is determined by specifying the phase offset and phase width shown in *Figure 1*, as a percentage of the respiration cycle. Both parameters are adjustable to any patient respiratory patterns. To manage an irregular respiratory pattern, Q.Static has optional cycle rejection. Hence, when fast and shallow respiration happens, the cycle and corresponding data can be rejected. Q.Static also allows the user to extend the scan time per FOV, enabling comparable statistics as in static acquisition.

Compared to conventional static images, Q.Static leads to images with reduced motion blurring and enhanced quantification at the cost of count statistics.[4]

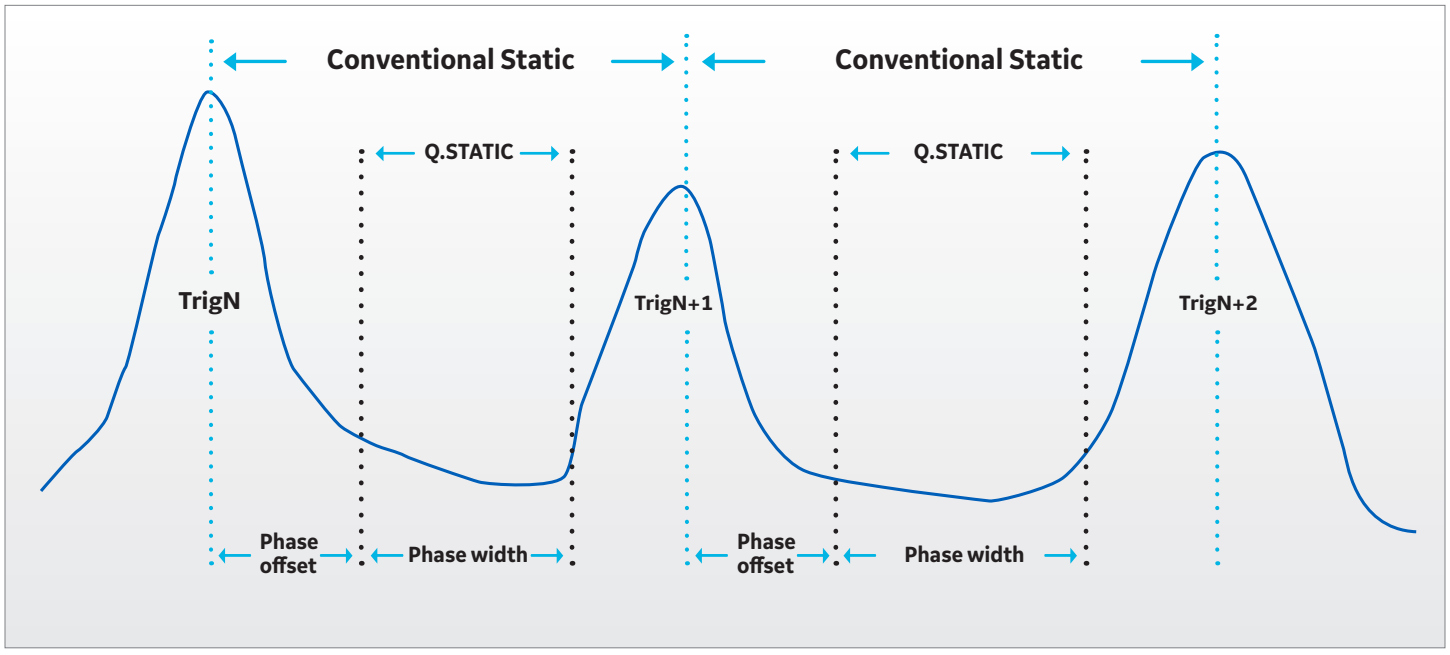

Figure 1. Typical patient respiratory curve with a longer quiescent phase with little respiratory movement.

4D Gated

4D Gated is an additional acquisition mode that collects coincidence events at the different gates of the respiratory cycle, as illustrated in *Figure 2*. For each respiratory gate, a PET image volume is created, showing the impact of respiratory motion on anatomy movement or image features. This type of output helps understand the range of movement and identify the original location of the lesions.

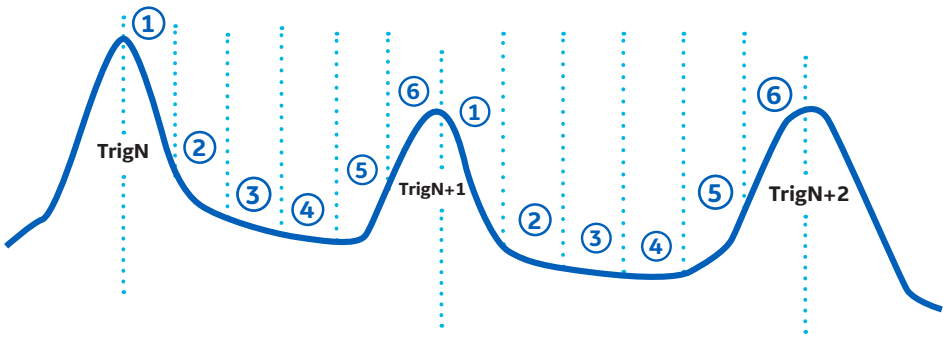

Figure 2. Illustration of patient respiratory cycle with 6 different gates.

Q. Freeze

Q.Freeze is a non-rigid registration post-processing technique based on a multi-resolution optical flow methodology developed to correct PET image data for respiratory motion. It receives as an input the gated images and uses 100% of the PET coincidence events. The technique generates a single PET image volume with the benefits of frozen patient motion and reduced image noise.[5] Multi-resolution optical flow is a two-step technique that allows to target first the global motion pattern and then focus on refining the results with the details provided in the higher resolution levels of the image; consequently, inhibiting small size features from affecting the registration of the larger structures. Optical flow is then followed by viscosity and elasticity regularization modeling of the tissue to prevent motion overcorrection. The frozen images are finally generated based on statistical median algorithm applied on voxel level.

