TECHNICAL NOTE

Cylindrical Inversion Pulse for the Reduction of Cardiac Motion Artifacts in Contrast-enhanced Breast MRI

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We proposed a simple technique for reduction of cardiac-related motion artifacts on contrast-enhanced images in the breast by using cylindrical regional-suppression technique (CREST) that can directly suppress the heart signals. The purpose of this study was to select the optimal scan parameters and to evaluate the feasibility in the breast. We demonstrated that the optimized CREST could dramatically reduce the cardiac-related flow artifacts without any penalty to the acquisition time, signal-to-noise ratio and contrast-enhanced lesion-to-parenchyma contrast.

Keywords: *contrast-enhanced magnetic resonance imaging, breast tumor, motion artifact, cylindrical pulse, inversion pulse*

Introduction

In breast MRI, motion artifacts due to cardiac motion inevitably appear, particularly in images after contrast media injection.[1,2] Such artifacts can often impede the diagnosis. One of the most effective solutions is swapping the phase-encoding direction,[1,2] but it does not yield satisfactory results in some cases.

In this study, we attempted an unexpected usage of a cylindrical inversion pulse (known as time-spatial labeling inversion pulse),[3–5] as a direct heart-signal suppression, to suppress cardiac motion artifacts on the contrast-enhanced images in the breast cylindrical regional-suppression technique (CREST). The purpose of this study is to select the optimal scan parameters (inversion delay) and to evaluate the feasibility in the breast.

Materials and Methods

A total of 12 patients who underwent contrast-enhancement were examined with 3.0 Tesla whole-body clinical system (Achieva TX, Philips Healthcare, Best, The Netherlands). The study was approved by the local institutional review board, and

written informed consent was obtained from all subjects. All images in this study were acquired after routine clinical scans.

Figure 1 shows the scheme of CREST method. CREST is based on a 2D spiral inversion radio-frequency pulse with gradients in both frequency and phase directions[5] that enables a cylindrical inversion in the head–foot direction. The diameter of the cylindrical pulse and center location of the pulse are freely adjustable. The CREST pulse is placed directly on the heart and data sampling is done at the null point of the blood signals, to reduce artifacts effectively.

The study consists of two parts: 1) selection of optimal inversion delay time and 2) feasibility evaluation of optimized CREST sequences.

Selection of optimal inversion delay time

Since CREST technique is based on an inversion recovery pulse, we should always select optimal inversion delay (TI). To this end, we investigated the optimal inversion delay on 3D segmented T_1-weighted gradient echo T_1-turbo field echo (T1TFE) in six patients with contrast-enhanced breast examination by comparing the signal-to-noise ratio (SNR) of the heart and the standard deviation (SD) of the background signals as markers of the severity of the artifacts.

In 3D T1TFE, for instance, the fat suppression pulse is typically shared over a large number of echoes (TFE shot) for achieving efficient fat suppression while preventing prolongation of acquisition time. CREST pulse is also shared due to same reason. Hence, the interval of each shot (shot interval, equal to TR) is an important factor in order to determine optimal TI. In this study, we determined the optimal TI with two different situations as follows: (a) shot interval is kept constant (TI of 50, 100, 150 ms, shot interval of 300 ms),

