

Dark-Blood Delayed Enhancement Imaging: New Developments in the Imaging of Myocardial Viability

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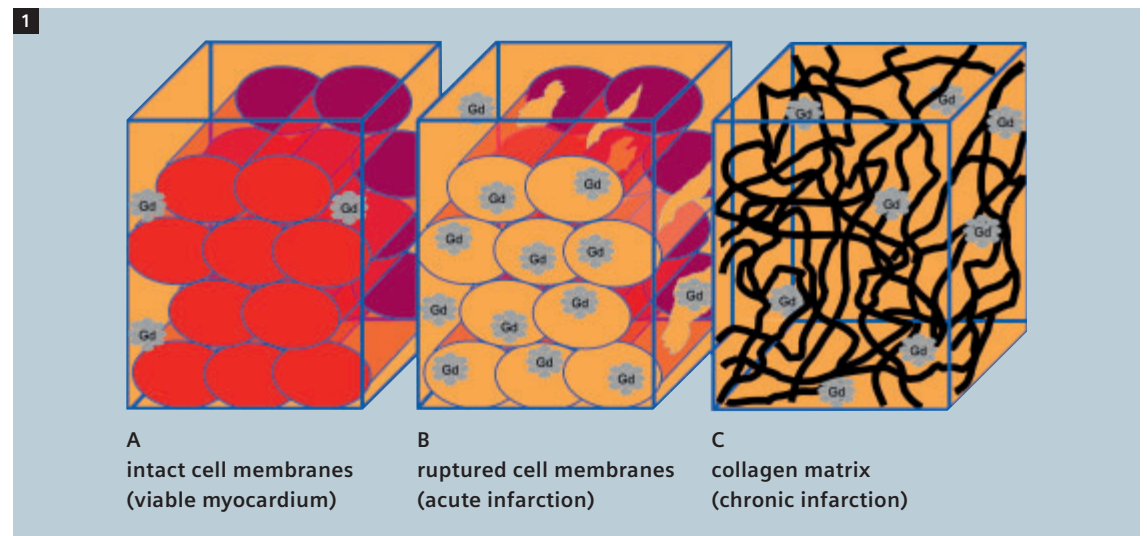
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Introduction

The MR delayed enhancement technique allows the precise assessment of myocardial viability [1]. After intravenous injection, gadolinium-based contrast agents passively diffuse into viable (living) and infarcted (dead) myocardium (heart tissue). Dead myocardium, either chronically (scar) or acutely infarcted, appears bright in these MR images, whereas viable tissue appears dark. In viable myocardium, the contrast agent is confined to the extracellular space which makes up only ap-

