

# Technical Aspects and Errors of Triggering and Synchronization in Gated Single Photon Emission Computed Tomography Myocardial Perfusion Imaging

## Abstract

Gated imaging, as a technically demanding procedure, requires special attention and effort to fulfill the technical adequacy and accuracy of the study, based on the available standard guidelines. One of the essential requirements to be met by both technologists and physicians, in nuclear cardiology, is triggering and synchronization as a fundamental subject of gating. There are many sources of gating errors that produce imaging artifacts and, in some occasions, render the images uninterpretable or the quantitative analyses less accurate. Sufficient knowledge of recognition of these artifacts and understanding of their related mechanisms (from physical and technical perspectives) enable the technologists and physicians to promote their performance in daily practice. In this article, intended as a readily practical technical review for nuclear medicine practitioners, it is aimed to present the technical and computer aspects of triggering and synchronization as well as the related errors during imaging.

**Keywords:** *Gated single photon emission computed tomography, myocardial perfusion imaging, triggering and synchronization*

## Introduction

Gating is currently an indispensable part of the existing modalities for cardiovascular imaging. Triggering and synchronization, as a basic and fundamental concept in gating, control the acquisition and partitioning of data to produce the perfusion and function information of the left ventricle (LV) during the cardiac cycle. The present article provides a detailed review of the technical and computer aspects of triggering and synchronization in gated single photon emission computed tomography (SPECT) and related errors practical to both technologists and physicians to improve their knowledge in daily practice.

## Physical and Technical Basis of Triggering

Gated SPECT myocardial perfusion imaging is currently an established and validated diagnostic tool for concomitant assessment of the status of regional LV myocardial perfusion and function during the cardiac cycle (i.e., systole and diastole).<sup>[1-3]</sup> To accomplish this purpose,

due to practical reasons, the cardiac cycle is divided into a finite, but optimized, number of intervals, each representing a brief period of the cardiac cycle so that the imaging system should be coupled, or in other words synchronized, with the electrocardiographic (ECG) signal of the patient being imaged to achieve the purpose of partitioning of data. Synchronization between the ECG signals of the patient and count recording and image acquisition can be considered as the mainstay of gating. When the imaging system is synchronized with the ECG signal, the acquisition starts with the appearance of a specific signal, then ends, and immediately starts over with the appearance of the next similar signal. The duration intervened between the two similar signals is assumed as a cardiac cycle, and this period is divided into a number of intervals (specified by the user) in multiple fashions.<sup>[4-10]</sup> Most commonly, the R wave in the ECG signal, which is readily recognizable and distinguishable from other waves in the ECG, is used as a starting point for acquisition and count recording. Thus, the period between two consecutive R waves is considered as a single cardiac cycle. The term “gating”

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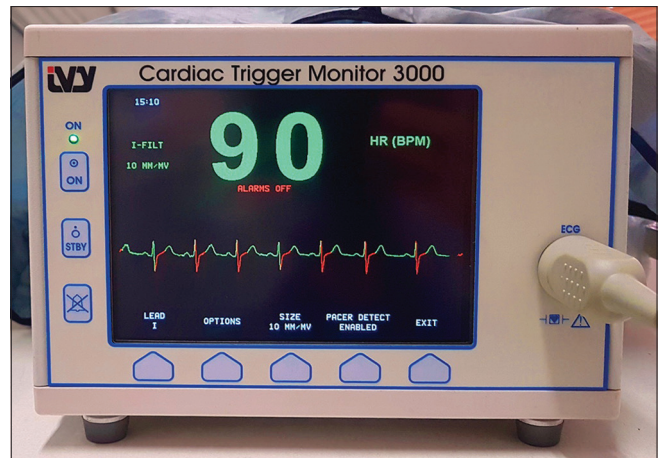
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probably comes from the notion that the acquisition and data recording are “controlled using a signal as a gatekeeper” with which every event is given the permission to be laid and recorded in the correct time and position, or in other words, this reduces mis-registration of data to minimal amounts. This signal “stimulates” and “triggers” the opening of the “gate” (i.e., the start of a specific cardiac cycle) and closure of it (i.e., the end of that cardiac cycle). The mentioned signal is commonly called as the trigger signal and is produced in the cardiac trigger monitor (CTM) device when an R wave in the patient’s ECG is detected and is then transmitted to the imaging system through a connecting cable. The computer in the imaging system receives the trigger signal and alternates between “on” and “off” modes. This “on-and-off alternation” is in synchrony with the consecutive R waves or cardiac cycles and thus arranges the sequence of detected events into appropriate partitions.<sup>[7-10]</sup> Furthermore, it has been shown that, instead of using ECG signals for triggering, other physiologic signals such as the peripheral pulse wave can be used alternatively for synchronization and produce almost similar results.<sup>[11]</sup>

