

GE Healthcare

MotionFree PET/CT

White paper



Introduction

This publication is part of a series of white papers aimed at communicating the importance of each component in the image chain of a PET/CT study.

From data acquisition to the creation of images available for diagnostic interpretation, each component of the image chain has a critical function in the generation of high-quality images. Some of the most important elements in the PET/CT image chain are: the detector (scintillation crystal type and length and photomultiplier tubes PMTs), the coincidence processor, the image reconstruction algorithm, data processing and prescription management, and patient motion-correction techniques. The best image quality is delivered when all these components are well matched to the imaging situation. This paper will focus on advanced PET/CT motion-correction techniques available in the industry.

Modern PET/CT imaging techniques have led to widespread use, primarily in helping physicians to manage cancer patients from diagnosis through therapy and follow-up. Despite this progress, many PET/CT studies suffer from image degradation due to patient motion during the image data acquisition. Motion can occur due to normal breathing, heartbeat or simply gross patient motion during the exam. The type and severity of image degradation induced by patient motion depend on scan location, time of acquisition, irregular heart rate, magnitude of respiratory motion and/or imaging sequence. The effects can include blurring and image misregistration. There are several techniques available to minimize the effects of patient motion, including medication that reduces cardiac rate, breath holding, cardiac/respiratory gating and advanced reconstruction techniques.

GE Healthcare has a long history of addressing this clinical challenge, starting in 1993 with the introduction of gated PET imaging in the Advance PET System¹. Our PET/CT scanners are designed to improve image quality (IQ) by using MotionFree solutions, including MotionMatch, the latest technology to address motion artifacts.

In the following pages, we will concentrate on the strategies and exclusive features currently available in GE Healthcare PET/CT scanners that minimize the effect of patient motion on IQ quantitation, and will describe the MotionFree applications available to reduce motion artifacts.

Understanding motion effects

The human body is subject to motion in all the places you would commonly picture it to be: the beating heart, the lungs as you breathe in and out, and the abdomen whose soft tissues move in conjunction with respiration among other variables. Although advances in CT technology have enabled high-speed acquisitions that can capture images nearly instantly, a typical PET scan requires more time to optimize the number of counts needed for image reconstruction. This typically takes from 1 to 3 minutes per bed position. The impact of motion over such a time period results in images with blurring and misregistration, much like a photograph that has been exposed to a nighttime cityscape with moving traffic.

Common methods used to minimize such motion artifacts include medication to lower cardiac rates and breath holds. Respiration may be comfortably suspended for 10–20 seconds by means of breath holding. However, PET acquisitions can be several minutes and breath holding techniques are difficult to perform. Lung, liver, pancreas and other thoracic and abdominal tumors may move as much as 30 mm because of breathing.

Motion artifacts lead to two major effects: First, it affects the accuracy of quantitation, producing a reduction of the measured standard uptake value (SUV). Second, the apparent lesion volume is overestimated. The first affects the visibility, or contrast, of the lesion. The second results in an increase in the planning target volume (PTV), and consequently a greater radiation dose to the normal tissues².

SUV indicates how active a tumor is by providing a semi-quantification of the metabolic activity in the lesion³. Studies show a significant variation in lesion SUVs between end of inspiration and end of expiration phases (up to 24%) and even greater variation among all the phases of the respiratory cycle (up to 30%)⁴.

Figure 1 shows an example of the variation in tumor position during the respiratory cycle. Without knowing the exact position of the neoplasm at a given time, this motion artifact directly impacts the radiotherapy planning, treatment and eventually interpretation of treatment response over time. Motion artifact can also compromise contouring and result in less accurate tumor delineation, increasing dose and damage to healthy tissue during treatment.⁵

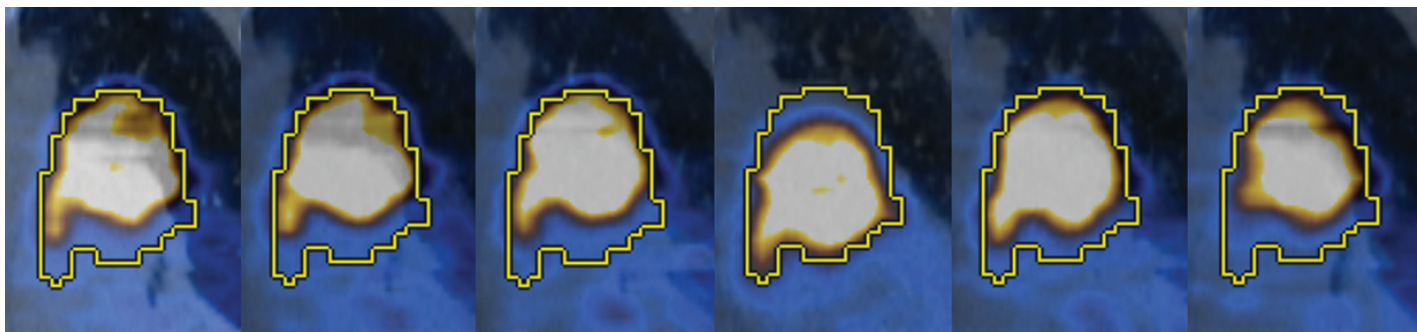


Fig 1. Tumor position variation during respiration

Image courtesy of Holy Name Hospital

Benefits of motion correction

Motion correction techniques attempt to follow the patient anatomy while motion occurs during the exam. The main clinical application drivers for motion correction are diagnostic imaging, radiation treatment planning and radiotherapy. In PET imaging, motion correction can improve lesion detectability and help build clinical confidence in the interpretation of study findings. Some of the documented benefits of motion correction are: more precise fusion of PET and CT images, increase in SUV accuracy compared with non-gated studies², and improvement in volume measurement of small lesions. Figure 2 shows an example of the benefits of motion correction in PET studies.