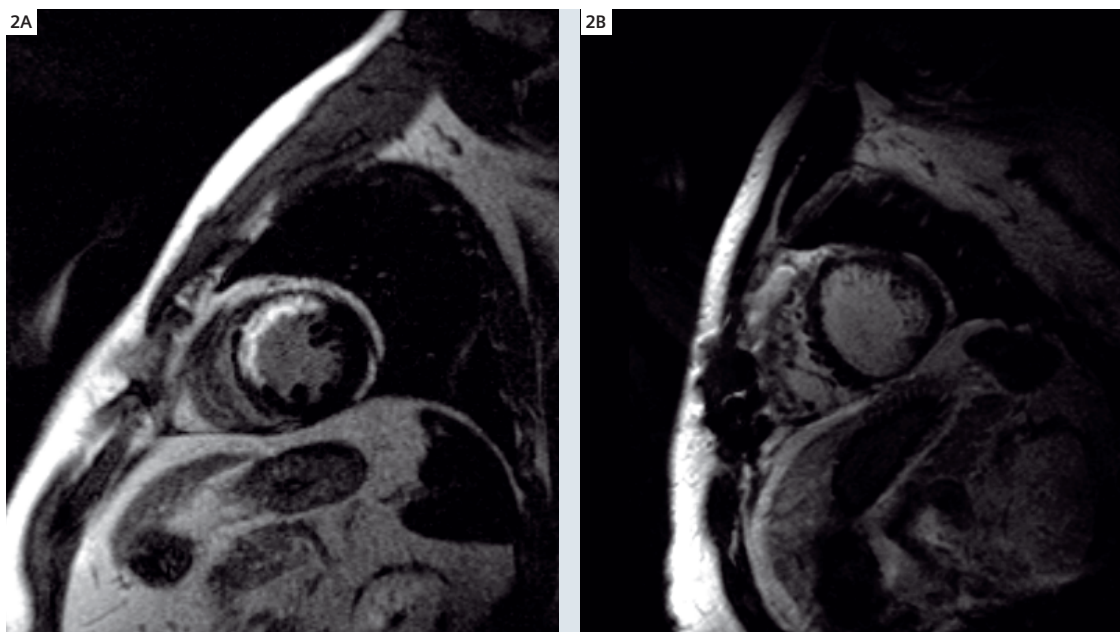
proximately 20% of the tissue volume (orange region of Fig. 1A). The volume available for contrast agent distribution ('distribution volume') is small. In acutely infarcted myocardium ruptured cell membranes allow the agent to enter the intracellular space (Fig. 1B). The distribution volume now includes both the intra- and extracellular space and is increased resulting in higher contrast agent concentrations as compared to viable myocardium [2]. In chronic infarction (scar) the contrast agent

CMR Delayed Enhancement imaging allows accurate assessment of myocardial viability.



1 **A:** Model of living myocardial cells: The Gadolinium-based (Gd) contrast agent is confined to the extracellular (orange) space. **B:** Acutely infarcted myocardial cells: The contrast agent can distribute in the extracellular (orange) space, but due to ruptured cell membranes also in the intracellular (red) space. The volume available for distribution is increased compared to A. **C:** Scar (chronic infarction): In this setting, the contrast agent can also distribute in a larger volume than in A.

(Modified from: Shah DJ, Judd RM, Kim RJ; "Assessment of Myocardial Viability"; Chapter 35 in "Edelman (Editor) et al.: Clinical Magnetic Resonance Imaging"; Vol 1, 3rd Edition, Saunders Elsevier, 2006.)



2 **A:** An MR image showing an anteroseptal myocardial infarction in a short axis view of a human heart acquired with the “gold standard” inversion-recovery TurboFLASH technique. **B:** A similar view in a different human heart where a thin subendocardial infarct is disguised by the isointense blood pool.

can distribute in the interstitial space between the collagen strands, and the distribution volume is also increased (Fig. 1C). Regions of myocardium with increased concentrations of gadolinium will have shorter T1 relaxation times. The T1-reduction in infarcted territory compared to healthy tissue can be visualized with a heavily T1-weighted pulse sequence such as inversion-recovery TurboFLASH [3]. Consequently, myocardial viability can be imaged. Due to the high spatial resolution of MRI the transmural extent and the location of ischemic injury are easily determined [4], and even tiny infarcted areas can be readily identified. This technique is now considered to be the gold standard for the assessment of myocardial viability. Figure 2A shows a delayed enhancement viability image of an anteroseptal infarct in a short-axis slice of a patient’s heart.

Limitations of the standard technique

In conventional delayed enhancement imaging, small subendocardial infarcts can sometimes be difficult to detect as they may have similar image intensities as the blood pool. A thin subendocardial infarct in figure 2B is disguised by the isointense blood pool. These types of infarcts can be difficult

