The Various Definitions of TR

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Introduction

In the practice of Cardiac MRI, various definitions of the parameter TR (Time of Repetition) have evolved as gated pulse sequence have become increasingly complex. Understandably this causes significant confusion among most users. In some cases, the original concept of TR seems to be lost. This article describes the various definitions of TR.

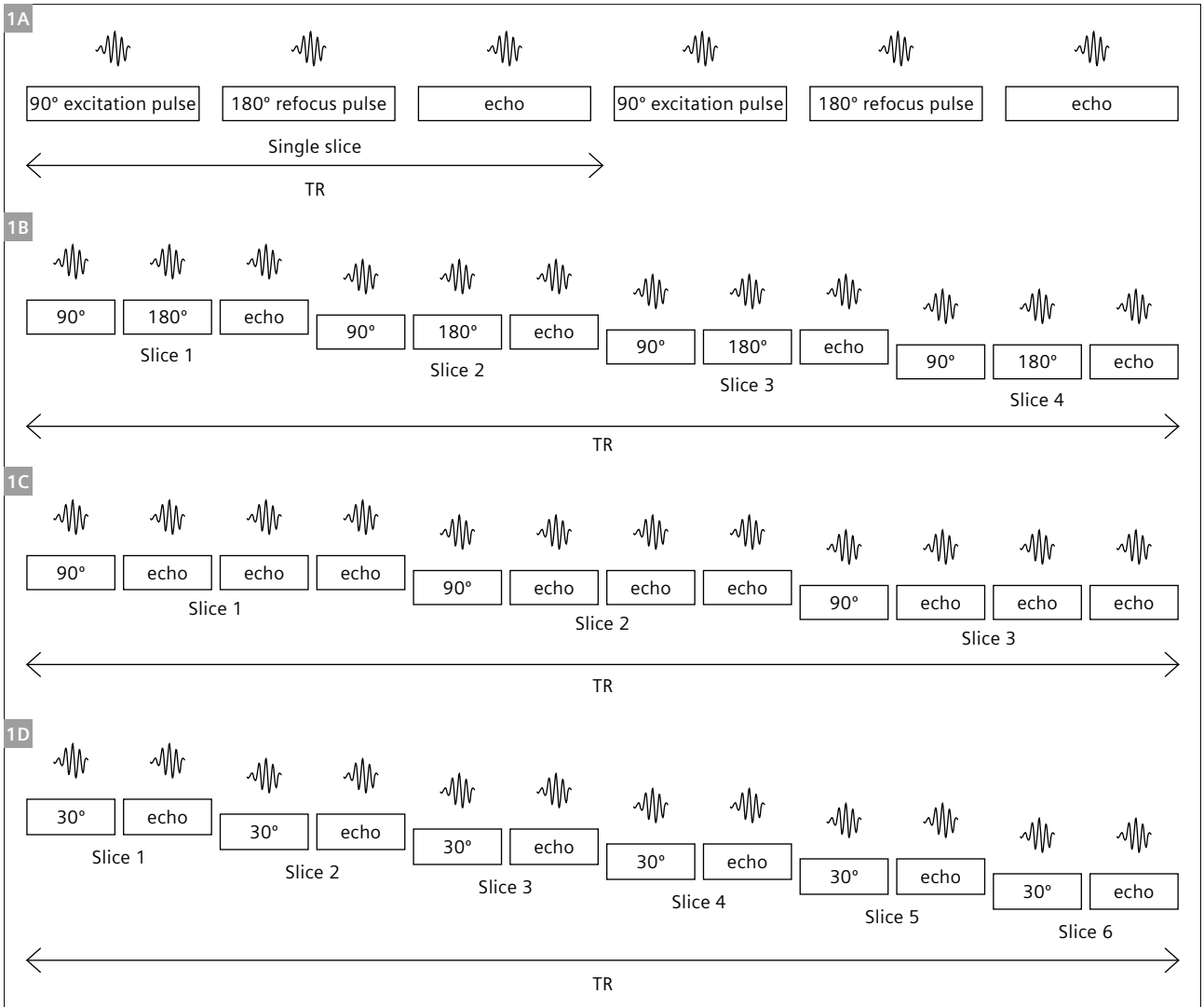


Figure 1:
1A: Single-slice Spin Echo pulse sequence.
1B: Multi-slice Spin Echo pulse sequence.
1C: Multi-slice Turbo Spin Echo pulse sequence.
1D: Multi-slice Gradient Recalled Echo pulse sequence.

Definition 1

The conventional definition of TR is the repetition time between successive excitation pulses for the same slice. This is demonstrated by a single-slice Spin Echo (SE) pulse sequence in which each slice consists of a 90° excitation pulse, a refocusing pulse, and an echo (Fig. 1A).

This conventional definition of TR also applies to a multi-slice SE pulse sequence in which as many slices as possible are interleaved within the selected TR (Fig. 1B). For T1 weighting we typically select a relatively short TR (< 1000 ms),or for T2 weighting a relatively long TR (> 2000 ms).

This conventional definition of TR also applies to a multi-slice Turbo Spin Echo (TSE) pulse sequence in which each slice consists of a single excitation pulse with multiple refocusing pulses and multiple echoes (Fig. 1C). Since there are more echoes per slice, a TSE sequence requires fewer repetitions than a SE sequence with the same TR, but accordingly fewer slices may be acquired within the selected TR.

This conventional definition of TR also applies to a multi-slice Gradient Recalled Echo (GRE) pulse sequence which contains no refocusing pulses at all (Fig. 1D). Each slice consists of a single excitation pulse and a series of gradient reversals to form an echo. TR is defined as the time between successive excitation pulses for the same slice in a GRE sequence, just like in SE and TSE sequences.

