How to Deal with Arrhythmia in Cardiac MRI

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Introduction

Cardiac magnetic resonance imaging (CMR) in patients with arrhythmia is challenging. This article discusses indications, imaging techniques, and issues with CMR in arrythmia. Furthermore, it provides solutions for improving image quality and suggests a workflow for dealing with arrythmia during the examination process.

Arrhythmias are common and affect electrical conduction throughout the heart. They can range from benign to life-threatening and be caused by various factors. The management of arrhythmias requires accurate diagnosis and characterization of the underlying mechanism, which is often challenging. Multiparametric myocardial tissue characterization with CMR provides insights into the underlying causes of various cardiomyopathies. In recent years, CMR has become an established imaging modality in clinical routine to assess structural heart disease. However, it is challenging to perform a high-quality CMR examination in patients with arrhythmia. This is because the condition often causes image artifacts, which make qualitative and quantitative analyses difficult.

Arrhythmias may result in skipped or ectopic heartbeats, causing issues with data acquisition and image reconstruction. This results in degraded image quality and therefore inferior diagnostic accuracy. To solve this issue, different image acquisition approaches are available to improve image quality. However, in some scenarios, they may increase scan time. An often-used approach is arrhythmia detection/rejection [1]. This software-based solution can be applied to balanced steady-state free precision sequences (bSSFP, or TrueFISP) when using retro gating to cover the complete cardiac cycle, but it increases scan time. Real-time cine imaging is a different approach where all data needed is acquired in a single heart-beat, but one that comes at the cost of image quality [2]. In recent years, new techniques such as compressed sensing have become available [3]. Compressed sensing accelerates the acquisition and reduces scan time in the case of segmented imaging or increases resolution in case of single-shot real-time imaging. An alternative is prospective triggering [1] and reducing the acquisition window to more or less only covering the systole. All these approaches may overcome issues with arrhythmia in CMR and make the scan more efficient with substantially better image quality.

Indications: Why is CMR important in arrhythmia patients?

Patients suffering from arrhythmia may have various underlying causes of cardiomyopathies. In non-ischemic cardiomyopathies (NICM), left ventricular ejection fraction (LVEF) is the primary marker to decide whether patients need a cardiac resynchronization therapy pacemaker (CRT-P) or a cardiac resynchronization therapy defibrillator (CRT-D), also known as implantable cardioverter defibrillator (ICD). Depending on the type of heart failure, these devices are either for primary prevention of cardiac arrest or to improve cardiac function. Typically, this is considered an indication if the LVEF is < 35%. However, some patients with NICM may be eligible for pacemaker/ICD placement, even when the LVEF is > 35%.

The first-line imaging modality for cardiac assessment is echocardiography. However, it lacks myocardial fibrosis analysis. CMR can help to identify the underlying causes of NICM and can further risk-stratify patients with multiparametric tissue characterization, mainly based on late gadolinium enhancement (LGE) [4]. CMR with LGE may help identify arrhythmogenic substrates. In patients with ventricular arrhythmias, CMR can identify structural heart disease in up to 25% of cases (e.g., myocarditis, arrhythmogenic right ventricular cardiomyopathy, dilated cardiomyopathy), even when patients have a normal echocardiography [5].

With regards to interventional procedures such as myocardial ablation, a pre-procedural CMR is essential to assess for areas of fibrosis, which are potential arrhythmogenic correlates. There is also a strong association between areas of LGE and ECG findings [6]. CMR also demonstrates efficacy in arrhythmia recurrence after ablation. This suggests CMR can be used to determine the optimal ablation approach, and therefore decrease the overall time required for the ablation procedure.

Usually, LGE imaging is performed with 2D inversion recovery T1-weighted sequences. However, a fast and high-resolution isotropic approach is needed to identify small areas of fibrosis. A suitable technique is 3D LGE imaging, which allows for more detailed LGE information. Data is available using a 3D LGE compressed sensing (CS) research application[1] with higher image quality and spatial resolution than 2D inversion recovery T1-weighted sequences. Recent publications have shown promising results with 3D LGE in combination with compressed sensing or other acceleration techniques [7–9] but these are not widely available yet.

Issues and problems with arrhythmia

CMR is the reference standard for assessing cardiac function and volumes [10]. However, in patients with arrhythmias, quantitative analysis can be hampered. This may have different causes, such as ectopic beats, atrial fibrillation, or issues with breath-holding. As a result of suboptimal image acquisition, image quality is degraded. Most commonly, images are blurred, which substantially decreases the delineation of the heart's epi- and endocardial contours [11]. This contributes to inaccurate cardiac volumes and function determination, and lower accuracy.

[1] *Work in progress. The product is still under development and not commercially available. Its future availability cannot be ensured.*

Techniques behind arrhythmia imaging and how to improve image quality

There are several strategies for arrhythmia imaging, depending on the severity of the irregular heartbeats.