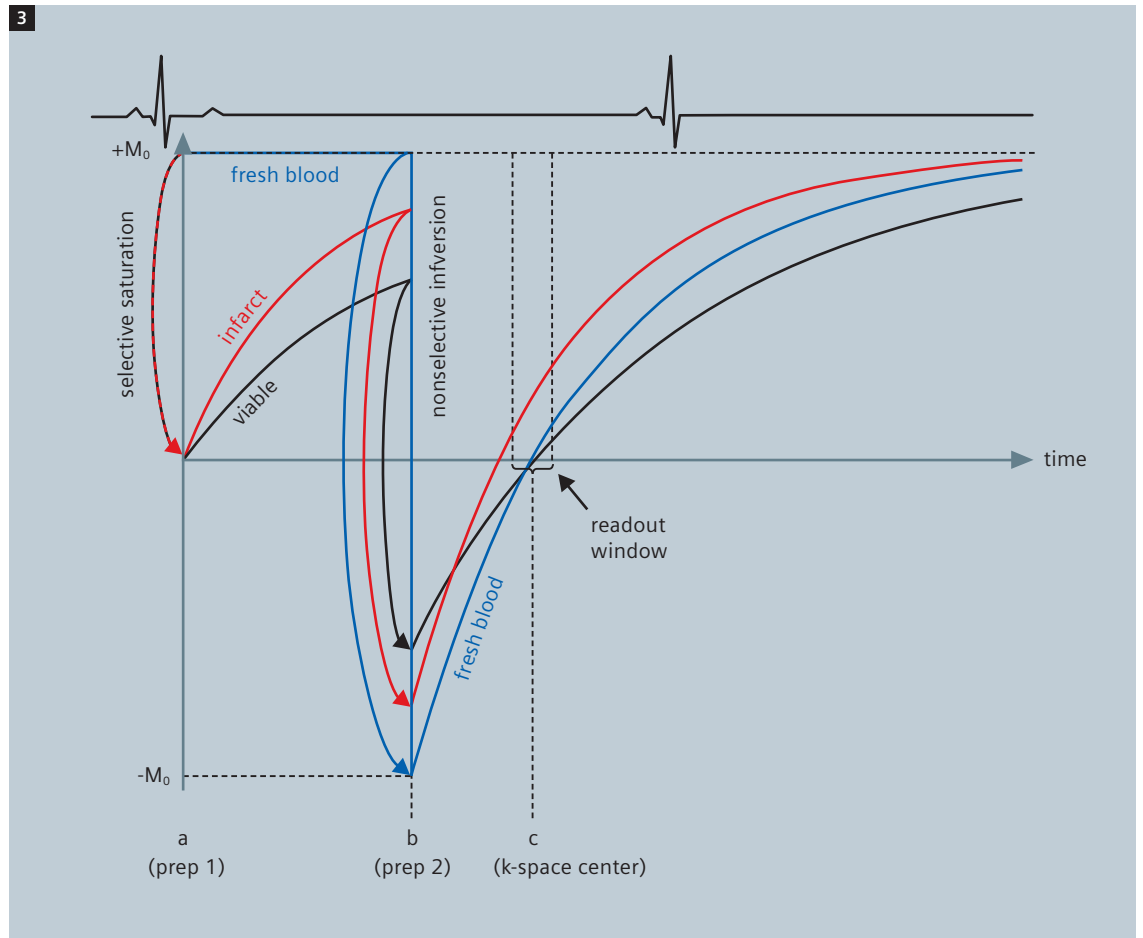
to detect especially if images are acquired early after contrast agent administration in order to increase patient throughput, or if the agent is only slowly cleared from the blood pool due to the patient’s cardiac and renal physiology. In these situations, the new dark-blood viability sequence described in this article can prove very useful. Image contrast between infarct and blood pool is much improved, and contrast between infarct and viable myocardium is slightly reduced, but remains sufficiently high.

Methods

The dark-blood viability sequence simultaneously nulls normal myocardium and blood (two different ‘T1-species’) after contrast agent administration. This goal is achieved through a double preparation scheme. It is different from the classic double IR black-blood preparation first described by Edelman et al. [5] where a non-selective inversion pulse is immediately followed by a slice-selective inversion pulse. This method is routinely employed by the black-blood HASTE sequence, but only works in the absence of a contrast agent. The dark-blood viability WIP overcomes this limitation by separating both preparation pulses in time. The first pulse usually occurs right after the R-wave

2D/3D PSIR and TurboFLASH/TrueFISP IR sequences are provided for delayed enhancement imaging in the Advanced Cardiac Package.

