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Reproduction of Motion Artifacts for Performance Analysis of Prospective Motion Correction in MRI

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Abstract

Purpose—Despite numerous publications describing the ability of prospective motion correction (PMC) to improve image quality in MRI of the brain, a reliable approach to assess this improvement is still missing. This work develops a method that accurately reproduces motion artifacts correctable with PMC, and enables the quantification of the improvements achieved.

Methods—A software interface was developed to simulate rigid body motion by changing the scanning coordinate system relative to the object. Thus, tracking data recorded during a patient scan can be used to reproduce the prevented motion artifacts on a volunteer or a phantom. The influence of physiological motion on image quality was investigated by filtering these data. Finally, the method was used to reproduce and quantify the motion artifacts prevented in a patient scan.

Results—The accuracy of the method was tested in phantom experiments and in vivo. The calculated quality factor, as well as a visual inspection of the reproduced artifacts shows a good correspondence to the original.

Conclusion—Precise reproduction of motion artifacts assists qualification of prospective motion correction strategies. The presented method provides an important tool to investigate the effects of rigid body motion on a wide range of sequences, and to quantify the improvement in image quality through PMC.

Keywords

prospective motion correction; motion artifact; motion tracking; real-time

INTRODUCTION

Patient motion in magnetic resonance imaging (MRI) remains problematic in both clinical routine and research. Even for a highly motivated patient it is difficult to stay completely

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immobile for the duration of an MRI examination. This problem has existed since the early days of MRI and has been investigated in detail for a number of imaging protocols. Artifacts caused by breathing motion, cardiac pulsation and involuntary head movements are common, especially during long image acquisitions. In routine structural imaging, motion artifacts often lead to reduced image quality, longer scan sessions, repeated examinations or even a failed diagnosis.

It has been shown that prospective motion correction (PMC) can reduce motion artifacts by using data from external tracking devices or navigators to adapt the field of view dynamically to the changes in the patient's head position [1–5]. Recent improvements made in the development of motion tracking systems bring the technique closer to application [6].

However, in contrast to retrospective correction methods, during a PMC-enabled experiment no uncorrected image remains for comparison, which makes a quantification of the improvements achieved through PMC based on a single experiment impossible. Usually, a second measurement without PMC is done [2, 3, 7]. The images are then compared visually or image entropy or other image metrics [4, 8] are used.

However, often this is not a fair comparison, since the motion occurring in the two imaging experiments cannot be identical. Retrospective simulation of motion artifacts using the image or k-space data is strongly dependent on the sequences used and is currently too computationally intensive to be practical.

One possible solution to the problem of validation in PMC is to perform corrected and uncorrected data acquisitions in an interleaved manner for each k-space line [9]. For sequences with short repetition times (TR), this enables one to acquire a corrected and an uncorrected image during almost identical motion. However, this doubles the duration of each scan, which makes it impractical for clinical studies. Moreover, the doubled scan time increases the likelihood and amplitude of involuntary motion. Additionally, the interleaved acquisition of corrected and uncorrected scans might result in unwanted spin history effects such as spin saturation or stimulated echoes. For example such effect could be due to an overlap of corrected and uncorrected slices in subsequent 2D excitations.

Another way to quantify the effect of PMC on a specific MR technique, would be the conduction of larger patient studies including image scoring by experienced radiologists and statistical analysis methods. However, for methodological developments a faster way of quantifying the improvements of PMC is desired.

In this work we present a method that enables the reproduction of all motion artifacts that can be corrected with PMC. This was recently introduced and briefly described for the investigation of the continuous update during diffusion weighted imaging [5]. However, the method is not specific to selected imaging methods and can be included in all sequences using PMC. Thus, the investigation of motion artifacts becomes much easier and facilitates the implementation of PMC in new sequences. The method can also be used to separately investigate the influence of different motion components (e.g., slow drifts, breathing, heart beat) on image artifacts.

With this technique, the effect of motion and PMC during MRI were investigated, to demonstrate the ability and flexibility of PMC to adapt MR acquisitions to patients' motion, and to reproduce artifacts suppressed by PMC for a quantitative validation of the correction method. In the presented paper the accuracy of the artifacts simulated is investigated in phantom experiments and in vivo. Additionally, the method is used to display the effect of various motions on different imaging sequences.

