

Navigator-gated and real-time motion corrected free-breathing MR Imaging of myocardial late enhancement

E. Spuentrup^{1,2}
A. Buecker¹
E. Karassimos³
R. W. Günther¹
M. Stuber^{2,4}

MRT der myokardialen Spätanreicherung während freier Atmung unter Einsatz einer prospektiven Navigator-Technologie mit Echtzeit-Schichtnachführung

Zusammenfassung

Zielsetzung: Das Ziel der Arbeit war die Entwicklung einer MR-Sequenz, welche eine Datenaufnahme während freier Atmung zur MR-Vitalitätsdiagnostik erlaubt. **Methoden und Ergebnisse:** Zur Eliminierung der Atemartefakten bei einer Datenaufnahme während freier Atmung wurde eine prospektive Navigator-Technologie mit Echtzeit-Schichtnachführung und ein lokaler Navigator-Rückstellpuls in eine MR-Sequenz zur Diagnostik der myokardialen Spätanreicherung implementiert. Patientenspezifische Inversions-Zeiten wurden mit einer vorgeschalteten Inversionszeit-Bestimmungssequenz mit variablen Inversionszeiten ermittelt. Diese Sequenz wurde ebenfalls während freier Atmung angefertigt. Die Diagnostik der myokardialen Spätanreicherung erfolgte mit der patientenspezifischen Inversionszeit und einer Schichtführung im Zwei-, Drei- und Vierkammerblick sowie in der kurzen Achse. 7 Patienten mit Myokardinfarkt wurden 12 Minuten nach Applikation von 0,2 mmol/kg Körpergewicht Gd-DTPA i.v. untersucht. **Schlussfolgerung:** Die neue MR-Sequenz mit Navigator-Technologie und Echtzeit-Schichtnachführung erlaubt die Datenakquisition zu Diagnostik der myokardialen Spätanreicherung einschließlich der Bestimmung der patientenspezifischen Inversionszeit während freier Atmung. Die Limitationen einer Atemhalte-Technik werden durch diese neue Technik behoben.

Schlüsselwörter

Magnetic Resonance Imaging · Myocardial Viability · Contrast enhancement · Navigator technology

Abstract

Purpose: A new magnetic resonance imaging approach for detection of myocardial late enhancement during free-breathing was developed. **Methods and Results:** For suppression of respiratory motion artifacts, a prospective navigator technology including real-time motion correction and a local navigator restore was implemented. Subject specific inversion times were defined from images with incrementally increased inversion times acquired during a single dynamic scout navigator-gated and real-time motion corrected free-breathing scan. Subsequently, MR-imaging of myocardial late enhancement was performed with navigator-gated and real-time motion corrected adjacent short axis and long axis (two, three and four chamber) views. This alternative approach was investigated in 7 patients with history of myocardial infarction 12 min after i.v. administration of 0.2 mmol/kg body weight gadolinium-DTPA. **Conclusion:** With the presented navigator-gated and real-time motion corrected sequence for MR-imaging of myocardial late enhancement data can be completely acquired during free-breathing. Time constraints of a breath-hold technique are abolished and optimized patient specific inversion time is ensured.

Key words

Magnetic Resonance Imaging · Myocardial Viability · Contrast enhancement · Navigator technology

Institutsangaben

¹Department of Diagnostic Radiology, Aachen University of Technology, Germany
²Department of Medicine (Cardiovascular Division), Beth Israel Deaconess Medical Center and Harvard Medical School, Boston, MA, USA
³Medical Clinic I, Aachen University of Technology, Germany
⁴Philips Medical Systems, Best, NL

Korrespondenzadresse

Dr. med. Elmar Spuentrup · Department of Diagnostic Radiology, University Hospital, Technical University of Aachen · Pauwelsstraße 30 · 52057 Aachen · Germany · Tel.: + 49-241-8088332 · Fax: + 49-241-8082411 · E-mail: spuanti@rad.rwth-aachen.de