### Cardiac Trigger Monitors: Engineering, Design, and Technical Specifications

There are a few commercially available devices designed for cardiac triggering for gated studies. CTMs by IVY Biomedical Systems Inc. are among the most widely used trigger monitors worldwide, and all the information regarding the trigger signal characteristics and device specifications and configuration in the present article is based on the data provided and supplied by this manufacturer [Figure 1]. However, the basic principles and mechanisms are almost similar. Through 3–4 leads attached to the patient’s chest, all receive and record the ECG signal and then detect and recognize the R wave. Then, as soon as a signal that meets the predefined criteria for being considered as an R wave, an output signal is generated and transmitted to the camera computer with minimal delay. The output signal used for triggering is a digital electrical pulse with various specifications among different manufacturers and also depends on the imaging system being connected to and is configured during manufacturing. It can also be assumed as a “square wave” which has two main specifications. The one is the width and the amplitude which are not adjustable by the user and the other is the polarity which can be selectable by the user on the display monitor and can be set as positive or negative [Figures 2a,b,c]. Normally, the device works with an input signal (i.e., ECG signal) of 1 mV and 1 pulse/s and generates an output signal with an amplitude of up to 5 V, a width of 100–150 ms (for PHILIPS and SIEMENS gamma cameras) and a delay <10 ms. For such an input signal, the device has a high R-to-R trigger accuracy (typically less than  $\pm 100 \mu\text{s}$  or  $\pm 1\%$ ). In situations with low-voltage



**Figure 1: Front panel of a trigger cardiac monitor device (IVY Biomedical systems, Inc. Model 3000 series) connected to a patient being imaged. On the display, the heart rate, the lead selected, and the real-time electrocardiographic signal are visible. There are buttons, below the display, to select and change the settings**

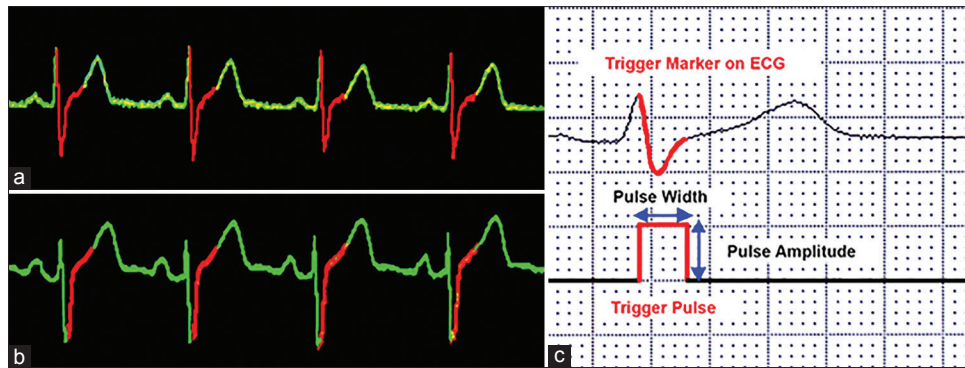
ECG due to a variety of reasons (e.g., marked obesity, large breasts, pericardial effusion, and poor contact of lead electrodes to the skin surface due to sweating or insufficient gel application), the increased impedance results in a decreased voltage of the input signal, and this, in turn, reduces the accuracy for detection of R wave and causes occasional interruptions during monitoring. The polarity of the trigger signal is defined based on the initial deflection or edge of the square wave. When the initial deflection is positive, the signal has a positive polarity and vice versa. The choice depends on the camera used for imaging based on the manufacturer’s recommendation.<sup>[12]</sup>

