Advancements in the ECG-Gated Contrast-Enhanced MR Angiography

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Introduction

For most of the current contrast-enhanced MR angiography (CE-MRA) examinations, the acquisition is optimized for the image contrast enhancement by matching the contrast arrival timing with the acquisition of the central phase encoding steps (i.e. time-to-center, TTC) [1]. The total scan time is kept short within a breath-hold length (less than 25 s) to suppress bulk breathing motion. Typically, the CE-MRA data are acquired without ECG-gating in a single continuous delayed centric trajectory (Fig. 1, non-gated CE-MRA). While, for most purposes, this approach is entirely satisfactory, in CE-MRA of the thorax the cardiac chambers and ventricular outflow vessels can be delineated with a certain degree of blurring with non-gated acquisition. To address this limitation, CE-MRA can be acquired with ECG gating, whereby the segmented data acquisition is synchronized with the cardiac cycle [2, 3, 4] (Fig. 1, gated CE-MRA).

The current product version of the CE-MRA sequence (fl3d_ce) supports ECG gating with a *rigid* trigger segmentation (Fig. 2, conventional gated CE-MRA). For every trigger pulse, the conventional gated CE-MRA acquires all phase encoding steps for a single value of the slice encoding gradient. The acquisition is then repeated in linear order for all slice encoding values. With a suitable trigger delay (TD), the center of *k*-space in the inner loop (i.e. phase-encoding) direction ($k_y = 0$) can be acquired outside of the systolic phase, where the cardiac motions are most prominent. With proper contrast injection timing, the arterial window can still be matched with the center of the *k*-space in the outer loop (i.e. slice encoding) direction. With this scheme, the total scan time corresponds to the average R-R interval multiplied by the total number of slice encoding steps.

The major drawback of this conventional gated CE-MRA approach is its acquisition inefficiency. A typical high-resolution non-gated CE-MRA protocol uses short TR times of 2.7 ms and less than 200 phase encode steps in k_y direction. Hence, the data acquisition window during each heartbeat is much shorter than the average R-R interval, which reduces the efficiency

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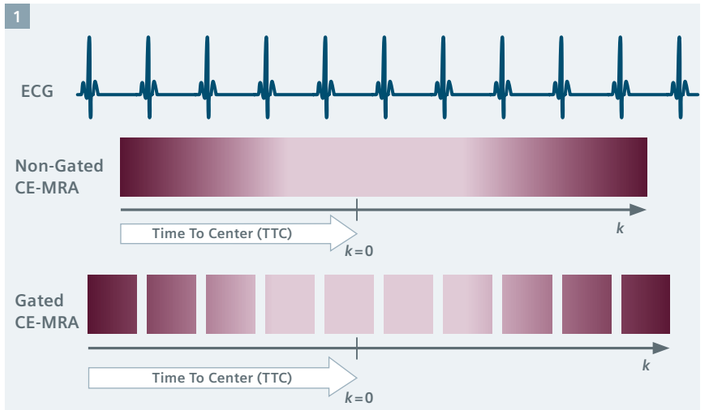

1 Non-gated CE-MRA vs. gated CE-MRA. Darker purple color bar represents the outer *k*-space in both phase (k_y) and slice (k_z) encoding steps, and the lighter purple represents the inner *k*-space. The center of both phase and slice encoding steps (k_y=0, k_z=0) is represented by *k*=0. Typically in CE-MRA, the contrast arrival timing is matched with the center acquisition of the phase and slice encoding steps (i.e. considering the time-to-center, TTC) for the optimal image contrast. For non-gated CE-MRA, the data is acquired in a single continuous delayed centric trajectory, where phase and slice encoding steps start from the outer k-space, then acquire inner *k*-space & *k*=0, and finally the rest of the outer*k*-space to complete the scan. For the gated CE-MRA, the acquisition is segmented (e.g. Fig. 2) and acquired in sync with the ECG-triggering.