With these three motion management technologies, GE Healthcare is addressing most of image artifacts and inaccurate quantification caused by patient respiratory motion. However, until recently, all the above motion management methods required a respiratory-gating device connected to the scanner[3] during the acquisition to generate the respiratory waveform. Device setup, positioning, monitoring and handling are challenging to the user, any misuse or malfunctioning of the device during the acquisition could cause blurred images or incomplete motion management results.

In addition, specifically for Q.Static when used with an external device, the user is required to pre-select the affected bed positions, which could be several adjacent FOVs to cover the area that includes respiratory motion. The default selection of the user is usually the FOVs covering the lung and abdomen region, assuming it is most often affected by patient respiratory motion, while respiratory motion may impact lower abdominal area as well. Moreover, not every lung or abdomen FOV may require motion correction. The impact of respiratory motion on anatomical regions depends on (1) the extent of respiratory motion relative to background noise, (2) the location of activity concentration and, (3) direction of movement. Hence, a unique solution is needed to address a number of these challenges.

[3] GE Healthcare's respiratory-gating device is an optional accessory to the Discovery PET/CT systems.

Method and Implementation

MotionFree is an algorithm based upon principal component analysis (PCA), that determines the magnitude of respiratory impact to the data. The method analyzes the coincidence data without the need for any external device.[8] [9] [10] [11] PET *sinograms* are a representation of coincidence data that are used to form 4D input to PCA: coincidence data coordinates (r, θ, z) and changes over time (t), such that a correlation of motion with location in the patient is available. Sinogram data are commonly used by the image reconstruction process to form volumetric images of activity concentration in the patient. The spatial location of a tracer-avid feature can be impacted by several different factors, and often the most dominant factor is respiratory motion (represented by changes of position over time). In order to extract respiratory motion information, PCA is used as a dimensionality reduction technique to derive the 1-D respiratory waveform directly from the data.

The MotionFree algorithm enables an automatic data analysis using collected PET coincidence events, i.e. 'list-mode' data, and, if the detected respiratory impact is above a configurable threshold, a respiratory waveform is derived from the PET list-mode data, and the waveform is used to derive per-cycle triggers. These triggers enable subsequent gated data processing, including the separation of the most quiescent portion of the acquired data, using the existing Q.Static acquisition mode. The MotionFree processing of PET list data also enables generation of 4D Gated PET data, since MotionFree produces triggers which can be used in any manner that device-generated triggers can be used. This 4D Gated PET image data can subsequently be processed with Q.Freeze.

PCA

PCA is a general data processing technique used to find a mathematical basis for a dataset where the basis vectors are ordered to explain the maximum variation (in terms of standard deviation) within the data.[12] An empirical example is shown in *Figure 3* along with a mathematical description of an application of PCA to dynamically-sorted PET list-mode data saved as *sinograms*.

The key concept in PCA is the determination of the 'weight factors' for the largest principal components (PC). These weight factors describe the variation over time (since temporal data was used) that arises due to that PC. If the largest variation computed from the data is consistent with motion from respiration, then the plot of those weight factors over time becomes the respiratory waveform. An example application of PCA using a heart-like shape with contraction and up/down motion is shown in *Figure 4*.

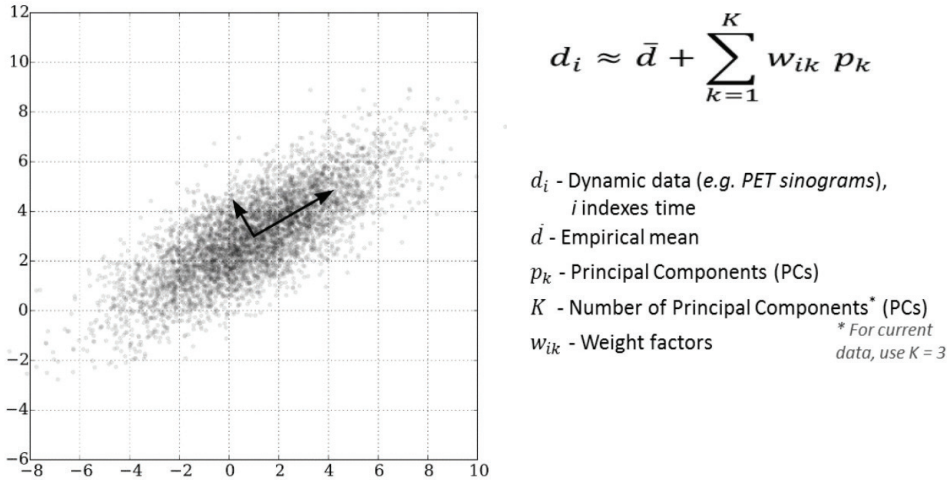

Figure 3. Example of a distribution of two-dimensional data where two orthogonal basis vectors describe the two main components of the variation in the data.