### Practical Technical Measures before Image Acquisition

Before start imaging, the technologist must ensure the secure attachment of the leads to the chest. Shaving and cleaning of the anterior chest skin and applying sufficient gel are helpful and prevent detachment of the lead pads from the skin and subsequently unwanted interruptions during imaging. It is also recommended to check for the ECG shown on the display for any arrhythmia, the suitability of the lead chosen, the voltage of the ECG signal, and the relative amplitude of the R and T waves, and then proper synchronization, to verify that the trigger output signal begins at the peak of the R wave using the “trigger marker” option. However, in newer generations of CTMs, the system is capable to select the appropriate lead automatically and is less susceptible to be influenced by insignificant arrhythmias and lower R wave amplitude compared to T wave.<sup>[8,12,13]</sup>

### Gating Errors as Applied to Triggering

A diagnostic-quality gated study provides useful information of the LV myocardial perfusion and, in particular, functions continuously during the cardiac cycle,



**Figure 2:** (a and b) Two strips of different leads of the electrocardiographic signal containing four consecutive beats displayed on cardiac trigger monitor. Red zone indicates the part of cardiac cycle coincident with trigger pulse production and transmission. The red zone normally starts from peak of R wave and, according to the width of trigger pulse, extends into ST segment of electrocardiographic signal. (c) Relationship of cardiac cycle to trigger pulse is shown. During every cardiac cycle, only one pulse is transmitted to camera that announces the occurrence of R wave or onset of ventricular systole to camera computer

from systole to diastole. This goal needs a good ECG signal from the patient being imaged and optimized transmission and processing in the upstream components of the imaging system. Gating errors due to incorrect triggering or synchronization can be categorized into two main types. The first one is resulted from improper recognition of R wave and the second one is produced by the inappropriate selection of the polarity of the trigger signal. These errors may cause difficulty in the evaluation of myocardial wall motion and ejection fraction (EF) estimation in the absence of any arrhythmia. The effects on the gated images and the related artifacts are discussed in detail.

Upstream to the CTM, another artifact that is worth noting is poor gating resulted from repetitive interruptions of trigger signal transmission from the CTM to the camera. In these circumstances, if the camera continues image acquisition, those projections will contain less count due to less number of recorded beats. The count–density curve and the sinogram will demonstrate “drop off” of the data and the classic striped pattern (horizontal lines with less brightness) in the corresponding projections, respectively.<sup>[14]</sup> In other imaging systems, the camera will stop acquisition and will not move forward to acquire the next projection. This lengthens the imaging time but does not generate the mentioned artifact.

### Errors Related to Improper Recognition of R Wave

As discussed above, the R wave is most commonly used for triggering which is coincident with the onset of the systole (i.e., LV contraction). After completion of the diastole, following the cardiac systole, next R wave appears and the next cardiac cycle begins. This sequence over one cardiac cycle is compatible with the pattern of decreasing of LV volume and then increasing to the initial level at the beginning of cardiac systole. Therefore, an asymmetrical U-shaped curve will be obtained. This curve is named “time–volume curve.” There is a couple of measures that

are derived from this curve such as end-diastolic and end-systolic LV volumes from the beginning point of the curve (highest value) and the lowest value around the mid-cycle, respectively. The difference between the two mentioned points (i.e., maximum value minus minimum value) addresses the stroke volume, and in patients with lower EF, the depth of the curve is reduced compared to that in normal patients. The slope of the curve at the downward and upward parts of the curve is related to the ability of the LV to eject and to be filled during systole and diastole, respectively. The overall shape of the curve is mainly preserved in most cardiac disorders, but considerable distortion in shape is mostly related to errors in triggering and gating. Therefore, this curve can be used as a quality control tool for accuracy of gated studies.<sup>[9,10,15]</sup>

Multiple patterns of distorted curve due to a variety of errors are available in the literature. Most of them are resulted from improper recognition of R wave for triggering, and other waves or waveforms are employed instead as a signal for triggering. In some circumstances, because of the inappropriate selection of the lead in the CTM, the T wave may dominate the R wave in amplitude and may be sensed and used as the signal for triggering. Here, the length of the “new” cardiac cycle exactly equals to that in normal R–R triggering, but the pattern of contraction of relaxation is opposite. The shape of the curve is also altered and seems inverted. It starts shortly before the end-systolic point, then enters the diastolic phase, and finally ends in the systolic phase before the end-systolic point.<sup>[9,10,16]</sup>