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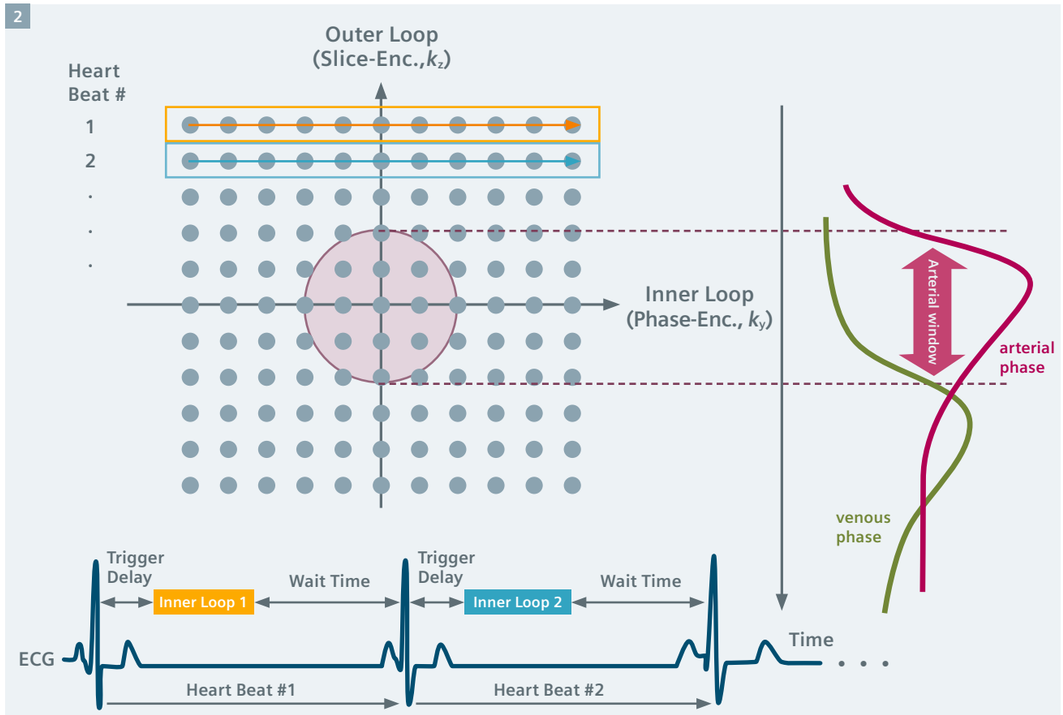

2 The conventional approach to ECG-gated CE-MRA. In each heartbeat, all phase-encoding steps of a single slice-encoding line are acquired. The TTC can be matched with the contrast timing since each triggered shot is acquired in linear order in slice direction.

of the acquisition. Furthermore, the conventional gated CE-MRA technique cannot reduce scan time by taking advantage of parallel acquisition technique (iPAT) and partial Fourier in phase encoding direction; if either of these parameters is modified, the total scan time remains the same since conventional CE-MRA only a single complete inner loop is played out per heartbeat, regardless of its duration.

Moreover, the unpredictable nature of the ECG-triggering adds some uncertainty to the gated CE-MRA method. While the sequence assumes a steady R-R interval and uses a fixed acquisition window, due to physiological irregularities (the R-R interval can vary during a breath-hold [5]) and mechanical imperfections (ECG detection device can fail), trigger events can be either detected too early or too late to substantially increase the scan time. The CE-MRA sequence has a strict timing requirement with the contrast arrival, and any deviation from this may result in a contrast washout with missed optimal timing.

This paper highlights recent advancements in the ECG-gated CE-MRA approach* that address these shortcomings. With these advancements, high-resolution, full coverage ECG-gated CE-MRA exams can be realized within a single breath-hold.

* The sequence is currently under development and is available as a work-in-progress package (#691B for VB17A and #791 for VD11D/13A); it is not for the sale in the US and other countries. Its future availability cannot be guaranteed.

Flexible trigger segmentation

To improve the efficiency of the rigid trigger segmentation in conventional gated CE-MRA, we propose a *flexible* approach (Fig. 3). Here, the inner loop is not restricted to a single dimension in *k*-space. The points that are sampled within the individual triggered segments are determined with a fuzzy pseudo-random algorithm. As a result, the size and shape of the triggered segments are no longer restricted. In addition, the flexible triggered segmentation can freely adjust the acquisition order, both *within* and *in between* triggered segments.