Definition 2

When a pulse sequence is cardiac triggered, the definition of TR can become a bit more complicated. Often the TR displayed in the user interface does not reflect the conventional definition of TR, but instead is used to define some other aspect of sequence timing relative to the cardiac cycle. In the discussion that follows, the TR displayed to the user will be denoted $TR_{protocol}$, while the effective TR, defined conventionally as the time between successive excitation pulses, will be indicated as $TR_{effective}$.

When cardiac triggering is used in a multi-slice spin-echo sequence, the $TR_{effective}$, according to the conventional definition, is the repetition time between successive heartbeats. This is demonstrated by a cardiac triggered multi-slice SE pulse sequence (Figure 2A), but may apply as well to multi-slice TSE and GRE pulse sequences. Each slice is excited only once per heartbeat, so $TR_{effective}$ equals the R-R interval. As the heart-rate increases, the $TR_{effective}$ decreases because the R-R interval decreases. Since each slice is acquired at a different phase of the cardiac cycle, this technique is often called a multi-slice multi-phase cardiac triggered pulse sequence. On the other hand, $TR_{protocol}$ for such a sequence is defined as the time actually used to acquire all the slices within the cardiac cycle.

A common method to increase the $TR_{effective}$ is to trigger the pulse sequence on every second or third heartbeat (Fig. 2B), in which case $TR_{effective}$ is twice or three times the R-R interval. This strategy is often used to control the image contrast for T2-weighted or IR-weighted pulse sequences.

Definition 3

Cardiac triggered cine pulse sequences create a movie effect of the beating heart or flowing blood by acquiring a series of images at different phases throughout the cardiac cycle. Various types of cine techniques include TrueFISP, Flash, Phase Contrast, and Grid-Tagging pulse sequences. The $TR_{protocol}$ definition for a cine sequence is the repetition time between consecutive cardiac phases, also known as the Temporal Resolution of the sequence. This definition of TR is demonstrated by a simple cardiac triggered cine pulse sequence (Fig. 3A), in which only one echo is acquired per cardiac phase (non-segmented). In this non-segmented acquisition, the $TR_{protocol}$ represents both the repetition time between successive cardiac phases (Temporal Resolution) and the repetition time between successive excitation pulses ($TR_{effective}$).

Often, however, multiple echoes are acquired per cardiac phase to reduce the required number of repetitions (Fig. 3B), a scheme called “segmented” data collection. In a segmented cine pulse sequence the $TR_{protocol}$ represents the repetition time between the center echo of successive cardiac phases (Temporal Resolution) but no longer represents the repetition time between successive excitation pulses ($TR_{effective}$). The Temporal Resolution in Figure 3B is five times longer than in Figure 3A, although the echo spacing ($TR_{effective}$) is the same in both.

If the center echo is re-sampled between successive segments, and echoes are shared from the prior and next segments, the Temporal Resolution can be improved by reducing the center-spacing between successive phases (Fig. 3C). In an “echo-shared segmented” cine pulse sequence, $TR_{protocol}$ represents the repetition time between the center echo of successive cardiac phases (Temporal Resolution), and is always less than the comparable $TR_{protocol}$ without echo-sharing. In this example of an echo-shared segmented cine pulse sequence, the total number of echoes acquired per repetition is six (5 + 1), however the $TR_{protocol}$ (Temporal Resolution) after echo-sharing is only three echoes (6 : 2).

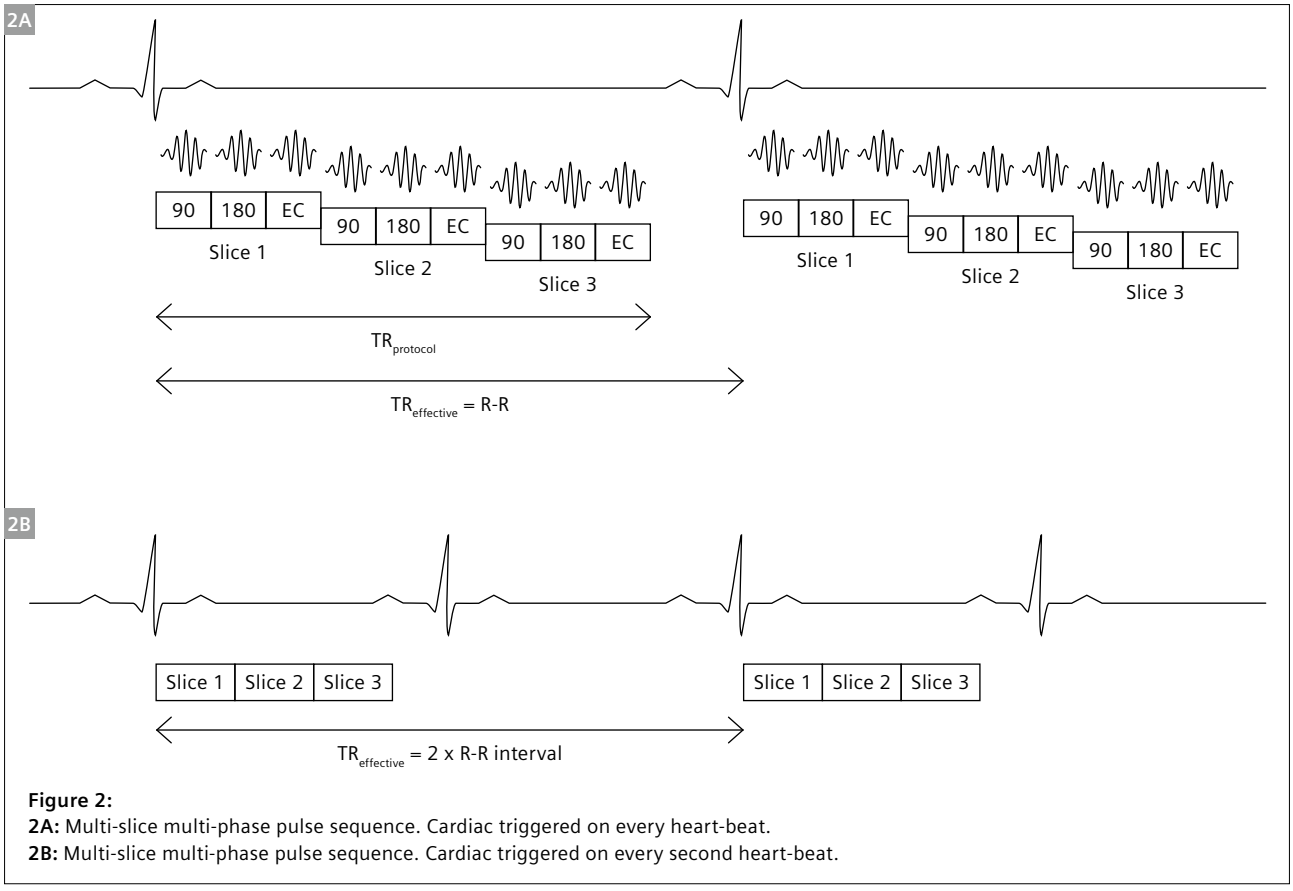
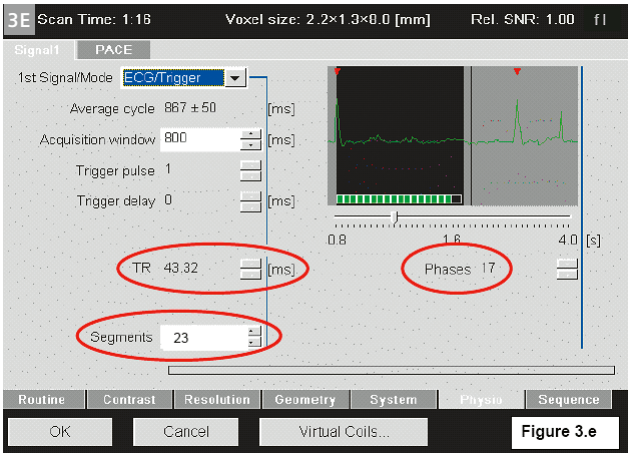