In circumstances in which R and T waves have almost equal amplitude, both may be sensed and employed as signals for triggering, and thus, one “real” cardiac cycle will be divided into two “falsely recorded” cardiac cycles. The first cycle (or R–T interval) is related to the systolic phase of the “real” cardiac cycle, and the second one (or T–R interval) demonstrates the diastolic phase. As these two phases have opposite patterns of contraction and relaxation, the superimposition of corresponding frames

from hundreds of cardiac beats will cancel out each other, and an “average” image of the LV throughout the cardiac cycle will be obtained similar to that in nongated studies. In contrast to perfusion images that may show no abnormality, the curve will be a roughly flat line and visually severe to profound wall motion abnormality (i.e., global hypokinesia) will be evident. The EF is also inappropriately reduced compared to the patient’s clinical picture or other diagnostic modalities.<sup>[9,16,17]</sup>

When bigeminy presents and R–R patterns are sensed during monitoring, the recorded cardiac cycle contains more than one true cardiac cycle as one “recorded” cardiac cycle. If the premature beats come after the end-systolic point, the shape of the curve looks like the letter “W.” A “double-contraction” or “biphasic-contraction” pattern has been used to describe this artifact.<sup>[9,16,18]</sup>

When R and T waves are sensed irregularly for triggering, complex patterns of the curve will be produced. There are other patterns of erroneous triggering that each has its own pattern and shape of the curve. For enthusiastic readers, more in-depth discussion of the various pattern of erroneous triggering is available in the literature.

Conventionally, the R wave was recognized by the CTM devices based on the relative amplitude of the waves (i.e., R wave relative to T wave). This approach employs the simplest algorithm (amplitude criterion) for the detection and recognition of the R wave. This approach may fail in circumstances in which the R wave is shorter in height compared to T wave in the selected ECG lead. A reasonable task is to change the guidance lead for triggering or to reposition the place of the lead electrodes on the skin relative to the heart. Therefore, it is generally recommended to select a lead with tall, positive, and monophasic QRS complexes with relatively shorter P and T waves. There are more sophisticated algorithms developed thereafter, which recognizes the R wave with much more accuracy even in ECG leads with a lower relative amplitude of the R wave. This algorithm recognizes the morphology of waves and also uses mathematical approaches (e.g., first derivative computation) [Figure 2b].<sup>[8,13,17]</sup>

### Errors Related to Inappropriate Selection of Polarity of Trigger Signal

The polarity of the trigger signal, as mentioned above, is determined by the initial deflection or edge of the square