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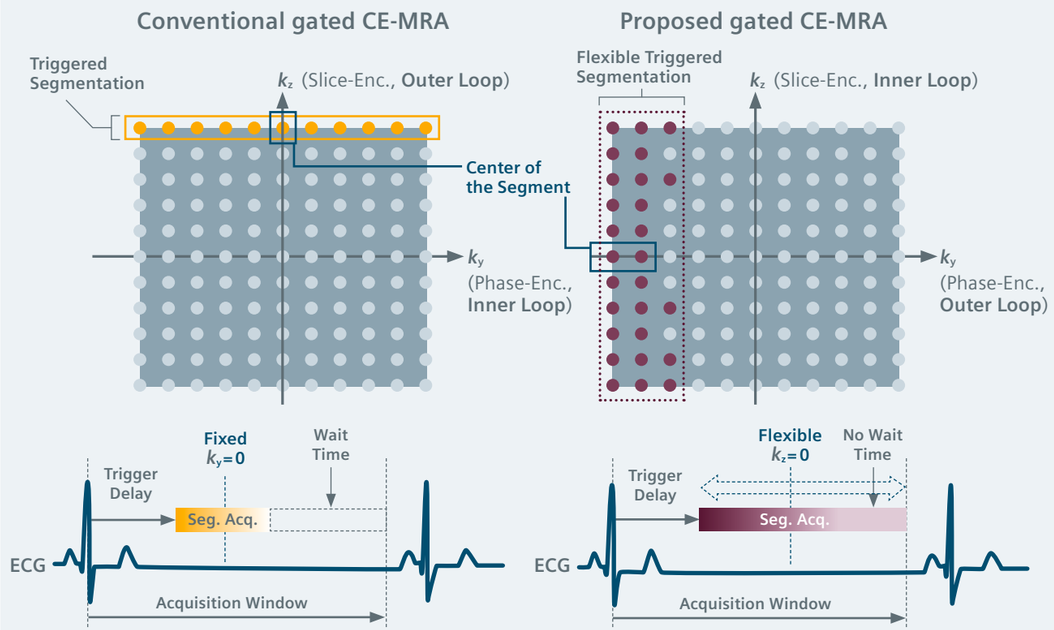

3 The conventional gated CE-MRA with rigid triggered segmentation vs. the proposed gated CE-MRA with flexible triggered segmentation. The flexible triggered segmentation can fill in any unnecessary wait time after the data acquisition window (seq. acq.), and thus more efficient. Note that even with the proposed flexible triggered segmentation, the total efficiency is around 70% due to the trigger delay needed for avoiding cardiac motion during systolic phase. Furthermore the center of the triggered segments can be specified with the flexible triggered segments, while the rigid triggered segments case will be fixed somewhere in the middle of the acquisition window.

Scan efficiency improvements with flexible triggered segmentations

With a flexible size of the triggered shots, the sequence can utilize essentially all of the available time in the acquisition window, which helps reduce unnecessary wait time. In practice, this alone can improve the scan efficiency of a gated CE-MRA acquisition to values close to 70%, which is more than twice the conventional gated CE-MRA of approx. 30%. Furthermore, the flexible segmentation is compatible with conventional scan time reduction methods such as iPAT, partial Fourier, and elliptical scanning.

The rigid trigger segmentation can potentially improve the scan efficiency by acquiring multiple complete phase encoding lines since each trigger segment acquisition is typically far shorter than the RR interval (as shown in Fig.3). This, however, is still restricted since the *in-vivo* RR interval can never match to the exact integer multiples of the complete phase encoding lines. Also the scan efficiency varies according to the actual heart rates, and on shorter extreme of the RR interval the gated CE-MRA cannot be performed.

Cardiac motion suppression with flexible center of the triggered segmentations

In the conventional gated CE-MRA, only the PE steps for a single partition encoding step are acquired. This corresponds to the comparatively short acquisition duration. In order to reduce the pulsatile cardiac motion, these triggered segment acquisitions are positioned in diastole (i.e. the quiescent phase with the minimal cardiac motion). With the proposed sequence, the time used for each individual triggered segment acquisition has been increased in order to use the RR interval more efficiently. In order to achieve this, we need a flexible reordering that (1) assigns more *k*-space points to each triggered segments, and (2) makes sure that the most important data points within each shot (lines close to *k*-space center, k_z=0 in Fig.3) are still acquired in diastole. In the proposed sequence, the linear-centric reordering (e.g. combination of linear and centric reordering, with simple example shown in Fig.4) enables this regardless of the size and the shape of the triggered segments. The user interface parameter 'Time-To-Center (TTC) per Heart Beat (HB)' (located on the Sequence Special Card) is utilized to specify the center of the triggered segment acquisition timing, and this can be set to anywhere within the acquisition window.

