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Accelerated time-resolved three-dimensional MR velocity mapping of blood flow patterns in the aorta using SENSE and k-t BLAST

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ABSTRACT

Purpose: To assess the feasibility and potential limitations of the acceleration techniques SENSE and k-t BLAST for time-resolved three-dimensional (3D) velocity mapping of aortic blood flow. Furthermore, to quantify differences in peak velocity versus heart phase curves.
Materials and methods: Time-resolved 3D blood flow patterns were investigated in eleven volunteers and two patients suffering from aortic diseases with accelerated PC-MR sequences either in combination with SENSE ($R = 2$) or k-t BLAST (6-fold). Both sequences showed similar data acquisition times and hence acceleration efficiency. Flow-field streamlines were calculated and visualized using the GTFlow software tool in order to reconstruct 3D aortic blood flow patterns. Differences between the peak velocities from single-slice PC-MRI experiments using SENSE 2 and k-t BLAST 6 were calculated for the whole cardiac cycle and averaged for all volunteers.
Results: Reconstruction of 3D flow patterns in volunteers revealed attenuations in blood flow dynamics for k-t BLAST 6 compared to SENSE 2 in terms of 3D streamlines showing fewer and less distinct vortices and reduction in peak velocity, which is caused by temporal blurring. Solely by time-resolved 3D MR velocity mapping in combination with SENSE detected pathologic blood flow patterns in patients with aortic diseases. For volunteers, we found a broadening and flattering of the peak velocity versus heart phase diagram between the two acceleration techniques, which is an evidence for the temporal blurring of the k-t BLAST approach.
Conclusion: We demonstrated the feasibility of SENSE and detected potential limitations of k-t BLAST when used for time-resolved 3D velocity mapping. The effects of higher k-t BLAST acceleration factors have to be considered for application in 3D velocity mapping.

1. Introduction

Rupture of an abdominal (AAA) and thoracic aortic aneurysm (TAA) can cause massive internal haemorrhage and quick death if not treated adequately and promptly. Aortic aneurysms occur when the infrarenal diameter of the vessel is at least 50% increased over normal diameter and may be asymptomatic for years. Rupture of AAA, the most common form of aortic aneurysm, occurs in about 1–3% of men aged 65 years or more, the mortality is 70–95%. Population-based AAA screening using ultrasonography and elective surgery helps to reduce AAA-related mortality [1,2]. Preliminary results of a TAA-screening program [3] indicated the possibility of early detection of patients with higher risk of developing TAA. Molecular and cellular mechanism in the vessel wall and the complex interaction between the aorta and the cardiovascular system are responsible for the pathologic changes [4]. Precise analysis and evaluation of blood flow patterns would be beneficial for a better understanding of the pathologic processes and may result in a theoretical model for prediction of risk and likelihood of serious adverse events [5].

Phase contrast (PC) MR imaging is a non-invasive technique which is useful for evaluation of blood flow physiology. PC-MRI requires bipolar gradients to compare the phase shift of moving spins in blood with that in stationary tissue surrounding the vessel. Therefore two steps of acquisition are necessary to enable quan-

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titative determination of velocities in one spatial direction, i.e. a flow-compensated reference scan and a flow-sensitive scan of the same volume of interest. Currently, time-resolved two-dimensional (2D) PC-MRI experiments with velocity encoding in one spatial direction are used in clinical routine for determination of blood flow parameters like peak velocity, flow, and stroke volume.

Time-resolved three-dimensional (3D) velocity mapping using PC-MRI allows for investigation of 3D blood flow characteristics covering both, the whole cardiac cycle and the whole cardiovascular volume of interest. Several studies have demonstrated that 3D velocity mapping is a reliable tool for detailed analysis and visualization of global and local characteristics of normal blood flow as well as pathologic flow features within the aorta [5–9]. However, this technique requires at least four acquisitions of the same volume of interest, i.e. one flow-compensated reference scan and three flow-sensitive scans. Therefore, the acquisition of the PC-MRI data, which are required for velocity mapping, may effort a long time. The measurement time of cardiac-triggered PC-MRI sequences depend on the number of phase-encoding steps and the heart rate. Unfortunately, investigations of the aorta requires, in addition to a large field of view (FOV), some form of respiratory compensation, which further increases the scan time.