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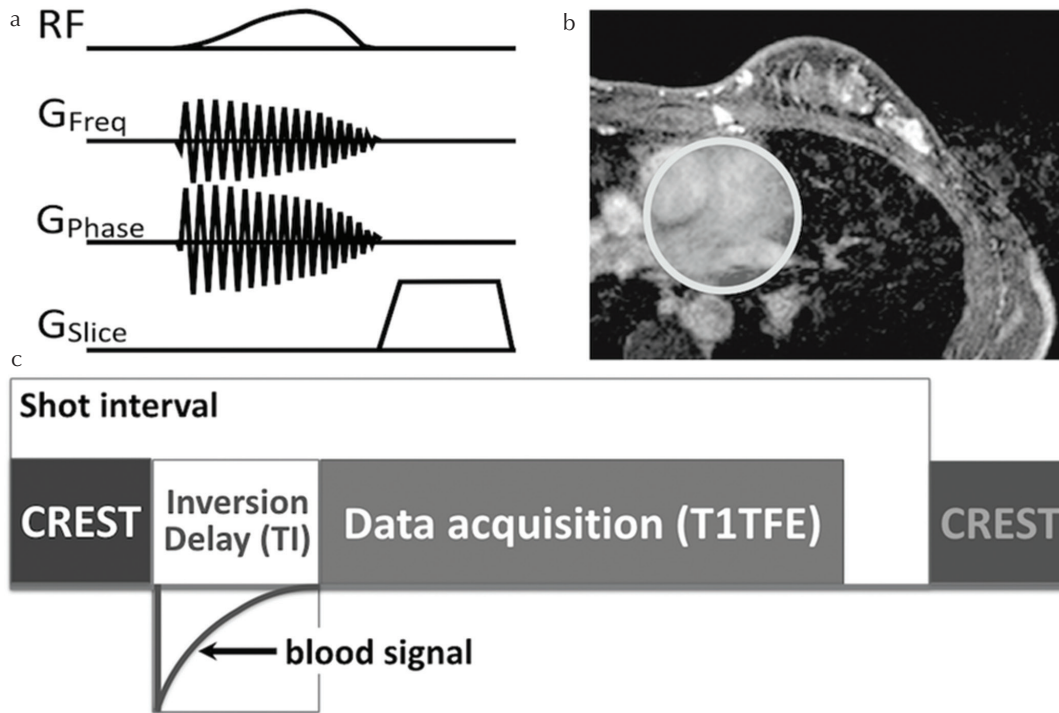E-mail: masami.yoneyama@philips.com

Fig. 1 Scheme of cylindrical regional-suppression technique (CREST) prepared sequence. CREST is based on a cylindrical inversion pulse, which consists of spiral excitation in frequency and phase directions and a spoiler gradient in the slice direction (**a**). CREST is placed directly on the heart (**b**) and data sampling is done at the null point of the blood signals (**c**), consequently artifacts would be reduced. CREST, cylindrical regional-suppression technique; T1TFE, T_1-turbo field echo; RF, radio-frequency.

(b) shortest shot interval is chosen regarding respective TI because longer shot interval leads to unwanted prolongation of total acquisition time (TI of 50, 100, 150 ms, shot interval of 100, 150, 200 ms, respectively).

The imaging parameters for CREST prepared 3D T1TFE were: axial imaging plane, FOV of 350 mm, in-plane acquisition matrices of 350 (phase encoding) and 350 (frequency encoding), 50 slices, slice thickness of 3.0 mm, TR of 4.4 ms, TE of 2.2 ms, flip angle (FA) of 10°, turbo factor of 12. The FA of CREST pulse was 180° and the duration of the pulse was 4.2 ms. A diameter of CREST pulse was fixed at 100 mm and the pulse was placed manually on the heart by referring axial survey-scan images. The spatial resolution and acquisition time were set to equal in each sequence for a fair comparison. In principle, we should use a high-resolution, isotropic-voxel 3D CREST-T1TFE as same as a routine sequence for an accurate comparison, but its use is very difficult because of a long acquisition time. Therefore, we applied 3 mm thick-slice fast 3D CREST-T1TFE in this experiment.

To determine the optimal inversion delay of the CREST for suppression of heart signals quantitatively, we measured the SNR of the heart. To allow quantitative SNR measurements, we used a noise measurement method proposed by Zwanenburg et al.[6] In this method, each sequence was repeated with the exactly the same receiver gains, but without any radiofrequency and gradient pulses. The reconstructed images showed only noise, including the noise added due to the sensitivity encoding (SENSE) reconstruction. The SD of a ROI encompassing the heart in the noise image was used as metric for the noise. Hence, this method can measure SNR correctly even if the SENSE reconstruction is used. We followed this method. Because this method can directly measure the "noise" as aforementioned, the SNR_{Heart} can be simply and directly calculated as follows:

$$SNR_{Heart} = SI \text{ (heart)} / SD \text{ (noise)},$$

where SI (heart) is the signal intensity of the heart, and SD (noise) is the standard deviation of the same location on the noise images. Circular-shaped ROIs with a diameter of 100 mm were placed on the heart on axial source images.

Subsequently, we attempted to quantitatively evaluate the effect of the CREST in suppression of ghost artifact; however, it is difficult to directly measure the signal of artifacts without contamination of the background such as lung and its small vessels. Here, the important point is that the signal of the lungs and its small vessels can be regarded as steady during the CREST preparation, because these structures are not affected by the CREST. On the other hand, the signal of artifacts should be suppressed by the CREST. Consequently, the SD of all these tissues together (consisting of the lungs and their small vessels) should be decreased if CREST works well. Thus, for the purpose of assessing the

effect of CREST in suppression of motion artifacts, the SD of these regions in the FOV outside the breast parenchyma ($SD_{Artifact}$) was measured. More specifically, a circular-shaped ROI was placed around the heart.