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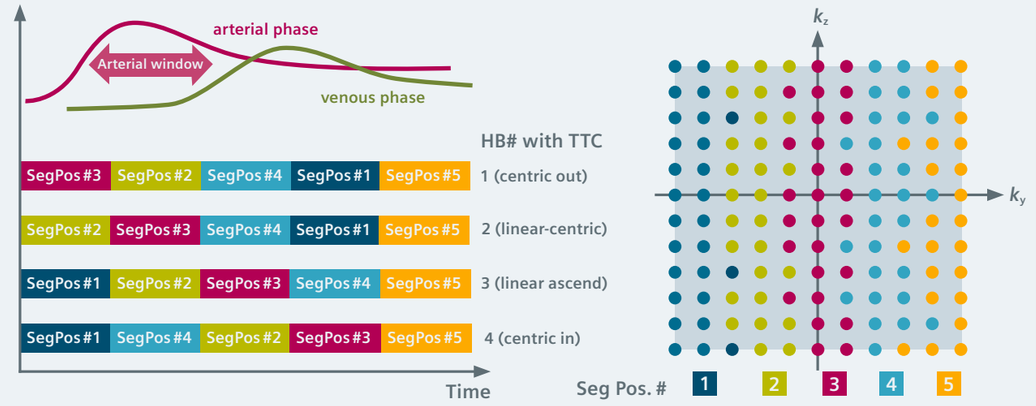

4 Schematic diagram of the flexible inter-triggered shot ordering. Each triggered shot is represented by the different color on the k_y-k_z map (right), and has assigned ShotPos# in linear ascending order. The figure on the left represents the overall triggered shot acquisition timing relative to the contrast injection. The overall TTC is defined as the time from the beginning of the scan to the acquisition of the center positioned segment (in above example, SegPos#3).

Contrast timing optimization with flexible triggered segments reordering

The order of the inter trigger shots is also flexible in the proposed approach. With the linear-centric algorithm, the user can specify when to acquire the triggered shot that encompasses the *k*-space center (k_y=0, k_z=0, ShotPos#3 in the example in Fig.4). In analogy to the 'TTC' parameter in the non-gated CE-MRA, the user interface parameter 'overall TTC' calculates and adjusts the triggered shot ordering to the closest match.

User interface (UI) improvements

From user perspective, the flexible triggered segmentation in the proposed gated CE-MRA translates into an intuitive UI experience: For TTC per HB, for the specific cardiac phase timing only one additional UI parameter was required. Other than capturing the cardiac cycle and setting few parameters (trigger delay and TTC per HB), all the other protocol parameters can remain the same as for a standard non-gated CE-MRA protocol. Unlike the conventional gated CE-MRA where other scan parameters such as matrix size, resolution, FOV and PAT factor determine the segmentation, and particularly the duration of a single shot. In the proposed CE-MRA, however, shot duration is automatically adjusted according to the subject's heartbeat.

Adaptive steady state triggering

The proposed gated CE-MRA has implemented the steady state triggering mechanism (i.e. RF pulses are played out without acquisition during the wait time and the trigger delay) in order to avoid signal variations in the segmented FLASH readout (Fig.5). In addition, the proposed gated CE-MRA

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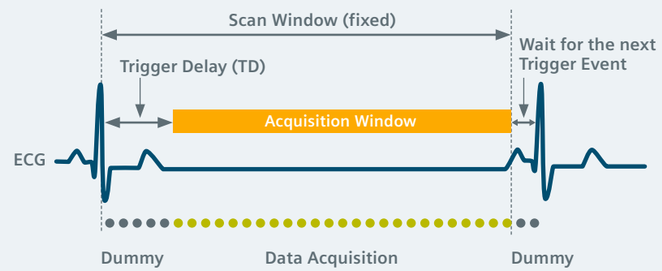

5 Steady state triggering. In order to maintain the magnetization in FLASH readout (represented as green dots), the steady state triggering continues to play out RF pulses without data acquisition during the wait time and trigger delay (i.e. Dummy pulses, represented as black dots).