Acceleration techniques such as sensitivity encoding (SENSE) [10] and k-t broad-use linear acquisition speed-up technique (k-t BLAST) [11] have been developed to reduce measurement times of MR imaging by reduction of the number of lines in k-space. SENSE combines the signals and the sensitivities from the individual channels of a multi-element phased-array surface coil to unfold the aliasing of the data due to the reduction of phase-encoding steps. The pixel values in the image are composed of both, the original position and the back-folded positions.

The k-t BLAST approach was specifically adapted for acceleration of MR imaging of periodically dynamic processes, where temporal changes in the image occur only in minor and predictable manner. k-t BLAST requires two stages of acquisition, a low-resolution training stage and an under-sampled stage for acquisition of the changing parts in the image, which were combined to an unaliased image. A known drawback of the k-t BLAST method is temporal blurring, which increases with higher acceleration factors [11–13].

The purpose of this study was to investigate the usefulness and potential limitations of SENSE and k-t BLAST for acceleration of time-resolved 3D velocity mapping of aortic blood flow in volunteers, and the feasibility for detection of changes in aortic blood flow patterns in patients with aortic disease. An additional aim was to quantify the differences in peak velocity measurements between the two acceleration techniques for all phases of the cardiac cycle.

2. Materials and methods

2.1. Human subjects

Eleven healthy volunteers (6 women and 5 men; mean age ± standard deviation (SD), 35 ± 10 years; age range, 18–56 years) with no history of cardiovascular disease were investigated in this study. Additionally, we examined two patients suffering from an aortic disease with our study protocol, a 76-year-old man with an aneurysm in the ascending aorta, and a 73-year-old woman with an ectasia in the ascending aorta. All subjects gave their written informed consent. The study protocol was approved by the local ethics committee.

2.2. PC-MRI data acquisition

All MR examinations were performed on a whole-body 1.5 T system (Achieva, Philips Medical Systems, Best, The Netherlands) using a five-channel cardiac coil. Survey images in sagittal and coronal orientation for localization of the aortic arch and a free-breathing SENSE reference scan were performed. The measurement time of the SENSE reference scan was 29.7 ms. An axial multi-slice balanced steady-state free-precession sequence perpendicular to the ascending aorta was obtained using the following parameters: 300 mm × 300 mm field of view, 224 × 224 matrix size, 6 mm slice thickness, 36 slices without gap.

For determination of the peak velocities and the flow curves of aortic blood flow 2D electrocardiogram (ECG) triggered PC-MRI experiments were performed in a single breath-hold using both SENSE with an acceleration factor (R) of 2 and k-t BLAST with an acceleration factor of 6. The differences in the acceleration factors are explained by the fact that we used the same acceleration factors for the 3D PC-MR sequences of the velocity mapping experiments. We aimed to have very similar data acquisition times for these two 3D PC-MR experiments, which were achieved with SENSE with $R = 2$ and k-t BLAST 6. The imaging planes were positioned perpendicular to the ascending aorta. The parameters were as follows: a segmented k-space turbo-field-echo (TFE) sequence with a turbo factor of 9 in case of SENSE and 4 for k-t BLAST, 350 mm × 300 mm (RL × AP) field of view, 144 × 124 acquired matrix size, 256 × 220 reconstructed matrix size, 10 mm slice thickness, flip angle of 15°, 24 heart phases, and 200 cm/s velocity-encoded value (VENC). Velocity encoding of blood flow was performed in feet–head direction. TR and TE were defined as the shortest possible values, which depended on the heart rate of the subjects. The values for TR ranged between 3.9 and 5.4 ms and for TE between 2.3 and 2.5 ms. Retrospective triggering with a phase percentage of 80% was applied for ECG synchronization. For the k-t BLAST experiment we acquired 11 low-resolution training profiles, resulting in net acceleration factors of 4.3. The temporal resolution for the PC-MRI experiments using SENSE ranged between 47 and 30 ms, those for the PC-MRI experiments using k-t BLAST ranged between 46 and 29 ms.