Figure 2:
2A: Multi-slice multi-phase pulse sequence. Cardiac triggered on every heart-beat.
2B: Multi-slice multi-phase pulse sequence. Cardiac triggered on every second heart-beat.

Figures 3D and 3E demonstrate an example of an echo-shared segmented GRE cine pulse sequence.
In this example the total number of echoes acquired per repetition is twenty four (23 + 1), however the effective temporal resolution with echo-sharing is only twelve echoes (24 : 2) with a spacing of 43.32 ms between the centers of successive phases.

- The total number of cardiac phases is 17.
- The number of echoes per phase is 23.
- The temporal resolution per phase is 43.32 ms.



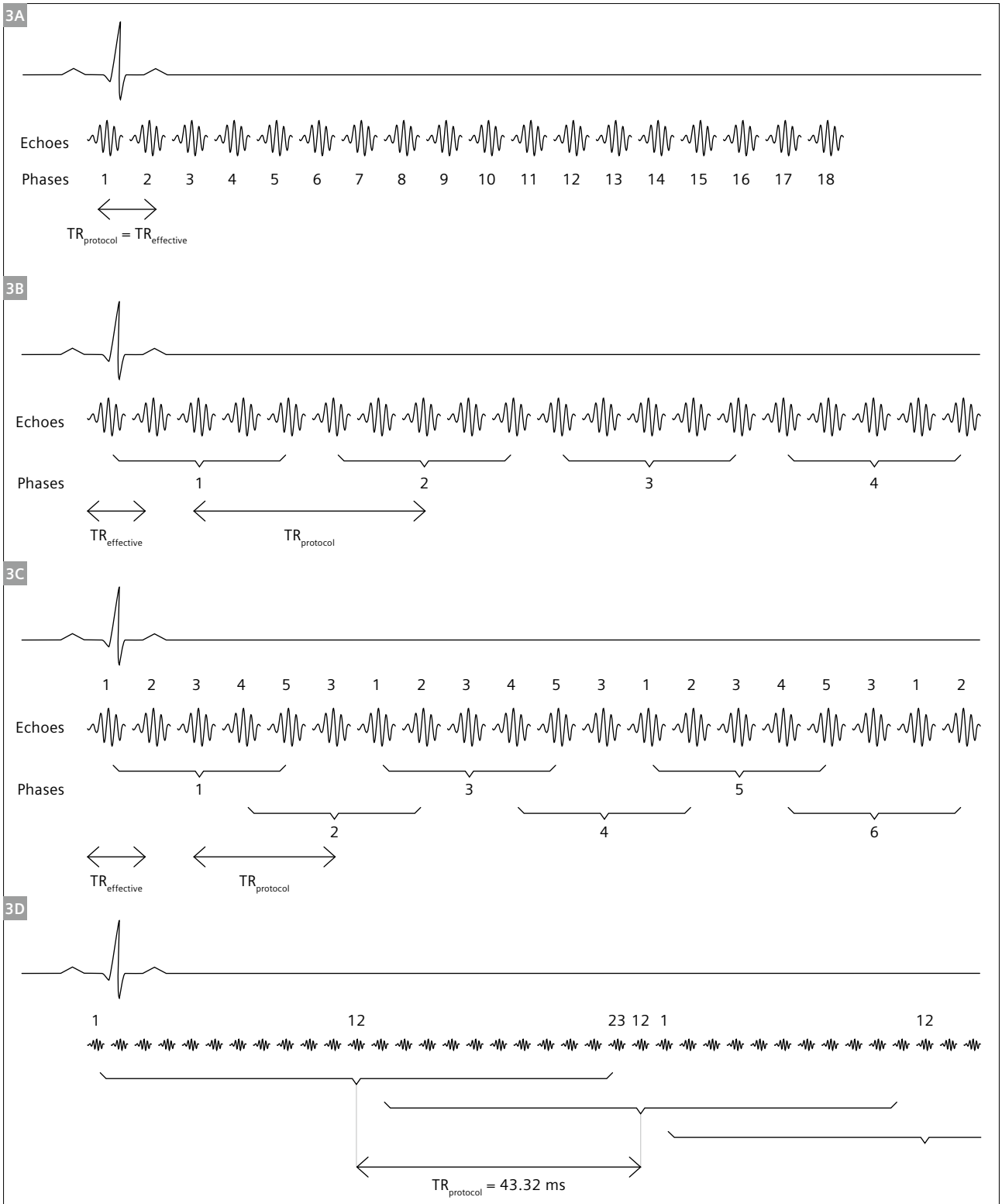


Figure 3:
3A: Cardiac triggered cine pulse sequence. Non-segmented data collection.
3B: Cardiac triggered cine pulse sequence. Segmented data collection.
3C: Cardiac triggered cine pulse sequence. Echo-shared segmented data collection.
3D: Echo-shared segmented GRE sine pulse sequence.

Definition 4