Data Acquisition

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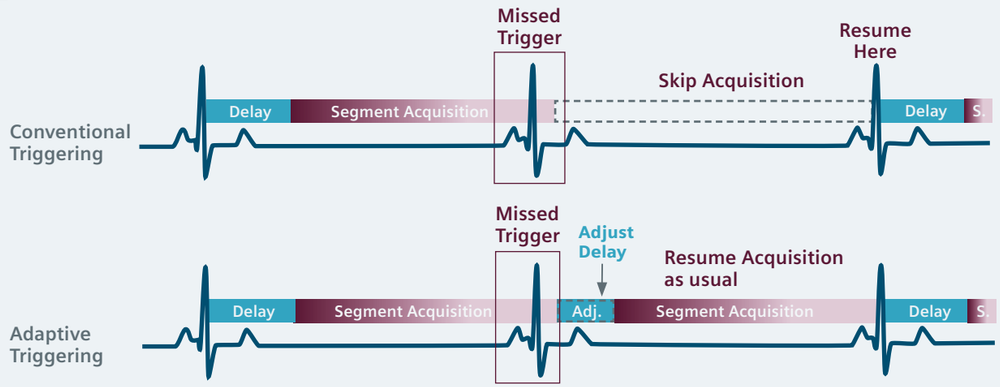

6 Schematic diagram of the early trigger case (missed trigger event). In the conventional case, any missed trigger will result in an unused RR interval. The adaptive triggering, on the other hand, will adjust the delay time to compensate the missed trigger time if it is less than the trigger delay.

automatically adapts the steady state triggering to compensate some of the commonly occurring trigger issues (i.e. early and late trigger detections). This *adaptive steady state triggering* ensures that the gated CE-MRA is completed in an efficient manner.

Early trigger cases

In the conventional approach, any trigger event that occurs within the acquisition window of the preceding shot is not detected. There are many cases where the R-R interval has been shortened just enough to miss the trigger event (i. e. the early trigger event). The goal of the adaptive approach is to salvage the early trigger event as much as possible and retain the original TD from the trigger event. Once the scan window is completed, the algorithm checks when the trigger event has occurred during the segment acquisition and then calculates the Missed Trigger Time (= the delay time since the latest trigger event). If a trigger event is detected during the acquisition, the TD of the next shot will be reduced accordingly.

Late trigger cases

In order to complete the gated CE-MRA in the case of an ECG trigger failure, it is important to enforce a trigger event after a pre-determined maximum wait time. After a maximum wait time (= 130% of R-R interval) has elapsed, the trigger event is enforced with TD = 0. If we observe the 2 consecutive maximum wait times (i.e. 4 total heart beats without an event), shorten the maximum wait time to 30% of R-R interval in order to complete the scan within the reasonable time.

Results and feedback

The proposed gated CE-MRA sequence has been tested on both 1.5T and 3T scanners at multiple research collaboration sites. The feedback is overwhelmingly positive thus far.

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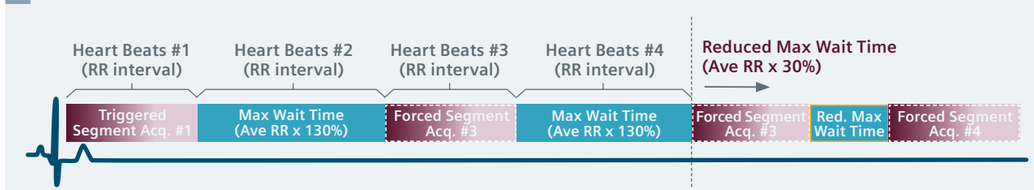

7 Schematic diagram of the late trigger case. When the maximal wait time occurs consecutively, which corresponds to the equivalent time of 4 RR intervals, and it is assumed that the ECG has failed. In anticipation of further delays, the maximum duration will be reduced for the remaining scan time to ensure the completion of the scan. If the ECG recovers, the sequence can revert to the regular trigger detection mode, but with reduced maximal wait time.