For investigation of time-resolved 3D blood flow patterns, oblique-sagittal multi-slice PC-MR sequences aligned with the aortic arch and accelerated with either SENSE ($R = 2$) or k-t BLAST (6-fold) were performed. The following parameters were the same for both sequences: 220 mm × 350 mm (FH × AP) field of view, 90 × 144 matrix size, 4.2 mm slice thickness, 14–16 slices, flip angle of 15°, and 18 heart phases. Again, as for the 2D PC-MR experiments, TR and TE were defined as the shortest possible values and depended on the heart rate (TR range, 4.2–4.5 ms and TE range, 2.5–2.7 ms). Retrospective triggering with a phase percentage of 80% was used for the PC-MR experiment in combination with SENSE, and prospective triggering in case of k-t BLAST. The trigger time delay was defined as the shortest possible value and ranged between 11 and 15 ms. The number of low-resolution training profiles was again 11 for the k-t BLAST experiment, resulting in net acceleration factor of 4.3.

VENC was individually determined for each subject from the previously performed 2D PC-MRI experiments to obtain optimal signal-to-noise (SNR). For this purpose the 2D single-slice PC-MRI data were evaluated using the QFlow software package provided by the manufacturer of the MR scanner and installed on the console of the MR scanner. The maximum systolic peak velocity was calculated and 10% of the value was added to avoid aliasing of velocity encoding. In order to enable velocity encoding of blood flow along all three spatial directions, both multi-slice PC-MR experiments (with SENSE 2 and k-t BLAST 6) were performed in three subsequent examinations using velocity encoding in anterior–posterior, left–right, and feet–head direction, respectively. The experiments were performed in free breathing using a navigator to compensate for respiratory motion. The navigator echo pulse was performed just before each shot, also termed leading navigator, and was positioned at the diaphragm.

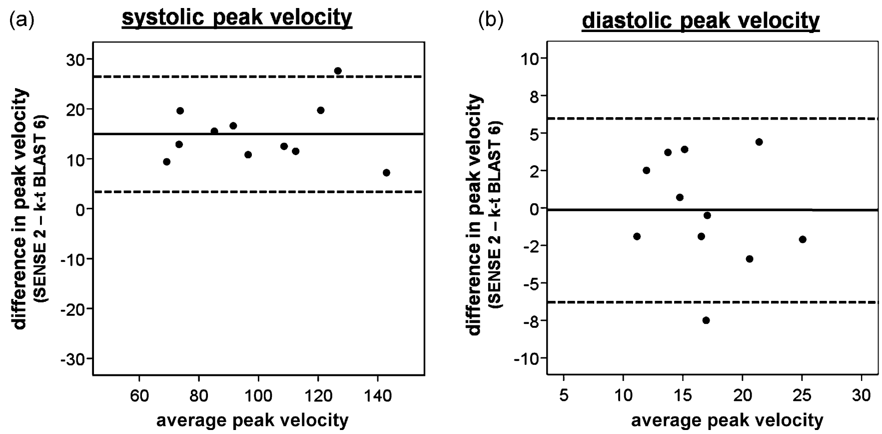

Fig. 1. Bland–Altman plots for (a) systolic and (b) diastolic peak velocity in the ascending aorta. The *y*-axes represent the differences in peak velocity between PC-MRI experiments using SENSE 2 minus PC-MRI experiments using k-t BLAST 6 in units of cm/s. The *x*-axes represent averaged velocity of the accelerated PC-MRI experiments in units of cm/s. The solid lines represent the mean of the difference in peak velocity. The dashed lines represent the mean ± 2 × standard deviation.