1. Cine imaging strategies

a) Standard retrospective gating

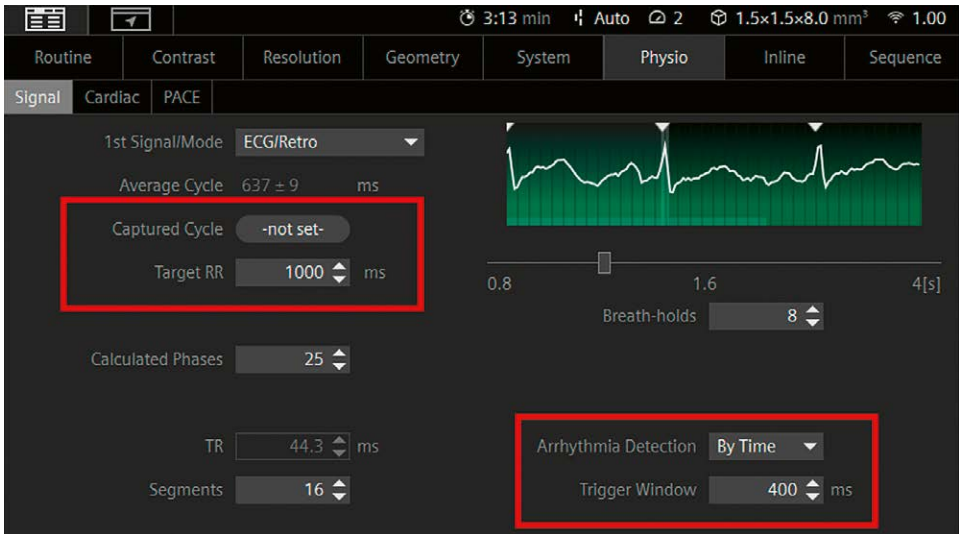
Usually, regular segmented TrueFISP cine images are acquired during a breath-hold over several heart-beats for one to three slices in a retrospective fashion. Retrospective image acquisition of a defined RR interval is performed after triggering the ECG R-peak to the next heartbeat. All image data is collected and, during the reconstruction process, assigned to a specific cardiac phase. Retrospective gating assumes a periodicity of the temporal motion of the heart. Hence, this method may be prone to arrhythmic heartbeats as the final image is based on data from several heartbeats, which will lack a constant periodicity in cases of arrhythmia. Therefore, arrhythmic heartbeats may result in image artifacts and degrade image quality.

One way of dealing with relatively mild arrhythmia is to use arrhythmia detection/rejection. This method allows the rejection of irregular RR intervals and relies on cardiac frequency as the basis of a regular heart rate. Variations in the RR interval over a certain threshold are rejected and not used for image reconstruction. In addition, another heartbeat after the arrhythmic one will not be used (Fig. 1).

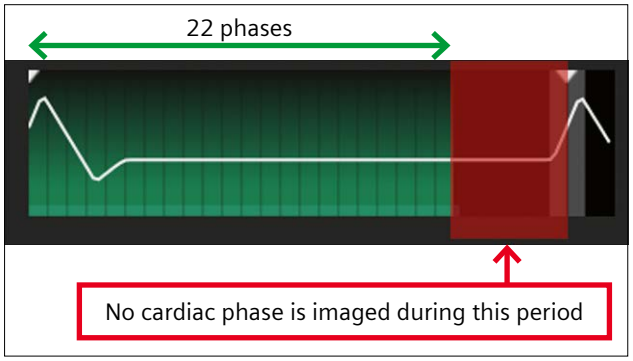
While this imaging technique might improve image quality in mild arrhythmias, it may be inefficient for specific patient populations as it increases scan time due to the rejection of specific cardiac cycles. It may be prone to errors in specific, "constant" arrhythmias, such as long–short–long RR intervals.

To use arrhythmia detection, switch it on ("By Time") in the Physio/Signal card (Fig. 2). Next, set the target RR

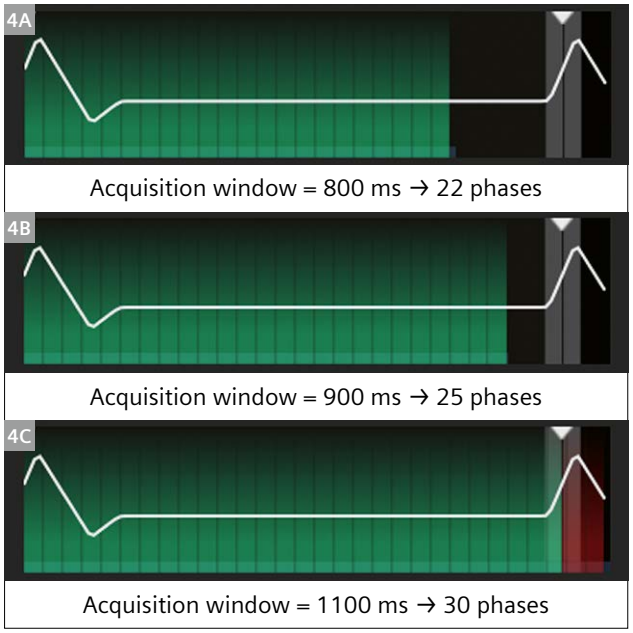
1 Arrythmia detection: rejecting heartbeats.