Demonstration of efficiency of CREST

To validate the usefulness of adding CREST in breast imaging, we compared quantitatively the image quality, including degree of motion artifact (SNR_{Heart} and $SD_{Artifact}$), SNR of the breast parenchyma and lesion-to-parenchyma contrast, in the six patients who have enhanced solid tumor. Because cardiac motion artifacts typically affect the left side of breast more strongly than the right side, we chose the patients with left-sided tumor.

The signal intensity of the breast parenchyma should not be suppressed by CREST. To confirm that the CREST does not affect the breast parenchyma signals, SNR of the breast parenchyma (SNR_{Breast}) was calculated as follows:

$$SNR_{Breast} = SI \text{ (breast)} / SD \text{ (noise)},$$

where SI (breast) is the signal intensity of the breast parenchyma, and SD (noise) is the standard deviation of the same location on the noise images.

Moreover, the contrast-enhanced tumor-to-parenchyma contrast should also not be decreased by CREST. To confirm that the CREST does not negatively affect the contrast, contrast-to-noise ratio (CNR) of enhanced solid tumor on the left side of the breast and breast parenchyma ($CNR_{Tumor-Breast}$) was also calculated. The $CNR_{Tumor-Breast}$ was calculated with the following equation:[7]

$$CNR_{Tumor-Breast} = [SI \text{ (tumor)} - SI \text{ (breast)}] / [SD \text{ (tumor)}^2 + SD \text{ (breast)}^2]^{1/2}$$

where SI (tumor) is the signal intensity of the enhanced solid tumor, SI (breast) is the signal intensity of the breast parenchyma, and respective SDs (SD [tumor] and SD [breast]) are the standard deviation of the same locations on the noise images.

One of the authors (M.Y., with more than 15 years of experience with MRI), who was blinded to the type of image under evaluation, placed ROIs over the left and right breast parenchyma and tumor (selected lesion with a diameter >10 mm and homogeneous solid enhancement, excluding lesion edges to avoid a partial volume effect and defining the ROIs carefully to avoid the parenchyma or vessels). Placement of the ROIs and size of cursor were matched for the different image sets in a given patient. We conducted all qualitative and quantitative analyses in a blinded manner.

To minimize bias in estimating the signal intensity of the breast tumors, which may be caused by the difference in time lag between contrast injection and imaging, we scanned two sequences in random order in all patients.

Finally, to demonstrate the improved visualization in the breast and/or axilla by adding CREST, images obtained 3D T1TFE without- and with CREST sequences were visually evaluated by two board-certified radiologists in a random and blinded manner. Visualization of lymph nodes at the level of axilla was assessed using a three-point grading scale (1 = fully obstructed by ghost artifacts, 2 = partially obstructed by ghost artifacts, 3 = well visualized). The visual assessment was performed on the monitor of a personal computer with the OsiriX Medical Imaging Software (Pixmeo, Geneva, Switzerland), and the observers were allowed to adjust the window level and width of the respective contrast-enhanced T_1-weighted images.

The imaging parameters for 3D T1TFE with/without CREST were: axial imaging plane, FOV of 350 mm, in-plane acquisition matrices of 350 (phase encoding) and 350 (frequency encoding), 150 slices, slice thickness of 1.0 mm, TR of 4.4 ms, TE of 2.2 ms, FA of 10°, turbo factor of 48, and accession time of 60 sec (without CREST) and 62 sec (with CREST).

Statistics

The SNR_{Heart}, $SD_{Artifact}$, SNR_{Breast} and $CNR_{Tumor-Breast}$ were assessed by using one-way repeated measures analysis of variance and post-hoc Tukey test, because the data were normally distributed according to Shapiro-Wilk normality test. Visual grades were compared between with- and without CREST using the Kruskal–Wallis test and the post-hoc Steel–Dwass test, because the data did not fit a normal distribution.