As mentioned above, we aimed to provide very similar acceleration and consequently data acquisition time for both experiments using SENSE and k-t BLAST, but showing the same parameters as far as possible. SENSE with $R = 2$ and k-t BLAST with an acceleration factor of 6 fulfil this requirement. In this context, data acquisition time meant the time the MR system is scanning and acquiring data. In our opinion comparison of real measurement times, i.e. time between start and end of sequence is not serious, because these times depend on heart rate variability, respiratory rhythm of the subject, and efficiency of the navigator for respiratory motion compensation too.

2.3. PC-MRI data analysis

For visualization of time-resolved 3D blood flow, the data of multi-slice PC-MR measurements accelerated with either SENSE or k-t BLAST were transferred to a personal computer (IBM ThinkPad T60p, Lenovo, Singapore) and loaded into the GTFlow software tool (GyroTools, Zurich, Switzerland). The magnitude and phase images from the PC-MR measurements in all three spatial directions are required for reconstruction of the dynamics of 3D blood flow. A vessel mask of the aortic arch was generated semi-automatically and edited manually. This vessel mask was used to suppress static tissue and to define the volume seed points for calculation and visualization of flow-field streamlines in order to determine differences in time-resolved 3D blood flow patterns between SENSE and k-t BLAST in volunteers and patients. Streamlines are curves that are instantaneously tangent to the velocity vectors of the flow field at a specific moment within the cardiac cycle. One obtains a time course of 3D perspectives of the static velocity vector field [14].

2.4. Statistical analysis

Data were analyzed using statistical software (SPSS 14.0, SPSS, Chicago, IL). The difference between the peak velocities measured with the 2D single-slice PC-MRI experiments using SENSE and k-t BLAST were calculated for each time point of the cardiac cycle. The mean difference of peak velocity for each heart phase was obtained by averaging over the individual values of all volunteers. Wilcoxon rank-sum test was used to calculate significance of difference between maximum peak velocities (i.e. the maximum value of the peak velocities for the whole cardiac cycle of a subject) measured with SENSE and k-t BLAST. A two-sided paired Student's *t* test was used to compare differences between the time series of peak velocities of the SENSE and the k-t-BLAST experiment for the two patients. A *P* value of 0.05 was considered significant. Peak velocity determined with SENSE 2 and k-t BLAST 6 were compared by calculating the average value and the mean difference ± 2 standard deviation (SD) limits of the differences between the two techniques according to the method described by Bland and Altman [15].

3. Results

All PC-MRI studies were completed within approximately 40 min. The mean heart rate of the volunteers was $69 \pm 10\,\text{min}^{-1}$

