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Reduction of respiratory ghosting motion artifacts in conventional two-dimensional multi-slice Cartesian turbo spin-echo: which k-space filling order is the best?

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Abstract
The two-dimensional Cartesian turbo spin-echo (TSE) sequence is widely used in routine clinical studies, but it is sensitive to respiratory motion. We investigated the k-space orders in Cartesian TSE that can effectively reduce motion artifacts. The purpose of this study was to demonstrate the relationship between k-space order and degree of motion artifacts using a moving phantom. We compared the degree of motion artifacts between linear and asymmetric k-space orders. The actual spacing of ghost artifacts in the asymmetric order was doubled compared with that in the linear order in the free-breathing situation. The asymmetric order clearly showed less sensitivity to incomplete breath-hold at the latter half of the imaging period. Because of the actual number of partitions of the k-space and the temporal filling order, the asymmetric k-space order of Cartesian TSE was superior to the linear k-space order for reduction of ghosting motion artifacts.

Keywords Turbo spin-echo · Cartesian · k-Space · Motion artifact · Breath-holding

1 Introduction

Two-dimensional (2D) multi-slice T_2-weighted turbo spin-echo (TSE) or fast spin-echo (FSE) imaging is one of the most important abdominal sequences in routine clinical use for detection and characterization of diseases. Practical problems that occur during these imaging procedures are mostly due to respiratory motion, which leads to blurring and image ghosting [1, 2]. To minimize artifacts from respiratory motion, breath holding or respiratory gating is commonly used in routine clinical practice [2]. However, gating can be ineffective in subjects with rapid or irregular respiration, particularly in patients with ascites. Furthermore, irregular respiration tends to considerably prolong the scan duration. To solve these problems, periodically rotated overlapping parallel lines with enhanced reconstruction (PROPELLER) has been shown to correct for rigid body motion as well as to distribute non-rigid motion into less regular artifacts than those of Cartesian acquisitions [3, 4], and parallel imaging has been used to achieve greater PROPELLER blade widths for improved motion correction in T_2-weighted body imaging [5]. In our experience, however, Cartesian TSE is still preferred over PROPELLER in breath-holding studies because PROPELLER with breath holding is not yet possible in the present sequences. On the other hand, various motion artifact reduction techniques in Cartesian TSE have been reported [6–10], such as modulation of phase-encode ordering and/or gradients, but these cannot yet be used in general clinical scanners. Interestingly, however, previous reports have suggested that the phase-encode ordering (k-space order) in Cartesian TSE is the most important factor for reduction of motion artifacts. Motion artifacts appear when the k-space is multiplied by a function that is periodic over ky; the periodicity of this function, the periodicity of its discontinuities, or both are the origin of the band pattern. Currently there are several types of k-space orders for TSE/FSE on clinical systems, and they should affect the resulting motion artifacts because of the differences in their

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segmentation and temporal ordering of the k-space; however, a comparison of such k-space orders with regard to their ability to reduce motion artifacts has not been performed so far.

In this study, we investigated the k-space orders in Cartesian TSE that could most effectively reduce motion artifacts under different breath-holding conditions. The purpose of this study was to demonstrate the relationship between k-space order and degree of motion artifacts using a moving phantom.

2 Theory

2.1 Types of k-space order in Cartesian TSE

The TSE or FSE sequence is widely used for the majority of routine imaging procedures; however, the scheme for filling echo signals in the k-space varies across MRI systems. Generally, the effective echo time (TE) is determined by the echo that is allocated at the central area of the k-space. In the conventional TSE/FSE technique, the first echo can be assigned at the center of the k-space (centric order), and the central echo in the echo train can also be assigned at the center of the k-space (linear order). On the other hand, the so-called asymmetric order [11–13] is a more unique method for enabling flexible TE without compromising image quality. In asymmetric TSE, the allocation of echoes is shifted by a certain number of k-space lines in the phase-encoding direction, as if echoes are scrolling on the k-space, while keeping relationships with the adjacent echoes of the centric order. Such echo shifts are automatically executed to allocate the effective TE based on the multiples of the echo spacing (ESP) proximate to the entered TE values, while maintaining the ESP, echo train length (ETL), and readout bandwidth. Consequently, compared with the conventional linear order, the asymmetric order technique allows selection of an arbitrary effective TE while keeping other parameters, including ESP, ETL, and bandwidth. In other words, the actual ordering in the asymmetric order technique is determined by TE, ESP, and ETL. Furthermore, signal differences between neighboring echo segments are maintained at a minimum level to prevent severe truncation artifacts, regardless of the actual amount of echo allocation shift (i.e., selection of arbitrary TE). To that end, asymmetric TSE adopts different filling orders in the first half and the latter half of scanning. That is, the k-space reordering of asymmetric TSE is divided into two phases on the temporal axis, and the actual number of partitions of the k-space is doubled as compared with those of the conventional linear k-space order.