METHODS

Hardware Setup

All experiments were performed on a Magnetom 3 T Trio, a TIM system (Siemens Healthcare, Erlangen Germany). An MR-compatible optical system was used for motion tracking [10] (Metria Innovation Inc, Milwaukee, USA). The system consists of an MR-compatible in-bore camera and a single encoded marker (MPT). For in vivo experiments the marker was fixed to a mouthpiece or attached to the nose of the volunteer using a small piece of modeling clay. The camera reports position information in six degrees of freedom (6 DoF, translations and rotations) with an adjustable frame rate of up to 85 fps. Different head coils were used: a single-channel TX/RX, a 12-channel phased array, and a 32-channel phased array (Siemens Healthcare, Erlangen Germany).

Software Interface

To perform a continuous coordinate update of the imaging sequences a dedicated software library for external prospective acquisition correction (XPACE), written by the authors was used. This library (libXPACE) receives input from an arbitrary tracking system providing positioning information in 6 DoF. It performs updates of all gradients and radio frequency pulses of the sequence during scanning [1]. The tracking data are logged to a file.

For this work, the software was extended so that instead of the data provided from the external tracking system it is now able to use a file containing position information in 6 DoF as a position input. This enables the simulation of motion at any time during the sequence, by changing the scanning coordinate system relative to the object. Note, that no additional programming effort is required to use this functionality with sequences for which PMC is readily available.

The basic principle of this technique is explained in Fig. 1. To retrospectively reproduce motion artifacts prevented in a patient scan (Fig. 1c), all position changes recorded during the real patient measurement are fed back to the scanner with the direction of motion reversed (Fig. 1d). This way, the relative motion between the scanning volume and the object is the same as it would have been without PMC during the first experiment (Fig. 1b and f). This second experiment can then be performed either in a well-trained volunteer able to remain immobile or a phantom, without prolonging the duration of the scan for the patient.

Pulse Sequences

Several imaging sequences were modified to perform PMC. First, position updates were introduced in a gradient echo sequence and a spin echo sequence before each excitation pulse. For the short echo times used, no further corrections (e.g. between excitation and readout) were implemented.

A more sophisticated correction scheme was applied to the third imaging sequence investigated, fast spin echo (rapid acquisition relaxation enhancement (RARE) [11]). In addition to the position update for each excitation pulse, a continuous correction during the echo train was implemented that adjusts the gradient coordinate system and RF frequencies and phases before every refocusing pulse.

Phantom experiments

Accuracy of reproduced artifacts—A moving gel phantom was scanned, using a gradient echo sequence, without applying motion correction, but including motion tracking during the whole experiment (TR = 140 ms, TE = 3.6 ms, voxel size = $1 \times 1 \times 3 \text{ mm}^3$,

encoding matrix = 192×192 , single-channel coil). The artifacts from this first experiment were then reproduced in a stationary phantom. Motion data, with the direction of motion reversed relative to the tracking data from the first experiment, were used by the scanner, running the same sequence with motion correction enabled. This experiment was repeated with the motion data time-shifted to account for the latency of the tracking system (28 ms).

Motion sensitivity of MR-sequences—The appearance of motion artifacts in the image depends on the amount of motion, its direction and the timing relative to the sequence. Here, the motion sensitivity of a fast spin echo sequence was investigated in detail (TR = 1000 ms, TE = 87 ms, voxel size = $0.27 \times 0.27 \times 3 \text{ mm}^3$, encoding matrix = 512×512 , 32-channel coil). The effects of translations and rotations on all three axes at different time points during the acquisition were reproduced. Movements with different amplitudes and velocities were assumed between excitation pulses and during signal readout.

In vivo experiments

All in vivo experiments were performed in accordance with a protocol approved by the local ethics-committee. Informed consent was obtained prior to each examination.

Accuracy of reproduced artifacts—To test the ability of the new method to reproduce motion artifacts with a sufficient accuracy in vivo, two measurements with a spin echo sequence were performed (TR = 150 ms, TE = 9.1 ms, voxel size = $1.1 \times 1.1 \times 5 \text{ mm}^3$, encoding matrix = 192×192 , 12-channel coil), one with a volunteer performing a position change during the measurement without PMC applied but with motion tracking during the whole experiment. The tracking data from this first experiment were then used to reproduce motion artifacts in a second experiment on the same volunteer. Prior to this second experiment the volunteer was asked to return to the original position and to stay as still as possible. To quantify the accuracy of the reproduction, the average edge strength (AES) [4] was used to compare the two data sets.