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Introduction

Over the last few years, magnetic resonance imaging (MRI) has been successfully implemented for imaging of myocardial viability [1–7]. Hereby, a “late enhancement” MR imaging technique has been used to depict scar tissue or necrotic myocardium with reduced potential benefit from revascularization. It has also been suggested that hypokinetic myocardium without late enhancement indicates hibernating myocardium [1]. The “late enhancement” in necrosis was explained by the prolonged contrast media accumulation in the region of myocardial infarction [1,3–5,8] late (> 5 min) [6] after contrast media administration, regardless of wall motion abnormalities [5] or revascularisation [3]. As currently implemented, “myocardial late enhancement” is commonly detected by a cardiac triggered T_1 -weighted breath-hold sequence [2]. To enhance contrast between necrotic and viable myocardium, an inversion pulse is commonly applied to suppress normal myocardium, whereas necrotic regions appear signal enhanced [2]. A subject specific inversion time, which is crucial for maximized contrast, is typically obtained from a series of breath-hold scout scans with variable inversion times post contrast agent administration. Subsequently, the inversion recovery scan with optimized inversion time is repeated in multiple anatomical orientations using serial 2D breath-hold acquisitions [1,2]. However, many patients may not easily sustain prolonged breath-holds [9], sufficient recovery time for the patient in-between serial breath-hold is needed and major operator involvement exist. Therefore, we sought to develop a free-breathing approach which allows for complete data acquisition without breath-holding and time efficient inversion-time determination. Hereby, prospective navigator technology [10] including real-time motion correction [11] was combined with an inversion recovery technique and real-time adaptive incremental inversion time delays for assessment of myocardial viability. Further, the impact of a local “navigator restore” [12] for improved navigator performance in an inversion recovery sequence was investigated.

Methods

A navigator-gated and real-time motion corrected free-breathing cardiac triggered, segmented k-space T_1 -weighted inversion recovery sequence with real-time adaptive incremental inversion time delays was implemented on a commercial 1.5 T Gyroscan ACS-NT whole body MR system (Philips Medical Systems, Best, NL) equipped with a cardiac software (INCA2) and a commercial PowerTrak 6000 gradient system (23 mT/m, 219 μ s rise time). For signal acquisition, a commercial 5-element cardiac synergy coil was used.

Sequence for imaging of myocardial late enhancement

MR imaging of myocardial viability was performed 12 min after i.v. contrast media administration (0.2 mmol/kg body weight Gd-DTPA, Magnevist, ScheringAG, Berlin, Germany).

An RF spoiled 2D T_1 -weighted (TR/TE 7.5/3.8 ms, respectively) cardiac triggered, segmented k-space, gradient echo sequence was used for MR imaging of myocardial late enhancement. Further sequence parameters included a field-of-view of 390 mm with a 256 \times 152 scan matrix and a slice thickness of 10 mm. 19

excitations with a constant flip angle of 150 were applied during diastole of each R-R interval, resulting in an acquisition window of 143 ms. Two signal averages were performed. A non-selective 180° inversion pulse preceded the imaging sequence for suppression of normal myocardium (Fig. 1).