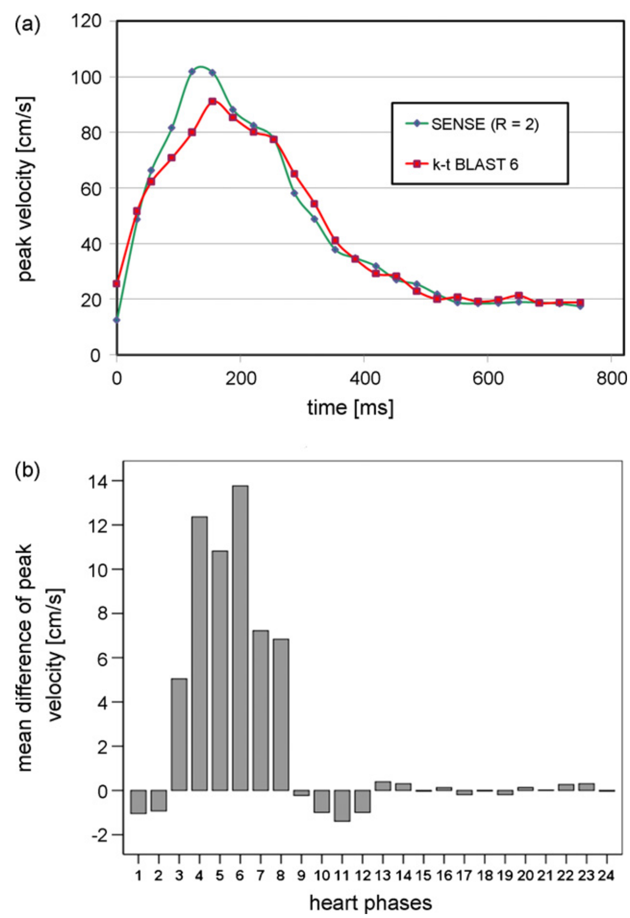

Fig. 2. Temporal evolution of blood flow in the aorta of a 33-year-old female volunteer by 3D streamlines for six successive systolic time frames measured with PC-MRI in combination with SENSE ($R = 2$) (upper row) and k-t BLAST 6 (lower row). The color code is overlaid in the upper left image. The times are listed on the images in the lower row.