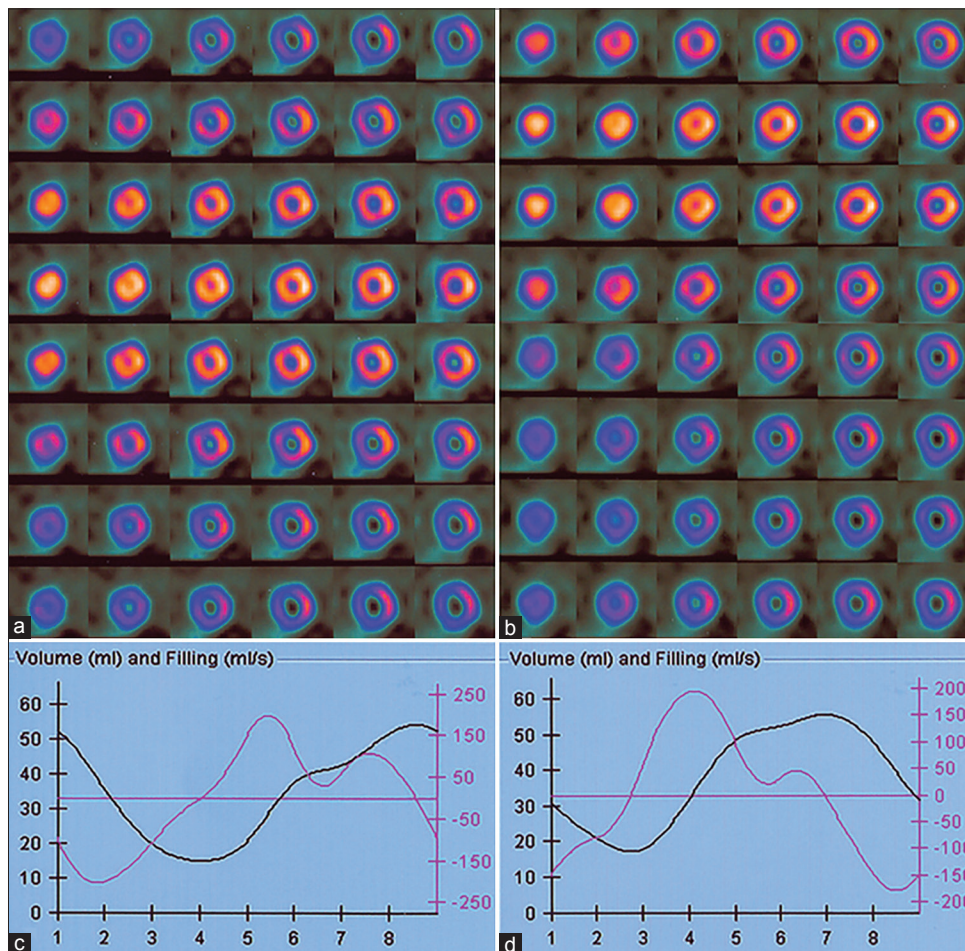


Figure 3: (a and b) Eight short-axis tomographic slices of two 8-frame gating scans in a single patient acquired with positive polarity (a) and then with negative polarity (b) of the trigger signal. (c and d) The corresponding time-activity curves resulted from gated studies

wave and determines the occurrence of R wave in the patient's ECG. This, in turn, switches the camera computer from "off" mode to "on" mode and induces the beginning of count collection and assignment of them to the specific cardiac cycle and frames in gated imaging.<sup>[12]</sup> This item, particularly in older versions of devices, is selectable by the user. The choice (positive or negative) depends on the specifications of the imaging system. Positive polarity should be selected on the CTM when coupled and synchronized with a camera that works in synchrony with the positive trigger signal and vice versa. This item is adjusted and set on installation, and during a major service, otherwise, the setting should remain unchanged. In circumstances in which incongruence exists between the polarity of the trigger signal produced in the CTM and the camera, there will be a time delay in switching the camera computer from "off" to "on" mode. In other words, the camera computer switches on at the end of the trigger pulse. Therefore, the recorded cardiac cycle begins somewhere during the systolic phase, instead of the onset of systole. This issue results in a forward shift in the time-activity curve, and thus, a sine-like curve will be produced instead of the typical U-shaped curve. The length of the shift on the x-axis equals the width of the square wave of the trigger signal (i.e., 100–150 ms or about more than one frame in 8-frame gating and two frames in 16-frame gating).<sup>[12]</sup> The effect of this issue on the erroneous measurement of the quantitative parameters of the systolic and diastolic function of the LV has been of notable importance. Unfortunately,

the effect on EF calculation is not clear or adequately investigated. As presented in Figure 3, eight short-axis tomographic slices of two 8-frame gating scan in a single patient acquired with positive polarity [Figure 3a] and then with negative polarity [Figure 3b] of the trigger signal. All other parameters for acquisition and processing are identical. Figure 3c and d also reveals time-activity curve of the gated studies in Figure 3a and b, respectively. As can be seen in Figure 3a, a normal and expected pattern of contraction of the LV (here, increases and then decreases in activity of the myocardial walls or myocardial thickening) is evident. The end-systolic phase is compatible with the fourth frame. The related curve also demonstrates a typical U-shaped appearance. In Figure 3b, the mentioned pattern is seen as well, except that a shift in phases is evident. The first frame is not compatible with the end-diastolic phase but occurs somewhere in mid-systolic phase and the end-systolic phase is in the second or third frame. The corresponding curve also demonstrates a similar pattern, and there is a shift with a constant offset of 1–2 frame lengths. The measured indices of systolic function are as follows: EF: 72%, end-diastolic volume (EDV): 52 ml, end-systolic volume (ESV): 15 ml for positive signal; EF: 68%, EDV: 56 ml, ESV: 18 ml for negative signal.

