Technical consideration for dual ECG/ respiratory-gated cardiac PET imaging

Mark C. Hyun, CNMT, NCT, RT(N)(R)(CT), FASNC,[a,b,c] Jim Gerlach, CNMT, NCT,[a,b,c] Mathieu Rubeaux, PhD,[a,b,c] and Piotr J. Slomka, PhD[a,b,c]

[a] Division of Nuclear Medicine, Department of Imaging, Cedars-Sinai Medical Center, Los Angeles, CA
[b] Cardiac Imaging Research, Department of Imaging, Cedars-Sinai Medical Center, Los Angeles, CA
[c] Artificial Intelligence in Medicine Program, Cedars-Sinai Medical Center, Los Angeles, CA

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TECHNICAL BACKGROUND

The importance of spatial resolution in myocardial perfusion imaging (MPI) has been continuously emphasized over the years with improvements in both hardware and software advancement for acquisition and processing. These advances and innovations began from changes in acquisition parameters (e.g., collimator design, acquisition & orbit type, and attenuation correction) to utilizing emerging technologies with solid-state detectors in hardware, and from a simple filtered back projection reconstruction to iterative, resolution recovery and scatter correction reconstruction algorithm techniques in software. While these advances mostly apply to SPECT imaging, PET MPI has undergone a steady evolution improving various aspects of imaging as well, including improvements in spatial resolution. Unlike any other organ imaged in nuclear medicine, improving the image resolution in SPECT or PET cardiac imaging still remains challenging due to inherent cardiac contraction, respiratory movement, and patient body motion during the image acquisition. It is especially true with traditional SPECT, where the scan duration is much longer as compared to PET MPI. However, during cardiac PET acquisition, collection of data in list-mode has become available for routine use, allowing for multiple image reconstructions from a single dataset, including static, gated, dynamic, and respiratory-gated images (Fig. 1). In this paper, we review few recent publications and their technical considerations for dual ECG/respiratory-gated cardiac PET imaging in an attempt to recover the spatial resolution loss due to cardiac and respiratory motion.

Reprint requests: Mark C. Hyun, CNMT, NCT, RT(N)(R)(CT), FASNC, Division of Nuclear Medicine, Department of Imaging, Cedars-Sinai Medical Center, Los Angeles, CA; *Mark.Hyun@cshs.org*

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TECHNICAL SUBSTANCES

ECG Gating

In ECG-gated SPECT or PET MPI, cardiac cycles are divided into temporal bins according to the detected R waves. ECG-gated image datasets are formed by reconstructing an image of each mutually corresponding data bin and arranging these images in a series (Fig. 2). This image series represents an averaged cardiac cycle and each image corresponds to a certain phase in the cardiac cycle, which can be used for the determination of functional cardiac parameters, such as the ejection fraction (EF), end-diastolic (ED), end-systolic (ES) volumes, and ventricular wall motion. The perfusion image is then created by summing all ECG-gated image data. Note that these ECG-gated image datasets should have a better spatial resolution than the summed perfusion image.

Motion-Frozen (MF)

In order to further improve the image quality and accuracy of gated SPECT MPI in the display and quantification, a ''motion-frozen'' (MF) technique was proposed to eliminate the influence of cardiac left ventricle motion. In this method, ECG-gated SPECT images are analyzed after cardiac motion tracking of left ventricular (LV) endo- and epicardial surfaces using an image warping algorithm developed at Cedars-Sinai Medical Center (Figs. 3, 4). Such MF perfusion images have the same visual appearance as the ED frames but