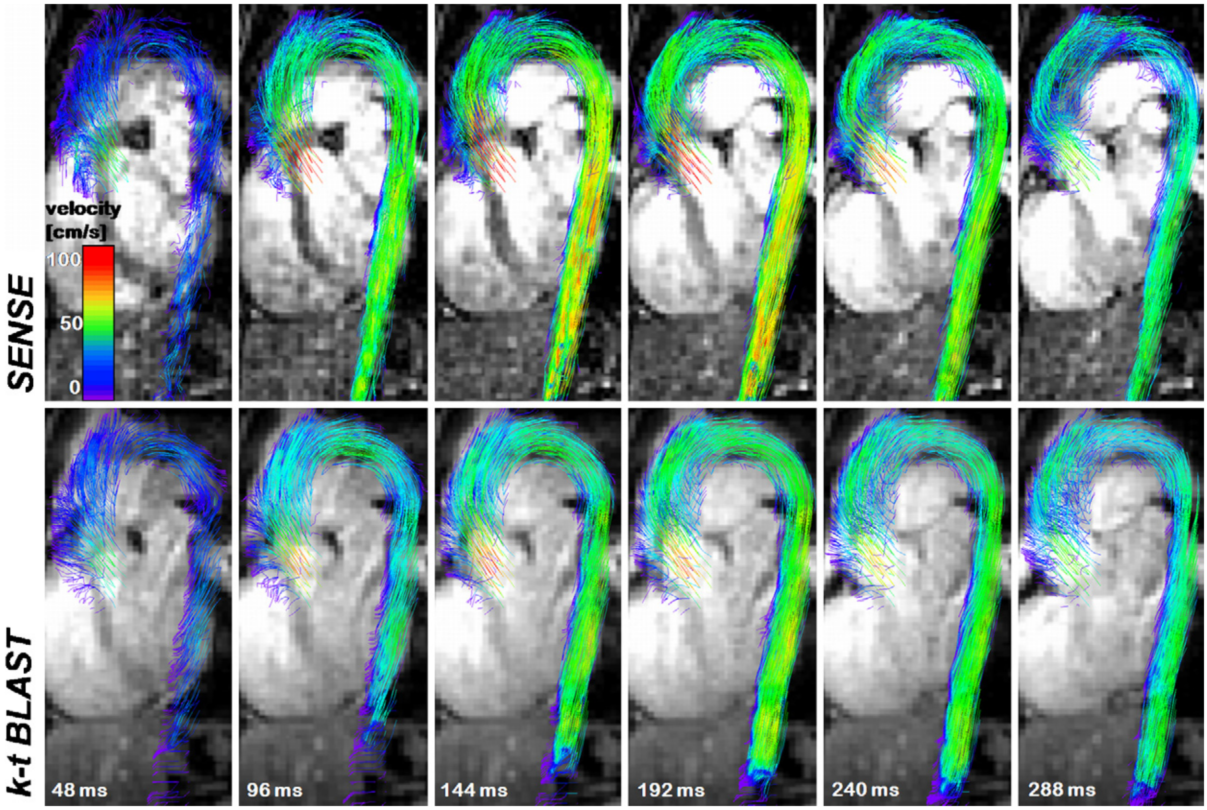

Fig. 3. Quantitative evaluation of differences in peak velocity measurements between SENSE 2 and k-t BLAST 6. (a) Peak velocity versus time curves of the blood flow in the ascending aorta of a 33-year-old female volunteer measured with 2D PC-MRI using SENSE 2 (green line) and k-t BLAST 6 (red line). (b) Diagram of the mean difference of peak velocity between SENSE 2 and k-t BLAST 6 averaged over all volunteers versus heart phases.

(range, 53–84 min^{-1}), for the patient with an aneurysm in the ascending aorta it was 67 min^{-1}, and for the patient with an ectasia in the ascending aorta, 87 min^{-1}. Total data acquisition times of the PC-MRI experiments for 3D velocity mapping, i.e. for all three velocity encoding directions, ranged between 5:30 and 6:54 min for SENSE 2 while those for the experiments using k-t BLAST 6 ranged between 5:33 and 7:15 min. The measurement time of the SENSE reference scan (approximately 30 ms) was added to the data acquisition times of the PC-MRI experiments using SENSE, to account for the acquisition time of the reference data which are required for SENSE reconstruction. The acquisition of the reference data for the k-t BLAST reconstruction (i.e. the low-resolution training stage) occurs during the individual experiments and, therefore, this time is already included.

3.1. Comparisons of peak velocities and flow curves

Fig. 1 is a graphic representation of the Bland–Altman analysis for systolic and diastolic peak velocities in the ascending aorta between PC-MRI measurements in combination with SENSE 2 and k-t BLAST 6. The analysis revealed a mean difference and hence an averaged underestimation of systolic peak velocity of 14.8 cm/s for k-t BLAST 6 compared to SENSE 2. The upper and lower limit was 26.5 and 3.2 cm/s, respectively (Fig. 1a). For diastolic peak velocity we found a marginal mean difference between the two acceleration techniques of −0.2 cm/s, and upper and lower limit of 7.1 and −7.5 cm/s, respectively (Fig. 1b).

The maximum systolic and minimum diastolic peak velocity for the patient with an aneurysm in the ascending aorta was 66.6 and 12.3 cm/s for the SENSE experiment, and 60.4 and 12.9 cm/s for the k-t BLAST experiment, respectively. A two-sided paired Student's t test revealed significant differences ($P = 0.0015$) between the time series of peak velocities measured with 2D PC-MRI either in combination with SENSE or k-t BLAST. For the patient with an ectasia in the ascending aorta we found a maximum systolic and minimum diastolic peak velocity of 78.1 and 21.2 cm/s for the SENSE experiment, and of 65.1 and 20.1 cm/s for the k-t BLAST experiment, respectively. Again, the differences between the time series of peak velocities of the two acceleration techniques were statistical significant ($P = 0.0018$).

Fig. 2a shows the peak velocity versus time curves of a healthy volunteer measured at the ascending aorta with the 2D PC-MRI experiment using SENSE 2 and k-t BLAST 6. One can see that the curve for SENSE 2 is narrower and higher compared to the curve for k-t BLAST. For all volunteers we found a significant difference ($P = 0.003$) in maximum peak velocities between SENSE 2 and k-t BLAST 6. The mean ± SD of the maximum peak velocities measured with SENSE 2 were 108 ± 25 cm/s (range, 74–147 cm/s), and those values for k-t BLAST 6 were 93 ± 24 cm/s (range, 64–139 cm/s). Fig. 2b shows a diagram of the mean difference of peak velocity versus heart phases, obtained by averaging the differences between peak velocities measured with SENSE 2 and k-t BLAST 6 of each heart phase for all volunteers. Positive values in the diagram represent a higher peak velocity for the 2D PC-MRI experiment using SENSE 2 and negative values represent a higher peak velocity for the 2D PC-MRI experiment using k-t BLAST 6. It is clear from that diagram, that k-t BLAST leads to a flattening and broadening of the peak velocity curve, which is equivalent with a temporal blurring of the measurement.