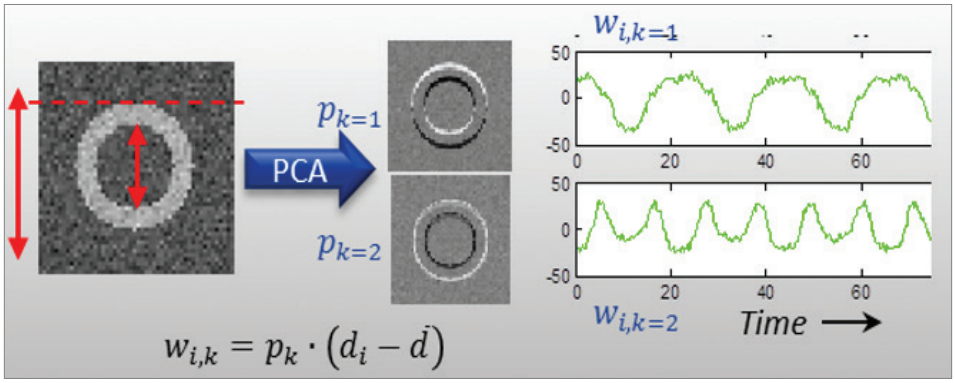

Figure 4. Example of a 2D simulation that has up/down motion with contraction. $P_{k=1,2}$ are the two largest principal components and $w_{i,k=1,2}$ are their weight factors which describe respiratory waveform (top-right) and contractile waveform (bottom-right), over time.

Step by Step

MotionFree algorithm is described by the following five automatic software only steps, as shown in *Figure 5*.

- *Step 1:* Acquire PET coincidence events using Q.Static acquisition mode
- *Step 2:* Generate reduced-dimension sinogram data
- *Step 3:* Apply PCA, using the reduced dimension sinogram data as input, and extract three largest principal components and weight factors, i.e. 1D signals as a function of time, then determine correct phase and flip the waveform accordingly. These signals may represent respiratory motion.
- *Step 4:* Apply Fast Fourier Transform (FFT) on the 1D signals. For each FFT, calculate the peak value within the respiratory frequency range (normal respiration is 2.5-10 sec period, or 0.1-0.4 Hz) and make a ratio of this peak value to the mean above this range. This ratio is a unitless index, "R", that represents the strength of the signal being respiratory-like, and it is used to determine whether the respiratory motion impact on the data is significant. The larger the number, the more the signal is respiratory-like and impactful, and vice versa.
- *Step 5:* The 1D signal with the largest R value is then transformed back to the time domain. A peak detection algorithm is then applied to derive per-cycle triggers.

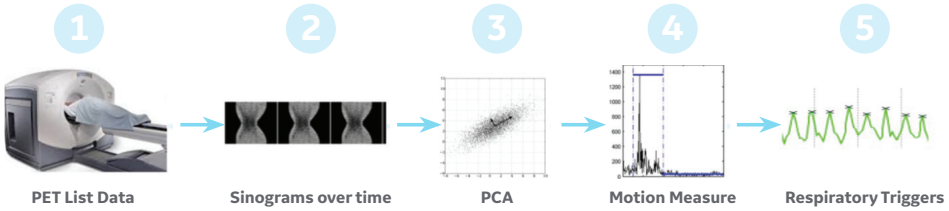

Figure 5. MotionFree algorithm flow.

If the calculated R value exceeds a pre-defined threshold, it indicates that respiratory motion may impact the resulting image quality and quantification. If the R value did not exceed the threshold, then it is likely that respiratory motion has a reduced impact on the activity within the FOV, and motion compensation may not benefit the scan – hence the FOV will be reconstructed as a static image and the scan will continue to the next FOV.

Q.Static prescription with MotionFree allows the user to choose to extend the Q.Static time per FOV to match the duration of a static time. Then, during scan, MotionFree decides on the fly (based on R) whether to extend the scan time and enact Q.Static. With this automated capability, motion correction is applied only when most likely to benefit the data, saving scan time and preserving high throughput while improving quality of scanning, quantitation and consequently the diagnosis.

Threshold

The threshold value determines whether the FOV being scanned should be corrected for motion or not, i.e. it is a surrogate of respiratory impact. As an example, *Figure 6* shows on the left a respiratory signal significantly differentiated from the noise, while on the right, no significant respiratory signal is detected. The default value is set to 15 as a pre-defined threshold prescribed as part of MotionFree protocol. This value may be adjusted by the user based on site preferences. A higher threshold means that only data with stronger respiratory signal compared to the noise will be corrected for motion. Decreasing the threshold means that more FOVs will be corrected for motion, even if the respiratory signal was not as strong.

The value 15 was chosen based on a preliminary data including hundreds of clinical cases, out of which the respiratory signal was derived using MotionFree. *Figure 7* plots the R values for all FOVs included in the clinical data study. All cases with R value above 15 utilized motion correction while the remaining cases were not significantly impacted by respiratory motion.

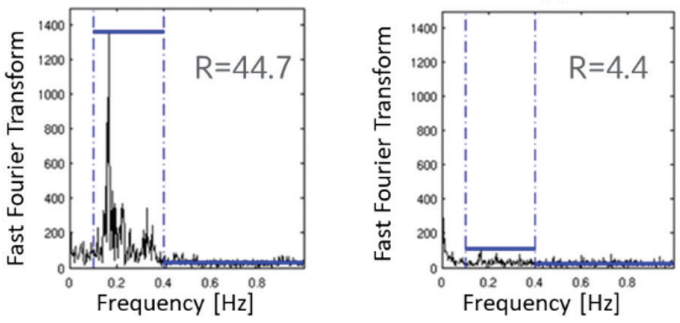

Figure 6. An example of strong respiratory signal compared to noise (left) and no respiratory signal detected (right).

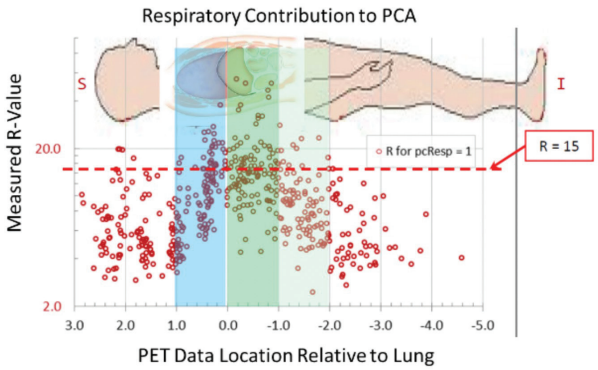

Figure 7. Measured R value vs. data location relative to lungs.