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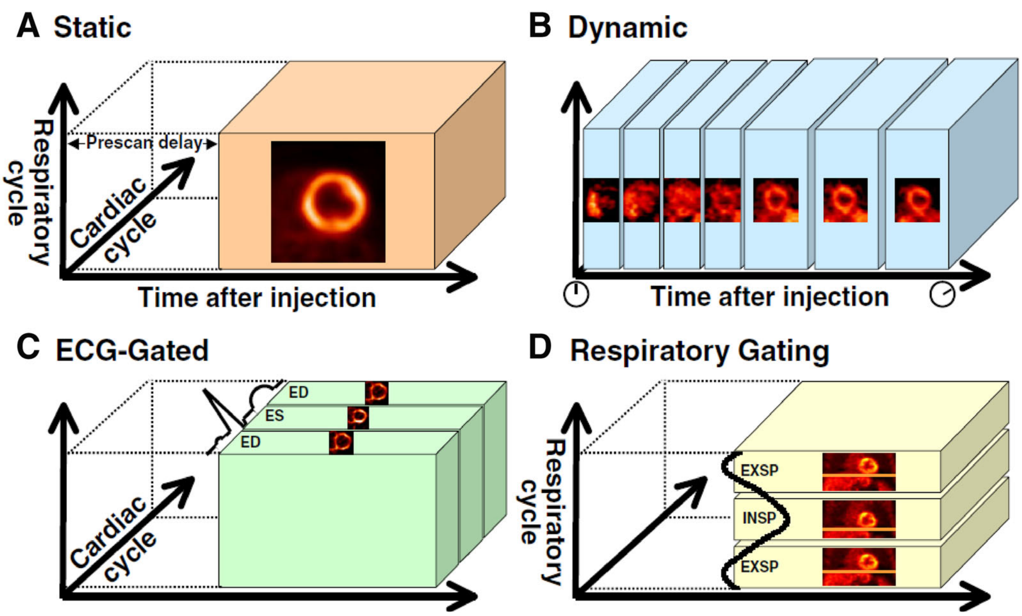

Figure 1. Multidimensional list-mode PET acquisition resampled in multiple formats at any time of acquisition. (**A**) Static images are reconstructed by summing all information after a predefined scan delay. (**B**) Dynamic images are obtained by serial temporal sampling at different times after injection. (**C**) ECG-gated images are obtained at multiple phases of cardiac cycle. (**D**) Respiratory-gated images can be obtained at different phases of the breathing cycle. (Reprinted with permission from Bengel et al.[1]).