2 Regular retrospective gated TrueFISP cine sequence with arrhythmia detection turned on.



3 Influence of acquisition window on coverage of the cardiac cycle.



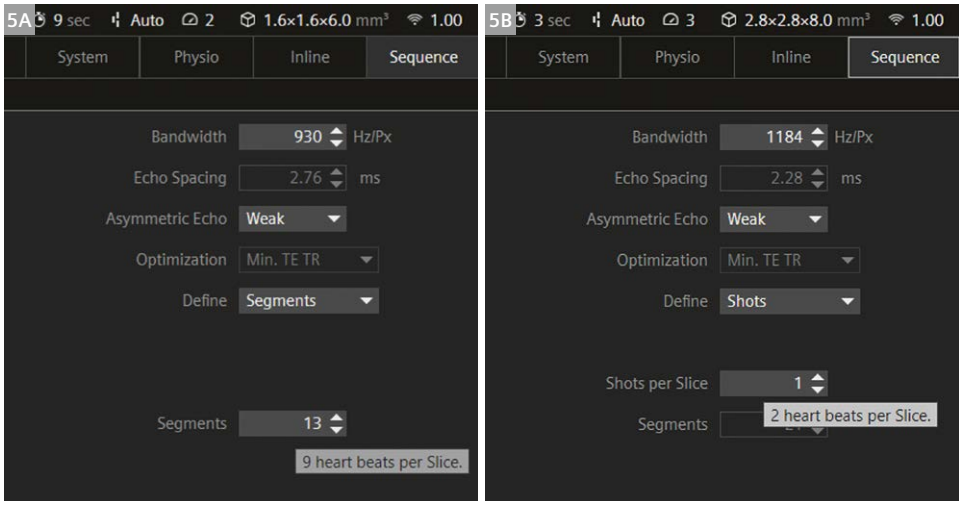
4 Influence of acquisition window on coverage of the cardiac cycle and number of phases: RR interval = 1000 ms, TR = 35.9 ms.

to the value that would be the "normal" RR interval (Fig. 2, left red box). This setting will allow the heartbeats with an RR interval of target RR -/+ ½ trigger window, which in this case is 800–1200 ms. The larger the trigger window, the more heartbeats are accepted, which may lead to blurrier images. A smaller window may lead to more heartbeats being rejected, but better image quality. However, that can come at the cost of longer scan times since more heartbeats need to be re-acquired, potentially leading to breath-holding times that exceed the patient's capabilities.

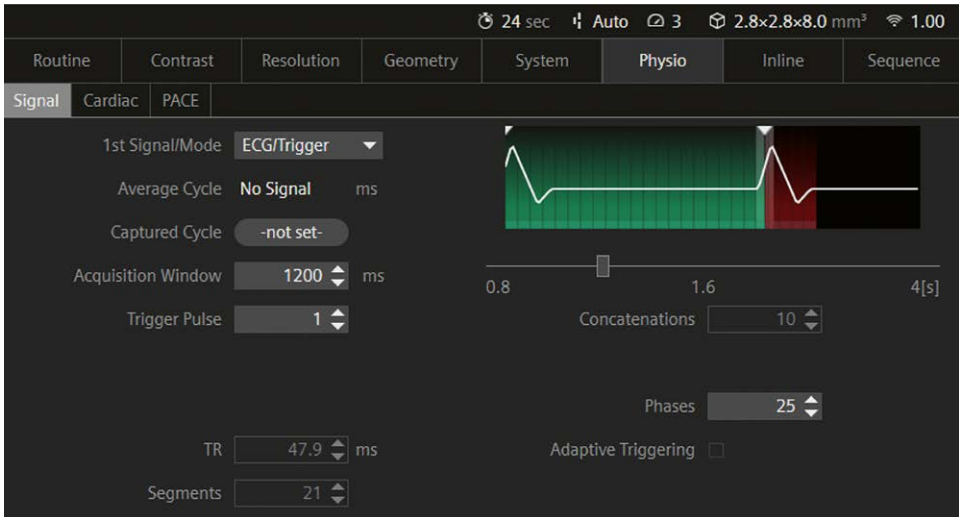
b) Prospective ECG gating

Another option for more severe arrhythmias is prospective ECG triggering. Data acquisition starts after estimating the number of cardiac phases within an RR interval. The data acquisition is triggered by each R-wave and stopped after the data of the estimated number of phases has been acquired. This means that part of the cardiac cycle is not captured in the images mainly end-diastole (Fig. 3).

The acquisition window can be set automatically by pressing the Captured Cycle button. However, it can also be set manually, and this might be the better choice when the RR interval changes from beat to beat. In both cases, watch the coverage of the cardiac cycle with the set acquisition window before applying the protocol to ensure the correct value has been set. The influence of the number of phases on capturing the cardiac cycle can be seen in Figure 4. When the number of phases is too low, a relatively long cardiac cycle phase is not imaged (Fig. 4A). The best scenario would be to stay as close as possible to the RR interval to ensure that as much of the cardiac cycle is visualized as possible (Fig. 4B). If the number of cardiac phases is chosen too high, more than the RR-to-RR interval is imaged. This would result in missing the R-wave for triggering, leading to degraded image quality and double the scan time (Fig. 4C).