Quantitative Analysis

Phantom Study

The performance of MotionFree was further demonstrated using a motion phantom with three 3.1 mL [68]Ge filled spheres, representing simulated lesions that have tracer uptake. The phantom used was a Quasar (Modus Medical Devices) programmable respiratory motion phantom (*Figure 8*, below). The nominal outer diameter, inner diameter = (19 mm, 18 mm) (3.1 ml) spheres were put in the moving portion of the phantom, separated by approximately twice their diameter. Different phantom motion patterns were used to represent clinically-derived normal and compromised pulmonary function (abnormal), producing an amplitude range of 2-15 mm and 8.5-15 mm over the entire waveform, respectively. Three sets of measurements were performed; one to test the response to motion along z-axis, another one to test all 3 axes (oblique angle) and a third one to test multi-FOV acquisitions.

Data were acquired for 4 minutes using Discovery MI, Discovery MI-DR and Discovery IQ PET/CT systems (GE Healthcare – Waukesha, WI). Q.Static, 4D Gated (using 6 gates), duration-matched static[4] and no motion data volumes were created – the latter serving as the reference. Q.Static was acquired with MotionFree option. The images were reconstructed using 3D OSEM iterative reconstruction (VUE Point HD) with the clinical reconstruction parameters recommended for each system.

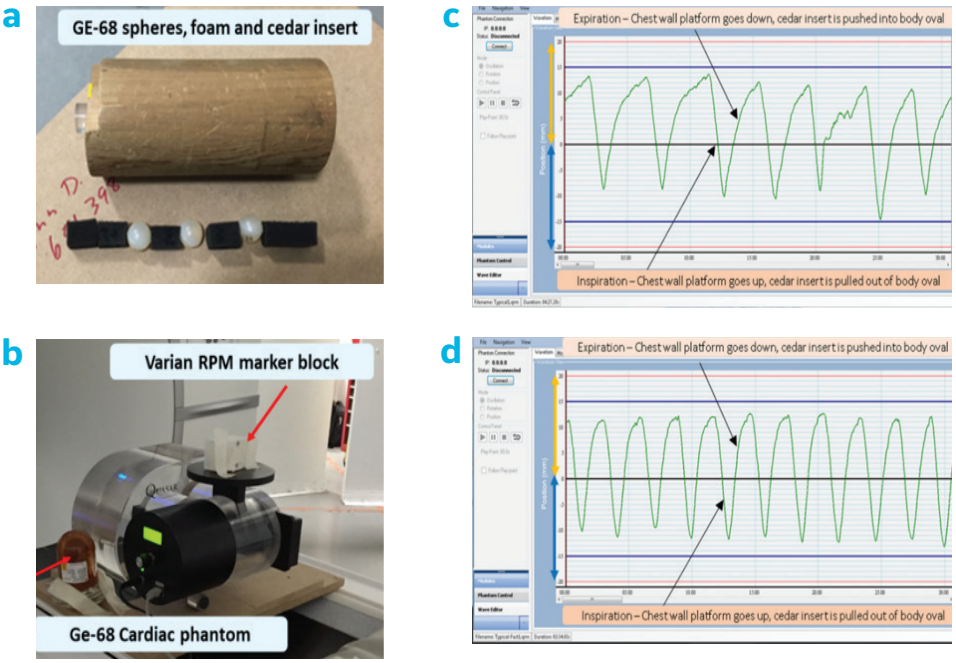

Figure 8. Three spheres separated with foam pieces, put inside a cedar insert to simulate lesions (a). Quasar phantom (b) used to simulate respiratory motion using normal (c) and abnormal (d) respiratory waveforms. A GE-68 based cardiac phantom (by Eckert and Ziegler Isotope Products Inc.) is used to model the left ventricle size.

[4] Duration-matched static data volumes are used for comparison to Q.Static data. The volumes were created by retrospective acquisition of the acquired data into shorter times. When comparing against Q.Static, the acquisition time was set to one-half in order to match Quiescent data duration (based on pre-populated reference quiescent phase with of 50% of respiratory cycle). When comparing against 4D Gated (6 gates) data volumes, the scan time was set to sixth to match a single gate.

Figure 9 shows an example of coronal images of the three spheres, created Q.Static acquisition with MotionFree. The results are compared with static images acquired with and without motion. Similar results were achieved for multi-bed acquisition (annulus phantom was added to the setup on each side of the quasar phantom). *Figure 10* shows quantitation results of the example in *Figure 9*(a). Quantitative improvements were recorded for SUV_{mean} and volume for all measurements, reaching up to a 30% increase in SUV_{mean} values and up to a 67% decrease in volumetric measurements.[5]