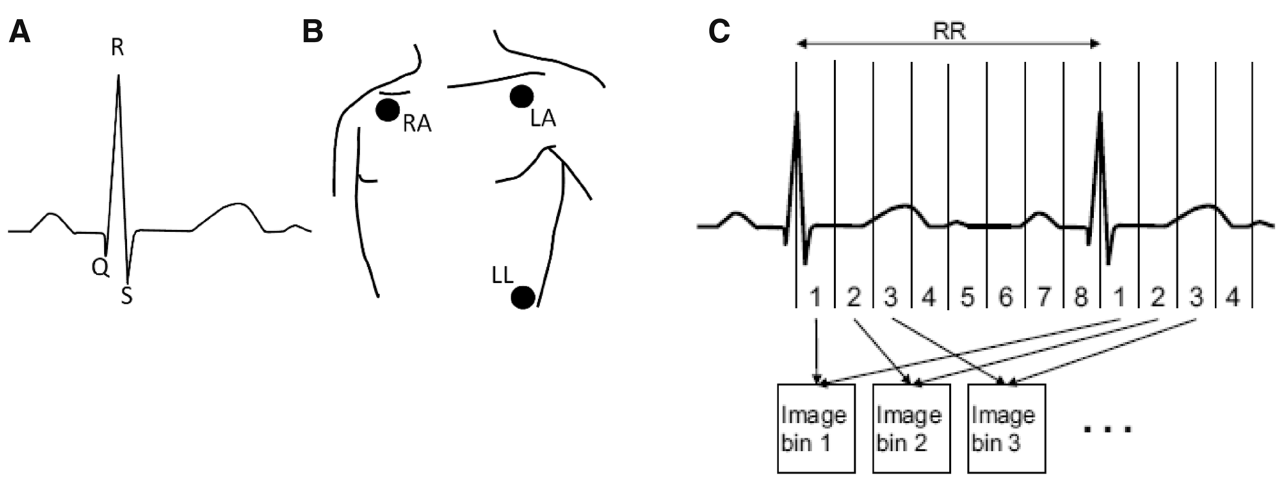

Figure 2. (**A**) ECG cycle with QRS complex. The R wave is commonly used as a timing trigger in ECG gating. (**B**) ECG lead placements (*RA* right arm, *LA* left arm, *LL* left foot). (**C**) The principle of cardiac ECG gating illustrating that the R-to-R intervals are divided into corresponding time bins, which are used to reconstruct images. (Reprinted with permission from Malmivuo and Plonsey[2]).

they contain counts from all cardiac cycles (Fig. 5), which leads to enhancement of the effective resolution of perfusion images and hence this improves the detection of coronary artery disease.

Respiratory Gating

The respiratory motion is one of the most common sources of artifacts in cardiac PET/CT hybrid imaging. These artifacts are due to the discrepancy between the

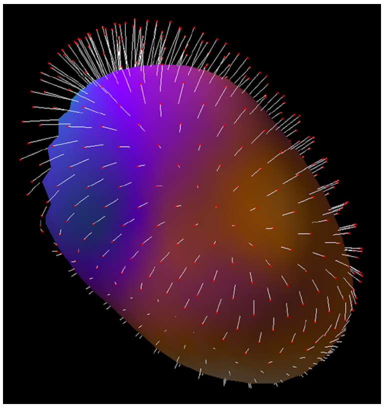

Figure 3. Illustration of displacement vectors used in image warping. ES epicardial surface is shown with perfusion data represented in color. Displacement vectors (*white*) show local motion between ES and ED. ED position of epicardial surface is marked with red points. (Reprinted with permission from Slomka et al.[3]).

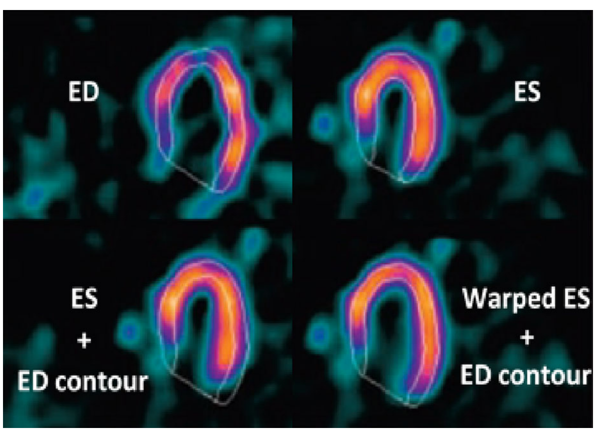

Figure 4. Example of image warping applied to ES frame. ED frame is shown with ED contour (*top left*); ES frame is shown with ES contour (*top right*). ES frame is shown with ED contour (*bottom left*); warped ES frame is shown with ED contour (*bottom right*). (Reprinted with permission from Slomka et al.[3]).

chest position on the CT and PET images (Fig. 6). PET image acquisition time is much longer than the CT image used for attenuation correction (AC) purpose, and the final image is an average of many breathing cycles. The respiratory motion artifacts may not be severe in PET-only scanner with transmission scan, but image blurring still remains due to the same amount of motion as the emission scan.

The most common location for the respiratory motion artifacts is at the base of the lungs/diaphragm area which causes the heart to move up and down. Initially, respiratory gating was utilized in nuclear oncology imaging with FDG PET to improve the sensitivity in order to increase the detection of small nodules in the lung. In radiation therapy, it is used to accurately define the tumor volume and position to precisely irradiate the tumor sites in the lung by continuous monitoring of the respiratory motion. Then, it has been applied in cardiac imaging in recent years to minimize respiratory motion artifacts.