Results

Tables 1 and 2 show the results of optimal TI selection with two different situations. When the shot interval was kept constant, both SNR_{Heart} and $SD_{Artifact}$ increased with increasing TI. The shortest value (50 ms) of TI showed the lowest value in both SNR_{Heart} and $SD_{Artifact}$ significantly (Table 1). Likewise, when the shortest shot interval was chosen regarding respective TI to minimize the prolongation of total acquisition time, the shortest value of TI showed the lowest value in both SNR_{Heart} and $SD_{Artifact}$

Table 1. Quantitative comparison of optimal inversion delay with constant shot interval

	Without CREST	With CREST		
Inversion delay (ms)	N/A	50	100	150
SNR_{Heart}	85.8 ± 7.0	17.7 ± 2.4[*]	22.4 ± 5.5[*]	28.1 ± 4.3[*,†,‡]
$SD_{Artifact}$	8.91 ± 2.46	4.40 ± 0.42	4.68 ± 0.41[*,†]	5.29 ± 0.83[*,†,‡]

Values are presented as means ± standard deviation (SD); The shot interval was held fixed at 300 ms; [*]$P < 0.05$ compared with "without cylindrical regional-suppression technique (CREST)"; [†]$P < 0.05$ compared with inversion delay of 50 ms; [‡]$P < 0.05$ compared with inversion delay of 100 ms. SNR, signal-to-noise ratio.

(Table 2). As a result, the shortest value of TI resulted in the most efficient suppression of cardiac artifacts in both parameter situations. Representative images are shown in Fig. 2.

Table 3 shows the results of the feasibility evaluation of CREST technique. Both the SNR_{Heart} and $SD_{Artifact}$ of "With CREST" were significantly lower than those of "Without CREST". On the other hand, the SNR_{Breast} and $CNR_{Tumor-Breast}$ of "With CREST" indicated similar values compared with "Without CREST". There were no significant differences. Accordingly, the optimized CREST sequence significantly reduced the cardiac artifact without any penalty to the SNR of breast tissue and lesion-to-parenchyma contrast. Representative images are shown in Fig. 3.

The results of visual assessment regarding the visualization of lymph nodes at the level of axilla are presented in Table 4. The visual grade of visualization of lymph nodes at the level of axilla was significantly better for "With CREST" than for "Without CREST".

Discussion

In this study, we evaluated the feasibility of CREST technique as a direct heart-signal suppression method on the contrast-enhanced images in the breast. First off, we investigated the optimal TI for maximizing the effect of CREST suppression pulse because this pulse is based on an inversion recovery pulse. From the results, we found out

Table 2. Quantitative comparison of optimal inversion delay with variable shot interval

	Without CREST	With CREST		
Inversion delay (ms)	N/A	50	100	150
Shot interval (ms)	91	99	154	204
Scan time (s)	15	17	26	34
SNR_{Heart}	49.8 ± 9.7	$5.9 \pm 2.6^*$	$12.1 \pm 2.6^{*,†}$	$21.6 \pm 4.9^{*,†,‡}$
$SD_{Artifact}$	3.93 ± 0.81	$2.24 \pm 0.44^*$	$3.34 \pm 1.11^{*,†}$	$3.77 \pm 0.93^†$