5 Segmented cine vs. real-time cine; **(5A)** segmented cine 1 + 8 heartbeats, **(5B)** real-time cine, 1 + 1 heartbeats.



6 Acquisition window in triggered real-time cine imaging.

In case of more severe arrhythmias, this technique may be used by setting the acquisition window to the shortest RR interval. However, this strategy will result in time intervals with no data collection. Therefore, it will underestimate quantitative parameters of the cardiac cycle outside of rather basic parameters such as ejection fraction. Some cardiac analysis software packages may not be able to handle stacks with a varying number of phases for ventricular analysis. They require a constant number of phases throughout the whole short-axis stack.

c) Real-time imaging

In the worst-case arrhythmic scenarios such as atrial fibrillation, bigeminy, or premature ventricular contractions, both strategies mentioned above may fail to produce reliable CMR images. Hence, developments over recent decades have introduced real-time imaging, which may be extremely helpful in severe arrhythmia. Real-time imaging is based on fast imaging sequences, which allow imaging with high (sub-second) temporal resolution [1]. Each cardiac phase is taken as a single shot instead of regular cine imaging, where data is collected over several heartbeats (typically 6 to 10) for each phase.

The first option is to use the R-wave to trigger data collection and then collect data over at least one heartbeat (Fig. 5). Each protocol has one dummy heartbeat to achieve a steady state before data collection. While the segmented cine collects the data over eight heartbeats, the real-time cine collects all cardiac phases in just one heartbeat.

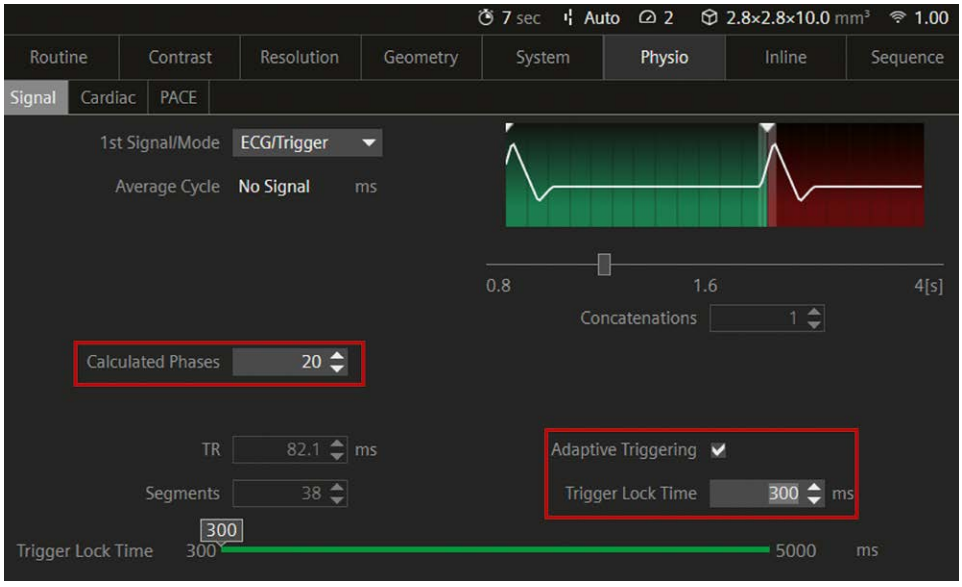
When using the real-time cine, the acquisition window should be set longer than the longest expected RR interval to ensure that the complete cardiac cycle is visualized. For example, when the RR interval is 1000 ms, the acquisition window should be set to 1200 ms, as shown in Figure 6. The data collected here can still be used for ventricular analysis, provided that the number of cardiac phases is the same over the complete short-axis images, but would require (manually) setting the diastolic and systolic phases in the postprocessing software.

The second option for real-time cine imaging is to use prospective adaptive triggering. Adaptive triggering will make sure that the same number of images are calculated for each slice, regardless of the number of phases that could be collected, and ensures that there are no issues with post-processing the images for ventricular analysis (Fig. 7).