In order to monitor and measure the respiratory motion, several devices and motion management systems were explored (Fig. 7). The Bellows device utilizes a pneumatic belt with varying pressure based on abdomen circumference. As breaths are taken, the coil around the patient expands and contracts to register the respiratory cycle signal. In the Active Breathing Coordinator (ABC) method, the breathing volume is measured by the device's mouthpiece. When the breath-hold volume is achieved, a balloon valve is activated to block airflow to the patient for a predetermined period of time to immobilize respiratory motion. The Real-time Position Management (RPM) system uses an infrared tracking camera and a reflective marker placed on the patient's chest or abdomen to measure the patient's respiratory pattern, and the range of motion can be displayed as a waveform (Fig. 8). These respiratory gating techniques utilize the acquisition of imaging data to specific points in the breathing cycle to minimize image blurring and other motion artifacts. They can be time-based or amplitude-based to find the end-expiratory image (Fig. 9). The images are used diagnostically and interventionally to coordinate radiation treatment beam on/off cycles and to protect healthy tissues during the breathing cycle.

Dual ECG and Respiratory Gating

Dual ECG and respiratory gating in PET/CT imaging has been explored by several groups with the use of external devices and/or software approaches. However, due to complex logistics and post-processing, the dual ECG and respiratory gating has not been widely adopted nor routinely utilized in current cardiac PET imaging. Simultaneous dual ECG and respiratory gating software technique has the potential to simplify the challenging logistics of dual gating for cardiac PET imaging. This software approach tracks the respiratory motion of the myocardium directly from the PET data using image processing algorithms without the external measurements of patient's respiration.

When dual gating is applied in cardiac PET imaging, preserving the image quality is very challenging

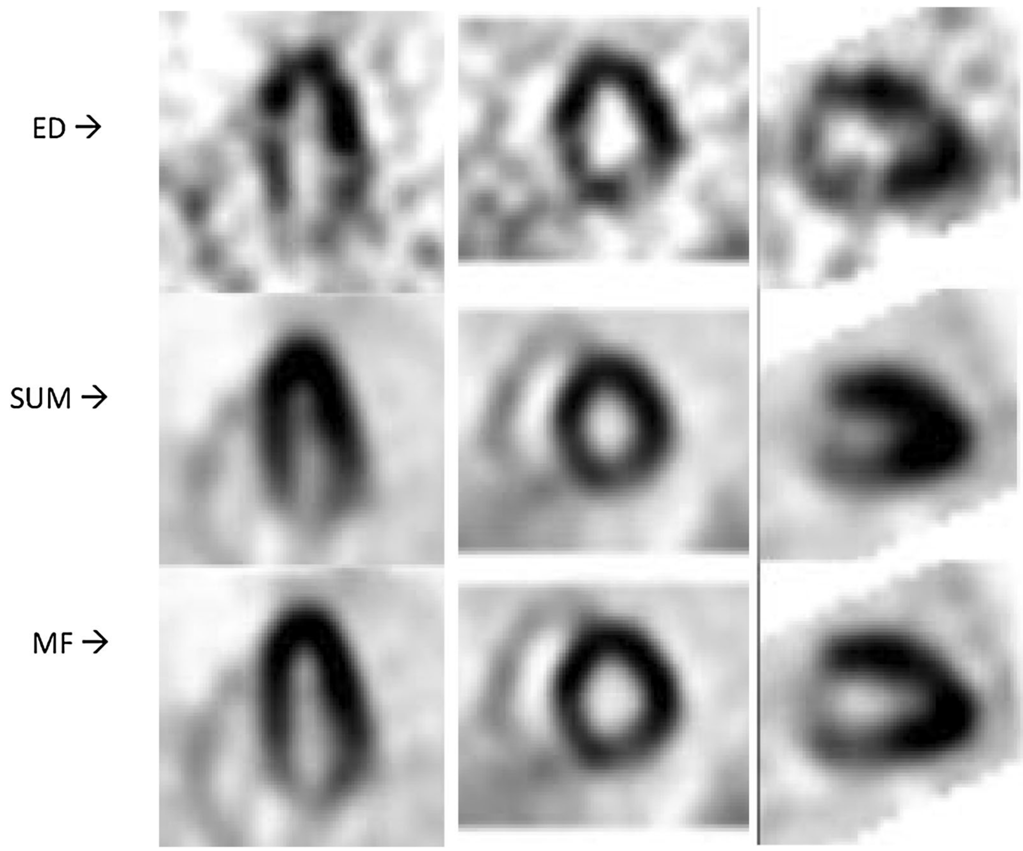

Figure 5. An example of MF perfusion images compared with ED only and summed perfusion images. (Reprinted with permission from Slomka et al.[3]).