Here, we focused on two important differences between linear and asymmetric orders: the actual number of partitions on the k-space segment and the temporal changes of the filling order. Thus, we attempted to compare the degree of motion artifacts between the linear and asymmetric k-space orders using a moving phantom. The methodological differences between the respective k-space orders in Cartesian TSE are illustrated in Fig. 1.

2.2 Motion artifact in Cartesian TSE

Theoretically, motion artifacts in conventional spin-echo imaging show a band pattern with a proper spacing depending on the product of the number of phase-encoding steps (Ny), motion frequency (F), and repetition time (TR; Ny·F·TR pixels), obtained almost 30 years ago with a more mathematical formulation [14]. On the other hand, in Cartesian TSE imaging, Madore [15] described the actual motion artifact as analogous to the convolution of the two band patterns consisting of an array with a spacing of Ny·F·TR pixels and an array with a spacing of the doubled number of ETL (2ETL) pixels when using the asymmetric k-space order. Additionally, Madore described there are three possible situations that cause different patterns of artifacts [15]:

1. Sometimes, the result of the convolution appears to have a spacing of 2ETL pixels
2. At other times, the result seems to have a spacing of Ny·F·TR pixels;
3. Often, however, there is no dominant contributor in the convolution, and the two arrays combine to create a visually complicated structure.

   That is, the structure of these band patterns is determined by the convolution of two band patterns; one or the other can predominate in the result, but often they combine to produce a visually complicated structure. Moreover, Madore also described the three rules of thumb to help us understand what can affect the structure [15]:

   (a) If we decrease F·TR enough, the 2ETL spacing predominates;
   (b) If we decrease ETL enough, the Ny·F·TR spacing predominates; and
   (c) If we increase A/FOV, where A is the amplitude of the motion and FOV is the field of view, we help the Ny·F·TR spacing predominate.

   If the TR, ETL, and A/FOV are kept constant, F is the most important factor affecting motion artifacts. The frequency of respiratory motion is commonly less than 1 Hz. According to Madore's work, lesser motion frequency allows the 2ETL spacing to predominate in the result of the convolution [15].