High resolution imaging RARE—The effect of PMC on a high resolution protocol was investigated in vivo in a cooperative volunteer instructed to stay as still as possible during a 10 minute scan (TR = 6500 ms, TE = 87 ms, turbo factor = 21, voxel size = $0.27 \times 0.27 \times 2 \text{ mm}^3$, encoding matrix = 768×612 , 32-channel coil). This experiment was performed with PMC applied. Tracking data were then separated into individual components to investigate the proportional influence of slow drifts and motion resulting from breathing and heartbeat. The respective motion artifacts were then reproduced on a stationary phantom to guarantee that no additional motion affects arise during the simulation.

Investigation of a patient scan—Finally, the method was used to reproduce the motion artifacts prevented in a patient scan. In a patient study currently being performed in our institution PMC was introduced in several standard sequences, such as MP-RAGE. In this work one of these scans was selected as an example and motion artifacts prevented in the patient scan were reproduced on a stationary volunteer and a phantom.

RESULTS

Phantom Experiments

Accuracy of reproduced artifacts—In Fig. 2a, the magnitude image of the stationary phantom is shown. The result of the uncorrected scan of a moving phantom is presented in the following image (2b). Prominent motion artifacts can be seen as expected given the strong motion performed. In Fig. 2c and d, the tracking data were used to reproduce the artifacts from the first experiment in a stationary phantom. Therefore, the phantom was

shifted back to the original position. In Fig. 2e–g difference images are shown: the first one (e) displays a slight shift between the position of the phantom in the first run and the new position.

The result of the reproduction is presented in Fig. 2c and the corresponding difference image (subtracting the reproduced from the original artifacts) is shown in Fig. 2f. The same experiment was repeated, including knowledge of the delay in the tracking data (28 ms). The results of this measurement are shown in Fig. 2d and the difference image (subtracting the artifacts reproduced including the latency from the original) is presented in Fig. 2g. Using the unprocessed tracking data already allows close reproduction of the artifacts of a motion experiment. However, as seen from the images in Fig. 2f and g, the use of a known latency for such reproduction further improves the results.

Motion sensitivity of MR-sequences—The results of the investigations on the motion sensitivity of the RARE sequence are shown in Fig. 3. In the first experiment, artifacts caused by slow motion during a turbo spin echo sequence were simulated for translations (Fig. 3a) and for rotations (Fig. 3b). The motion patterns simulated assumed a continuous drift purely in one degree of freedom over the whole measurement. For the images presented in Fig. 3a shifts of 1, 3, and 5 mm are simulated, in Fig. 3b rotations of 1, 3, and 5 degrees respectively. For each measurement the corresponding difference image is included, computed using an uncorrupted reference scan. The artifacts seen in these images result mainly from motion between excitation pulses since motion during the short readout train can be neglected for these slow motion patterns.

For faster motion patterns the artifacts caused by motion during the readout train become visible. These artifacts were simulated and are presented in Fig. 3c (fast translations) and Fig. 3d (fast rotations). The simulations were performed assuming a continuous drift over the whole measurement which was corrected before each excitation pulse. This way the simulated values (translations of 50 mm and rotations of 50 deg) may appear not to be realistic. However, this corresponds to a repeated motion with much lower amplitude but similar velocity. This resulted in residual motion of about 2 mm and 2 deg over the duration of the echo train.

The results in Fig. 3a and 3b indicate the importance of PMC at each excitation pulse. The appearing motion artifacts are often seen in in vivo TSE experiments. An additional correction during the readout seems to be necessary as soon as the motion is relatively fast and or a longer echo train is used (Fig. 3c). While this is mostly not the case for cooperative patients and the standard RARE protocol, it would become more important for particular imaging modalities, especially for single shot techniques such as SPACE or HASTE.

In vivo Experiments

Accuracy of reproduced artifacts—Figure 4a shows the image of a volunteer instructed to change head position during a short spin echo sequence. There was no motion correction performed and strong artifacts appear in the image. In Fig. 4b, these artifacts were accurately reproduced in a scan where the volunteer remained motionless. The artifacts reproduced correspond closely to these of the first measurement. When inspected in detail, minor differences can be seen which probably result from a slight difference in position at the start of each measurement. However, these differences seem not to influence the average edge strength (AES). The quality factor defined ($QF = AES_{ReproducedArtifacts} / AES_{OriginalArtifacts}$, [9]) is calculated to $QF = 0.9994$ when comparing both images. Since $QF \approx 1$, the edges in the reproduced image are as unsharp as in the original image.