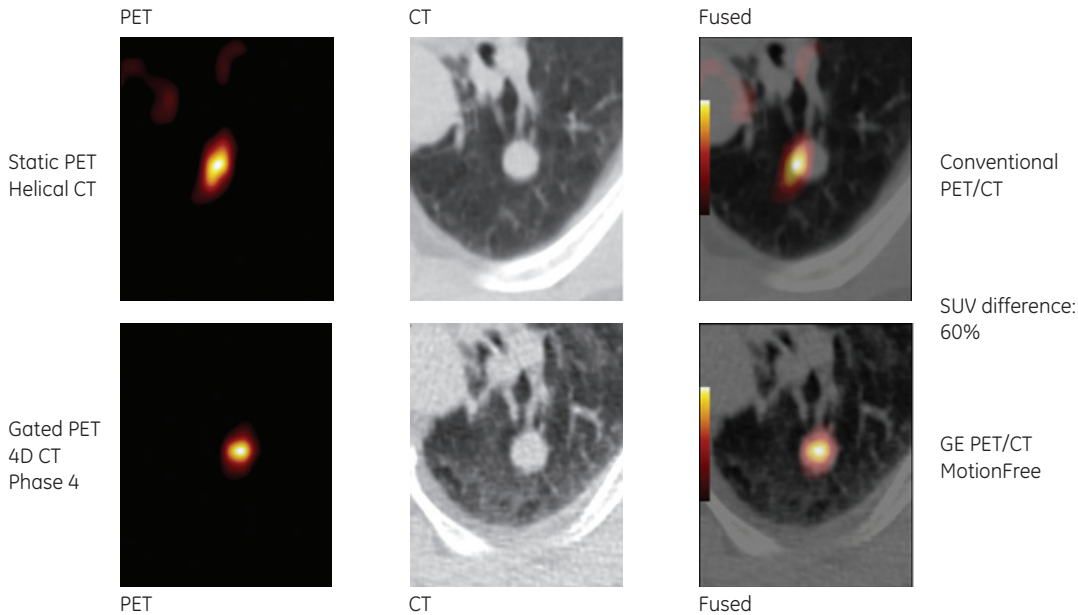


Fig 2. Benefits of motion correction

Image courtesy of HSR-Milan

Motion correction can also improve clinical confidence in lesion identification, patient management and treatment monitoring. In radiotherapy, being able to follow the tumor movement allows more accurate clinical target volume (CTV) definition and helps personalize the PTV⁶. This means that radiotherapists can more accurately target diseased tissues while leaving healthy tissues unharmed by radiation, improving response rates and minimizing the side effects of radiation to the patient. Being able to better define PTV and determine the exact phase for tumor treatment also results in optimized dose deposition accuracy.

Figure 3 illustrates an example of the space that may encompass tumor motion during respiration.

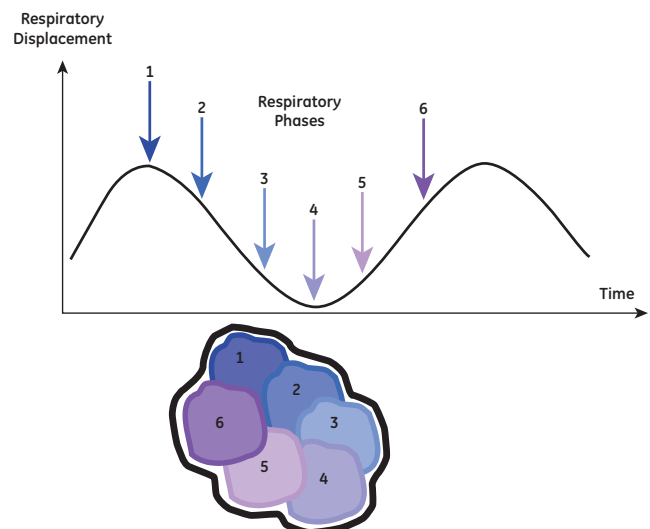


Fig 3. Volume of space that encompasses tumor motion

Motion correction can also improve contour definition and verify treatment progress over time, leading to reduced metabolic activity of the neoplasm⁷. Figure 4 shows a study in which the motion-corrected PTV is 45% less than the PTV defined without any correction.

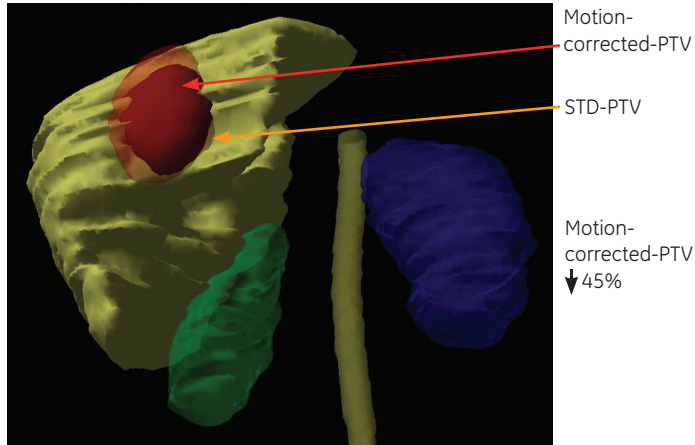


Fig. 4 PTV definition with and without motion correction
Image courtesy of HSR-Milan

What is needed for motion correction?

To successfully correct for motion artifacts in PET/CT imaging, the proper combination of scanner capabilities is required. Among the most important, we consider:

- Advanced reconstruction techniques with noise-reduction capabilities for high IQ
- Flexibility and efficiency when prescribing both the CT and PET protocols
- Respiratory and cardiac gating
- Accurate and effective PET attenuation correction

In PET/CT systems, the CT scan provides the attenuation map for PET attenuation correction. The ability to properly register the PET and CT images for a more effective attenuation correction (CTAC) significantly contributes to reduce the artifact associated with patient motion. This is especially the case for image artifacts caused by cardiac motion.

In the case of respiratory motion, better temporal resolution is sometimes desirable for tumor quantification in the thorax⁸. This need to match the temporal resolution of PET and CT has resulted in a method that gates the PET and CT acquisitions, called 4-dimensional (4D) PET/CT. This technique provides a better match of the PET and CT images and more accurate PET quantification⁸.

Gating a study simply means dividing the acquired image into individual time-stamped bins that correlate to phases of respiratory and/or cardiac motion by overlaying corresponding time-stamped data.

There are certain scanner capabilities needed to support gated 4D PET/CT:

- 1) Capability to gate the CT and PET acquisitions according to a specific location in the respiratory cycle, called trigger. The trigger synchronizes the PET and CT image data.

- 2) Ability to sort the PET and CT image data as a function of each cycle defined by the trigger.
- 3) Ability to match the sorted PET and CT data and properly register it as a function of time.

Figure 5 illustrates the minimum scanner capabilities required for 4D PET/CT motion correction.