Some cardiac triggered pulse sequences produce a single static image rather than cine images of the heart, and have yet a different definition of $TR_{protocol}$ (Figs. 4A, B). The $TR_{protocol}$ represents the minimum time needed to collect the train of echoes for a single diastolic-triggered segment. You should always set the $TR_{protocol}$ to its minimum possible value in this situation. You can still think of the minimum $TR_{protocol}$ as the Temporal Resolution of the sequence, but there is only one image produced rather than a cine series. This applies to any non-cine cardiac triggered pulse sequence containing no Inversion Recovery (IR) or Saturation Recovery (SR) preparation pulses. Examples of cardiac triggered pulse sequences using this definition of TR include TrueFISP 2D localizers and Flash 2D angiography techniques.

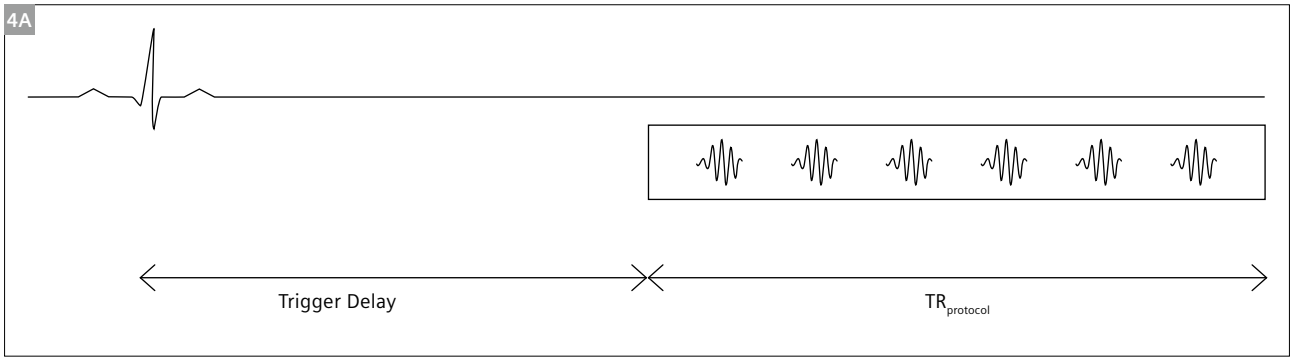
As demonstrated in the *syngo* Physio Taskcard for a segmented TrueFISP 2D localizer pulse sequence (Fig. 4B):

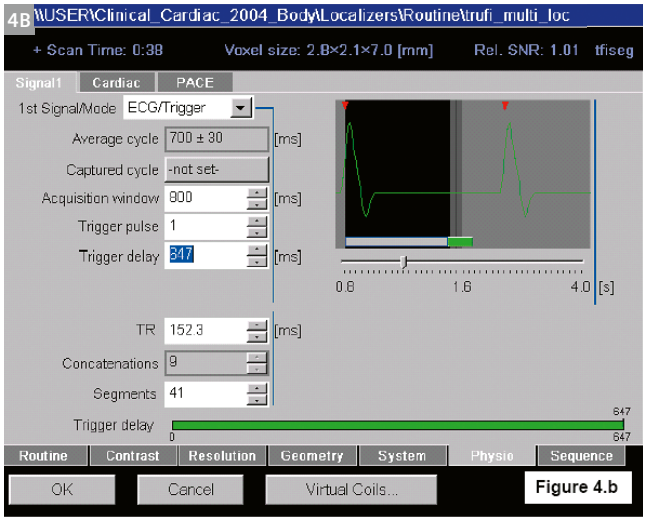
- The total number of echoes in the segment is 41.
- The temporal resolution of the segment is 152.3 ms (green bar).
- The trigger delay prior to the segment is 647 ms (grey bar).