3.2. Comparisons of 3D velocity mapping of aortic blood flow

The reconstruction of 3D flow patterns revealed attenuations in blood flow dynamics for k-t BLAST 6 compared to SENSE 2 for

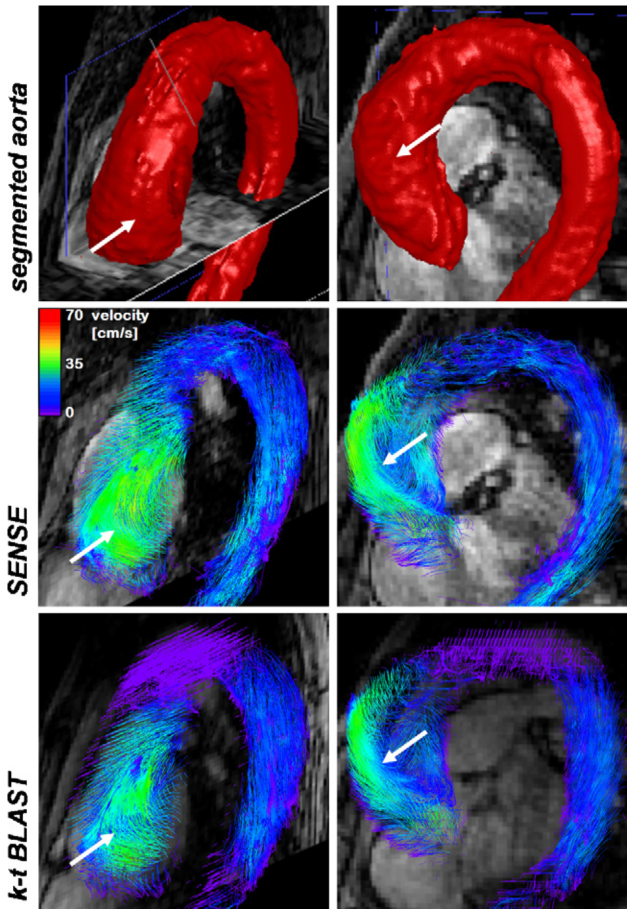

Fig. 4. Velocity mapping of a 76-year-old male patient with an aneurysm in the ascending aorta (marked with white arrows). Upper row: Segmented aorta (red volume) in oblique coronal (left hand) and sagittal (right hand) projections for better orientation. Streamlines at the early phase of the systolic cycle for projections in the same direction as in upper row measured with SENSE (R = 2) (middle row) and k-t BLAST 6 (lower row). The color code is overlaid in the lower left image.

all volunteers. One example of this finding is shown in Fig. 3, which depicts two time series of the reconstructed systolic flow measured with SENSE (Fig. 3, upper row) and k-t BLAST 6 (Fig. 3, lower row) of the same volunteer as in Fig. 2a. The numbers in the lower row represent the time points after the R-peak, which are valid for both time series.

Fig. 4 shows the reconstructed blood flow pattern of the patient with an aneurysm in the ascending aorta. The right hand column represents a sagittal view and the left hand side column an oblique coronal view at the aortic arch. The segmented vessel (red volumes) is presented in the upper row to serve the purpose of orientation. The flow patterns measured with PC-MRI in combination with SENSE 2 are depicted in the middle row and those measured in combination with k-t BLAST 6 are depicted in the lower row. The figure shows failure in reconstruction in the transverse aorta for the measurement using k-t BLAST (violet regions on the central images).