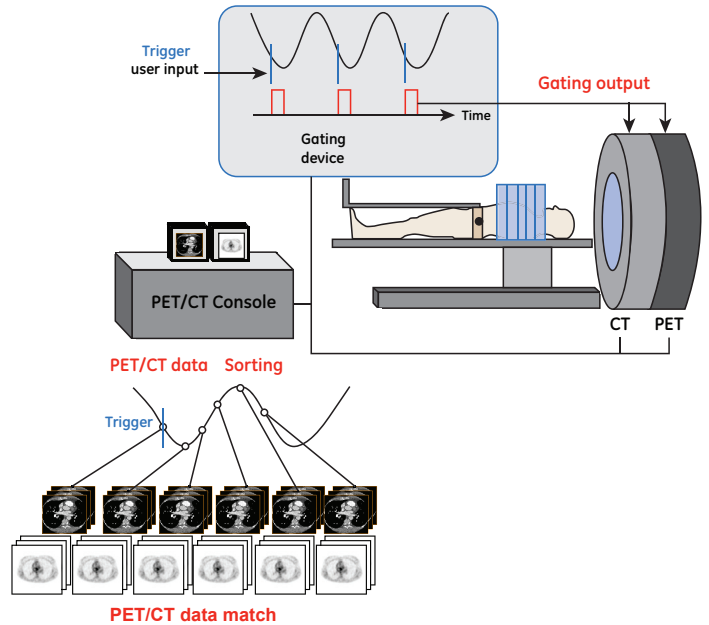


Fig. 5. 4D Gated PET/CT data acquisition

What GE offers: MotionFree PET/CT

GE's MotionFree PET/CT solutions include a vast list of applications and scanner capabilities that includes advanced image reconstruction, optimized exam prescription, respiratory gating and multimodality phase match. Figure 6 outlines all of the GE Healthcare solutions in the MotionFree family, including the latest technology to address motion artifacts available in Discovery PET/CT 600 and 690: MotionMatch.

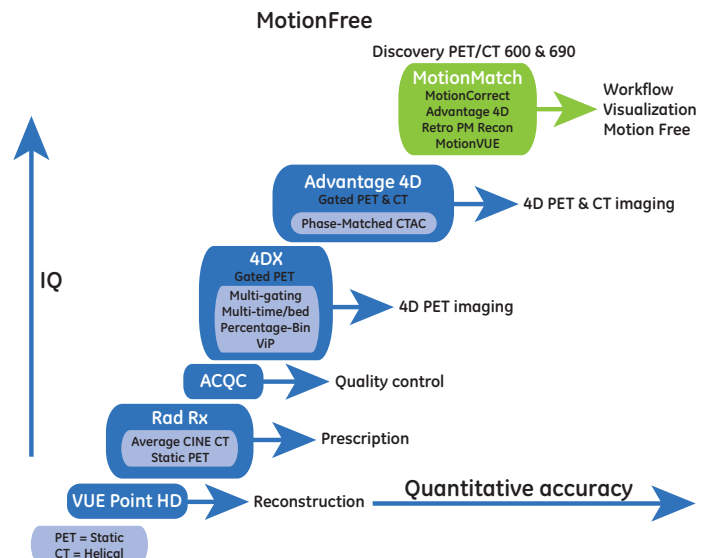


Fig. 6 – GEHC MotionFree Solutions

MotionMatch applications

The Discovery PET/CT 600 and 690 provide a new set of motion-management techniques jointly called MotionMatch. The purpose of these new applications is to improve the workflow for PET and CT respiratory gating, simplify data acquisition and enhance the clinical effectiveness of 4D phase-matched reconstruction. MotionMatch also provides improved visualization capabilities and provides better integration of the respiratory gating device by allowing direct transfer of the respiratory waveform file to the operator console.

MotionMatch applications are split into 4 new sub-components:

- a new **Advantage 4D**
- **MotionCorrect**
- **Retro Phase Match (PM) Reconstruction**
- **MotionVUE**

In the following pages we will provide a brief description of each technique in the MotionFree family of applications illustrated in figure 6.

Quantitative accuracy

VUE Point HD

GE Healthcare's MotionFree solutions start with image reconstruction, using the exclusive VUE Point HD, a true 3-dimensional iterative reconstruction (3D-IR) technique.

In the reconstruction of PET data, there are several correction parameters applied during the image-generation process: scatter, randoms, deadtime, attenuation, and normalization. One of the keys to making 3D-IR work is to incorporate the most possible parameters into the reconstruction itself for better results. In VUE Point HD, we have included all the parameters into the system model. The results show that VUE Point HD can improve signal-to-noise ratio (SNR) up to 30% compared to other reconstruction techniques, leading to a significant improvement in image resolution⁹.

Furthermore, our PET acquisition reconstruction controller in the Discovery PET/CT 600 and 690 utilizes GE Healthcare's exclusive IBM Blade Center™ technology. Driven by two quad-core processors and two cell broadband engine accelerators, the scalable IBM BladeCenter™ provides the ability to reconstruct fully 3D-IR and gated motion-corrected PET studies in 45-60 seconds per frame, depending on the configuration. These reconstruction times significantly improve time-to-image and enable image review while the patient is still on the table.

VUE Point HD significantly improves lesion quantitative accuracy and reduces PET image reconstruction time.

Lesion localization and quantification

Rad Rx

The image distortion or blur caused by patient motion can considerably affect the ability to precisely localize a lesion and accurately quantify its size. Using Rad Rx, the user can improve the attenuation correction of the PET images, resulting in improved lesion localization and greater than 50% change in SUV⁸.

Rad Rx allows the prescription of standard diagnostic CT protocols for CTAC in conjunction with PET acquisitions, all within the same exam.

A feature of Rad Rx is Average Cine CT, which enables the user to prescribe not only a helical CT, but also a Cine CT within the same protocol. The Cine CT group is prescribed over the diaphragm to be averaged with the helical CT for a more accurate CTAC. Figure 7 shows the workflow for Average Cine CT. The average of the Cine CT and helical CT minimizes the impact of mismatches over the anatomical regions affected by respiratory motion.

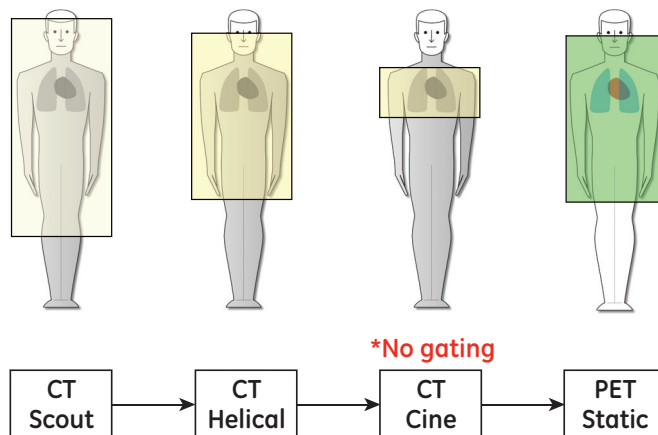


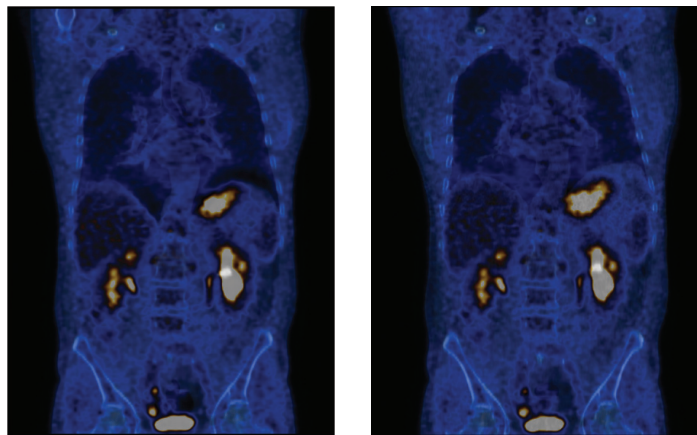
Fig. 7 Workflow for Average Cine CT (Rad Rx)

In helical CT the X-ray source continuously rotates while the table bed moves at constant speed. In Cine mode, the X-ray source rotates continuously while the table bed does not move.