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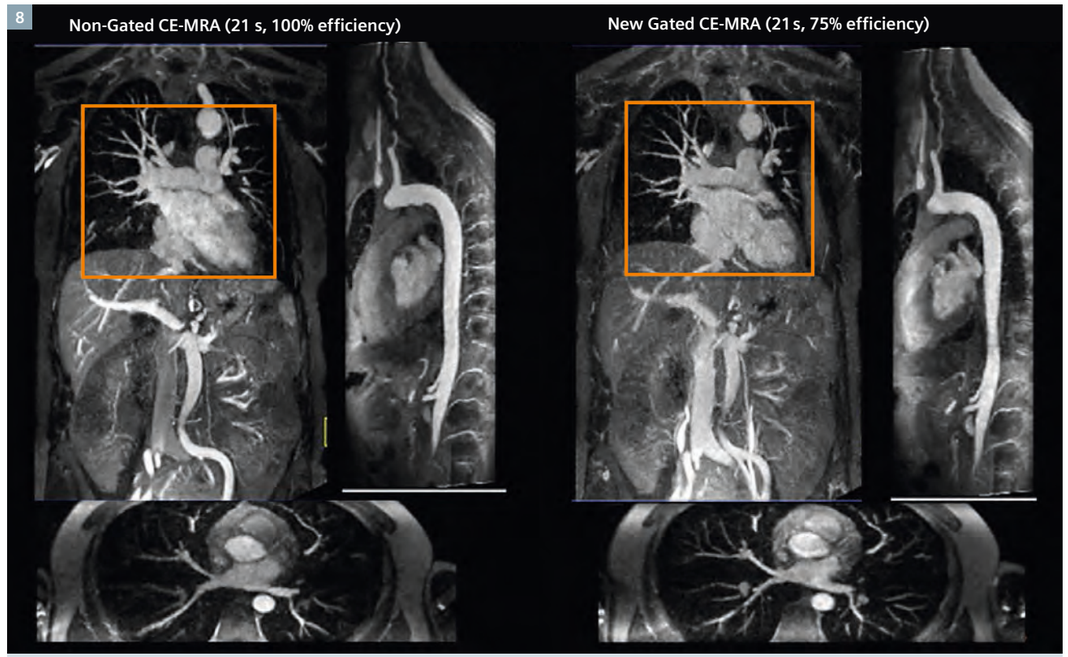
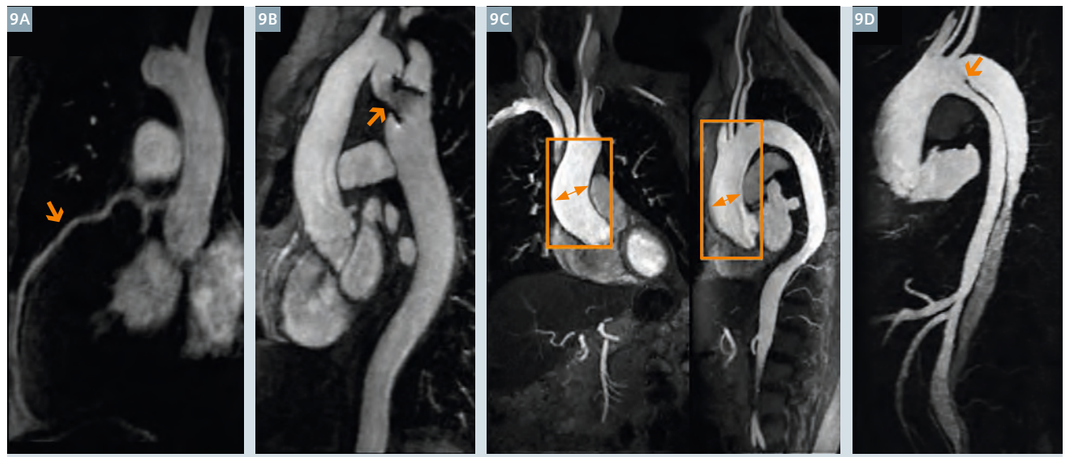