The works-in-progress dark-blood viability sequence simultaneously nulls myocardium and blood.



3 T1-relaxation curves of viable, infarcted myocardium, and blood when playing a selective SR pulse at time a and a non-selective IR pulse at time b. Due to the correctly chosen times between both preparations and the center of k-space at time c the curves of blood and viable myocardium cross zero simultaneously. Hence viable tissue and blood appear dark in the image. Magnetization in the infarct has recovered much more and appears bright. As fresh blood enters the imaging slice after the slice-selective preparation it only experiences the non-selective inversion pulse whereas myocardium experiences both.

For dark-blood viability imaging, myocardium and blood are prepared differently.

and is slice-selective. It is either a saturation-recovery (SR) [6, 7] or an inversion-recovery (IR) pulse [7, 8] as explained in the next section. The second preparation always is a non-selective inversion-recovery pulse. The time between the first and the second preparation and between the second preparation pulse and the readout (of the k-space center) are crucial for creating the desired dark-blood viability image contrast. Figure 3 shows the relaxation curves of viable (black line), infarcted myocardium (red line), and blood (blue line) when playing a selective SR (a – prep 1) and a later non-selective IR pulse (b – prep 2). Relaxation times in this simulation were chosen to mimic contrast agent concentrations that are

present 5 to 10 minutes after intravenous injection of a standard dose. Due to the correctly chosen times between preparations and readout the curves of blood and viable myocardium cross zero at the same time (c – k-space center) so that viable myocardium and blood appear dark in the image. Magnetization in the infarct has recovered much more and appears bright. Note that the technique works because myocardium and blood are prepared differently. Fresh blood enters the imaging slice after the slice-selective preparation. This fresh blood only experiences the non-selective inversion pulse whereas myocardium experiences both.

Using the sequence

TI parameters and image contrast

As it is impractical to manually determine the correct times between preparations and readout during a clinical exam, the sequence calculates these times automatically. Rather than specifying one inversion time TI as done in classic viability imaging (delayed enhancement) to null normal myocardium and user interface parameter TR to move the readout window to diastole, the user now provides two inversion times to simultaneously null normal myocardium and blood. The timing is then calculated by the sequence and the protocol parameters TR and TI are adjusted accordingly. TR and TI are still displayed, yet are no longer directly editable. Instead, the special card parameters "TI blood" and "TI norm myocard" are modified by the user leading to the correct setting of TR and TI. The Sequence/Special card with its TI input fields can be seen in figure 4. For completeness we note that nulling blood and normal myocardium at exactly the same time point as shown in figure 4 for reasons of simplicity will not provide the optimal diagnostic information. If both normal myocardium and blood are black it is difficult to make out the endocardial border and the myocardium. Therefore, it is advantageous to create an image where blood appears black, normal myocardium dark grey and infarct bright. This concept is already included in the WIP sequence and TI and TR are calculated accordingly.

Cardiac mechanics and timing parameters

Two conditions need to be fulfilled for the dark-blood viability sequence to work properly.