Rad Rx provides the flexibility to prescribe all CT groups within the same protocol. It is important to note that the Cine CT acquisition in this case is un-gated. Average Cine CT provides motion correction over the diaphragm without the need of a gating acquisition.

PET images corrected with Average Cine CT show significantly less breathing artifacts compared to PET images corrected only with helical CT⁸.

As seen in figure 8, the benefits of Average Cine CT can be combined with VUE Point HD to produce improved results in lesion localization and quantification.



Before MotionFree

After MotionFree

Fig. 8 Discovery PET/CT 600 – MotionFree: VUE Point HD + Rad Rx (Average Cine CT)

Image courtesy of Istituto Nazionale Tumori "Fondazione G. Pascale", Naples, Italy

Research indicates that using Average Cine CT may also accurately correct for attenuation of cardiac PET images, helping to reduce the effect of respiratory motion on cardiac studies^{10, 11}.

Lesion detectability and visualization

MotionCorrect

This tool is part of the new MotionMatch applications available on the Discovery PET/CT 600 and 690. It outputs the Average Cine CT after it has been prescribed with Rad Rx for user's visualization and review.

MotionCorrect generates a time-averaged Cine CT image series for better CTAC and also allows the user to view the averaged Cine image series in addition to the Cine CT. The visualization of the Cine CT was the only capability available before MotionCorrect. Figure 9 illustrates the workflow for MotionCorrect.

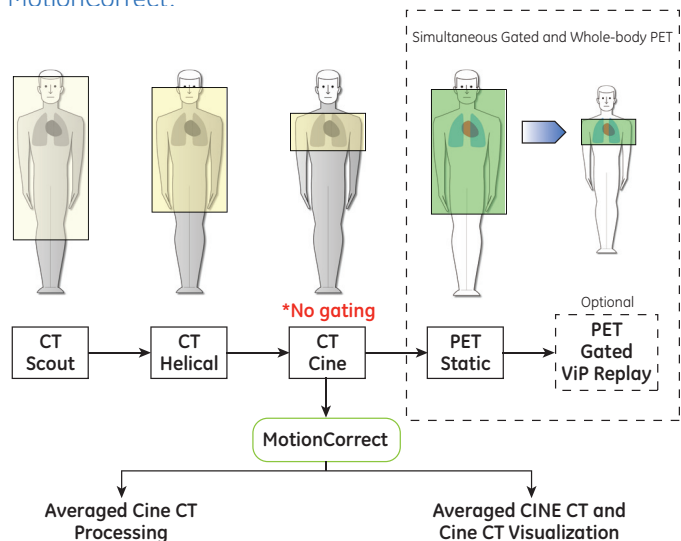


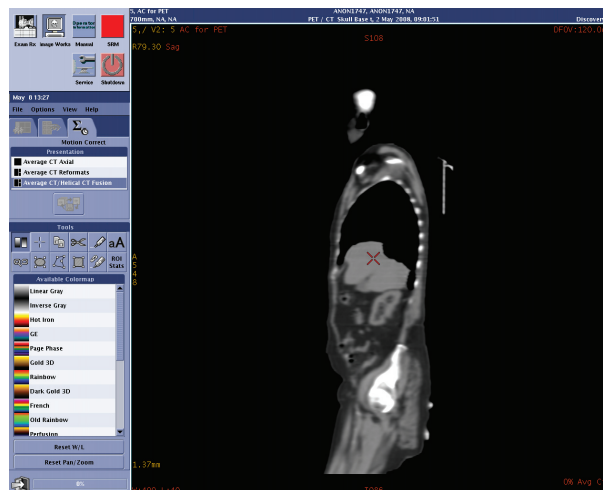
Fig. 9 Workflow for MotionCorrect

The process runs in two modes: prospectively during the acquisition of the Cine CT, or retrospectively as a standalone application.

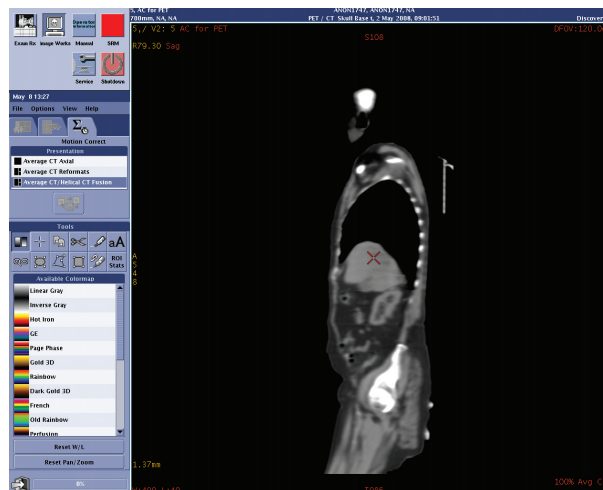
The tool also accepts single CT helical and Cine multi-group series. The Cine CT multi-group generates a volume of data (Cine CT volume) across time, which is also averaged with the CT helical for CTAC. The resulting CTAC provides better matching of the average respiratory location during the PET acquisition over the region of interest.

Once the correction is completed, the tool allows visualization of 3D orthogonal views of the averaged Cine and helical volumes side-by-side or interactively fused with each other. It also provides visualization of gated or static PET data with the Cine CT averaged data generated by it.

MotionCorrect processes the Cine CT images in less than 1 minute, depending on the length of the Cine acquisition, and adds visualization of the averaged Cine CT series for better lesion detectability. Figure 10 illustrates the benefit of using the Cine CT acquisition averaged with the helical CT for CTAC. The image on the left contains 0% of Average Cine CT, only helical CT. The image on the right illustrates the results of averaging Cine CT to the helical CT for CTAC.