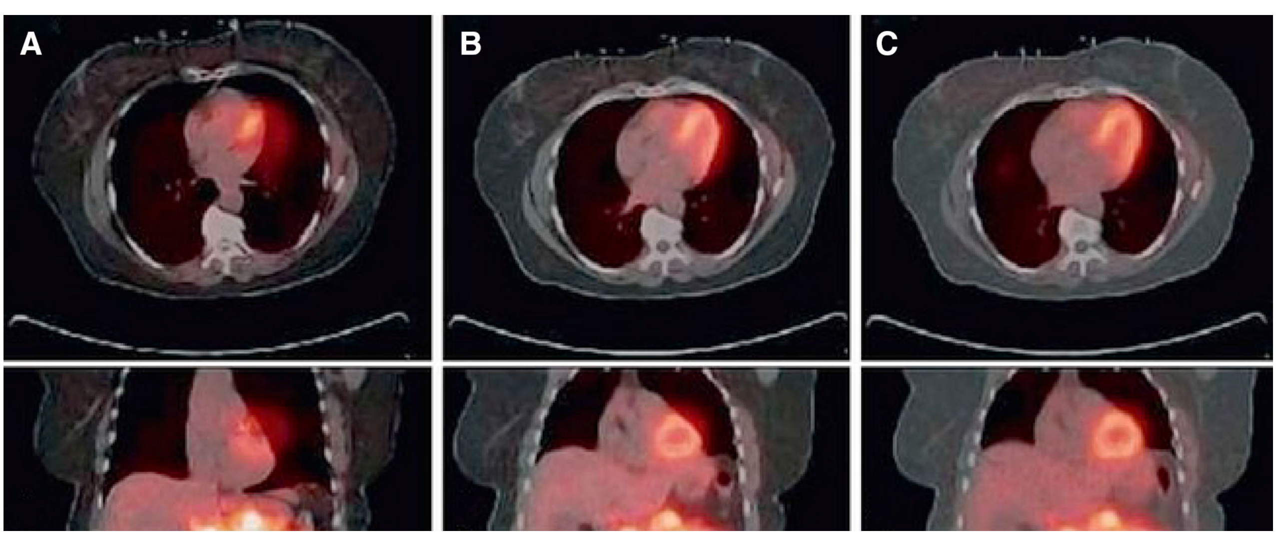

Figure 6. An example of 3 different CT protocols for AC. (**A**) Breath-hold CT at inspiration. This is not suitable for AC. (**B**) Free-breathing low-pitch CT. (**C**) Free-breathing time averaged cine CT. In **B** and **C**, note the superior alignment between the PET and CT images compared with the breath-hold CT. (Reprinted with permission from Votaw and Nye[5]).