1) The slice-selective preparation and data

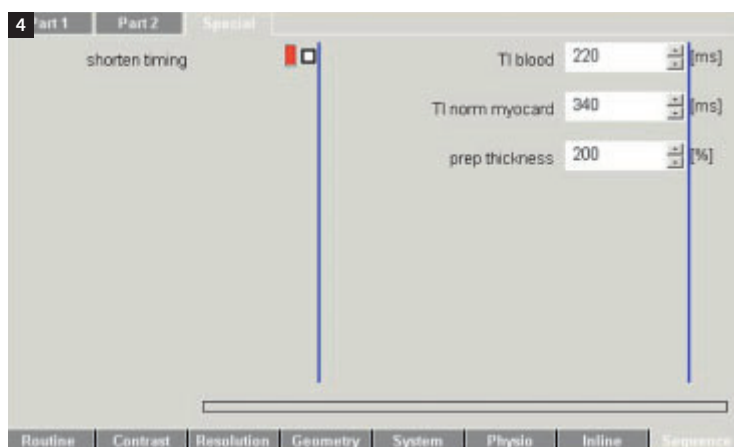
readout need to occur when the heart is in approximately the same position, see figures 5A and 5B. This ensures that the imaged slice is homogeneously prepared. In 5A the slice-selective preparation occurs immediately after the R-wave prior to the onset of systolic contraction and the readout occurs during mid to late diastole of the same heartbeat. In 5B the slice is prepared during mid to late diastole of one heartbeat, and the readout occurs during the same cardiac phase of the next beat. Also, the preparation thickness is usually twice as thick as the readout-slice to homogeneously prepare the readout slice even if it is not positioned exactly in the center of the preparation slice. The preparation slice thickness is a special card parameter and defaults to 200% of the imaging slice thickness. In case of insufficient blood exchange the user may reduce this number to e.g. 170%, but when reduced too much, the myocardium may no longer be homogeneously prepared.

2) In order to replace the selectively prepared blood by fresh blood a systolic contraction needs to occur between the slice-selective preparation and the readout. It is physically impossible to null blood and at the same time to not null infarcted tissue despite their similar T1 values, unless they are differently prepared. This can only be realized through fresh blood in the imaged slice.

Depending on a patient's heart rate, the timing approach of either figure 5A or 5B will work better. The "shorten timing" checkbox on the left side of the Sequence/Special card offers additional timing flexibility. When checked a selective SR pulse is played, otherwise a selective IR pulse is played. As signal recovers faster after a SR pulse than after

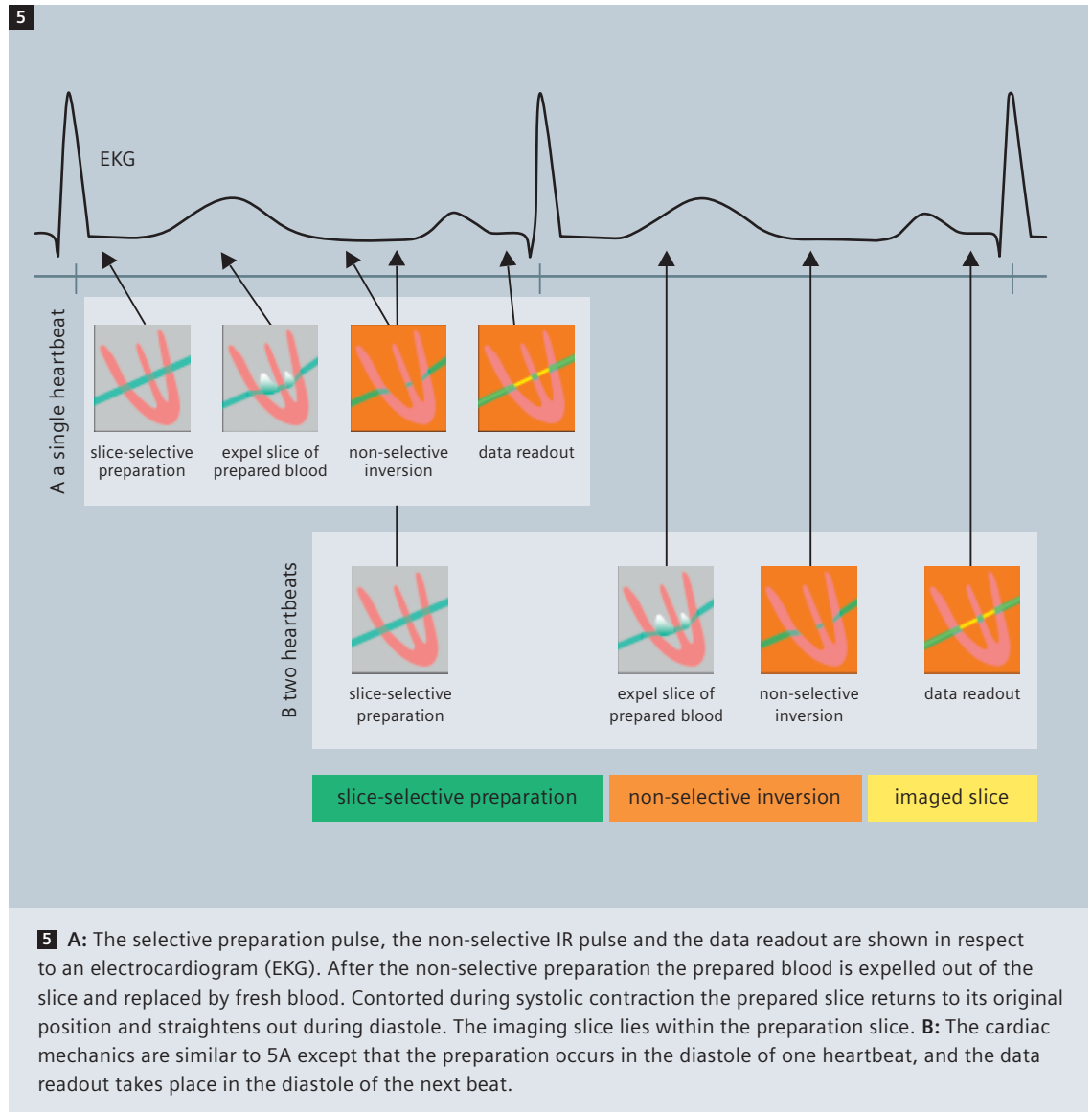
For delineation of endocardial border and myocardium, blood-pool will appear black, whereas the myocardium will appear dark grey.