0% Average Cine



100% Average Cine

Fig. 10 MotionCorrect output of 0% Average Cine and 100% Average Cine Image courtesy of Gundersen Lutheran

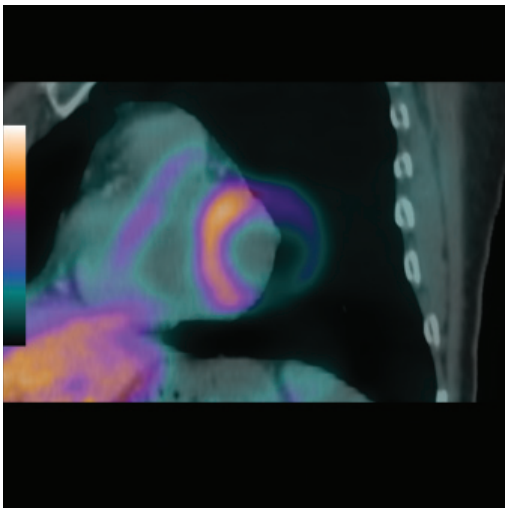
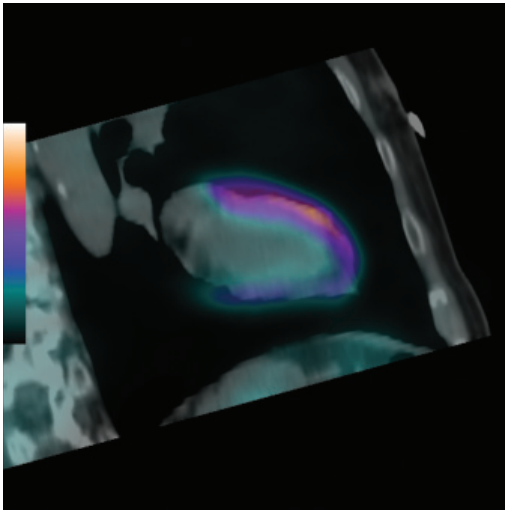
Cardiac alignment

ACQC

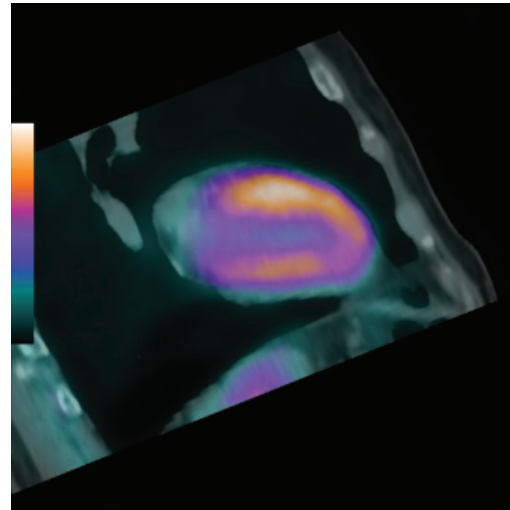
Attenuation Correction Quality Control ensures proper cardiac registration between the PET and CT datasets by allowing the users to visually match the alignment of the two acquisitions if they feel it is necessary. In doing so, the tool keeps track of how much the PET must be shifted to align with the CT and automatically inputs this data into the reconstruction. ACQC also eliminates the need for repeating CTAC acquisitions by allowing the user to utilize the same CTAC for both the rest and stress PET acquisitions. Figure 11 illustrates how images correctly registered to the CT show proper alignment.

ACQC was developed to complement Average Cine CT for even better CTAC. ACQC allows the user to correct for imaging mismatches without repeating the Cine CT protocol, and therefore, it helps optimize the dose delivered to the patient. The output-averaged Cine series from MotionCorrect may be used in ACQC to better compensate for cardiac and respiratory motion.

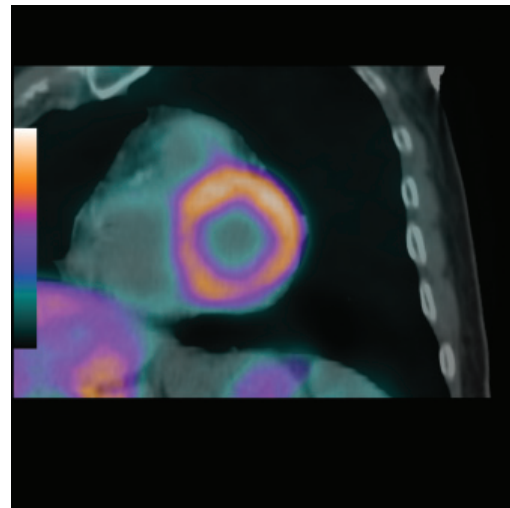
Rb-82 cardiac images are not properly registered to the CT causing a misregistration artifact.



Before MotionFree



Rb-82 cardiac images are now correctly registered to the CT showing proper alignment



After MotionFree

Fig 11. ACQC applied to images reconstructed with VUE Point HD for proper cardiac alignment

Radiation treatment planning

4Dx

Gated PET acquisition was the first step toward motion-free PET imaging. The most important application of Gated PET imaging is in radiation treatment planning. It allows users to see where the tumor was at a given time and how it moves during patient respiration. The ability to see the tumor in its different positions as a function of the respiratory cycle significantly improves radiotherapy planning^{12,6}.

GE Healthcare pioneered motion management with 4D Gated PET, which was introduced as part of the 4Dx family of applications.

Gated PET is a technique based on the principle of physiological gating. It uses an external device to monitor respiratory or cardiac movement during the acquisition and then uses correlated time stamps to sort the PET data into “bins” defined by the different phases of the respiratory or cardiac cycle. Figure 12 illustrates the gating and sorting techniques for a respiratory Gated PET acquisition.

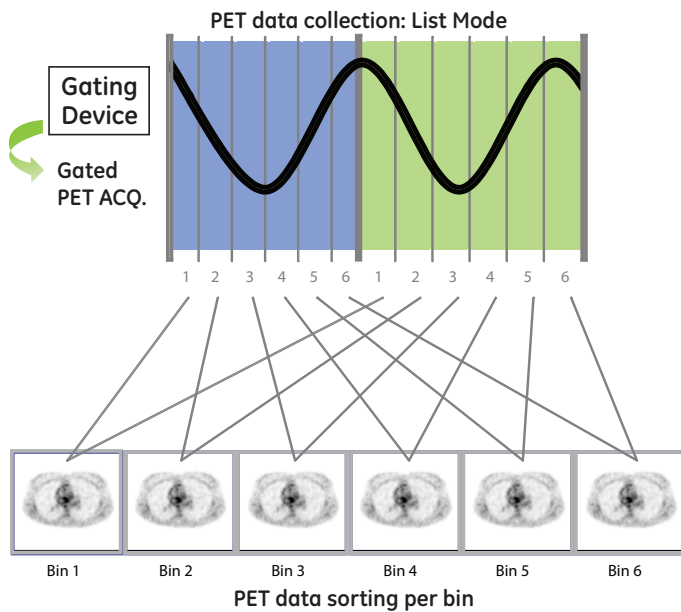


Fig. 12 PET data gating and sorting

Gated PET imaging helps clinicians account for organ motion during radiotherapy treatment, resulting in limited doses to critical organs while delivering higher doses to the target.