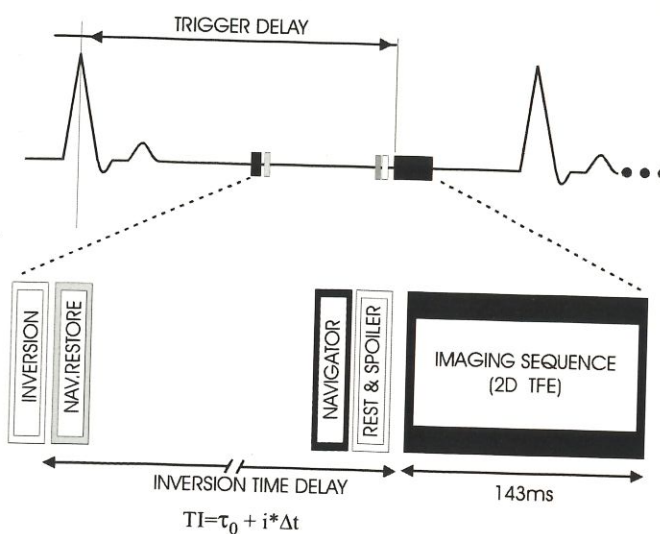


Fig. 1 Schematic of the navigator-gated and real-time motion corrected free-breathing, segmented k-space, cardiac triggered inversion recovery sequence. A local “navigator restore” follows the inversion pulse in order to ensure high navigator performance. The inversion time (TI) can be incremented by Δt increments in run-time during the scan for determination of the optimized inversion time. Hereby, the shortest inversion time τ_0 as well as the increments Δt for increased time delays is specified by the user together with the number of incremental steps (n) ($i = 0 \dots n-1$).

Determination of subject specific inversion time

For the determination of the subject specific inversion time, a serial acquisition with user specified incremental inversion times was performed. Hereby, the shortest inversion time τ_0 as well as the increments Δt for increased time delay are specified by the user together with the number of incremental steps (n) ($i = 0 \dots n-1$) (Fig. 1). These incremental inversion times were adapted in real-time on the system during the same scan. Thus, only one sequence and navigator preparation was needed for investigation of all inversion times and no user interactions or dead-times were necessary in-between serial increments.

Real-time navigator technology for respiratory motion artifact suppression

A 2D selective RF pencil excitation pulse with a flow compensated read-out of 256 data points in the longitudinal direction was used as the right hemi-diaphragmatic navigator [10,13]. If the navigator detected lung-liver interface position falls within a user specified range (gating window), the data are accepted for image reconstruction, otherwise the data are discarded and remeasured during the subsequent R-R interval. The navigator excitation flip angle was 30° with a navigator diameter of 25 mm and 9 cycles in k-space using a sinc-shaped RF pulse [14]. For all studies, a 5 mm gating window was used. In addition to navigator gating, prospective adaptive real-time motion correction (= “tracking”) of the imaged slice position [11] in all three spatial coordinates was performed [10]. This was accomplished

by the prospective adaptation of the frequency of the RF excitation and by the adaptation of acquisition phase and frequency [10]. A fixed superior-inferior correction factor of 0.6 [15] was used. The navigator was in closest temporal proximity to the imaging portion of the sequence using ultra fast navigator evaluation to avoid motion artifacts during the time delay between navigator interface position detection and imaging [16].

Navigator restore

Because a minimized time delay between navigator and imaging portion of the sequence is crucial for improved image quality [16], the navigator was positioned in-between the inversion pulse and the imaging portion of the sequence (Fig. 1). However, using such a sequence the magnetization of the liver is reduced at the time point of the navigator read-out due to the preceding non-selective inversion pulse. As a consequence, navigator performance may be substantially reduced [12] as demonstrated in Fig. 2. Therefore, we implemented a 2D selective navigator restore pulse which can be selectively enabled on the operator console as previously described for black blood coronary MR-angiography [12]. Such a navigator restore pulse locally re-inverts the magnetization at the dome of the right hemi-diaphragm for subsequent navigator lung-liver interface detection.

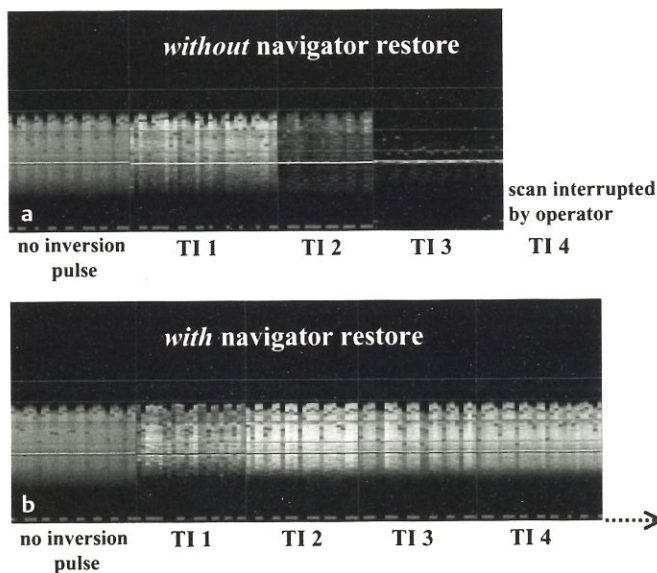


Fig. 2 Navigator interface as presented at the operator console. In (a) no navigator restore is applied, resulting in a reduced navigator performance. Using the navigator restore (b) a well defined lung-liver interface is seen for all the investigated incremental inversion times.