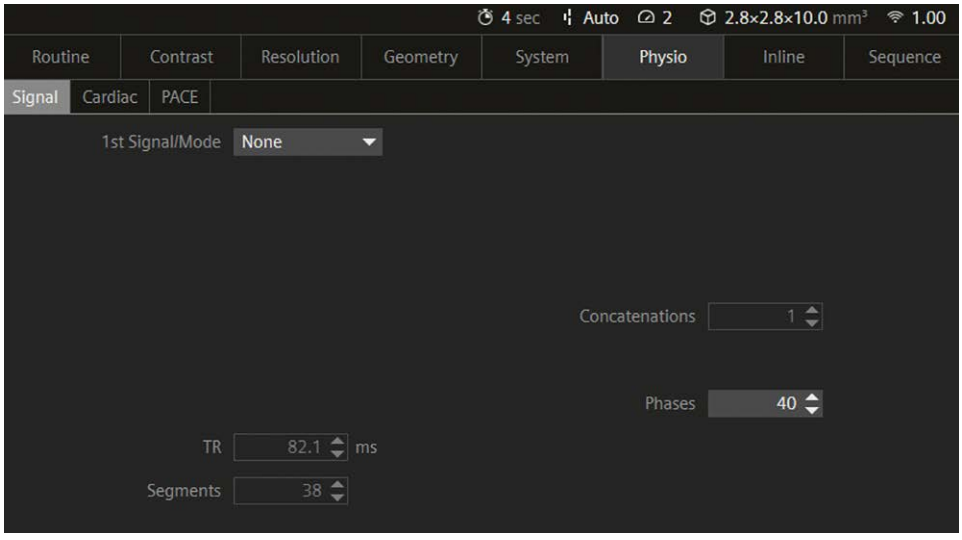
The number of calculated phases can be set in the same way as for retrospective cine imaging. The trigger lock time defines the minimum acquisition window, which can exclude (very) short RR intervals within the acquisition of the short-axis stack. The advantage of using adaptive triggering is that the whole cardiac cycle is covered and that the same number of images are acquired for each slice, and each slice contains all phases between two RR intervals, like retrospective cine imaging.

The second option is to use no trigger at all for real-time images. The only thing to consider here is to ensure that at least one full cardiac cycle is covered. Since no R-wave is used as a trigger, there is also no acquisition window to set. Therefore, we need to make sure that we collect enough phases to cover a full RR cycle. This scan length is determined by defining the number of phases, for example, 3284 ms (40 × 82.1 ms) (Fig. 8).

This technique is relatively robust to motion and allows the acquisition of images without gating: During free breathing, all image data from a full cardiac cycle will be acquired. However, the high temporal resolution limits the image quality and spatial resolution of conventional real-time images. Therefore, combining real-time imaging with other strategies, such as efficient sampling



7 Real-time imaging with adaptive prospective triggering.

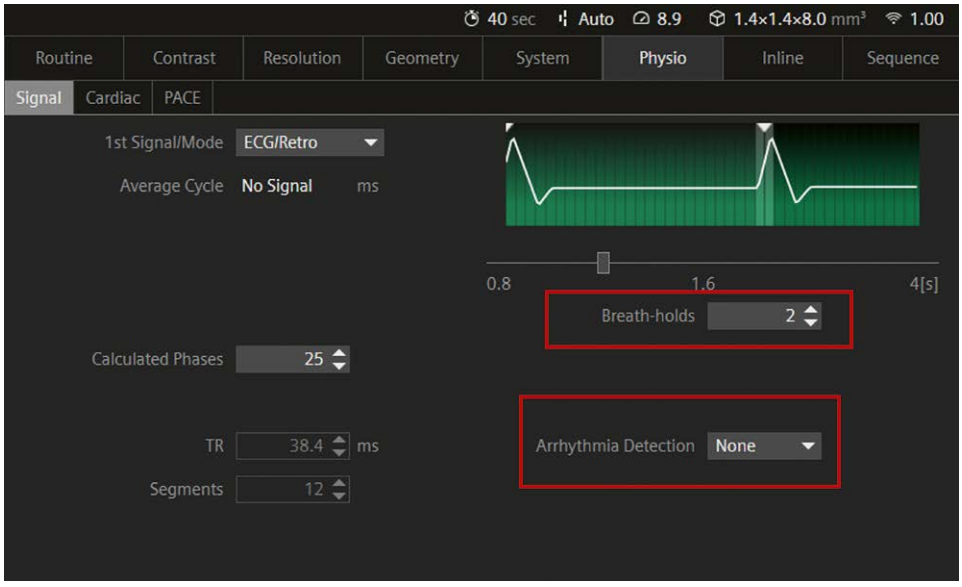


8 Number of phases in non-triggered real-time cine imaging.

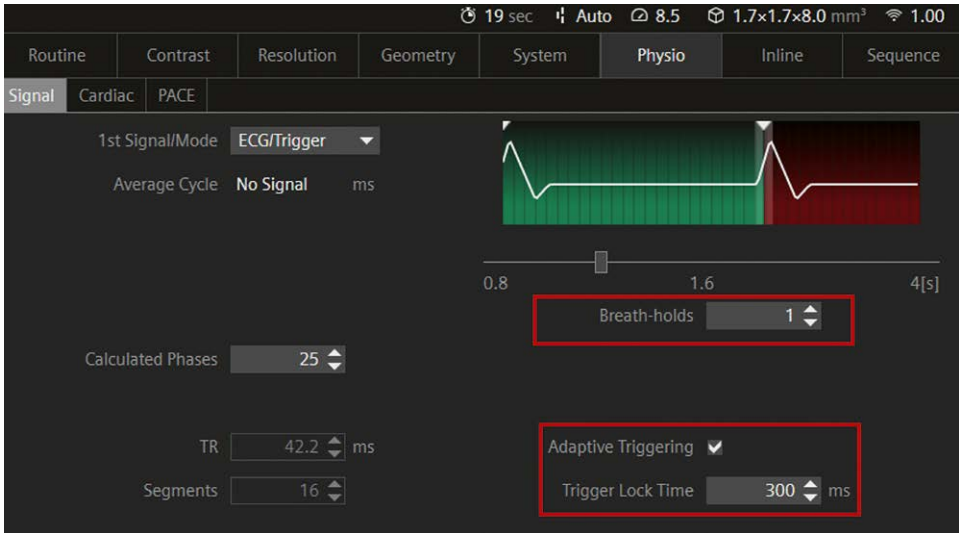
trajectories and reconstruction techniques, has shown benefits when acquiring 2D and 3D cardiac imaging with high spatiotemporal resolution [1]. One of these strategies is the combination of real-time imaging with CS. Compressed sensing is a way of accelerating MRI acquisition by acquiring fewer data through random under-sampling of the *k*-space. Random under-sampling of *k*-space will lead to noise-like artifacts in the image, which are reduced by exploiting the inherent data sparsity (compressibility of imaging data) and nonlinear iterative reconstructions. This combination enables the acquisition of cardiac images during free breathing at a similar temporal and spatial resolution with comparable image quality to conventional segmented TrueFISP cine sequences, but with the acquisition time of the real-time sequence. In other words, data is collected within two heartbeats, and the entire short-axis stack can be acquired in just two breath-holds (Fig. 9).