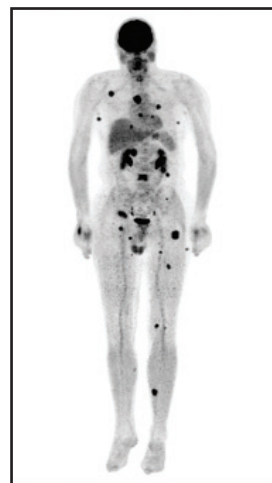
4Dx also includes a series of features that provide additional PET gated prescription capabilities. They further enhance motion correction and add flexibility during the PET acquisition:

- Routine multi-physiological (dual) gated PET exams, which enable the user to prescribe the acquisition of respiratory and cardiac gating signals simultaneously within the same PET exam

- Multi-bed gated PET exams, which allows the user to acquire gated data over several bed positions
- Variable acquisition time per bed position, which enables longer acquisitions over the diaphragm, resulting in higher quality gated data for motion correction without a major increase in overall exam time
- Phase Percentage Binning, which allows the user to gate the PET acquisition based on percentage of the respiratory phases
- Simultaneous static, gated and dynamic scans within the same protocol
- Volume Imaging Protocol (ViP) Record and Replay

ViP Record enables advanced list mode (coincidence event data) acquisition, allowing customers to use ViP Replay to retrospectively play back the PET data with alternate protocols without the need for a new acquisition. The user could therefore see and compare what a patient image looks like at 3 minutes per bed, 2 minutes per bed or any other variation without rescanning the patient.

When gating information is acquired, the user is able to create a PET gated series from the same PET static acquisition. In addition, when dual gating is acquired, ViP Record also enables playback of either cardiac or respiratory gating, allowing multiple gated reconstructions within the same exam. Figure 13 shows an example of the potential applications for ViP Record and Replay. This image was acquired with a Discovery PET/CT 600 using variable time per bed position. In this case 60 seconds per bed position was used in the torso and 30 seconds per bed position for the legs, optimizing the exam time to 12 minutes total.



60 sec/FOV x 8 for Torso
 30 sec/FOV x 7 for legs
 12 minutes total scan time
 174.2 lbs/79 kg
 68.1 in/173 cm
 8.0 mCi/296 mBq
 59 min uptake

Fig 13 Discovery PET/CT 600 Whole-body PET image with variable time per bed position

Image courtesy of University of Milan – Bicocca, San Gerardo Hospital, Monza, Italy

Quantification for therapy planning

Advantage 4D

GE Healthcare led the development of 4D PET/CT by introducing Advantage 4D in 2002, the first manufacturer to offer this technology. This technique uses the same principle of respiratory gating to sort both the PET and CT data into bins defined by the different phases of the respiratory cycle.

Advantage 4D allows more precise planning for delivery of radiation to tumors that move when a patient breathes. The 4D images essentially create a video sequence of how the tumor moves during the breathing cycle. This provides clinicians with more data to guide the planning process by which they determine the optimum radiation dose to the target that decreases the risk of toxicity to surrounding tissue.

Figure 14 illustrates the 4D PET/CT acquisition techniques and alignment process in Advantage 4D.

Both PET and CT images are acquired during free breathing. The CT is acquired in gated Cine mode over the region affected by motion. The PET is acquired in List mode. The respiratory information is used to rearrange the CT images into bins as shown in figure 14. The same process is followed with the PET data. The CT bins and the PET bins are then matched to provide a more accurate CTAC and improve image registration. The results show better spatial match between CT and PET findings and better lesion detectability⁸.