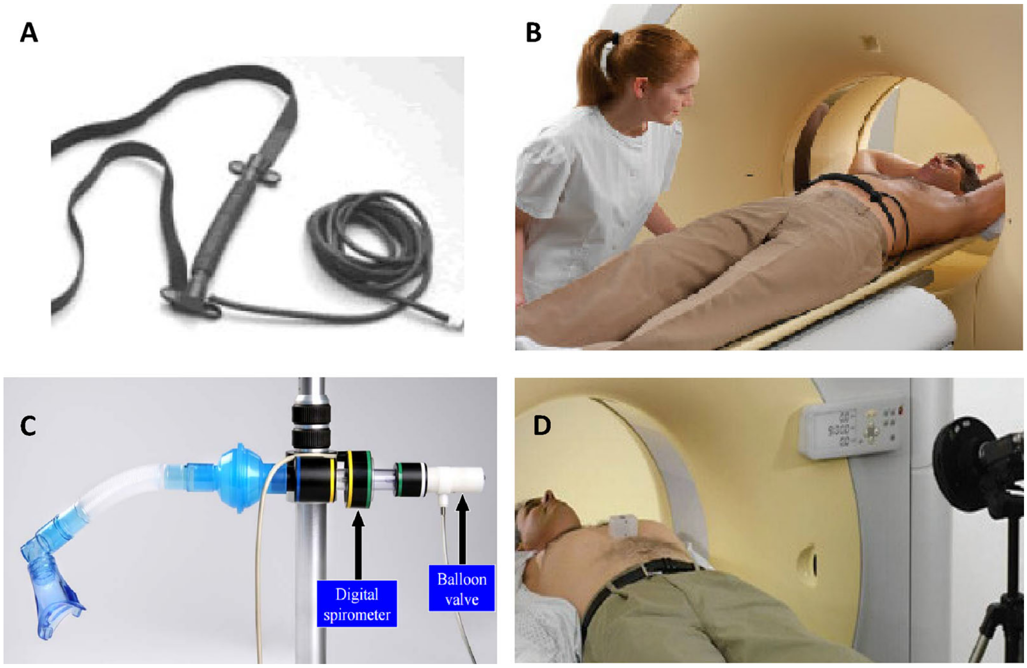

Figure 7. (**A**) Bellows device. © GE Healthcare Service Shop. (**B**) Bellows device placed on the patient's abdomen. (**C**) Active Breathing Coordinator (ABC) device. © 2016 Aktina Medical. (**D**) Real-time Position Management (RPM) system. http://clinical.netforum.healthcare.philips.com/us_en/Explore/White-Papers/PetCT/Routine-clinical-application-of-4D-Time-of-Flight-PET-CT.

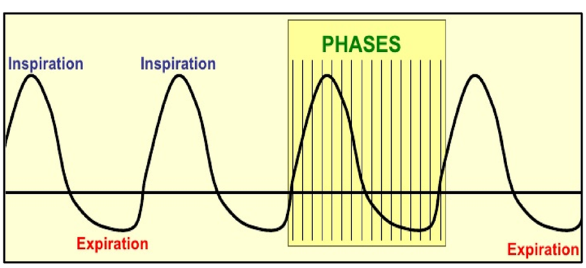

Figure 8. A respiratory waveform illustrating the inspiration and the expiration of a normal breathing. Cycle is divided into phases for respiratory gating sequence. The image acquisition can be timed usually near end-expiration when respiratory movement is minimal. (http://www.slideshare.net/kathrnrt/respiratory-gating-with-imrt).

since the count statistics from individual gated images are much lower than the ungated images. However, dual gating image has been shown to allow better resolution of the myocardial walls as compared with ungated or ECG-gated images in FDG F-18 studies. In order to maintain appropriate count statistics, an extended acquisition time is required to overcome the under-sampled count data from ECG and respiratory gating, which may significantly increase patient discomfort. It can also be more challenging when using short-lived Rb-82 in cardiac PET/CT imaging.

More recently, dual-gated cardiac imaging using a novel PET radiotracer (Flurpiridaz F-18), which demonstrated improvements in image resolution, contrast, and contrast-to-noise ratio (CNR), was applied with motion-frozen methods (Figs 10, 11). While Flurpiridaz F-18 for cardiac PET imaging is still under investigational use, it offers promising properties (e.g., shorter positron range, higher extraction fraction, longer half-life) and enhanced image resolution for accurate diagnosis of coronary artery disease. In conclusion, dual ECG and respiratory gating technique is feasible with Flurpiridaz F-18, which provides high-quality motion-free perfusion images with improved contrast and image resolution.