Description of experiments

Subjects

Free-breathing MR imaging of myocardial late enhancement was performed in 7 subjects (43–81 years old) with history of chronic myocardial infarction (11–19 months prior to MR imaging, $n=2$) or acute myocardial infarction (6–21 days prior to MR examination, $n=5$). Myocardial infarction was localized in the posterior ($n=2$), inferior ($n=1$), anterior ($n=1$) and anterior-septal wall ($n=3$). ECG, laboratory findings, X-ray angiography, echocardiography and cine MR-imaging were available in all patients. Informed consent was obtained from all participants < 24 h prior

to MR examination. All subjects were examined in the supine position.

Determination of subject specific inversion time and impact of navigator restore

For determination of the subject specific inversion time, 5 incremental inversion times ranging from 190 to 330 ms in steps of 35 ms were used in a short axis view ($\tau_0=190$ ms, $\Delta t=35$ ms, $n=5$). For investigation of the impact of the navigator restore, firstly this scout scan was performed without navigator restore pulse and subsequently repeated with navigator restore pulse. The subject specific inversion time with optimal myocardial suppression was visually assessed and navigator efficiency was compared.

MR-imaging of myocardial late enhancement

For MR-imaging of myocardial late enhancement, the sequence with the subject specific inversion time was repeated in multiple anatomical views (two, three and four chamber view as well as in parallel to the short axis (7–10 slices without slice gap), respectively). Image quality (diagnostic/non diagnostic) was assessed by two investigators on consensus basis using the 16 segment model. Diagnostic image quality was defined as no or minor motion artifacts, sufficient signal suppression of normal myocardium and sharp delineation of myocardial border/necrotic (signal enhanced) regions. Enhanced motion artifacts, insufficient signal suppression of normal myocardium or enhanced blurring at the border of normal myocardium/necrotic regions was set to non-diagnostic image quality.

For quantitative analysis, contrast-to-noise ratio (CNR) of the hyperenhanced areas vs. normal myocardium and blood-pool vs. normal myocardium was calculated from user specified regions of interest (ROI) drawn in all views with signal enhancement. The signal enhanced myocardium, the blood-pool in the left ventricle, the non-enhanced myocardium and a region of air anterior to the chest wall were evaluated. Hereby, CNR was defined as: $CNR_{\text{hyperenhanced myocardium vs. normal myocardium}} = (\text{Signal}(\text{ROI}_{\text{enhanced myocardium}}) - \text{Signal}(\text{ROI}_{\text{non-enhanced myocardium}})) / \text{SD}(\text{ROI}_{\text{air}})$ and $CNR_{\text{blood-pool vs. normal myocardium}} = (\text{Signal}(\text{ROI}_{\text{blood-pool}}) - \text{Signal}(\text{ROI}_{\text{non-enhanced myocardium}})) / \text{SD}(\text{ROI}_{\text{air}})$,

where $\text{SD}(\text{ROI}_{\text{air}})$ was defined as the standard deviation of the background signal outside the chest.

Results

All scans were successfully completed without complications. In all subjects two, three and four chamber views as well as 7–10 slices in parallel to the short axis could be acquired and CNR could be evaluated in all patients. A diagnostic image quality was found in all segments in all patients. Due to data acquisition during free-breathing, no interruption in-between serial inversion times (TIs) or adjacent slices for patient recovery occurred, and no operator involvement during scanning (i.e. no patient instructions) was needed. Total measurement time was < 10 min during free-breathing for determination of the subject specific

inversion time together with detection of myocardial late enhancement.