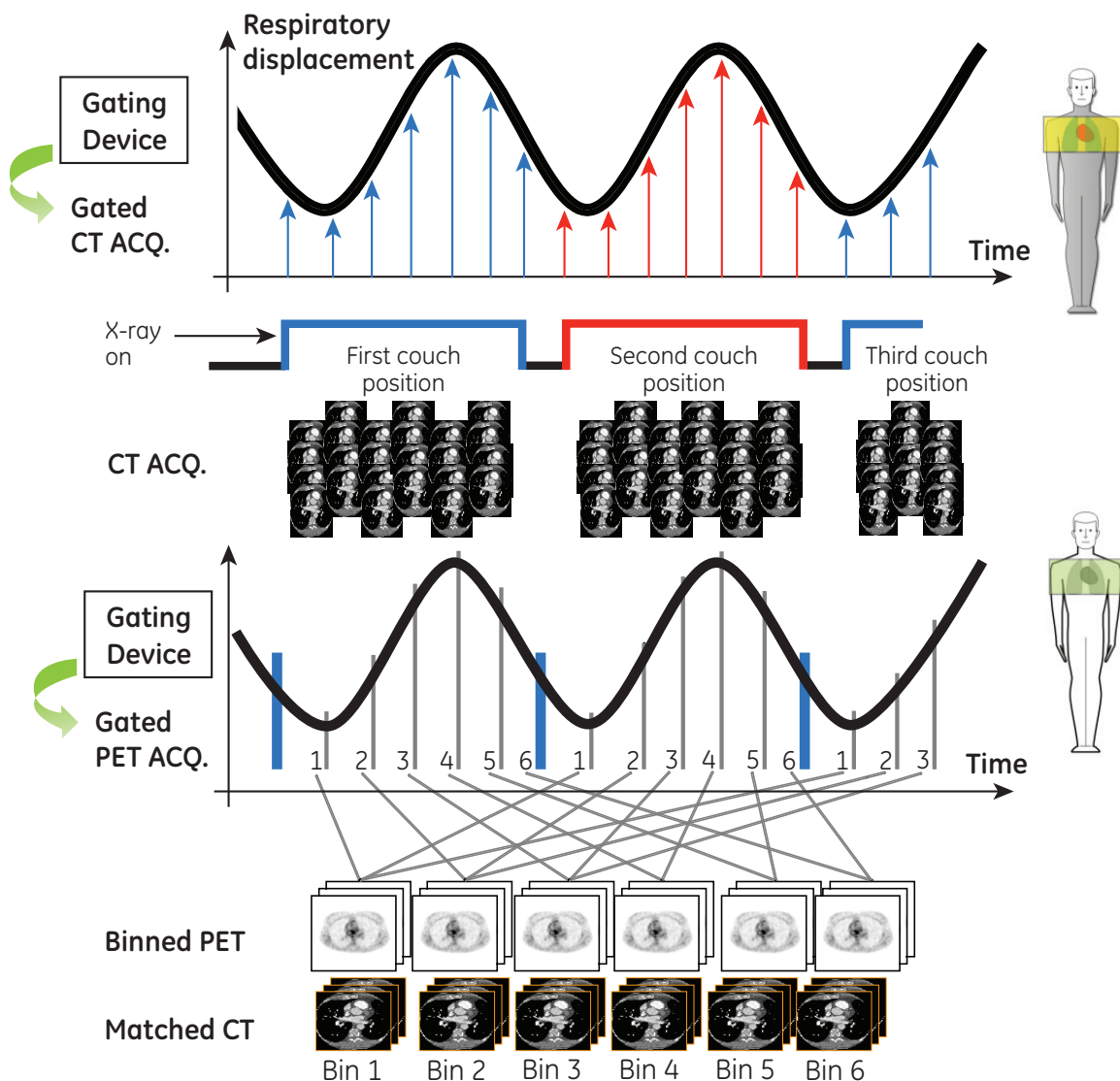


Fig. 14 4D PET/CT data sorting and phase-match between PET and CT data

Figure 15 illustrates the workflow for a 4D phase matched-gated study using Advantage 4D. The respiratory waveform and the Cine CT images are transferred to the GE Advantage Workstation®, where the CT binning is processed. The reconstruction of the gated 4D PET and the matching to the 4D binned CT takes place in the PET/CT operator console.

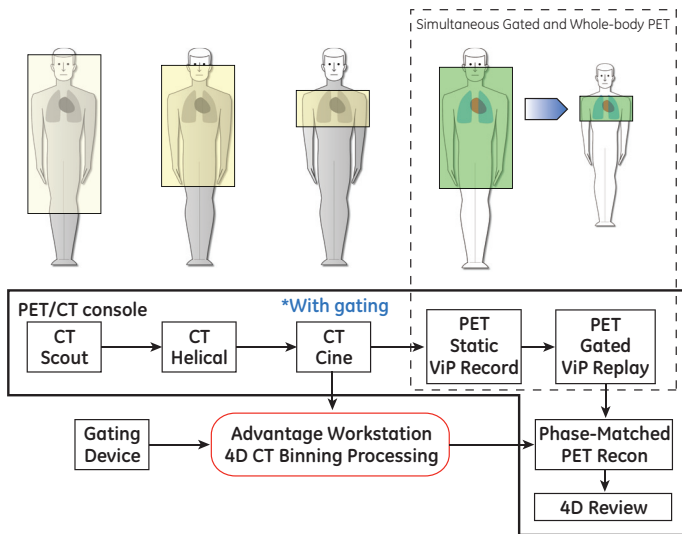


Fig. 15 Advantage 4D Workflow

Once the phase-match is complete, clinicians can select the segment of the breathing cycle during which the tumor is in the most stable position for treatment. Radiation is then delivered only during that segment of the cycle.

Studies show an improvement in the target-to-background ratio, and a more accurate measurement of the SUV when using respiratory gating compared with ungated techniques. In one patient, respiratory gating showed a 28% reduction in the total lesion volume, and a 56.5% increase in the SUV². These examples illustrate the improvements in quantification for therapy planning provided by Advantage 4D.

Figure 16 shows an example of the overall IQ and SUV quantification improvement of a 4D phase matched-gated study compared to a non-gated study.

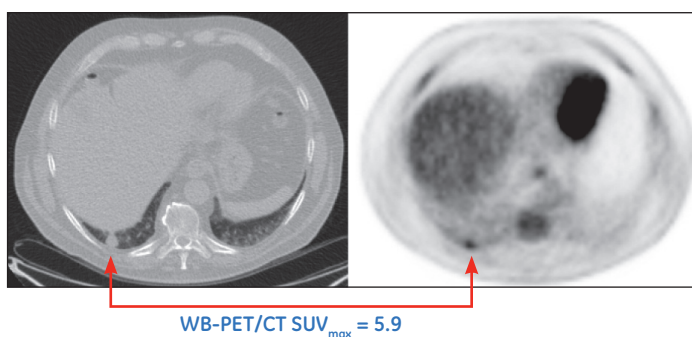


Fig. 16 4D Imaging – IQ and SUV quantification impact
Image courtesy of HSR-Milan

Optimizing workflow and improving treatment

MotionMatch Advantage 4D

The new Advantage 4D in MotionMatch enables 4D PET/CT directly on the console, significantly optimizing the workflow of phase-matched gated studies and consequently improving radiotherapy planning and treatment.

The new Advantage 4D takes the Cine CT images with the respiratory file and automatically rearranges the images into respiratory bins of data on the operator console. The tool displays which Cine CT images are selected by bin and allows user-selection of the output images in a single multi-bin series or in multiple single-bin series. This is done retrospectively as a standalone application selectable from the Image Works browser. Figure 17 illustrates the workflow of the new Advantage 4D in MotionMatch.

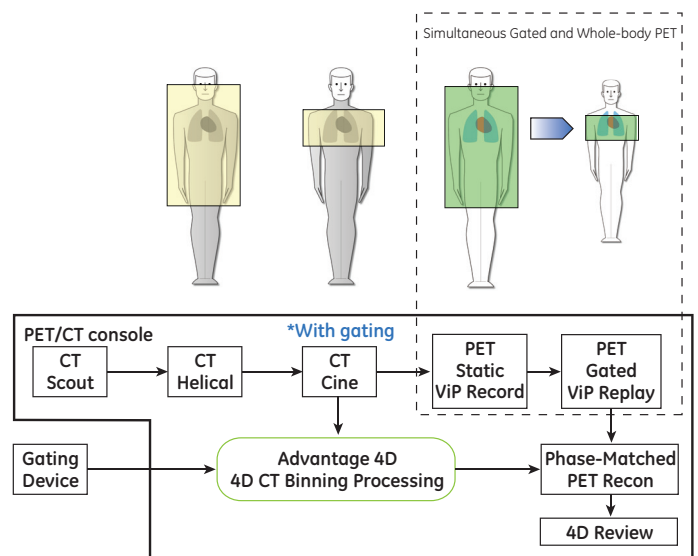
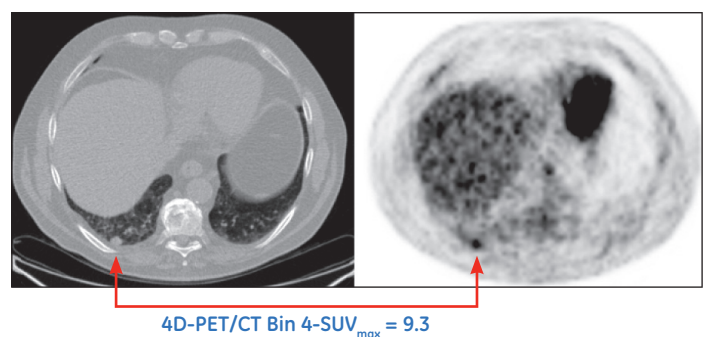


Fig. 17 New Advantage 4D workflow in MotionMatch



The optimization of the workflow allows the user to obtain CT binned images in less than 1 minute and complete the PET/CT phase-match process in one single location. Figure 18 shows the new Advantage 4D user interface in the PET/CT operator console, where the Cine CT images are assigned to a particular target respiratory phase.