CONCLUSION

Cardiac, respiratory, and patient motion can degrade PET image quality and limit the effective image resolution that can be achieved by dual ECG and

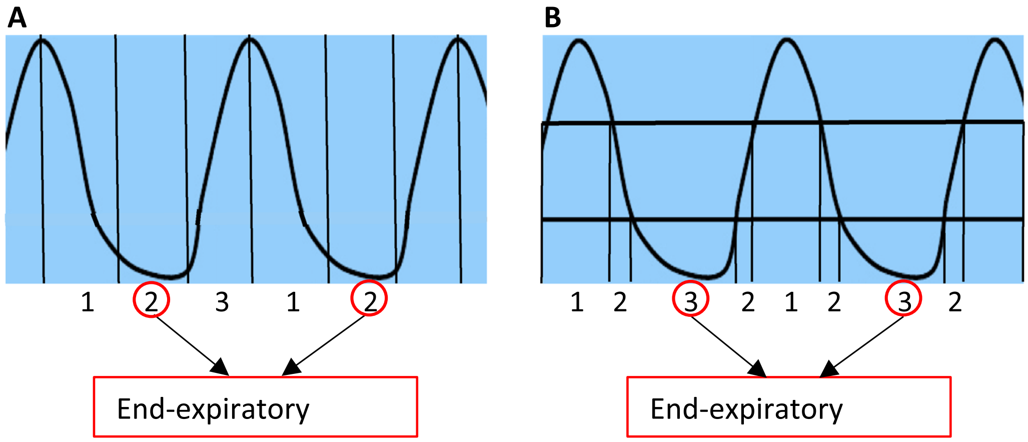

Figure 9. (**A**) Time- and (**B**) amplitude-based respiratory gating. This illustrates how end-expiratory image data are collected in typical respiratory gating approaches.