Real-time cine imaging can also be combined with CS, which only needs one heartbeat per slice for data collection and produces images much closer to segmented cine imaging. When used with adaptive triggering, the complete cardiac cycle is visualized in just one breath-hold (Fig. 10).

There is growing evidence that the techniques described above can acquire reliable basic quantitative parameters, such as ventricular volumes and ejection fraction, with high correlation and good agreement to conventional sequences, even in patients with arrhythmias [12–16]. However, under-sampling of the cardiac cycle (e.g., by prospective gating or dedicated *k*-space sampling)



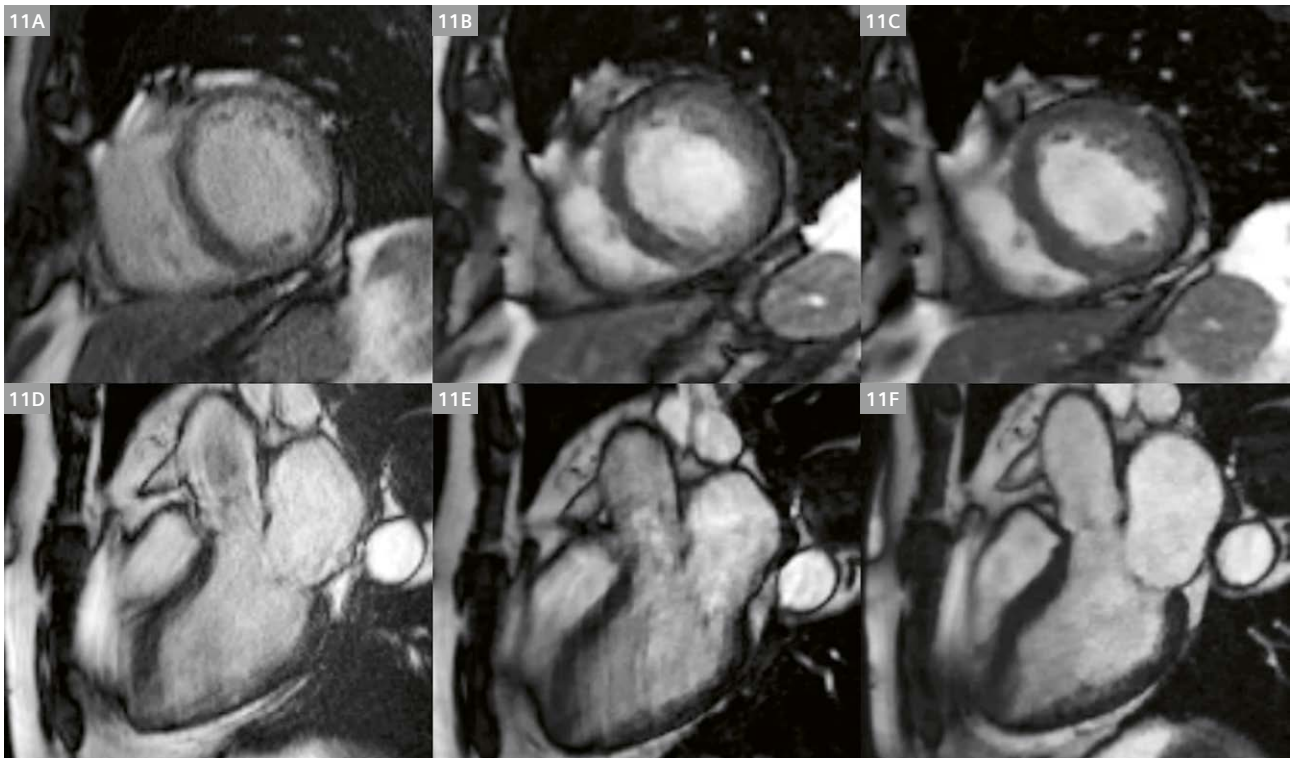
9 Retrospectively gated CS cine sequence without using arrhythmia detection. This is a protocol with 10 slices to cover a complete short-axis stack.