Values are presented as means ± standard deviation (SD); $^*P < 0.05$ compared with "Without cylindrical regional-suppression technique (CREST)"; $^†P < 0.05$ compared with inversion delay of 50 ms; $^‡P < 0.05$ compared with inversion delay of 100 ms; SNR, signal-to-noise ratio.
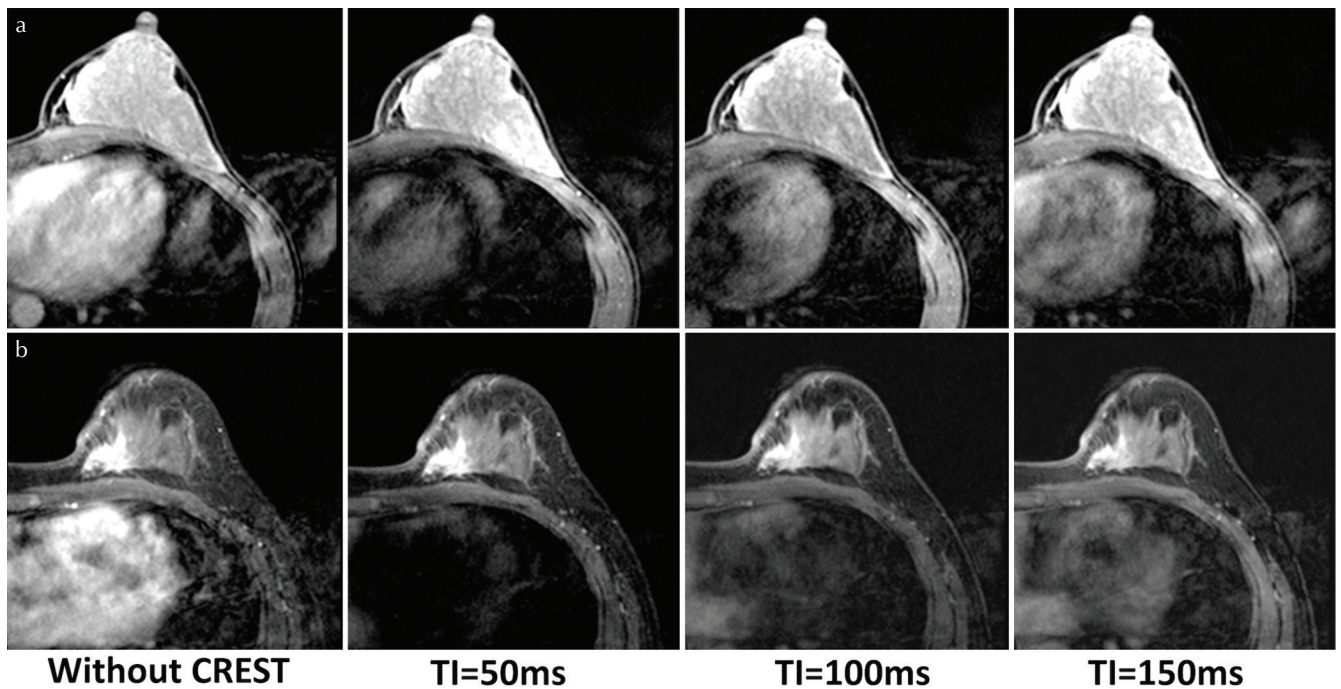

Fig. 2 Representative images of different inversion delays (TIs) in two different situations. (**a**) cylindrical regional-suppression technique (CREST) without- and with variable TIs (50, 100 and 150 ms), with constant shot interval (300 ms). (**b**) CREST without- and with variable TIs (50, 100 and 150 ms), with shortest shot intervals in respective TI (100, 150 and 200 ms. The purpose of this parameter setting is to prevent prolongation of acquisition time). In both parameter situations, the shortest value of TI (50 ms) resulted in the most efficient suppression of cardiac artifacts.

that the shortest TI value results in the most efficient suppression of the blood signals in the heart. Because T_1 relaxation time of blood is considerably shortened due to the contrast media, the possible shortest TI value (<100 ms) would be matched to the null point of blood signals in the heart. Thus, the shortest value should be chosen as optimal TI for most effectively reducing the motion artifacts. Subsequently, we evaluated the feasibility of this optimized technique in patients with the contrast-enhanced breast examination and also evaluated whether CREST pulse negatively affects the image quality. The SNR of the heart was

Table 3. Quantitative comparisons of SNR, artifact level, and contrast-noise ratio (CNR) between 3D T1-turbo field echo (T1TFE) without cylindrical regional-suppression technique (CREST) and with CREST

	Without CREST	With CREST
SNR_{Heart}	49.8 ± 9.7	5.9 ± 2.6*
$SD_{Artifact}$	3.93 ± 0.81	2.24 ± 0.44*
SNR_{Breast}	45.5 ± 7.7	45.2 ± 3.29
$CNR_{Tumor-Breast}$	40.8 ± 6.2	38.2 ± 2.6

Values are presented as means ± standard deviation (SD); *$P < 0.01$ compared with "Without CREST".

Table 4. Comparison of visual grades between 3D T1-turbo field echo (T1TFE) without cylindrical regional-suppression technique (CREST) and with CREST

	Without CREST	With CREST
Visualization of lymph nodes at the level of axilla	1.0 ± 0.0	2.6 ± 0.5*
(1 = fully obstructed by artifacts, 2 = partially obstructed by artifacts, 3 = well visualized)		

Values are presented as means ± standard deviation (SD); *$P < 0.01$ compared with "Without CREST".

significantly reduced and hence the degree of ghost artifacts dramatically decreased by combining CREST. This indicates that the optimized CREST sequence worked well for suppressing cardiac signals with high robustness. On the other hand, SNR of breast parenchyma and CNR between breast parenchyma and tumor maintained the same level with "Without CREST". That is CREST did not affect for the signals of breast parenchyma, tumor and lymph nodes, except the heart. Thus, the optimized CREST does not impair the image quality such as SNR and tumor-parenchyma contrast while enabling high effectiveness for artifact reduction.