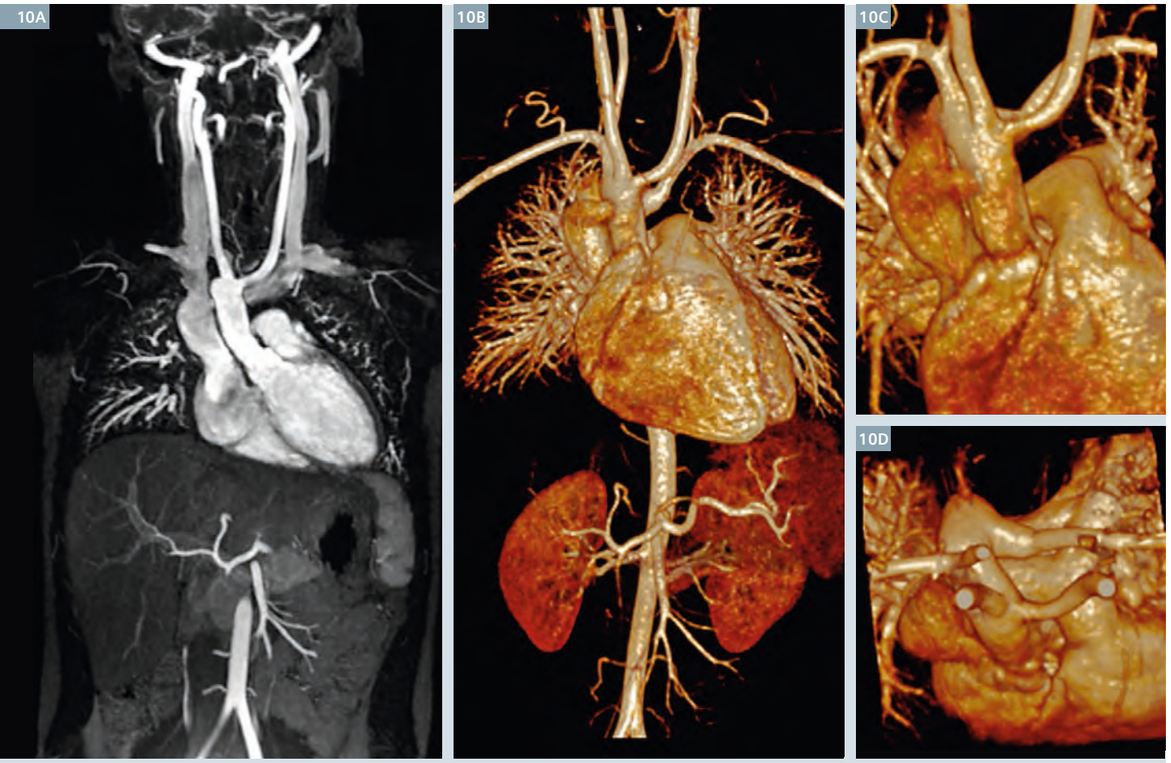
8 Direct comparison of the non-gated vs. gated CE-MRA on the same healthy volunteer. Reformatted thinMIPs of coronal (native acquisition orientation), sagittal and axial orientations are shown. The acquisition parameters are identical, except the gated CE-MRA has few additional parameters in TTC per HB, Acquisition window, and trigger delay. Also the gated CE-MRA has acquired with the elliptical scan to help compensate the efficiency loss.

Imaging details: 1.5T MAGNETOM Avanto (software version *syngo* MR B17A), 6-channel body matrix coil + spine coil, 3D FLASH (fl3d_ce) readout, coronal orientation, GRAPPA with integrated reference scans, iPAT acceleration factor 3, FOV 375 × 500 mm^2, matrix 288 × 512, voxel size 1.3 × 1.0 ×1.3 mm^3, 120 slices (67 slice encoding steps with partial Fourier 6/8 and slice res. 66%), TTC 6 s, total scan time 21 s.
For the gated CE-MRA only: TD 150 ms, TTC per HB set at quiescent mid diastole.



9 Various clinical results with the proposed gated CE-MRA as obtained on a 1.5T MAGNETOM Avanto. All images are reformatted thin MIPs based on the original coronal acquisition data. **(9A)** Left arterial descending coronary artery. **(9B)** Stent lumen narrowing, post repair of aortic coarctation. **(9C)** Dilation of ascending aorta due to aneurism. **(9D)** Aortic dissection.

Imaging parameters are identical to those provided with figure 8.



10 A clinical result with the proposed gated CE-MRA obtained on a 3T MAGNETOM Trio with Tim. 12-year-old patient with congenital heart disease (CHD) vascular ring case with 1st pass gated CE-MRA. The image was acquired in an anesthetized pediatric patient who could perform 'perfect' breath-holds. **(10A)** Coronal thin MIP of the original data. **(10B)** Volume-rendered reconstruction of the gated CE-MRA in coronal view. **(10C)** Volume-rendered reconstruction, zoomed in at the vascular region. **(10D)** Volume-rendered reconstruction, zoomed in and rotated for visualizing the vascular ring.