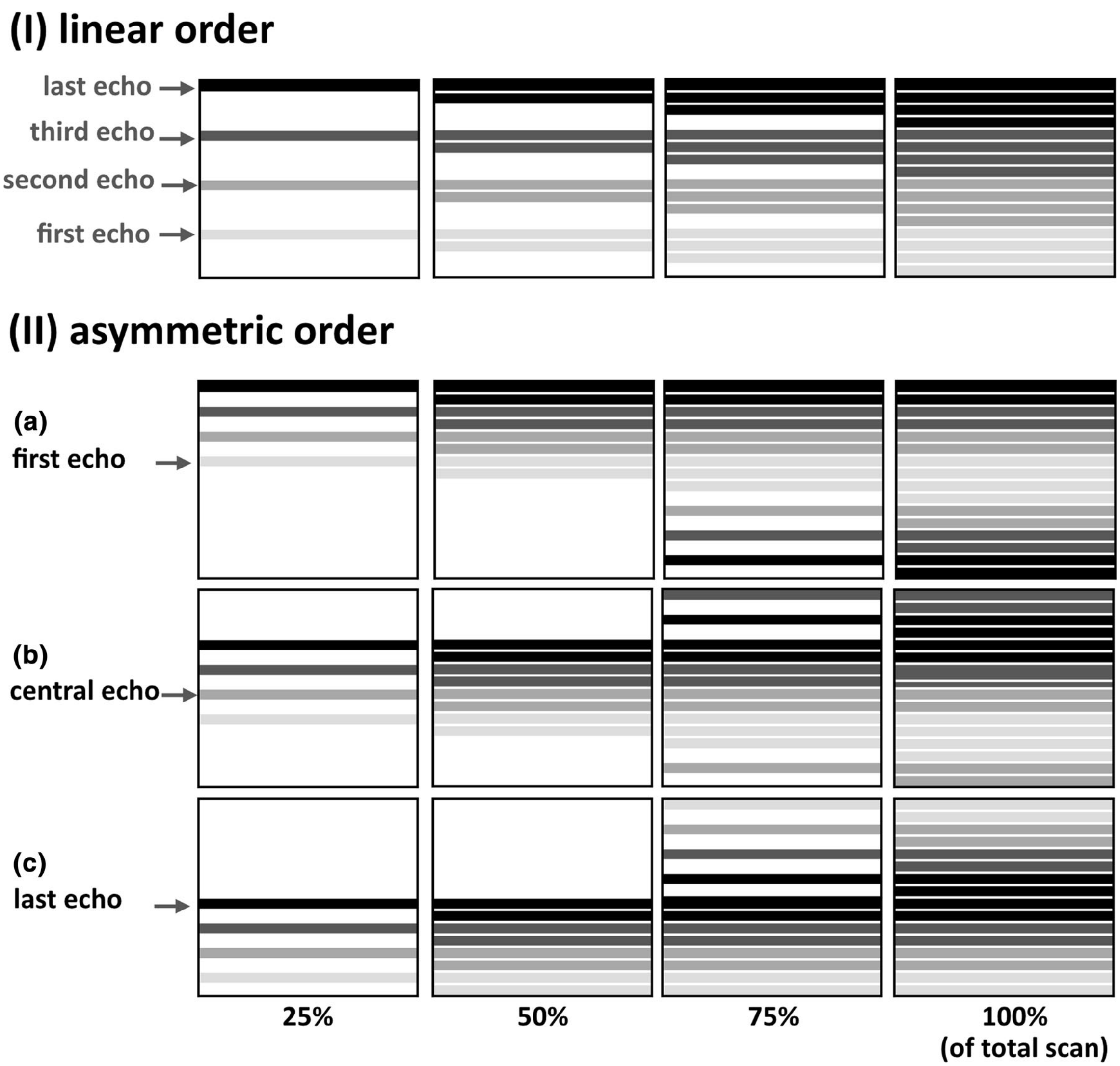

Fig. 1 The methodological differences between the respective k-space orders in Cartesian TSE sequence. **I** Linear order. The central echo in the echo trains can only be assigned at the center of the k-space, and echoes are sequentially filled in the overall k-space. **II** Asymmetric order. Arbitrary echo, for example; first echo (**IIa**), central echo (**IIb**), and last echo (**IIc**) in the echo trains can be assigned at the center of the k-space. Echoes are scrolled on the k-space while keeping relationships with the adjacent echoes. The asymmetric order adopts different filling orders in the first half and the latter half of scanning to prevent severe truncation artifacts. Thus, k-space of the asymmetric order is divided into two phases on the temporal axis, and then the actual number of partitions of the k-space is doubled as compared with those of the linear k-order