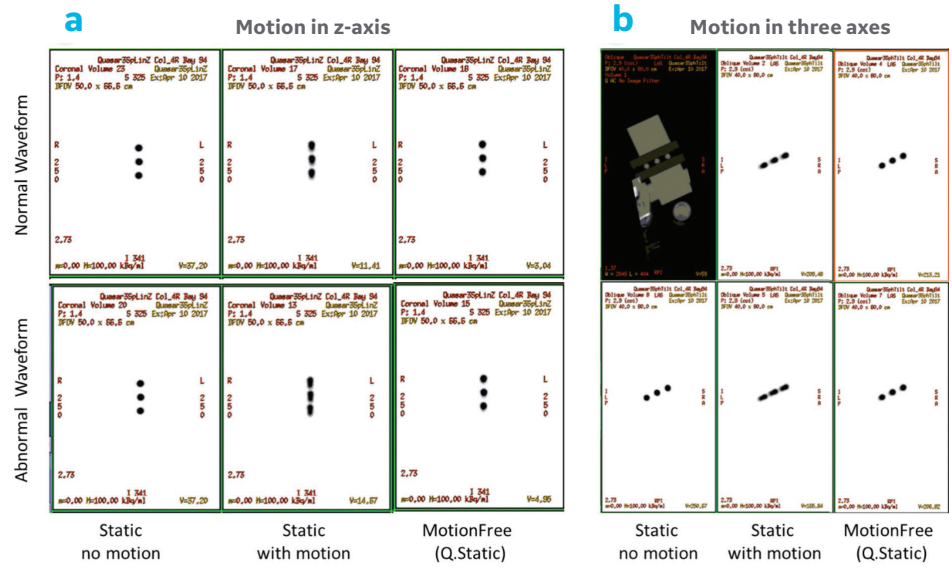

Figure 9. PET coronal view of Ge-68 spheres for motion in z-axis (a) and the three axes (b) using the Quasar normal and abnormal respiratory waveform for DMI-4R and OSEM reconstruction method. Left to right (a+b): duration-matched static with no motion, duration-matched static with motion, and MotionFree with Q.Static.

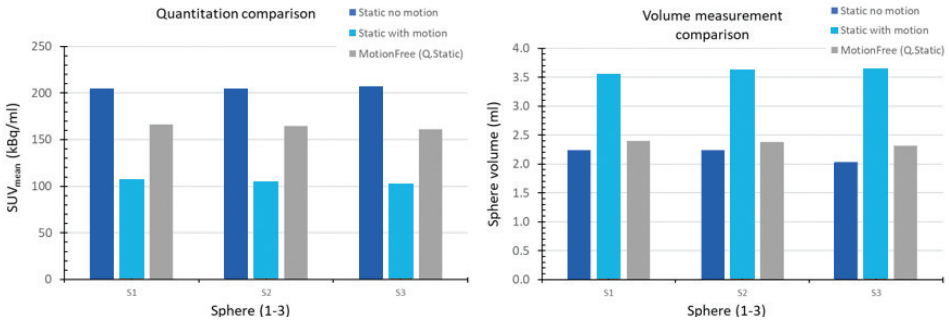

Figure 10. Comparison of quantitation (left) and volume (right) for the data shown in Figure 9 for normal waveform and motion along the z-axis. Comparison results are similar for the other configurations.

Reconstruction of the images with Q.Clear,[13] GE Healthcare's unique fully converging reconstruction method, have demonstrated a further increase in SUV_{mean} values. The combination of MotionFree and Q.Clear improves measurements by up to 46%[6] when compared to OSEM with no respiratory motion correction applied, for both normal and abnormal respiratory waveforms.

Images generated using MotionFree were also compared to images generated using device-based respiratory motion correction.[7] The Real-time Position Management (RPM) system, by Varian, was used as the gating device. Motion in three axes were measured, using the phantom with normal and abnormal patient-based respiratory waveforms. The differences in quantitation between motion correction with MotionFree and motion correction with RPM were -6.7% to 1.1% in SUV_{mean} and -0.9% to 5.4% in volume measurements. These differences show that MotionFree is a substantially equivalent alternative for PET respiratory motion correction to device-based methods.[8]

[5] Compared to non-processed (STATIC, no motion-correction) data. As demonstrated in phantom testing using a typical and fast respiratory model and OSEM reconstruction". In total, 15 measurements were recorded. Percent improvements were measured as the ratio of the difference between MotionFree or duration-matched static with motion to the static with no motion (ground truth).

[6] As demonstrated in phantom testing measured on a Discovery MI-4R.

[7] Comparison was performed against static images with no motion, as the ration of the difference between MotionFree and static with no motion to the static images with no motion.

[8] As demonstrated in phantom testing using a typical and fast respiratory model and OSEM reconstruction.

Clinical Images

GE Healthcare has designed MotionFree to be able to retrospectively analyze acquired data (list-mode data of static acquisition for instance) and correct for motion. Using the prospective and retrospective capabilities, a clinical evaluation of MotionFree was conducted to assess performance. Some of the clinical cases are shown below to emphasize the different benefits of MotionFree. All clinical cases were reconstruction with full quantitative corrections, including attenuation correction with a single CT acquired either with tidal breathing or during end expiration, depending on site preferences.

Clinical case #1 (*Figure 11*) shows enhanced image quality highlighted by better delineation of the anatomy within the abdomen region, where motion was automatically detected by MotionFree and corrected for by Q.Static. Lesions are more defined qualitatively and quantitatively with increased SUV_{max} and decreased volume. Better differentiation could be seen between adjacent lesions. Some lesions were barely seen with the duration-matched conventional static image.

