A Robust and Simple Technique for the Suppression of Artifacts Arising From Long T1 Species in Segmented Inversion Recovery Sequences

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Introduction: Delayed enhancement imaging employing the ECG-gated segmented IR TurboFlash sequence (gradient echo) is considered the clinical gold standard for the detection of myocardial infarction. Although image contrast between infarct and viable myocardium is excellent, there is increased susceptibility towards even faint bright artifacts, since viable myocardium is depicted dark. A common artifact arises from long T1 species (2 - 3 s) such as pericardial and pleural effusion, and spinal fluid. This ghosting artifact is caused by signal oscillations due to the periodic inversion pulses; the long T1 signal has not reached steady state. Even leading "dummy heartbeats" (same IR and readout, and recovery heart beats (HB) as during imaging, but without acquiring data) as already done in the standard sequence are insufficient to achieve steady state. Importantly, the artifacts may not always present as obvious discrete ghosts, but may be smeared across the image due to an irregular heart rate or imperfect breath hold. They can obscure or mimic infarcts. Placing a saturation slab over the long T1 region is not possible for pericardial effusion as it destroys the region of interest. Also, it requires time and experience to place the slab. Fig. 1 a) shows ghosting of the spinal fluid (red arrows) in a patient. We present a robust technique to completely suppress these artifacts by driving the long T1 species into immediate steady state through a single saturation recovery (SR) pulse timed relative to the first IR pulse. It was implemented into Flash and SSFP sequences and tested in a phantom and four patients on a MAGNETOM Avanto (SIEMENS Healthcare, Erlangen, Germany) MR scanner. The optimal timing of the SR pulse was determined experimentally and theoretically. The ghosting was quantified for the current standard and the new technique virtually eliminating all ghosting artifacts with the new method.

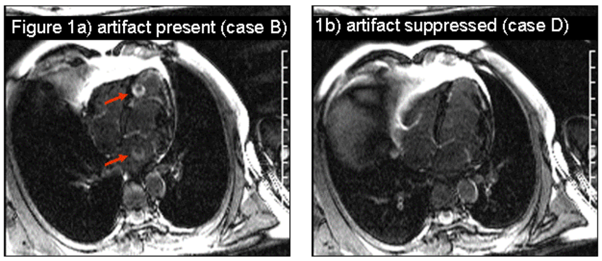
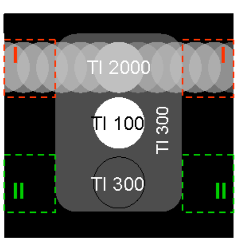


Figure 1a) artifact present (case B) 1b) artifact suppressed (case D)

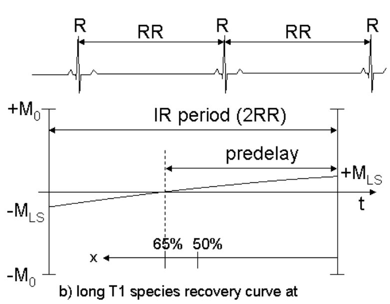
Methods:
Experiment 1: In a phantom (Fig. 2a) we acquired segmented IR TurboFlash images with the following parameters: TI 300 ms, trigger pulse 2, fov 500 x 500 mm, matrix 256 x 180, segments 15, flip angle 15°, receiver bandwidth 130 Hz/pixel, TE 3.85 ms, TR 8.9 ms, RF spoiling on, slice thickness 6 mm. We tested four combinations of new SR pre-pulse and standard dummy heart beats: A) pre-pulse off and dummy HB off (–Pre–HB), B) pre-pulse off and dummy HB on (–Pre+HB), C) pre-pulse on and dummy HB off (+Pre-HB), and D) both on (+Pre+HB). The time between successive IR pulses (IR period) was 2400 ms and the SR pulse was played 1200 ms prior to the first IR (x=50%, see Fig 2c). *Experiment 2:* To assess the effect of the predelay on the artifact suppression in C, we defined the relative predelay x as predelay divided by the IR period expressed in percent (Fig. 2b, c). We varied x from 35% to 100%. We repeated the acquisition for three different RR intervals (800, 1000, 1200 ms) with one recovery beat after each imaging heart beat ("trigger pulse" 2) resulting in a 1600, 2000, and 2400 ms IR period, respectively. We repeated experiments 1 and 2 for Flash without RF spoiling and for SSFP. *Artifact quantification:* We measured the standard deviation outside the phantom in regions I and II (Fig. 2a), defined an artifact measure ATM by dividing the standard deviation of region I by that of region II, subtracted 1, and expressed it in percent (Fig. 2e). The rationale for this formula was that the standard deviation of region I is a function of the long T1 ghosting and other effects, whereas that of region II is only a function of the other effects. An ATM of 0% indicates that no long T1 artifacts are present and any larger ATM means long T1 ghosting. *Formula:* We derived the formula for the optimal predelay to immediately achieve steady state of the long T1 species with one SR pre-pulse as function of its T1 and the IR period (2*RR) and compared the calculated with the values measured in exp. 2. *Patients:* We repeated exp. 1 in patients with pleural or pericardial effusion.