Determination of subject specific trigger delay and impact of navigator restore

In all patients, individual inversion times could be obtained from the free-breathing scout scan with incremental inversion times (Fig. 3). Without navigator restore, in 7/7 patients, the signal of the lung-liver interface was suppressed at patient specific inversion delays (Fig. 2), and these scans could subsequently not be completed due to insufficient navigator performance (efficiency < 5%). Signal of the liver was attenuated to variable degrees when compared to the images without preceding inversion pulse, dependent on the inversion time (star in Fig. 3). In contrast to this, the local navigator restore substantially improved navigator interface definition. This resulted in a high navigator efficiency ranging from 38 to 62%, independent of the inversion times, and subsequently the subject specific inversion time could be easily evaluated in all cases.

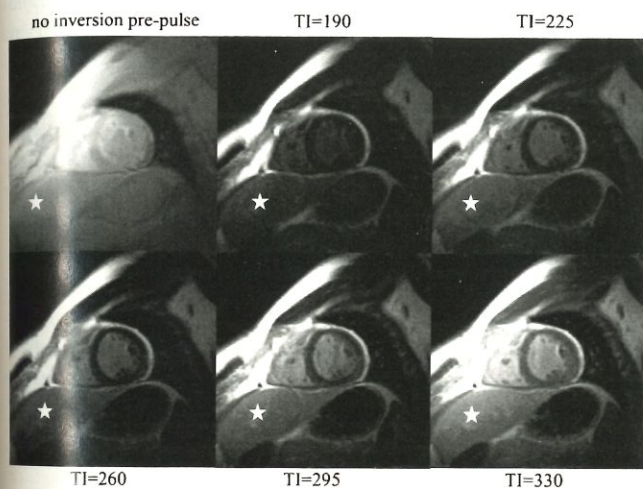


Fig. 3 65-year-old male patient. Navigator-gated free-breathing cardiac triggered inversion recovery sequence for definition of the subject specific inversion time. In the image in the upper left, no inversion pulse was applied in order to demonstrate the signal reduction of normal myocardium by the non-selective inversion pulse preceding the imaging portion of the sequence (TI 190–330 ms). Signal of liver (star) is reduced by the inversion pulse, resulting in a reduced navigator interface definition (Fig. 2). In this case, a TI of 260 ms was chosen as the optimal inversion time for suppression of normal myocardium.

Visual assessment of myocardial suppression yielded an optimal inversion time of 225 ms (n = 2), 260 ms (n = 4) and 295 ms (n = 1).

Free-breathing multiple view sequence for detection of myocardial late enhancement

In all cases, breathing artifacts could be successfully suppressed (Figs. 3–5) and regions of myocardial late enhancement could be visualized with high contrast while normal myocardium was signal suppressed (CNR hyperenhanced myocardium vs. normal myocardium = 23 ± 7 , CNR blood-pool vs. normal myocardium = 14 ± 4). In Fig. 4a and b, representative double-oblique acquisitions in parallel to the short axis and two chamber view of a patient with acute myocardial infarction are shown. In this example, signal from myocardium was suppressed with