Imaging parameters: 3T MAGNETOM Trio, a Tim system (software version *syngo* MR B17A), 6-channel body matrix coil + spine coil, 3D FLASH (fl3d_ce) readout, coronal orientation, GRAPPA with integrated reference scans, iPAT acceleration factor 4, FOV 312 × 500 mm², matrix 285 x 608, voxel size 1.1 x 0.8 x 1 mm³, 120 slices (67 slice encoding steps with partial Fourier 6/8 and slice res. 66%), TR 2.86 ms, TE 1.04 ms, TTC 6 s, TD 50 ms, TTC per HB at quiescent mid diastole, total scan time 20 s.

In clinical practice, cardiothoracic CE-MRA is typically acquired without ECG gating, with high resolution and within a single breath-hold (e.g. coronal orientation to cover the whole chest, image matrix 288 × 512 (phase × read), slices 120, slice resolution 66%, partial Fourier 6/8 (corresponding to 67 partition encoding steps), GRAPPA with iPAT factor 3, and voxel size 1.3 × 1.0 × 1.3 mm³, total scan time 21 s). With the conventional gated CE-MRA, the same resolution is impossible to achieve within a breath-hold; the corresponding protocol would either take too long (in the example above, 67 heart beats, or 50–60 seconds) or would be limited with respect to its coverage in slice direction (with a maximum breath-hold duration of approx. 25 s, the conventional gated CE-MRA only allows about 25–30 slice encoding steps).

The proposed gated CE-MRA with flexible triggered segments, however, matches the typical non-gated cardiothoracic CE-MRA protocols in both resolution and coverage, all within a slight increase in breath-hold (typically 1-2 seconds or less). Despite the scan efficiency improvements, the proposed sequence still has ~70% efficiency compared to the 100% efficiency of the non-gated counterpart. The ~30% efficiency loss in the gated CE-MRA has been mostly compensated by the elliptical scan and slightly less slice oversampling (and thus able to minimize an extra breath-hold to be in 1-2 seconds or less). The pulsatile cardiac motion artifacts of the ECG-gating is evident when the sequences are directly compared on the same volunteer with identical scan parameters and contrast injection profile (Fig. 8). Many clinical study cases have shown improved vascular image quality that would not be possible without ECG gating (Figs. 9, 10).

The adaptive steady state feature increases confidence in the use if gated CE-MRA technique instead of a clinical standard non-gated CE-MRA. Among the feedback cases, early trigger events were detected occasionally (about 10% of the feedback study cases have shown slight shortening of the R-R interval). All of these early trigger cases were completed within a single breath-hold (slightly shorter than predicted total scan time), and none of them had shown adverse effects such as washed out contrast or excessive motion artifacts. No feedback cases had shown late triggering, i.e. the ECG-triggering did not fail in any of these cases, and the R-R interval change (extension) was never significant enough to enforce a trigger event.

Conclusion

The conventional ECG-gated CE-MRA has been available for more than a decade. While the benefits of ECG-gated CE-MRA in the cardiac pulsatile motion reduction are well documented, the technique has remained a niche application, mainly due to its low scan efficiency (only about 30%) and its limited slice coverage (only 25-30 slice partitions within a breath-hold). In addition, physiological and mechanical imperfections of the ECG-triggering might have led to reduced user confidence. The overall robustness of non-gated CE-MRA might have out weighted the benefit of the gated CE-MRA, so that the mainstream cardiothoracic CE-MRA had been acquired without ECG.

The proposed gated CE-MRA addresses these major drawbacks of the conventional gated CE-MRA. With the flexible trigger segmentation, the proposed gated CE-MRA now provides vastly improved scan efficiency (about 70% or above) and is no longer restricted in terms of slice coverage. The adaptive steady state triggering ensures a CE-MRA scan completion in a very efficient manner, and further improves the robustness of the sequence. The proposed gated CE-MRA has high potential as a viable option for high-resolution cardiothoracic CE-MRA. Further clinical research collaborations and tests are warranted.

Acknowledgments

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