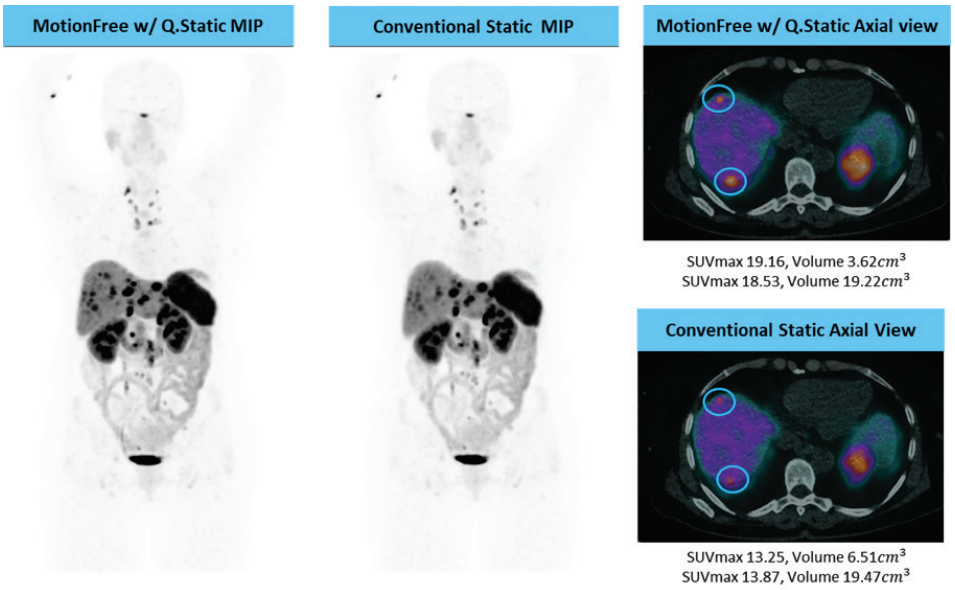

Figure 11. ***Clinical case #1*** *ET Coronal MIP and Axial fused image acquired with DMI-5R, reconstructed as Q.Static with MotionFree (left) and as a static image (right). Injected tracer: Ga-68 Dotatate. Injected dose: 119.4 MBq/3.77 mCi. Uptake time: 64 mins. Patient's BMI = 26.5kg/m². Courtesy: Zurich University Hospital.*

Clinical case #2 (*Figure 12-left*) shows a lesion in the pancreatic area that is clearly seen in MotionFree image in comparison to it's blurred shape in the duration-matched conventional static image.

Clinical case #3 (*Figure 12-right*) shows a small liver lesion that could have been missed due to blurring caused by respiratory motion in the duration-matched conventional static image.

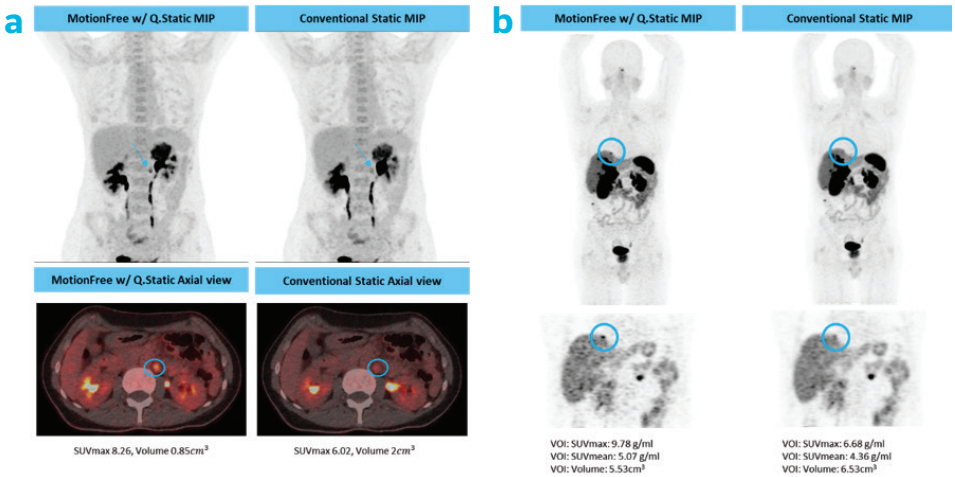

Figure 12. ***Clinical case #2*** *(a) Eye to Thighs MIP and Axial fused images acquired with DMI-5R and reconstructed as Q.Static image with MotionFree (a left) and as a static image (a right). Injected tracer: F-18 FDG. Injected dose: 90.5 MBq/2.45 mCi. Uptake time: 57 mins. Patient's BMI = 19.9kg/m². Courtesy: Zurich University Hospital.*

Clinical case #3 *(right) Eye to Thighs MIP acquired with DMI-4R and reconstructed as Q.Static with MotionFree (b left) and as static image (b right). Injected tracer: Ga-68 Dotatate. Injected dose: 232.36 MBq/ 6.28 mCi. Courtesy: Stanford.*

Clinical case #4 (*Figure 13*) shows a large right lung mass that is significantly blurred in the conventional static MIP due to respiratory motion. When correcting for motion, both RPM and MotionFree have similarly demonstrated improved quantitation in SUV and volume measurements, in addition to the overall qualitative image quality. Images generated using Q.Static with MotionFree were retrospectively acquired from the original Q.Static scan with RPM, using the same scan time and Q.Static prescription.