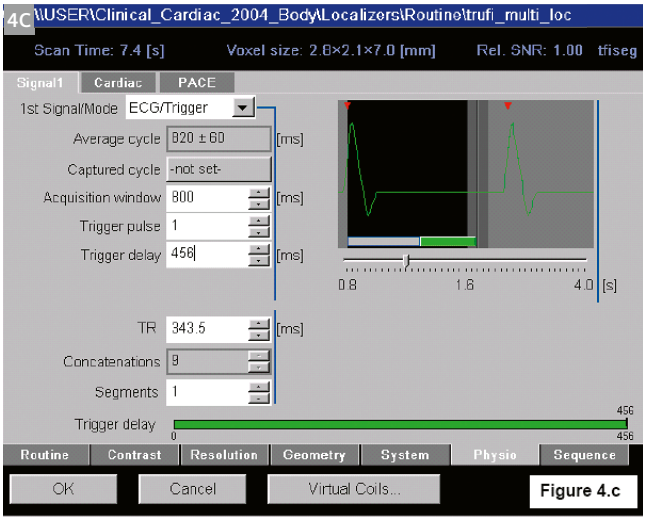
In the previous example of a TrueFISP 2D localizer pulse sequence (Fig. 4B) only 41 echoes were collected per heartbeat, so several heartbeats were required to completely create the image. Such a scheme is known as "segmented" data collection. However, the same pulse sequence could be slightly modified to operate as a "single-shot" data collection in which all the echoes needed to create the image are collected in one long segment within a single heartbeat (Fig. 4C). The temporal resolution is still defined as the minimum time to collect all the echoes (minimum $TR_{protocol}$), but it is much greater than in the previous example because many more echoes are collected in the segment.

As demonstrated in the *syngo* Physio Taskcard for a single-shot TrueFISP 2D localizer pulse sequence (Fig. 4C):

- There is only 1 segment which contains of all the required echoes.
- The temporal resolution of the segment is 343.5 ms (green bar).
- The trigger delay prior to the segment is 456 ms (grey bar).







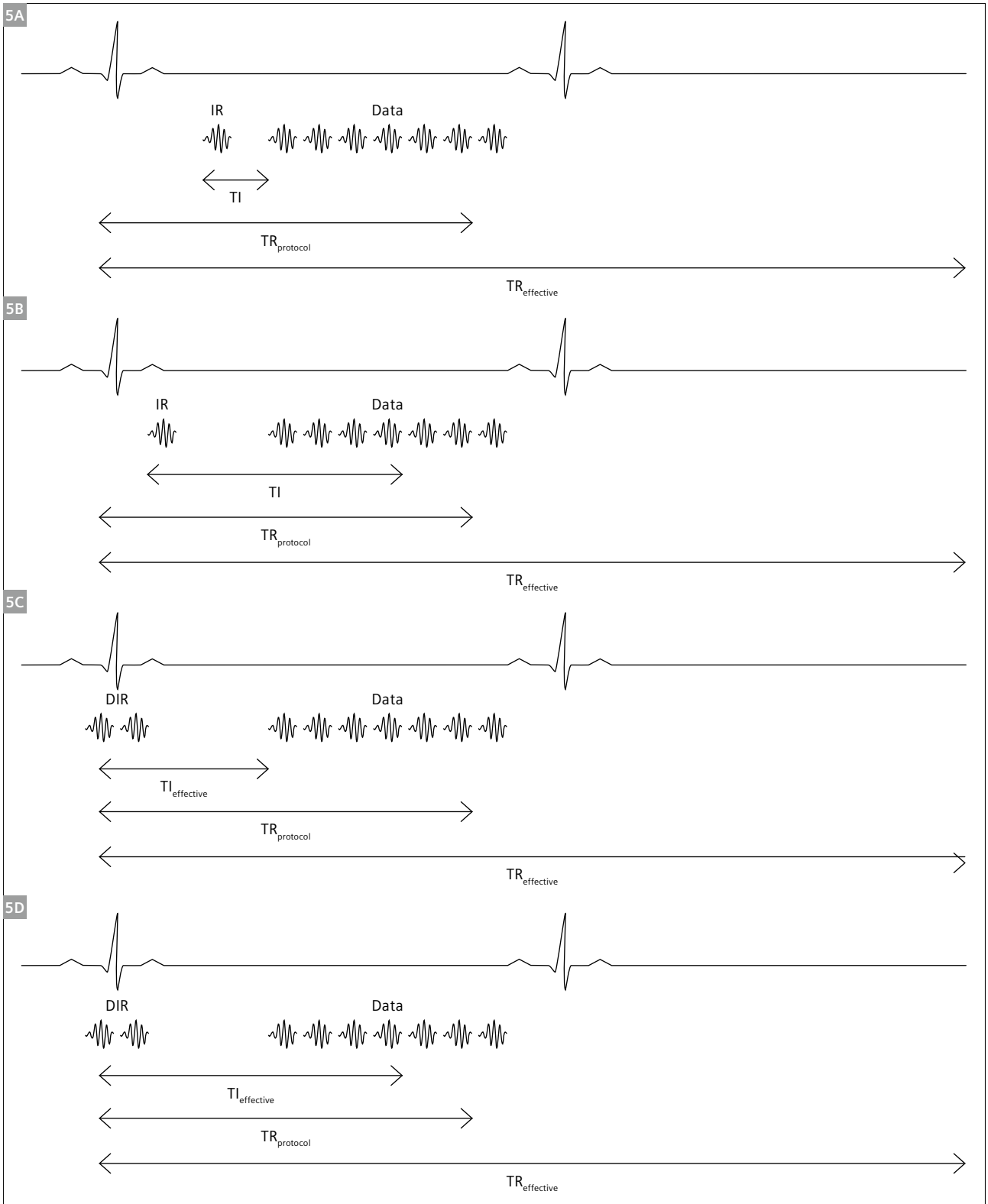
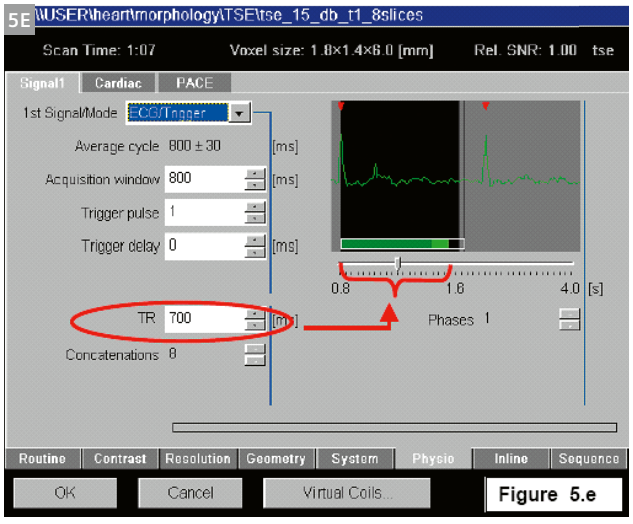