2.3 Hypothesis

The respiratory motion frequency is usually less than 1 Hz; thus, the ghosting motion artifacts due to respiration in the asymmetric order should be dominated by the 2ETL pixel pattern as aforementioned. That is, the degree of ghost artifacts would depend on ETL and the actual number of k-space segments. Here, linear and asymmetric orders indicate different manners of k-space segmentation due to their respective ordering. Specifically, in the linear order, actual partitions of the k-space segmentation are simply equal to the ETL because the effective TE is always determined by the TE of the central echo in the echo trains. In the asymmetric order, on the other hand, the actual partitions of the k-space segmentation are double the ETL because the partitions for respective allocated echoes are shifted properly on the k-space to minimize the differences in signal intensity between neighboring echoes while assigning the arbitrary effective TE. We hypothesized that these differences in k-space segmentation would indicate different artifact patterns. Moreover, we can imagine that the temporal stability of breath-holding along the k-space filling time course of TSE acquisition is an important factor. In an incomplete breath-hold, the failure of the breath-hold (i.e., diaphragmatic drift) should occur in the latter half of the scanning procedure and predispose the imaging to motion artifacts. In asymmetric TSE, the most central k-space sector is acquired only at the early stage, which is the most reliable period of breath-hold. The data for the latter half may be acquired with poor breath-hold, but it hardly affects the image quality because such data only fill the peripheral k-space. On the other hand, since the linear technique acquires the near-central part of k-space throughout the acquisition, it may exhibit stronger ghosting than the asymmetric TSE due to poor breath holding, which may happen at the end of a long acquisition. Thus, our hypothesis is that the asymmetric TSE may be tolerable for a failure in breath holding occurring in the latter half of the scanning.

3 Materials and methods

A 3.0-T whole-body clinical imager (Achieva, Philips Healthcare, Best, The Netherlands) using an 8-element head coil was used for all experiments. A mechanical ventilator (LTV1200 Ventilator, Pacific Medico, Tokyo, Japan) and hand-made bottle phantom were used as a moving phantom to investigate the effect of the k-space order on motion artifact reduction in Cartesian TSE. This device could manually and flexibly adjust the ventilatory frequency. The amplitude of the respiration-mimicking phantom movement was approximately 3 cm. To simulate the liver and surrounding subcutaneous fat tissue that can reproduce the ghost artifacts in the abdomen, the bottle phantom had a laminar structure; the upper section was filled with lard, while the lower section was filled with 0.5 mmol/L superparamagnetic iron oxide (SPIO, Resovist, Bayer Yakuhin, Osaka, Japan) solution. An overview of the moving phantom is illustrated in Fig. 2.

To investigate our hypothesis, we attempted to simulate the following situations using a moving phantom:

(I) The phantom breathed freely during the entire scan time (free breathing);
(II) The phantom held its breath in the first half period and then breathed freely during the latter half (failure of breath holding);
(III) The phantom breathed only once in the first half of the scan time with arbitrary timing (unexpected motion).

The actual simulated and acquired motion patterns are shown in Fig. 3. For the free-breathing situation, the actual motion frequency of the phantom was set to 0.27 Hz (16 respirations per minute, the average value of the typical respiratory rate for a healthy adult [16]).

To quantitatively assess the ghost artifacts caused by respiratory-simulated motion, we directly measured the actual pixel intervals of the ghost artifacts (artifact intervals) on images in the free breathing situation (I) with different k-space orders. First, to define the ghost artifacts, we measured the standard deviation (SD) of the noise existing outside of the phantom. We defined the ghost artifact as the object that indicated intensity of the noise outside the phantom above 6SD. Subsequently, we directly measured the actual pixel intervals of the artifacts that corresponded to the phantom using line profile (Fig. 2d). The measurements were performed by two experienced technologists (M.Y., Y.I.) in consensus. Moreover, we assessed the average values of the results of the experiments on 3 different days to obtain more accurate results.