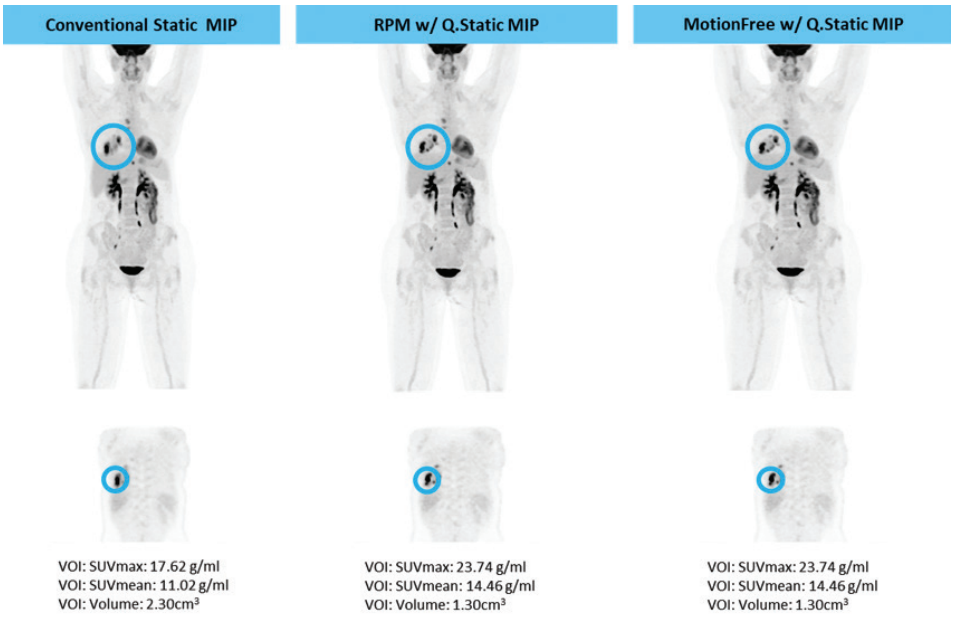

Figure 13. ***Clinical case #4*** *Eye to Thighs MIP acquired with DMI-DR, as a static image (left), Q.Static with RPM (middle) and Q.Static with MotionFree (right). Injected tracer: F18-FDG. Injected dose: 418.1 MBq/11.3 mCi. Courtesy: Froedtert Hospital.*

Clinical case #5 (*Figure 14*) is showing a critical case where MotionFree may potentially change diagnosis. The resulted images of Q.Static with MotionFree highlights a single feature that is not identified in the static image.

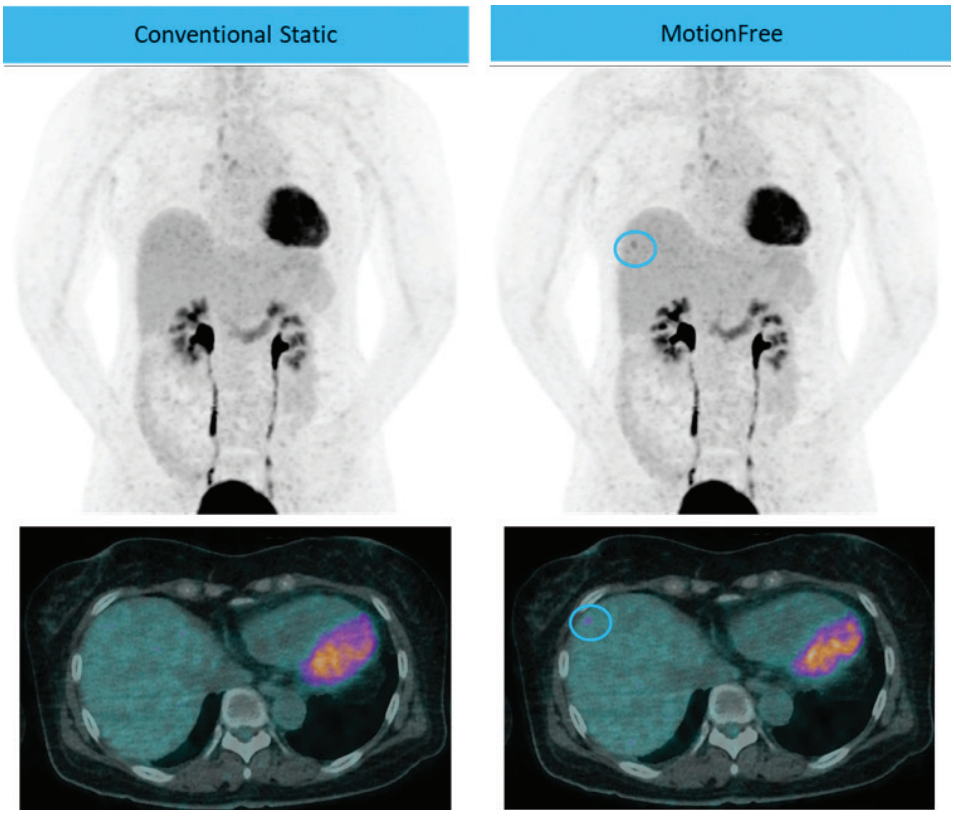

Figure 14. ***Clinical case #5*** *Eye to Thighs MIP acquired with DMI-DR, as a static image (left) and Q.Static with MotionFree (right). Injected tracer: F18-FDG. Injected dose: 89.1 MBq/2.41 mCi. Uptake time: 72 mins. Patient's BMI = 20.0 kg/m². Courtesy: Zurich University Hospital.*

Clinical case #6 (*Figure 15*) is highlighting the power of combining MotionFree with Q.Clear reconstruction in boosting image quality and further improving quantitation.