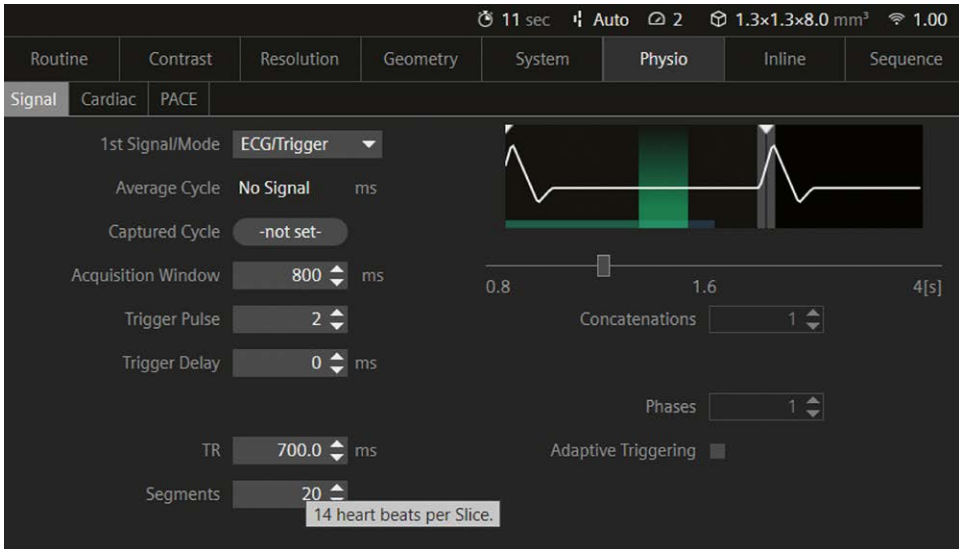
10 CS real-time cine imaging with adaptive triggering. This is a protocol with 10 slices to cover a complete short-axis stack.

may affect more advanced quantitative imaging parameters of cardiac function, such as strain imaging [17]. It should be used cautiously for performing serial investigations of patients with different imaging strategies. Furthermore, the described techniques improve image quality in patients with arrhythmias (Fig. 11).

2. Late gadolinium enhancement (LGE) imaging
Similar to TrueFISP cine imaging, several options exist to reduce artifacts due to arrhythmias in LGE images. The standard technique for LGE imaging uses a segmented TurboFLASH (tfl) sequence, which acquires data over several heartbeats (Fig. 12).



11 Image quality improvement in a patient with arrhythmia, using CS and adaptive triggering. Panels **11A** and **11D** show standard retrospectively gated cine TrueFISP images without arrhythmia detection. Panels **11B** and **11E** show retrospectively gated images with CS but no arrhythmia detection. Panels **11C** and **11F** show prospectively gated images with CS and arrhythmia detection. The last two panels demonstrate significant image-quality improvement compared with the standard cine TrueFISP images. Panels 11A–11C: SAX views; panels 11D–11F: 3-chamber views.



12 Standard TurboFLASH LGE imaging (14 heartbeats).

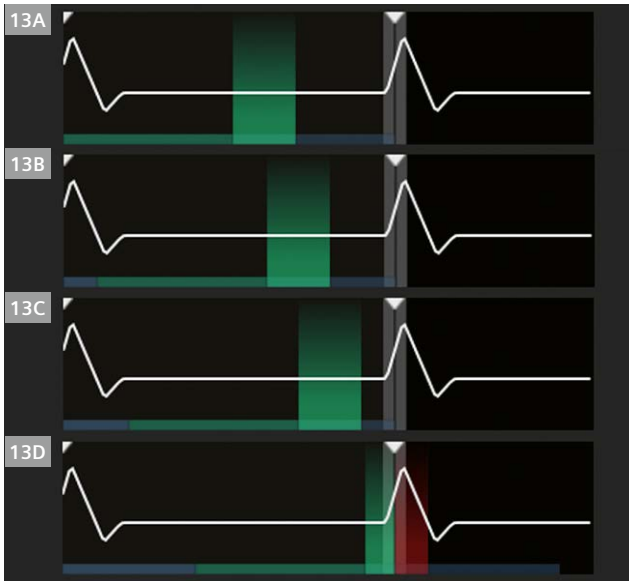
For patients with arrhythmia, several heartbeats within this period could be either shorter or longer than the anticipated RR interval. The protocol can automatically capture the cycle and automatically set the TR and acquisition window. However, depending on the variation in the heart rate, it might be better to set the acquisition window, TR, and trigger delay manually instead. The sequence timing should be set so that data is acquired during the diastolic phase. Generally, TR is kept constant, and trigger delay (TD) is used to move the data acquisition time to the part of the cardiac cycle with the least cardiac movement during the diastolic phase. Figure 13 shows the influence of TD on the data acquisition time graphically, as seen in the user interface. Situations such as those in Figure 13D should be avoided because the data acquisition occurs (partly) during the systolic phase. Besides motion artifacts, this also causes the next R-wave to be missed, leading to a (much) longer breath-hold time for the patient.