Besides, an increase of acquisition time by adding of CREST is slight like a few seconds; hence, it would be clinically allowable. Consequently, the CREST pulse with shortest TI could dramatically reduce the cardiac-related flow artifacts without any penalty to the acquisition time, SNR and contrast-enhanced lesion-to-parenchyma contrast.

The CREST technique can be easily applied to routine clinical studies because this prepulse is based on an alternative usage of relatively common procedure for unenhanced MR angiography known as time-spatial labeling inversion pulse.[3–5] Clinically, the CREST would be helpful for the diagnosis of tumors especially that exist at the peripheral area of the breast. Additionally, this technique has a potential that also helps the diagnosis of lymph node metastases, which exist at the axilla. Moreover, this may also have a possibility for application to other body parts that similarly suffers from ghosting flow artifacts due to the pulsatile flow of the arteries, such as thoracic spine, because this is a prepulse and can therefore easily combine with other pulse sequences such as turbo spin echo.

There are several limitations in our study. First, although we have demonstrated that the CREST pulse does not negatively affect the image quality, still there is a concern that it may cause unwanted signal loss in adjacent tissues because the CREST pulse and its profile property is theoretically susceptible to magnetic field inhomogeneities. Clinically, CREST might affect the diagnosis of the parasternal lymph
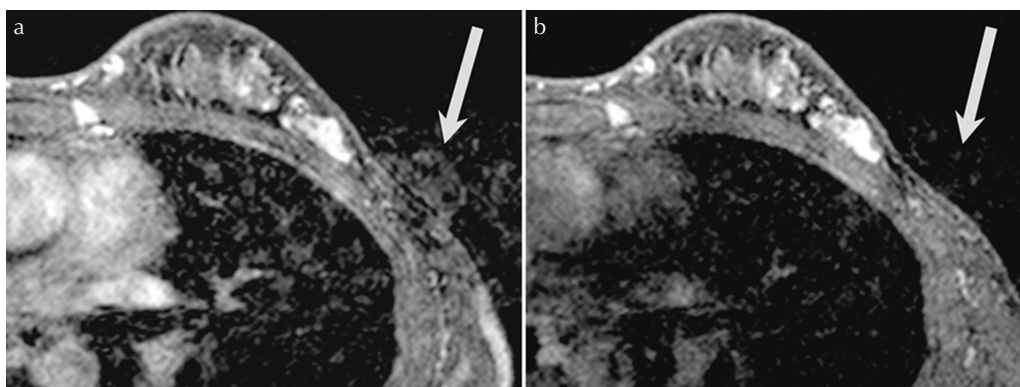

Fig. 3 Representative images of contrast-enhanced 3D T1-turbo field echo (T1TFE) without cylindrical regional-suppression technique (CREST) (**a**) and with CREST (**b**) in the breast. CREST could significantly reduce the cardiac artifact (arrow).

node metastases. To confirm whether the CREST pulse provides negative effect for adjacent tissues, the accuracy of excitation profile of CREST pulse (and the influence of its side lobes) should be investigated in future study. Second, we adopted the inversion (180 degree) pulse for suppressing flow artifacts; however, the saturation (90 degree) pulse is typically applied for such purpose. It is unclear that which pulse is better for the purpose of this study. Nevertheless, we believe that inversion-based pulse we used in this study is superior to saturation pulse because the inversion method can lead the signals into their null point and then almost completely reduce the artifacts. Finally, because this study evaluated only few numbers of patients, further clinical investigation is needed for validation of this method.

In conclusion, we propose a simple and effective method for reduction of cardiac motion artifacts on contrast-enhanced images in the breast by using CREST.

Conflicts of Interest

Masami Yoneyama, Masanobu Nakamura and Makoto Obara are the employees of Philips Electronics Japan. Tomoyuki Okuaki and Marc Van Cauteren are the employees of Philips Healthcare Asia Pacific. The other authors have no conflict of interests.

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