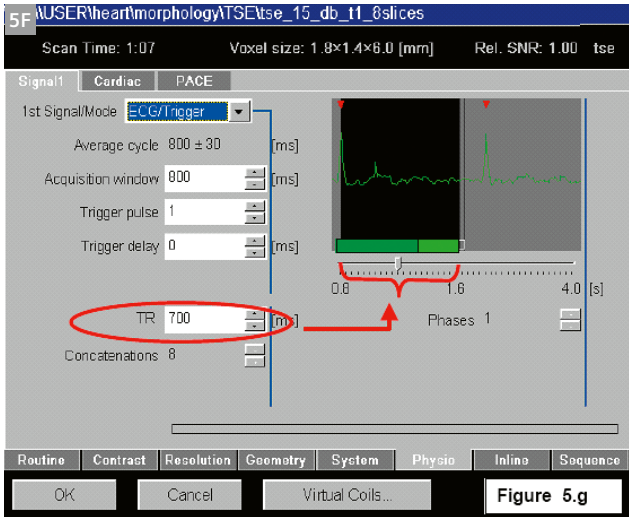
Figure 5:
5A: Cardiac triggered IR TSE pulse sequence. Adjust TI for optimal fat nulling.
5B: Cardiac triggered IR GRE pulse sequence. Adjust TI for optimal myocardial nulling.
5C: Cardiac triggered DB TSE pulse sequence. Adjust $TR_{protocol}$ for optimal blood nulling.
5D: Cardiac triggered DB GRE pulse sequence. Adjust $TR_{protocol}$ for optimal blood nulling.

Definition 5

Yet another definition of TR applies to a cardiac triggered pulse sequence containing an Inversion Recovery (IR) preparation pulse (Figs. 5A, B). The $TR_{protocol}$ is defined as the time between the QRS trigger and the end of the data segment, and is used to adjust the timing of the data segment within the cardiac cycle. In an IR TSE pulse sequence the TI is defined as the time between the IR preparation pulse and the beginning of the data segment (Fig. 5A), and is typically adjusted for optimal fat nulling. In an IR GRE pulse sequence the TI is defined as the time between the IR preparation pulse and the center of the data segment (Fig. 5B), and is typically adjusted for optimal myocardial nulling. In these sequences the data segment is typically acquired every other heartbeat, so the $TR_{effective}$ is twice the R-R interval.

In order to null the signal from flowing blood, we can apply a Double Inversion Recovery (DIR) preparation pulse at the QRS trigger and wait several hundred milliseconds to acquire the data segment in the late diastolic portion of the cardiac cycle (Fig. 5C). The DIR pulse, also known as a Dark Blood (DB) pulse, is available for Turbo Spin Echo, TrueFISP, and TurboFlash pulse sequences. The TR in the protocol ($TR_{protocol}$) is defined as the time between the DB pulse and the end of the data segment. Since there is no TI available in a DB protocol, the $TR_{protocol}$ is used to adjust the location of the data segment for optimal blood nulling. Figure 5C demonstrates a cardiac triggered DB TSE pulse sequence in which the effective inversion delay time for blood nulling ($TI_{effective}$) is measured from the DB pulse to the beginning of the data segment. Figure 5D demonstrates a cardiac triggered DB GRE pulse sequence in which $TI_{effective}$ is measured from the DB pulse to the center of





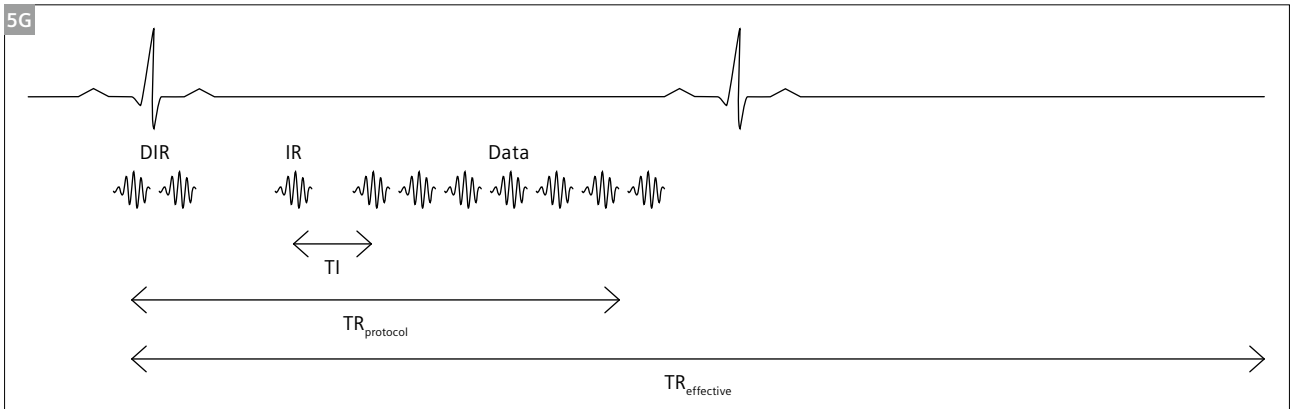


Figure 5:
5G: Cardiac triggered DB STIR pulse sequence. Adjust $TR_{protocol}$ for optimal blood nulling. Adjust TI for optimal fat nulling.

the data segment. In these sequences the data segment is typically acquired every other heartbeat, so the $TR_{effective}$ is twice the R-R interval.