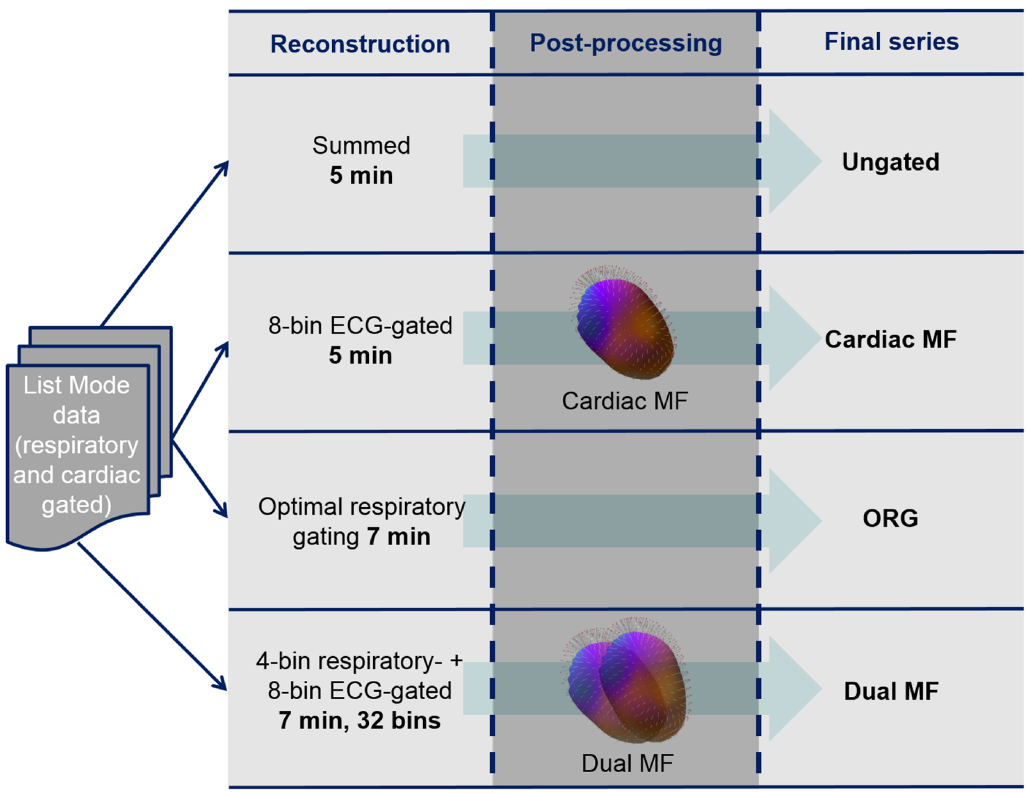

Figure 10. Overview of reconstructed datasets. *MF* motion-frozen, *ORG* optimal respiratory gating, *dual MF* cardiac and respiratory MF processing. After processing, all final series are static. (Reprinted with permission from Slomka et al.[4]).

Respiratory gating method. Although respiratory gating has not been widely adopted in cardiac PET imaging, due to complex logistics and post-processing requirement, when combined with motion-frozen (MF) registration technique, dual ECG and Respiratory-gated PET imaging with Flurpiridaz F-18 is feasible and improves image resolution for the accurate detection of coronary artery disease.

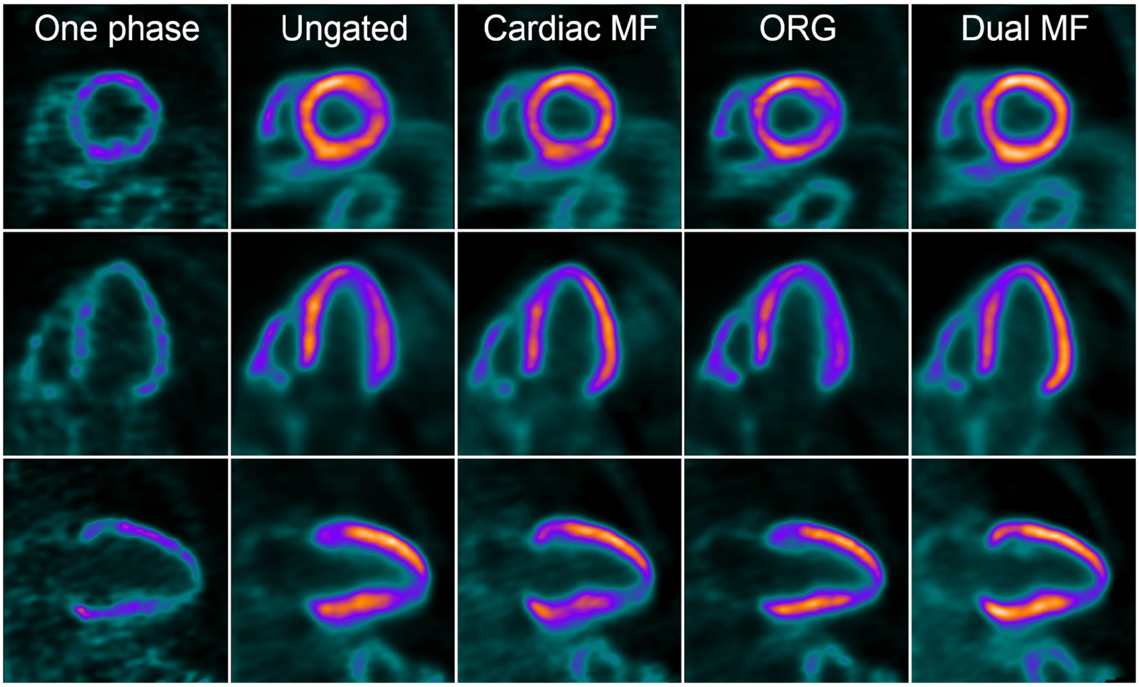

Figure 11. Flurpiridaz F-18 stress image acquired in dual ECG and respiratory gating. *One phase* one ECG gate in end-inspiration, *Cardiac MF* ECG gated with MF, *ORG* optimal respiratory gating, *Dual MF* ECG and respiratory gating with MF. (Reprinted with permission from Slomka et al.[4]).

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