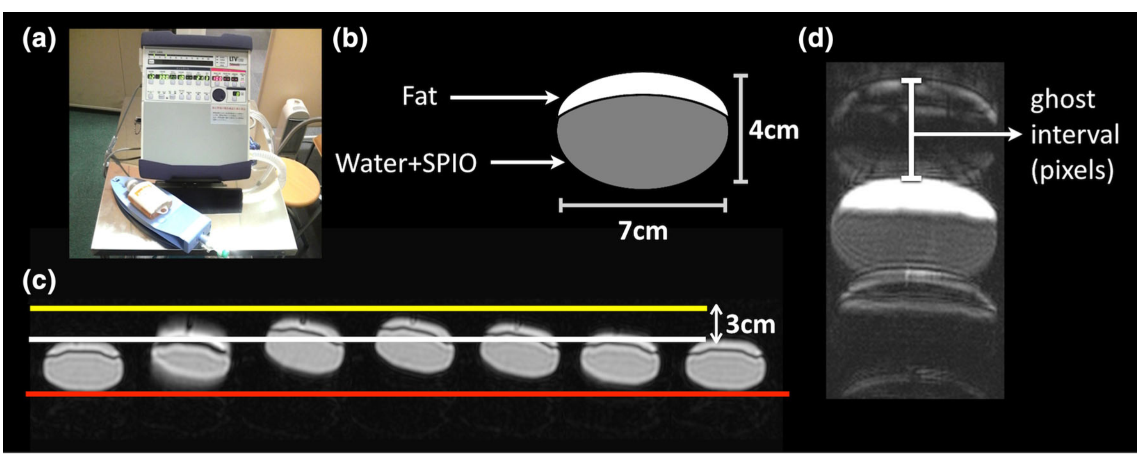

Fig. 2 An overview of the moving phantom. The phantom consisted of a mechanical ventilator (**a**) and a bottle phantom (**b**). The bottle phantom had a two-lamina structure (fat filling the upper section and superparamagnetic iron oxide solution (SPIO) filling the lower section) and was placed at the tip of the ventilator pump. The ventilator could manually and flexibly adjust the ventilatory frequency. The amplitude of the respiration-mimicking phantom movement was approximately 3 cm (**c**). For quantification of actual motion artifacts, we directly measured the actual intervals between tip of both artifact and phantom as a ghost interval using line profile (**d**)

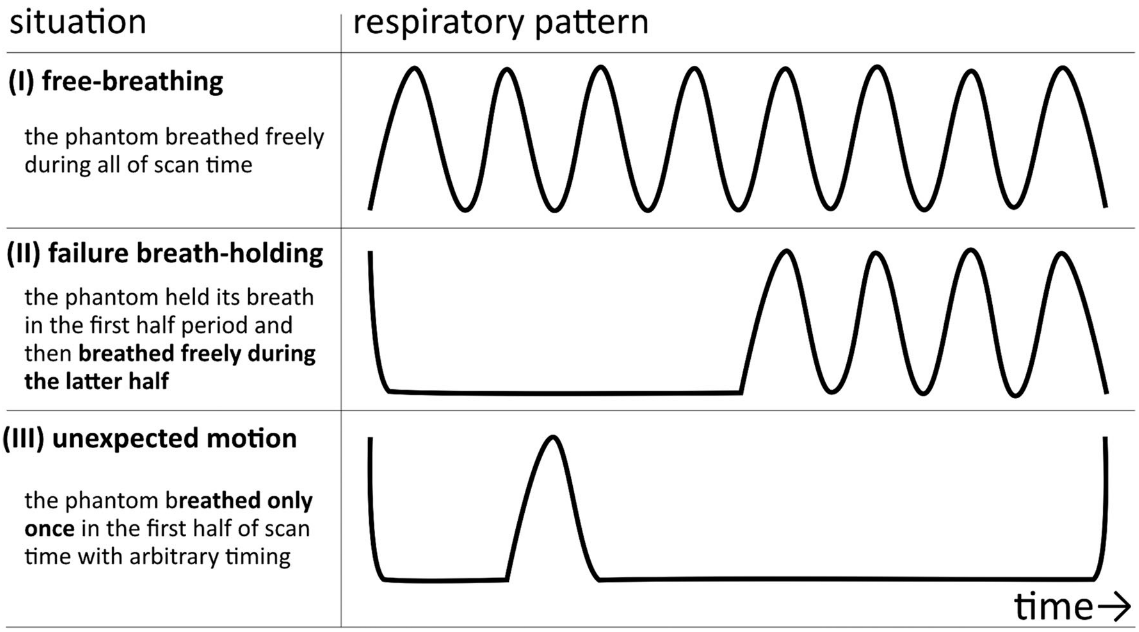

Fig. 3 The simulated and acquired motion patterns of the moving phantom

The measurements were performed using a personal computer equipped with OsiriX Medical Imaging Software (Pixmeo, Geneva, Switzerland), and the observers were allowed to adjust the window level and width and to measure the signal intensity of the ghost artifacts on the respective images.