For choosing between an IR or SR pulse a „shorten timing“ checkbox is provided.



4 The Sequence/Special card showing the "shorten timing" box on the left and the input boxes for inversion times of blood, normal (viable) myocardium, and relative preparation slice thickness on the right.

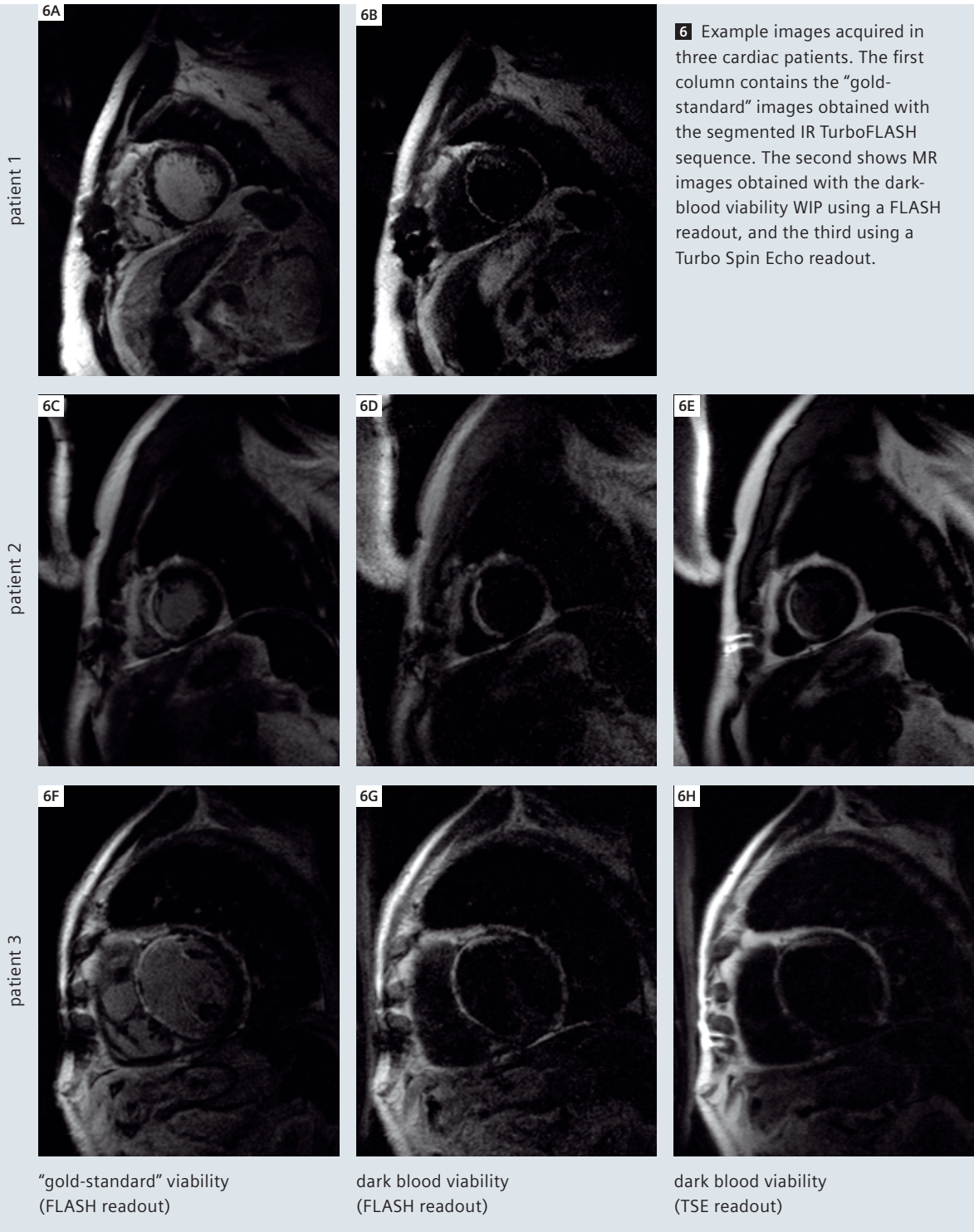
The dark blood viability works-in-progress sequence comes with a FLASH and a TSE readout.