Results: *Phantom experiment 1:* The ATM values were measured as A) 449.6, B) 92.2, C) 39.2, and D) 10.8. Fig. 3 shows the ATMs as horizontal lines for comparison with exp. 2. The images on the right of Fig. 3 are in accordance with these numbers exhibiting severe (ATM > 150), strong (150 ≥ ATM > 50), weak (50 ≥ ATM > 15), and no visible artifacts (15 ≥ ATM). *Phantom experiment 2:* We plotted the ATM values versus the relative predelay x. All ATM curves showed a minimum between x = 55% and 66%. The minimum ATMs are 16.5 at x = 59.4% (RR 800), 8.6 at x = 62.5% (RR 1000), and 4.8 at x = 65.5% (RR 1200 ms), see red, black, and blue arrows. SSFP results are omitted due to space limitations. *Formula:* The formula for the optimal predelay was derived (Fig. 2d) and x_{opt} calculated as 56.8 (RR 800), 58.5 (RR 1000), and 60.1 (RR 1200) for T1=2885 ms. The measured optimal predelays were shorter than the theoretically calculated, most likely due to the saturation effect of the readout. *Patients:* Fig. 1b) shows the effective suppression of the spinal fluid ghost with method D (x =50%), whereas it is not suppressed with standard method B.

Conclusion: The new technique D achieved about a nine-fold (92.2/10.8) artifact reduction compared to the standard method B. Method A which uses no artifact suppression at all (not standard) resulted in the largest ATM. Exp. 1 shows that the SR pre-pulse both without and with dummy HB (C and D) are effective yet simple methods to suppress artifacts from long T1 species and improve segmented IR image quality, see ATMs in Fig. 3. C requires one HB less than B, yet performs better. Method D achieved the best suppression, but took one HB longer than B. Exp. 2 shows that the optimal suppression is a function of the predelay and the IR period, and that for any tested predelay and heart rate (C800, C1000, C1200) the new suppression pre-pulse performs better than the standard dummy HB alone (B). The technique can easily be implemented into any scanner manufacturer's software and be automatically activated whenever the sequence is run in a segmented IR mode. We favor method D as it does not require a precise predelay tuning.



a) phantom: bottles with different T1 species (2000 ms 'long T1 species', 100 ms 'infarct'), 300 ms 'normal myocardium', in a tub of TI = 300 ms fluid.



b) long T1 species recovery curve at steady state and parameters

c) definition of relative predelay x:

$$x = 100\% \cdot \frac{predelay}{IRperiod}$$

d) optimal relative predelay x as function of the IR period and long T1:

$$x_{opt} = 100\% \cdot \ln\left(\frac{2}{1+e^{\frac{-IRperiod}{longT_1}}}\right)$$

e) definition of artifact measure ATM:

$$ATM = 100\% \cdot \left(\frac{stdev(I)}{stdev(II)} - 1\right)$$

Figure 2

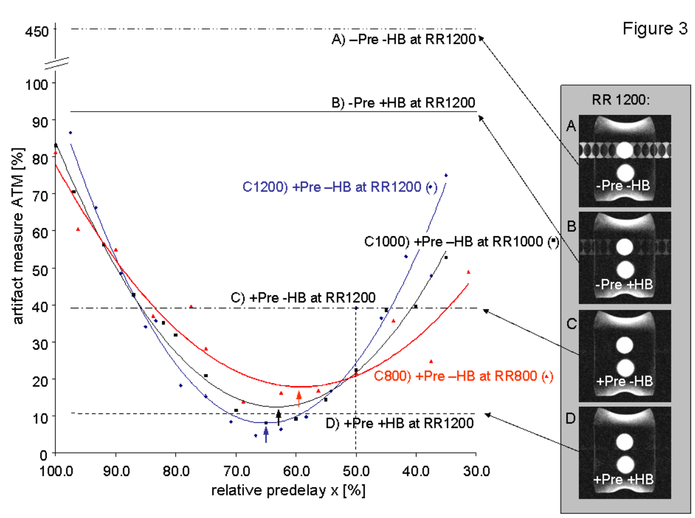


Figure 3