High resolution imaging—Figure 5a shows an image of a cooperative volunteer from a ten minute high resolution RARE scan with PMC. The motion artifacts prevented with PMC were investigated: Low-pass and band-pass filtering of the tracking data provides information about the drift during the scan, while motion caused by breathing, and even movements caused by the beating heart can be detected and separated. These different components of the tracking data are shown in Fig. 5b.

These filtered tracking data were used to simulate motion artifacts in a stationary phantom. The results are presented in Fig. 6. The first image column shows the artifacts simulated with the drift data, which underlines the importance of the PMC. These artifacts would have significantly decreased the image quality of the in vivo image. The second image column shows the result of the simulation done with the data showing breathing motion. These slow movements with an amplitude of about 0.1 mm do not seem to cause any significant artifacts. The motion caused by the cardiac cycle (i.e., the ballistocardiogram [12]) shows a similar amplitude but occurs with a much higher velocity. The artifacts caused by cardiac-related motion can be seen in the third column in Fig. 6.

Being able to reproduce artifacts from the motion that originates from the cardiac cycle does not automatically mean that they were corrected during the in vivo experiment. Since these movements are relatively fast, the latency of the correction feedback loop has to be considered. An improvement of the image quality can only be seen if the difference between the position assumed by the scanner and the real position is smaller than what it would be without the correction. This difference is plotted in Fig. 7 for three latency values. For a latency of about 30 ms (Fig. 7b), which has to be considered for our tracking system, the amplitude of the residual error is as high as in the original motion plot (Fig. 5b III). In our in vivo image this would result in small residual motion artifacts we would not be able to fully correct for with the current system. When we assume even higher latencies (e.g. 60 ms, Fig. 7c), the residual error increases and would result in additional motion artifacts caused by this difficulty in the correction of fast position changes. Shorter system delays (e.g. 20 ms, Fig. 7a) are needed on attempt to at least partially be able to correct for such fast motion. Luckily the ballistocardiogram is small in amplitude and causes only negligible blurring artifacts.

Investigation of a patient scan—In Fig. 8, the results of the patient experiments are presented. The images of the motion corrected patient scans are shown in Fig. 8a and b. Then the same protocols were run on a volunteer (Fig. 8c and d), first without any modification for comparison and then including the tracking data from the respective patient scan. In the second image of Fig. 8c and d, the artifacts prevented in the patient scan are reproduced using the tracking data recorded previously. While the artifacts appearing in the first experiment (Fig. 8c) are clearly visible, using tracking data from the second patient scan for reproduction of artifacts seems to have only minor influence on the image presented (Fig. 8d). Under the assumption of a stationary volunteer, the resulting artifacts can be used as a measure for the improvement of image quality in the patient scan. However, unintended head motion during simulation will certainly influence the quality of the acquired images and precludes simulations on patients. In particular, the simulation of artifacts resulting from head motion due to heartbeat or breathing is not possible in vivo.

Additionally to the artifacts reproduced in vivo, the same measurements were performed on a phantom to exclude unintended head motion (Fig. 8e and f). These images can only give an estimate of how the patient images would look without motion correction as contrast and structures are not consistent with the brain scan. However, phantom scans would provide a reliable measure when used for quantification of the improvements made. For both phantom experiments (Fig. 8 e and f) the quality factor is calculated as an example for a possible quantification. By calculating the quality factor of the first dataset (Fig. 8 e, $QF = 1.120$) and

the one of the second dataset (Fig. 8 f, $QF = 1.105$) the artifacts prevented by PMC can be reliably quantified for both experiments and a comparison between the improvements due to PMC during both patient scans becomes possible.

DISCUSSION AND CONCLUSIONS

The validation and fair comparison of PMC results has previously been problematic, since the resulting image cannot be compared to an uncorrected scan fulfilling the same imaging conditions. Especially when used in clinical routine, a quantification of the improvements needs to be done without interaction with the actual patient scan. Existing methods rely on the exact repetition of an acquisition [2, 3, 7] or double the duration of a single scan [9] to quantify the improvements made. The method presented here enables the reproduction of the prevented motion artifacts under controlled conditions on a phantom or a stationary volunteer and thus allows a fair comparison between different subjects. This can be investigated retrospectively if needed and does not cause any prolongation of the MR-investigation, or additional discomfort for the patient.