The actual scan parameters for 2D Cartesian TSE with both linear and asymmetric k-space orders were as follows: field of view (FOV), 256 mm; matrices, 256 × 256; resolution, 1.0 mm^2; single slice; slice thickness, 6.0 mm; TR, 4000 ms; TE, 90 ms; ETL, 24; echo spacing, 7.2 ms; pixel bandwidth, 289 Hz; and acquisition time, 44 s.

4 Results

The attempted breathing situations using a moving phantom were successful in all subjects. Measured artifact intervals (pixels) were 25.8 ± 0.3 for the linear order and 48.7 ± 0.7 for the asymmetric order. Representative moving phantom images with respective k-space orders in three types of situations (free breathing, failure of breath holding, and unexpected motion) are shown in Fig. 4. First, in the free-breathing situation, the actual spacing of ghost artifacts in the asymmetric order was visually higher (doubled) than that in the linear order. Second, in the failure of breath holding situation, the motion artifacts in the asymmetric order were clearly lesser than those in the linear order. The asymmetric order clearly showed less sensitivity to incomplete breath-hold at the latter half of the imaging time period. Finally, in the unexpected motion situation, the ghost artifacts occurred from the one-time sudden motion during the first half of acquisition regardless of the k-space order, and such artifacts could be seen with similar spacing as in the respective k-space orders in the free breathing situation.

5 Discussion

Although TSE is one of the most important abdominal sequences in routine clinical use, it is very sensitive to motion and suffers from severe ghosting motion artifacts if breath holding fails. The actual pattern of ghosting motion artifacts in TSE is based on the result of a convolution of two banding patterns: one with a spacing of Ny·F·TR pixels and one with a spacing of 2ETL pixels. Previous studies demonstrated that ghosting motion artifacts with 2ETL spacing predominate when decreasing F·TR or A/FOV, whereas Ny·F·TR spacing predominates when diminishing ETL [15].

In this study, we investigated the influence of k-space orders in Cartesian TSE for reduction in ghosting motion artifacts under breath holding conditions using a moving phantom. We obtained several findings to improve our understanding of ghosting motion artifacts due to respiratory motion. First, in the TSE sequence, ghost artifacts occurred not only from periodic motion but also from sudden motion only once during acquisition, and such artifacts could be observed as with a spacing of 2ETL pixels in asymmetric order. This result is in accordance with Madore's theory [15] that ghosting motion artifacts