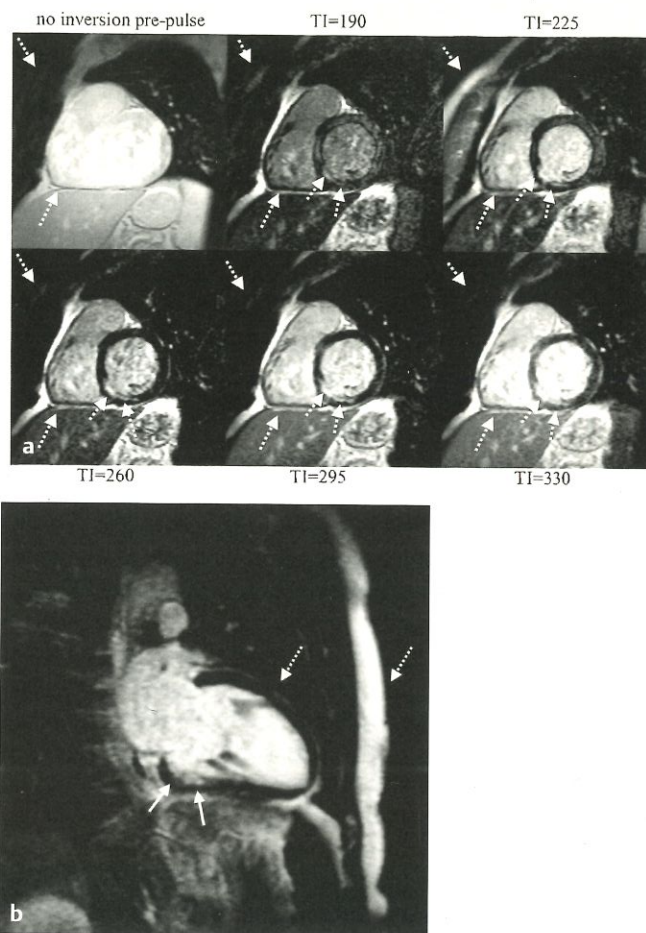


Fig. 4 43-year-old male patient 12 days after acute myocardial infarction. (a) Navigator-gated free-breathing cardiac triggered inversion recovery sequence with variable inversion times (TI (ms)). Best suppression of normal myocardium is seen with a 260 ms inversion time. The subendocardial infarction is readily apparent (arrows). Breathing artifacts are completely suppressed (dashed arrows). However, minor intrinsic cardiac motion is still visible, probably due to relatively high cardiac frequency (80–85 beats/min) in this patient. (b) Two chamber view with a 260 ms inversion time. The subendocardial infarction is seen again with a high contrast (arrow). No breathing artifacts are visible (dashed arrows).

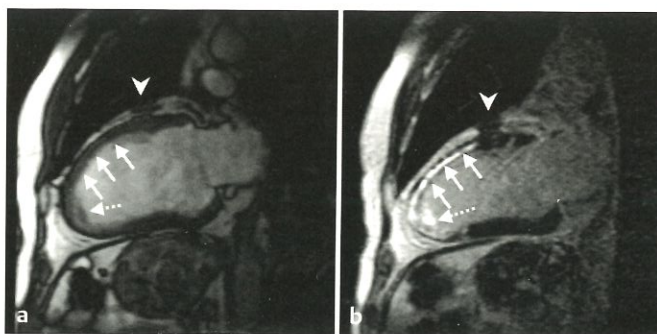


Fig. 5 61-year-old male patient with history of anterior myocardial infarction 19 months ago. (a) Diastolic steady state free precession (TR 3.4 ms, TE 1.7 ms, cine 20 heart phases) functional MR-imaging demonstrating myocardial thinning of the anterior wall (arrows) and an apical left ventricular thrombus (dashed arrow) as known from echocardiographic follow-up examinations. (b) Two chamber view of the navigator-gated free-breathing cardiac triggered segmented k-space inversion recovery sequence (TI 260 ms). Subendocardial late enhancement of the anterior wall and apex indicates scar tissue (arrows). In this case, a signal enhancement of the thrombus comparable to the scar tissue was found. Again, no breathing artifacts are visible. Note the stent in the LAD (arrow head).

a 260 ms inversion time, whereas the region of myocardial infarction (arrows) demonstrates markedly enhanced signal intensities with a high contrast. Respiratory motion artifacts are almost entirely suppressed, while minor cardiac motion artifacts are visible. In Fig. 5, a patient with history of chronic myocardial infarction (19 months prior to MR imaging) is shown. It demonstrates a large subendocardial region of late enhancement in the anterior wall and at the apex, suggesting the presence of scar tissue.