The new method was used to simulate arbitrary motion artifacts in different sequences. For the development of PMC sequences this technique offers an important tool to investigate the effect of coordinate updates at different time points of the sequence and to understand the motion artifacts expected. Compared to an alternating acquisition of two images [9] this new method allows the accurate simulation of intrascan motion artifacts e.g. from motion during diffusion encoding periods [5] or during the echo train. This includes the possibility to investigate PMC-enabled sequences with respect to their sensitivity to inaccurate tracking data due to latencies or measurement noise [13]. In this work examples were presented for a RARE sequence. However, the method is not limited to these two imaging techniques and can be used whenever PMC is applied in a particular sequence.

The accuracy of the method was tested in phantom experiments and in vivo. The results of these measurements demonstrate the ability of the technique to accurately reproduce artifacts and underline the importance of short latencies when prospectively correcting for fast motion. With this method, motion artifacts due to arbitrary motion can be reproduced, as long as they can be prevented with PMC. For example, the effects of changing B_0 field inhomogeneities or RF coil sensitivities during actual motions cannot be simulated using the proposed method. This might reduce the accuracy of the reproduced artifacts when parallel imaging techniques are used. Also subject motion within non-linear areas of the gradient system cannot be perfectly corrected by PMC and thus the related artifacts cannot be accurately reproduced by the presented method. Another reason for remaining differences between original and reproduced artifacts might be the discrete time grid used for PMC and simulations. In [5] a technique is presented to reduce the time between correction (or simulation) steps to about 2 ms; however, motion during these finite sequence elements is not taken into account. On the other hand, for the purpose of a quantification of PMC-relevant improvements these effects are of minor interest as they are not taken into account by the correction method itself. In this work the average edge strength was used to quantify differences between uncorrected scans and measurements using PMC as suggested in [4, 9]. However, the average edge strength is just one possible quantification metric and other approaches could be combined with the technique of reproducing motion artifacts.

A high resolution scan was performed on a volunteer who was instructed to remain as still as possible. PMC was used to correct for slow position drifts and small head motion resulting from breathing and the heart beating. The observation of such microscopic head motion was reported [9, 10] but the effect of PMC has not been investigated so far. In this work, the artifacts prevented during this scan were then reproduced on a phantom separately for the

slow drift, the breathing motion and the fast movements resulting from the cardiac cycle. The results display the importance of PMC during high resolution imaging but also show that a shorter latency might be necessary when fast motions occur. Long latencies make the correction of such fast motion impossible and can even lead to additional artifacts.

The problem of quantifying improvements achieved by prospective methods is not limited to the correction of motion artifacts. For example, real time shimming has been shown to reduce image artifacts resulting from B_0 changes during a dynamic acquisition [14] or high resolution T_2^* imaging [15]. While the method presented in our work was used to simulate artifacts by feeding back motion data to the scanner, the same principle could be used to reproduce artifacts prevented by real time shimming or other prospective correction methods. All parameters used to perform a specific prospective correction could be used to retrospectively investigate the improvements achieved. For navigator-based corrections, it might be possible to extend this method to apply the simulated motion during the navigators as well as during the imaging sequences, thereby allowing the testing of multiple variations of PMC methods on the same motion set.

While PMC can greatly reduce motion artifacts when correcting for the true position changes, it fails and can even create new artifacts when the applied update does not represent the true position of the measured object. This issue has to be kept in mind whenever PMC is used in new sequences. The presented technique provides a means to perform such investigations under controlled conditions. However, the simulated artifacts can only be as accurate as the tracking data provided. Corruption or inaccuracies of the tracking data (e.g. loss of tracking, non-rigid body motion, or measurement noise) collected during an in vivo scan would not only result in remaining artifacts in the corrected image but also lead to an imperfect simulation of the artifacts. The use of filters on the acquired tracking data helps to reduce such imperfections and can be applied to the tracking data prior to the artifact reproduction.

In conclusion, this work shows that the retrospective reproduction of motion artifacts is both a possible and advantageous extension to PMC. The technique presented enables a quantitative comparison of motion artifacts prevented, and accurate investigations of the effects of motion and correction on arbitrary sequences using PMC.

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Figure 1.