Phase histogram of the gated studies [Figure 4], similar to that in Figure 3a with positive and Figure 3b with negative polarity of the trigger signal, and their corresponding polar plots of phase analysis are displayed. The x-axis of the coordinates of phase histogram represents the length of a

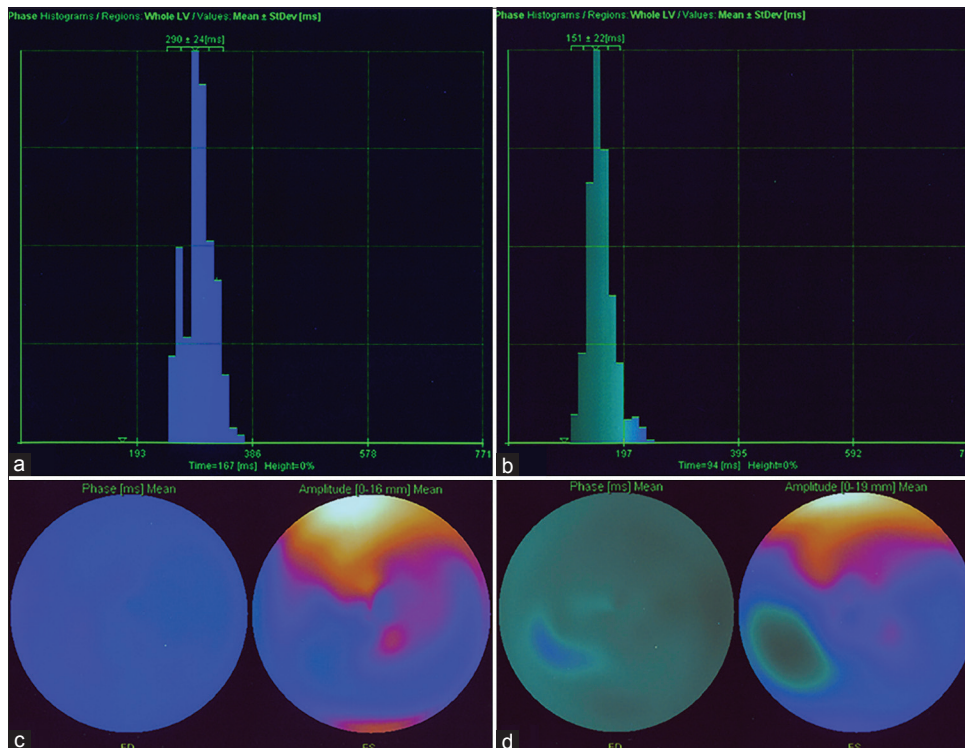


Figure 4: (a and b) Phase histogram of the gated studies as in Figure 3a with positive and Figure 3b with negative polarity of the trigger signal and their corresponding polar plots of phase analysis. (c and d) The corresponding polar plots of phase and amplitude from gated studies

cardiac cycle or R–R interval in milliseconds, here about 800 ms. Figure 4a shows a normal pattern of mechanical synchrony of LV myocardium (phase peak  $\pm$  standard deviation:  $290 \pm 24$  ms with narrow dispersion). The narrow and peaked phase histogram appears at the expected time for end-systolic phase. A homogenous pattern throughout the LV is also evident in Figure 4c. Figure 4b and d reveals a similar appearance (narrow and peaked histogram and homogenous pattern in polar plot) except the time at which the contraction of the LV myocardium occurs (phase peak: 151 ms). All the results are in accordance with the results presented in Figure 3 that a delay is present in the recording of the onset of the cardiac cycle.

## Conclusion

Technical proficiency and qualifications are required for satisfactory performance in nuclear cardiology laboratories. Knowledge of accurate triggering and synchronization and related gating errors is an important item of these requirements for both technologists and physicians.

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## Conflicts of interest

There are no conflicts of interest.

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