an IR pulse, the time between preparation and readout is shortened, and higher heart rates can be accommodated. The combination of the “shorten timing” checkbox with the timing schemes of 5A or 5B gives the user sufficient options to accommodate any heart rate.

Instead of adjusting the user interface parameters TI and TR during the scan, the scanner operator

now adjusts one TI to null blood and a second TI to null normal myocardium. The scanner operator should possess a basic knowledge of cardiac mechanics as it is required to place slice-selective preparation and data readout in the correct cardiac phases. Only then a homogeneous imaging slice preparation and sufficient blood exchange can be ensured.



Available sequences

Whereas the preparation scheme is identical for all sequences included in the WIP package the data readout techniques vary. For software version *syngo* MR B13 (including MAGNETOM Avanto and MAGNETOM Trio, A Tim System) a segmented Flash, segmented TrueFISP, Turbo Spin Echo (TSE), single-shot Flash, and single-shot TrueFISP version are available. For *syngo* MR 2004A (including the MAGNETOM Sonata) a segmented Flash and Turbo Spin Echo version exists.

Results

Figure 6 shows representative example images acquired in three cardiac patients. The first column contains the “gold-standard” images obtained with the segmented IR TurboFLASH sequence. The second shows MR images obtained with the dark-blood viability WIP using a FLASH readout, and the third using a TSE readout. The images of patient 1 are of particular interest as the gold-standard does not reveal the thin infarcted subendocardial rim in the septum, but the dark-blood viability technique does. The images of patients 2 and 3 show that the infarcted regions in all dark-blood images match those of the gold-standard.

Conclusions

We have described a new dark-blood viability technique that employs a precisely timed double-preparation scheme to render blood black, normal myocardium dark-grey, and infarct bright. When care is taken to ensure that the preparations occur at the proper times in the cardiac cycle, homogeneous preparation with sufficient blood exchange occurs, resulting in high quality dark-blood delayed enhancement images.

The dark-blood viability sequence leads to a better delineation of thin subendocardial scars from the blood-pool.

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