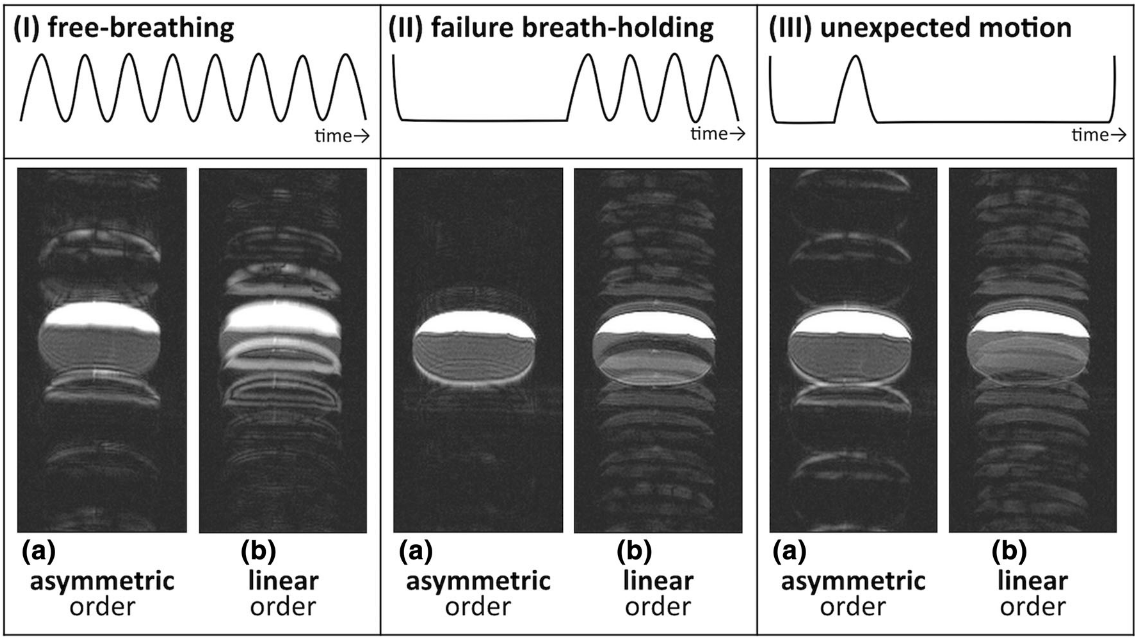

Fig. 4 Representative moving phantom images with respective k-space order in each simulated motion pattern. **I** Free breathing. The spacing of ghost artifacts in the asymmetric order **Ia** was visually increased (doubled) compared with that in the linear order (**Ib**). **II** Failure of breath holding. The motion artifacts in the asymmetric order **IIa** were visually smaller than those in the linear order (**IIb**). **III** Unexpected motion. The ghost artifacts were caused by sudden motion only once during the first half of the acquisition duration regardless of the k-space order (asymmetric order: **IIIa**, linear order: **IIIb**), but spacing was different

would be dominated by the 2ETL pixels when the motion frequency is very low. Second, the actual spacing of ghost artifacts varied according to respective k-space orders even when the other scan parameters were kept identical. In the asymmetric order, the ghost artifacts appeared with a spacing of doubled ETL pixels, whereas in the linear order, they appeared with a spacing of pixels simply equal to the ETL. This suggests that these findings depended on the differences of the actual numbers of partitions of respective k-space orders. Consequently, because the asymmetric order basically widens the spaces of ghost artifacts compared to those in the linear order, the asymmetric order visually reduced the ghost artifacts. This suggests that other techniques that enable an increase in the actual number of partitions of k-space order without any penalty for spatial resolution, such as half-Fourier acquisition, also have the potential to visually reduce ghost artifacts. Hence, combining the asymmetric order and half-Fourier acquisition, if such combination is possible, may further reduce ghost artifacts visually by a greater widening of the spaces of respective ghost artifacts. Finally, we also demonstrated another important factor for motion artifacts. Our phantom study, which simulated the phantom holding its breath in the first half period and then breathing freely during the latter half, showed that the motion artifacts in the asymmetric order were significantly smaller than those in the linear order. Thus, the asymmetric order showed less sensitivity for incomplete breath-hold at the latter half of the imaging time period. In the linear order, any motions throughout the scanning influence the image quality. In contrast, in asymmetric TSE, acquisition is started in the central k-space sector, and the most central k-space sector is acquired at an early stage if the moderate (near-central) echo in the ETL is applied as the effective TE (Fig. 1, IIb); hence, this technique involves less influence of motion during the latter half of the imaging time. Consequently, we concluded that the asymmetric order is superior to the linear order in reducing ghosting motion artifacts for two different reasons: segment and temporal order on the k-space.

This study has several limitations. First, because this study only used phantom subjects, it is unclear whether similar results would be obtained with human subjects. Nonetheless, we believe that these results are valuable for understanding the causes of motion artifacts in the Cartesian TSE sequence. Second, it should be noted that the appearance of motion artifacts is affected by not only k-space ordering, but also other imaging parameters such as half-Fourier acquisition and parallel imaging. The influences of these parameters should be investigated in future studies. Finally, the influence of changing k-space order for image contrast and the detectability of small lesions is unknown. Hence, further investigation with human subjects and including other influential scan parameters is needed.

6 Conclusion

Because of its actual number of partitions of the k-space and temporal filling order, the asymmetric k-space order of Cartesian TSE is superior to the linear k-space order for reduction of ghosting motion artifacts when a long acquisition is applied with an artificially unsuccessful breath-hold.

Compliance with ethical standards

Conflict of interest Masami Yoneyama, Masanobu Nakamura are employees of Philips Japan, and Atsushi Takemura is an employee of philips Healthcare. Other authors have no conflicts of interests.

Research involving human participants and animals This article does not contain any studies with human participants performed by any of the authors. This article does not contain any studies with animals performed by any of the authors.

Informed consent Informed consent for this study was not required because no research involving human participants was undertaken by any of the authors.

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