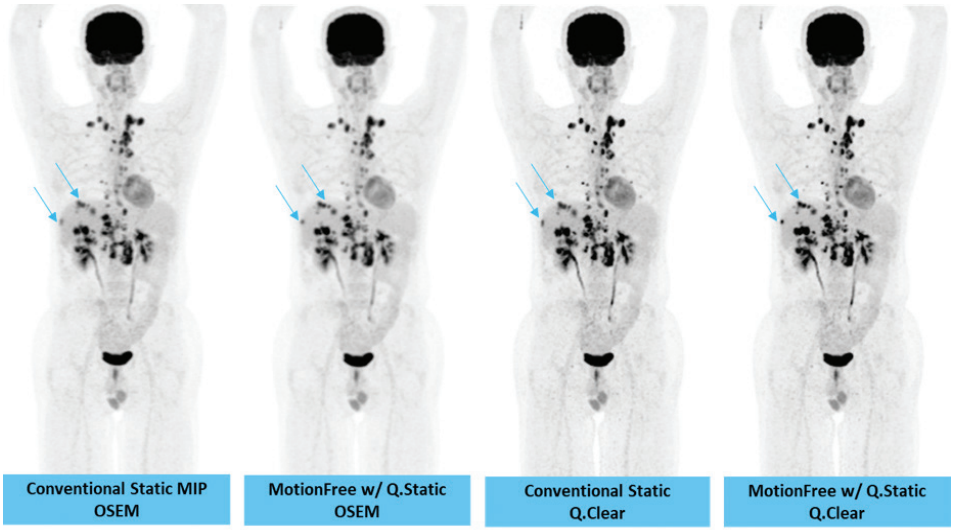

Figure 15. ***Clinical case #6*** *Eye to Thighs MIP acquired with DMI-5R, and reconstructed as a static image with OSEM (most left), as a Q.Static image with MotionFree (second from the left), as a static image with Q.Clear (third from the left) and Q.Static image with MotionFree (most right). Injected tracer: F18-FDG. Injected dose: 148.5 MBq/ 4.01 mCi. Uptake time: 74mins. Patient's BMI = 17.5kg/m². Courtesy: Zurich University Hospital.*

Workflow Improvement

MotionFree has been shown to be substantially equivalent alternative for PET respiratory motion correction to device-based methods from an image quality and quantitation perspective. Given this equivalence, MotionFree brings to the user significant benefits in the clinical workflow. It does not require any pre-scan setup and post scan management. In addition, it does not require visual monitoring during the scan to ensure that no failure in tracking or sensing the respiratory signal occurs, as can happen with device-based methods (see illustration in *Figure 16*).

These extra steps required by the device-based solutions are time consuming and error-prone,[9] impacting clinical routine, patient scheduling and smoothness of the procedure. MotionFree also improves patient comfort, as it does not require any device to be placed on the patient during scanning: one less thing for the patients to be concerned about and less time invested by the technologists in coaching patients or explaining the scan procedure.

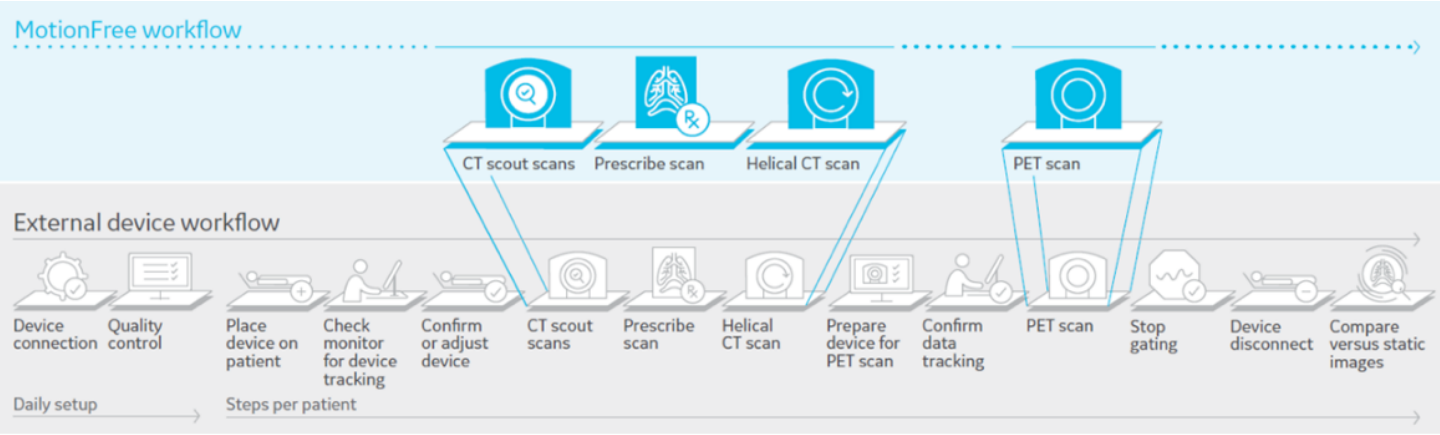

Figure 16. Illustrative description of clinical workflow enhancement when using MotionFree in comparison to device-base gating techniques.

[9] It avoids adding on average four minutes to patient procedure. In challenging cases, MotionFree avoids adding up to 11 minutes to patient procedure time, based on evaluation experience at Zurich University Hospital.

Summary

GE Healthcare has designed MotionFree, as a first device-less digital respiratory gating technique, to derive respiratory information from the coincidence events in each FOV and automatically detect and correct for motion using Q.Static, generating images free of motion. The feature can be used retrospectively with 4D Gated mode to generate multiple gates to see the motion, and subsequently one can correct for using Q.Freeze on the 4D Gated data.

MotionFree is designed to detect physiologic respiratory motion in real-time, meaning that the user is not required to pre-determine which PET FOVs will be impacted by respiratory motion. Hence, MotionFree automatically and seamlessly detects motion, decides on the fly if a scan should be extended per the user's prescription, and corrects for motion-generating images free of motion only for the anatomical areas that require it. Further, the software provides the user the ability to prescribe which beds should be screened with MotionFree and which not to screen. Finally, the user can retrospectively apply MotionFree on previously acquired scans, enabling motion correction using previously-acquired data.

MotionFree brings simplicity and the benefit of knowing the respiratory motion impact to every scan for every patient. Phantom studies have demonstrated quantitation and volumetric improvements for moving features. Q.Clear further improved MotionFree processing by demonstrating an up to 46% boost in SUV_{mean} accuracy in comparison to duration-matched static scan reconstructed with OSEM.[10] Equivalence was also demonstrated between MotionFree and RPM. Finally, clinical cases have demonstrated significant benefits to image quality and quantitation using MotionFree in comparison to duration-matched static images.

[10] As demonstrated in phantom testing using a typical and fast respiratory model measured on a DMI with a 20 cm AFOV.

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Imagination at work

June 2019
JB68144XX