The first option for improving image quality is to use a single shot rather than a segmented sequence. These protocols can typically be found in the heart/tissue characterization/trufi ir with "overview" in the protocol name (Fig. 14).

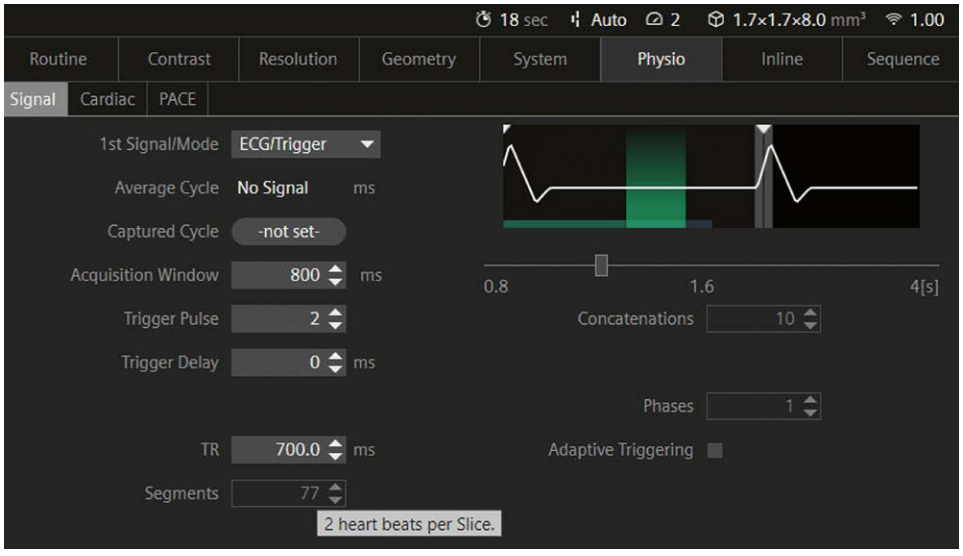
The data acquisition in single-shot phase-sensitive inversion recovery (PSIR) sequences requires only two heartbeats. Therefore, there is less chance of issues with varying RR intervals due to arrhythmias, and it can be easily repeated. To use only one heartbeat, the reconstruction on the Contrast/Common card can be switched to Magnitude only. In that case, only one heartbeat is needed.

The second option for improving image quality in arrhythmia patients is to use HeartFreeze. HeartFreeze is a free-breathing single-shot acquisition with multiple averages and motion correction (Fig. 15).

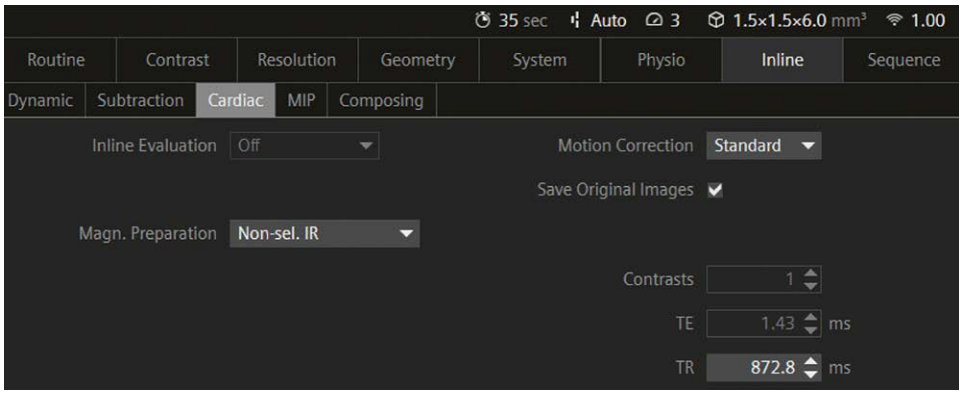
The number of averages is typically 8, and 75% of the most similar averages (after motion correction) are used to generate the image with multiple averages. The main advantages of this technique are that it reduces the chance of motion artifacts because it is a single-shot technique, and it has motion correction, which reduces the shot-to-shot variation (due to arrhythmias). Moreover, because it is a free-breathing technique, there is less chance of acquisitions where the patient cannot (or can no longer) hold their breath due to the long cardiac exam with many breath-holds. These types of images are acquired at the end of the exam.



13 Influence of trigger delay on time of data acquisition: **(13A)** TD = 0 ms, **(13B)** TD = 100 ms, **(13C)** TD = 200 ms, **(13D)** TD = 400 ms



14 Example of a single-shot LGE protocol.



15 HeartFreeze: Motion correction in the Inline/ Cardiac parameter card.

Conclusion

Cardiac MRI is an integral part of the diagnostic algorithm for patients with arrhythmia. Challenges in image acquisition may be overcome with dedicated techniques added to usual TrueFISP cine sequences, such as arrhythmia detection/rejection, or real-time cine imaging with or without CS and adaptive triggering. Assessment for fibrosis with LGE sequences can also be optimized in arrhythmia. All these approaches may result in more efficient scan times and improve image quality, which leads to more accurate cardiac assessments and better patient care.

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