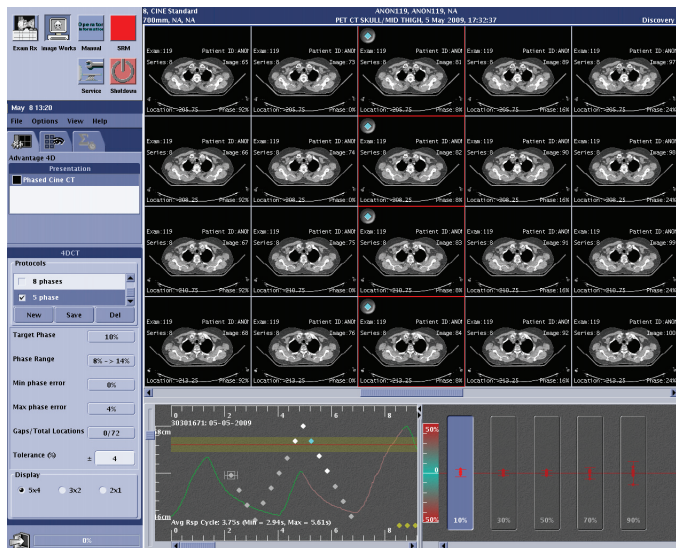


Fig 18. Cine CT image selected per bin

So now, instead of having to transfer data between scanner and workstation, improving workflow allows users to see the tumor at a given time and how it moves in the individual phases directly in the operator console.

Personalizing gated radiotherapy

Retro Phase Match (PM) Reconstruction

Retrospective Phase Matched Reconstruction allows selection of a specific binned CT series, for CTAC, and then automatically phase matches and reconstructs the respective PET binned data. Retro PM Reconstruction complements the new Advantage 4D by allowing the user to mix and match different CT bins to different PET bins manually, giving flexibility to potentially improve the outcome of the phase-match process.

Improving the phase-match process can enhance lesion quantification and reduce the PTV around the tumors so that radiation dosage can be increased without increasing the risk of toxicity. Users can now tailor the target volume and gate the treatment to give larger doses per fraction and complete the treatment in a shorter time.

Visualization is key

MotionVUE

This application allows the user to review the images processed with MotionCorrect, Advantage 4D and Retro PM Reconstruction. The user is able to view and save the binned images, including fused review of binned PET and binned CT. It also allows the viewing of a Cine loop through different gates of the data and

provides volume views in standard orthogonal views (in separate or fused viewports) for easy alignment check. Figure 19 illustrates where MotionVUE is used in the motion-correction workflow.

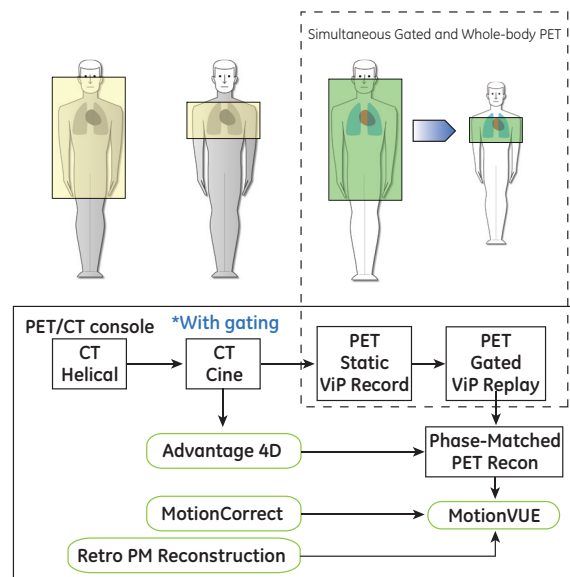


Fig. 19 MotionVUE workflow

MotionVUE's flexibility allows the user to load any combination of PET and/or CT series:

- Binned CT or binned PET only
- Binned CT with static PET or gated PET
- Binned CT with static and gated PET

MotionVUE also accepts the binned CT volumes generated by the Advantage 4D applications. Figure 20 illustrates an example of the capabilities of MotionVUE.

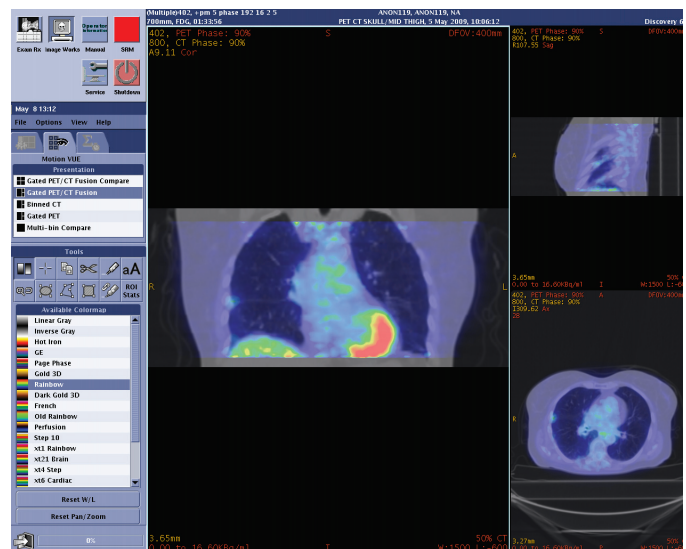


Fig. 20 MotionVUE - review of Gated PET/CT fusion

Summary

Patient motion can significantly deteriorate image quality in diagnostic imaging, directly compromising the user's ability to identify and localize disease and diminishing the effectiveness of the radiotherapy treatment. Motion correction not only improves IQ and lesion detectability but also has a major impact on patient management by improving clinical confidence in accurate target definition, treatment planning and response follow-up.

GE Healthcare pioneered advances into MotionFree PET/CT, and continues to lead the way to improved image quality and clinical results. The applications and technologies outlined here clearly show how GE can help provide improved information about lesion size, volume, SUV and enhanced quantitative measurements for smaller lesions. These tools can better help customers depict neoplastic disease and tailor radiotherapy for improved treatment planning, delivery and response evaluation, all of which may improve clinical patient management.

The applications in the MotionFree PET/CT family can significantly enhance image quality and correct for involuntary motion, providing high-definition PET image processing, streamlining workflow and enhancing clinical results.

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