Discussion

The detection of myocardial viability is important for treatment decisions [1] like revascularization. Recently, improved MR imaging techniques [2] have shown to reliably detect myocardial viability and necrosis. Hereby, a breath-hold technique with a non-selective inversion pulse for suppression of normal myocardium 5 to 30 min after contrast media administration [2, 5, 7] was successfully applied, which allowed for high contrast display of necrotic myocardium. However, many patients cannot sustain prolonged breath-holds [9]. Furthermore, time constraints associated with breath-holding may compromise optimal signal-to-noise ratio or prevent from data acquisition with sufficient spatial resolution, which may be needed for detection of small necrotic regions or right ventricular involvement. When compared to the inversion time determination in serial breath-holds, a free-breathing method may offer the advantage not to be interrupted by recovery periods in-between incremental TIs or subsequent adjacent single slice scans. Therefore, the aim of the present work was to develop a free-breathing approach for detection of myocardial late enhancement in order to remove the above mentioned time constraints of a breath-holding technique.

Prospective real-time motion corrected navigator technology has shown to suppress respiratory motion artifacts in cardiac MR for 2D data acquisition and even for submillimeter 3D acquisition [10,11]. However, the use of navigator technology for free-breathing MR imaging of myocardial late enhancement may be compromised by the non-selective inversion pulse preceding the navigator. This inversion pulse not only nulls signal from myocardium, but also suppresses the liver signal (Fig. 2,3). As a consequence, the navigator lung-liver interface detection may substantially be compromised (Fig. 2) with subsequent failure to detect the lung-liver interface for respiratory motion artifact suppression. One potent solution may include a navigator preceding the inversion pulse. However, for navigator-gated and real-time motion corrected free-breathing MR imaging, a minimal time delay between navigator and imaging portion of the sequence has shown to be crucial for improved image quality [16]. Consequently, closest temporal proximity of the navigator to the imaging portion of the sequence is imperative. Therefore, the navigator was positioned in-between the inversion pulse and the imaging portion of the sequence (Fig. 1). To overcome penalized navigator interface detection performance due to the inversion pulse, we implemented a navigator restore for compensation. This 2D RF pencil beam locally re-inverts the signal at the dome of the right hemi-diaphragm immediately after the inversion pulse [12]. As a consequence, signal of the navigator interface is no longer suppressed by the inversion pulse (Fig. 2) although global liver signal (outside the navigator restore pulse) was marked-

ly reduced (Fig. 3). Thus, successful navigator gating with high navigator efficiency and variable inversion times was ensured, whereas in all scans without the navigator restore, navigator performance was insufficient with subsequent inability to collect MR data. With the presented free-breathing approach and the navigator restore pulse, MR-imaging of myocardial late enhancement can be completely acquired during free-breathing. The subject specific inversion time can be efficiently determined during a single scout scan with a series of incremental inversion times. Using a local right hemi-diaphragmatic navigator restore, no interference with the regions of interest (i.e. myocardium) exists, which is important for effective myocardial suppression by the inversion pulse.

In our preliminary work, we implemented a 2D free-breathing approach for MR imaging of myocardial late enhancement. With this free-breathing approach, diagnostic image quality was obtained in all segments in patients. Overall measurement time including the determination of the subject specific inversion time was less than 10 min in all cases. While comparison of total measurement times and image quality between a conventional breath-hold technique and our free-breathing approach remains to be investigated, time constraints associated with serial breath-holds [9] are removed. No recovery periods in-between serial slices are needed and no operator involvement during the scan exists. A free-breathing approach may also allow for investigations of the optimal time point of MR-imaging after contrast media administration, if one slice is serially repeated. Furthermore, free-breathing MR-imaging of myocardial late enhancement may potentially enable 3D data acquisition with enhanced signal-to-noise ratio and therefore potentially higher spatial resolution (i.e. smaller field-of-view), which may be helpful for the detection of smaller or sub-endocardial lesions, or the 3D segmentation of myocardial infarcts.

Conclusions

With the presented navigator-gated and real-time motion corrected inversion recovery methodology, myocardial late enhancement MR imaging during free-breathing is enabled. Hereby a navigator restore pulse is needed to ensure high navigator performance.

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