In the example of the *syngo* Physio Taskcard for a DB TSE pulse sequence (Fig. 5E) the TR of 700 ms includes the DB pulse (at the ECG trigger), the inherent inversion delay time (dark-green bar), and the data segment (light-green bar). Trigger delay must be zero because the inversion delay is included within TR.

If we add a third IR preparation pulse to a double IR TSE pulse sequence, we have a Dark Blood STIR pulse sequence (Fig. 5G). $TR_{protocol}$ is adjusted for optimal blood nulling and $TI_{protocol}$ is adjusted for optimal fat nulling. In these sequences the data segment is typically acquired every other heartbeat, so the $TR_{effective}$ is twice the R-R interval.

Figure 5F is an example of the *syngo* Physio Taskcard for a DB STIR pulse sequence. The dark-green bar within the TR includes the Double IR pulse and the inversion delay time for blood nulling. The light-green bar within the TR includes the single IR pulse and the inversion delay time for fat nulling, plus the data segment. Trigger delay must be zero because the inversion delay is included within the TR.

Another example is a FatSat IR Flash 3D pulse sequence for coronary angiography, without a Navigator pulse (Fig. 5H) or with a Navigator pulse (Fig. 5I). The TI is measured from the IR pulse to the beginning of the data segment (centric ordering) and is adjusted for optimal myocardial nulling. The FatSat pulse immediately precedes the data segment. The navigator pulse immediately precedes the FatSat pulse. There is no double IR pulse for blood nulling.

Definition 6

Yet another definition for TR is used in the IR- or SR-prepared GRE (TurboFlash or TrueFISP) pulse sequences (Fig. 6A). These sequences can be used for T1-weighted single-shot imaging that requires multiple slices acquired within a single heartbeat with high temporal resolution. $TR_{protocol}$ consists of the minimum time duration needed for the SR preparation pulse, plus the delay period thereafter, plus the data segment. $TR_{protocol}$ can be thought of as the "time per slice." TI is measured from the IR- or SR-preparation pulse to the center of the data segment, and is adjusted for optimal myocardial signal.

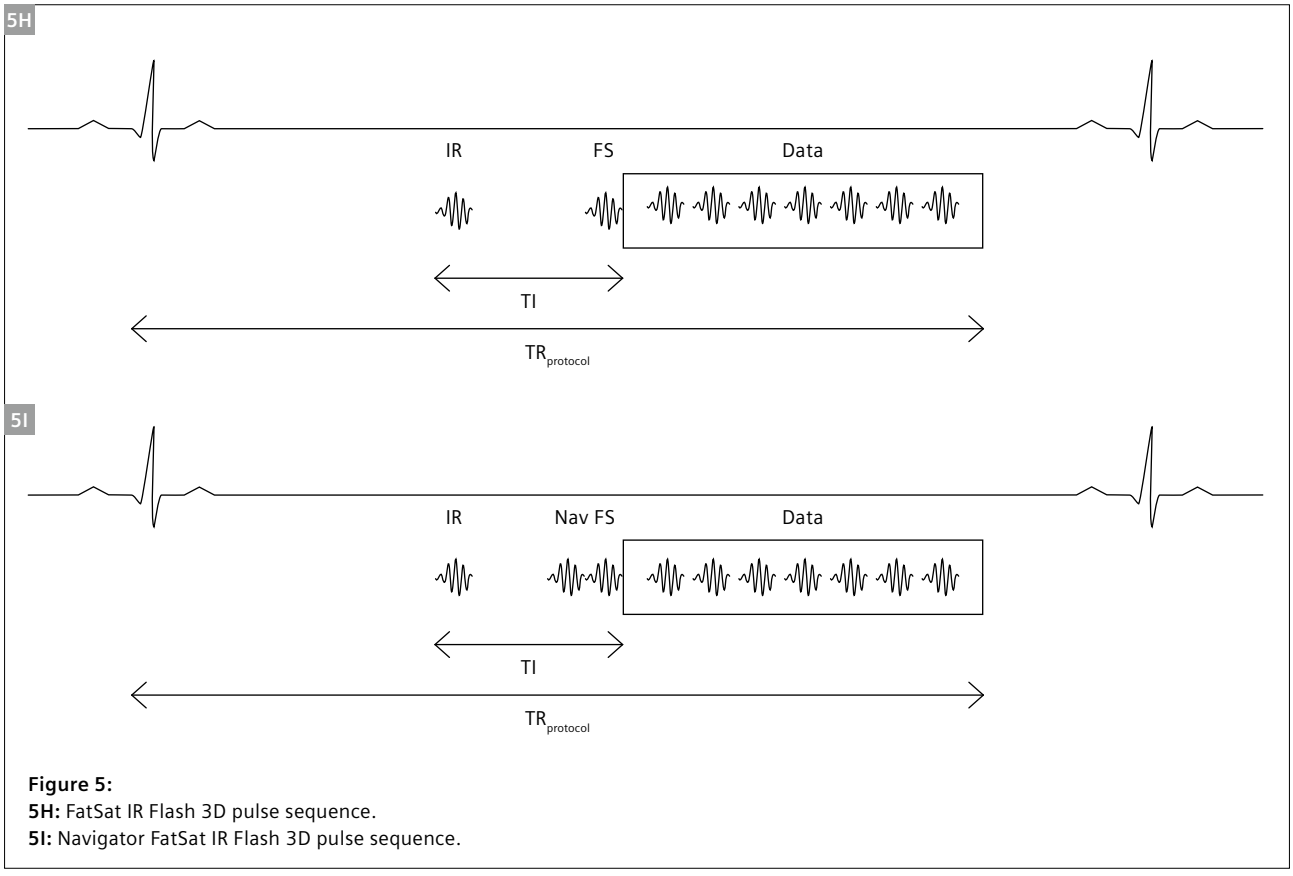


Figure 5:
5H: FatSat IR Flash 3D pulse sequence.
5I: Navigator FatSat IR Flash 3D pulse sequence.