The accurate reproduction of motion artifacts is based on the principle of artificially repeating the imaging situation of an experiment with PMC enabled. **a:** The ideal measurement without motion is shown. **b:** Motion during the experiment changes the relative position of the subject and the field of view. **c:** Prospective motion correction moves the imaging frame in accordance with the subject's motion. The imaging situation is the same as in the 'no motion' case (**a** and **e**). **d:** The tracking data recorded during an in vivo experiment are fed back to the scanner with the direction of motion reversed. The image with reproduced motion artifacts (**f**) corresponds to the one of the 'motion' experiment (**b**).

Figure 2.

Phantom experiments performed to test the accuracy of the new method are shown. The magnitude images are shown for **a**: the stationary phantom, **b**: the uncorrected scan of a moving phantom. Strong motion artifacts can be seen as expected given the strong motion performed. Then, the phantom was shifted back to the original position. **e**: the difference image displays a slight shift between the position of the phantom in the first run and the new position. The result of the reproduction is presented in **c** and the corresponding difference image (subtracting the reproduced from the original artifacts) is shown in **f**. The same experiment was repeated, including the latency of the tracking system in the reproduction. The results of this measurement are shown in **d** and a difference image (subtracting the artifact reproduced including the latency from the original ones) is presented in **g**.

Figure 3.

Artifacts caused by motion during a turbo spin echo sequence were simulated. A continuous drift in one degree of freedom over the whole measurement was assumed. For the images presented, shifts of 1, 3, and 5 mm are simulated (**a**), followed by rotations of 1, 3, and 5 degrees (**b**). For each measurement the corresponding difference image is included. Artifacts resulting from faster motion were simulated in **c** for translations and rotations. The results display the importance of PMC in between excitation pulses. An additional correction during the echo train seems not to be necessary as long as the motion is relatively slow and a small turbo factor is used.

Figure 4.

a: shows the image of a volunteer instructed to change position during a short spin echo sequence. There was no motion correction performed and strong artifacts appear in the image. **b:** The artifacts were accurately reproduced on the motionless volunteer. The artifacts reproduced correspond to these of the first measurement. When inspected closely, minor differences can be seen, which probably result from a slightly different position at the start of each measurement.

Figure 5.

a: An image of a cooperative volunteer from a ten minutes high resolution RARE scan with PMC is presented. The image shows some small residual motion artifacts. **b:** Filtering of the tracking data from the previous experiment provides information about **I:** slow head drifts in a typical range of several millimeters, **II:** the motion caused by breathing, and **III:** movements caused by the beating heart. The head motion related to the cardiac cycle shows a similar amplitude as the breathing motion but occurs with a much higher frequency. Note that the plots shown are not to the same scale and show different axes, depending on the main component of the presented fraction.

Figure 6.

The tracking data presented in past Fig. 5 were used to simulate motion artifacts in a stationary phantom. In **a**: the artifacts reproduced with the drift data are shown. In the difference image (**d**: reproduced artifacts subtracted from an image without reproduced motion) strong artifacts are appearing. These would have caused significant artifacts in the in vivo image shown in Fig. 5a. **b**: the result of the reproduction done with breathing motion. These movements are slow and occur with a low amplitude of about 0.1 mm. The difference (**e**) image is almost free from artifacts. **c**: The reproduced artifacts resulting from head motion related to the beating heart can be seen. In contrast to the artifacts seen in (**d**) the effects of cardiac-related head motion mainly result in small differences in image intensity.

Figure 7.

Being able to reproduce artifacts originating from the cardiac cycle does not automatically mean that they were correct during the in vivo experiment. Since these movements are relatively fast, the latency of the correction feedback loop has to be considered. A improvement of the image quality can only be seen if the difference between the position assumed by the scanner and the real position is smaller than without correction. This difference is plotted for three latency values (**a**: 20 ms, **b**: 40, and **c**: 60 ms). The originally estimated cardiac related motion is shown in Fig. 5b **III**.

Figure 8.

For quantification of the improvements made by PMC the artifacts prevented during two patient scans were reproduced in a volunteer and a phantom. In **a** and **b** the results of the patient scans with PMC enabled can be seen. The artifacts prevented in these scans are then reproduced in a stationary volunteer (**c** and **d**). In both cases the first image shows the result of a measurement without motion. During the second measurement the tracking data recorded during the respective patient scan is fed back to the scanner and the artifacts that were prevented appear. The same experiments were performed on a phantom to exclude additional involuntary head motion (**e** and **f**).