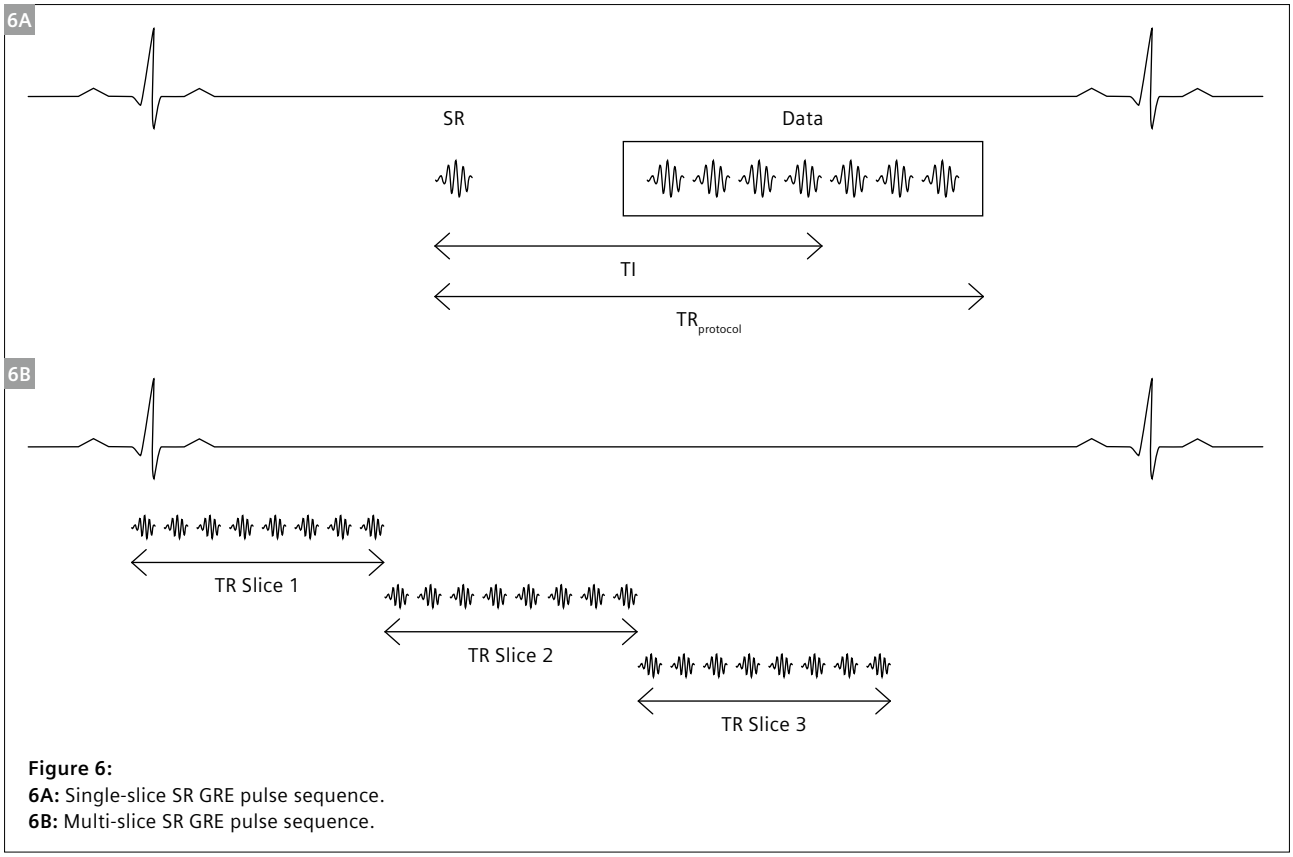


Figure 6:
6A: Single-slice SR GRE pulse sequence.
6B: Multi-slice SR GRE pulse sequence.

SR Data

In an SR GRE pulse sequence the data segment is a "single-shot" of all required echoes for the entire slice. Typically, 3 to 5 slices can be acquired within each heartbeat (Figs. 6B, C).

While the physical definition of TR will always mean only one thing, the time between successive excitation pulses, a number of variations have resulted from the necessity of controlling a pulse sequence within the cardiac cycle. Hopefully, this brief explanation with diagrams will make it a little easier for everyone to understand.

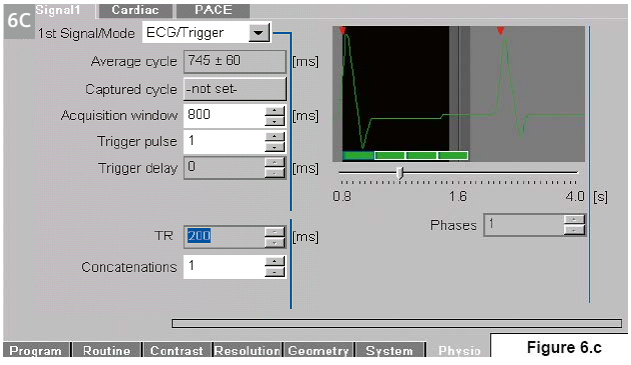


Figure 6.c

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