Fig. 5 shows sagittal views of flow patterns of systolic blood flow at three different time points for the patient with an ectasia in the ascending aorta. The upper row represents a series of reconstructed flow measured with PC-MRI using SENSE and the lower row using k-t BLAST. Attenuations in blood flow dynamics are seen on the images obtained using k-t BLAST. The series of images from the SENSE experiment show more and distinct vortices compared to those from k-t BLAST (marked with arrows).

4. Discussion

This comparative study addresses the feasibility and potential limitations of the acceleration techniques SENSE and k-t BLAST for 3D velocity mapping of blood flow in the aorta. It is the first report which investigated the outcome of 3D velocity mapping using PC-MRI in combination with k-t BLAST in vivo. We used a high acceleration factor of 6 for these experiments for two reasons. First, an acceleration factor below 6 would have rendered the measurement time significantly longer than that needed for the experiment using SENSE (R = 2) and therefore unacceptably long for patients. Furthermore the results would not be comparable. Second, one purpose of the study was to assess the limitations of the k-t BLAST approach and to detect potential artefacts associated with the application of this technique. Our results demonstrated a decrease in the detection of temporal dynamics for 3D blood flow in the aorta as well as failure in the reconstruction of normal and pathologic blood flow patterns. The former finding can be explained by the known temporal blurring associated with the k-t BLAST approach. For the latter we assume that the reduction in signal-to-noise ratio is too strong for reliable reconstruction of flow-field streamlines. For comparison of maximum peak velocity between SENSE and k-t BLAST experiments we obtained a significant difference between SENSE 2 and k-t BLAST 6 in ascending aorta. Maximum peak velocity is defined as the velocity with the highest absolute value in the ROIs over the heart cycle. Therefore, the difference in maximum peak velocity as well as the demonstrated broadening and flattering of the peak velocity diagram is an evidence for temporal blurring.

Temporal blurring of k-t BLAST was described in several reports for cardiac MRI [11,12,16] as well as PC-MRI flow measurements [13,17] and Fourier velocity encoding [18]. A good theoretical explanation for temporal blurring in k-t BLAST was published previously [11,12]. The under-sampled data of the acquisition stage are averaged over time. This temporal average data are subtracted from the corresponding data at each time frame [11]. Marshall [17] performed simulations of PC-MRI experiments using k-t BLAST on a carotid phantom and showed that the k-t BLAST technique can achieve satisfactory results with a acceleration factor up to 4-fold. Baltes et al. [13] demonstrated with their results that k-t SENSE approach, a further development of k-t BLAST, is a promising method for accelerating PC-MRI with a acceleration factor up to 5-fold. The flow curves which were evaluated from scans using k-t SENSE 5 agreed well with the reference flow curves.

Several authors have used time-resolved 3D velocity mapping for visualization and detection of normal and pathologic blood flow patterns in peripheral arteries [19], intracranial arteries [20,21] and the aorta [5,7–9,22]. In a study by Bammer et al. [20] the authors investigated, besides the effect of field strength and temporal resolution, the feasibility of parallel imaging for time-resolved 3D velocity mapping of the major intracranial vessels. The generalized autocalibrating partially parallel acquisitions (GRAPPA) method with reduction factors of 2 and 3 was used to reduce measurement times. The authors concluded from their data that, at 1.5 T, the reduction factors for GRAPPA should not exceed 2-fold acceleration because the accuracy of flow measurements was consistently impaired.

Several recent studies [23–27] examined the influence of pulsatile, turbulent flow on aortic wall stress by numerical analysis of hemodynamic factors contributing to the generation, proliferation, and rupturing of aortic aneurysms using simulated physiological waveforms and aortic aneurysm models. Khanafer et al. [26] suggested from their data that increased flow turbulence results in increased shear stress in aneurysms because the kinetic energy generated by turbulence impacting on the wall of the aneurysm increases fluid and wall shear stress at this site. This may be a mechanism for aneurysmal growth and eventual rupture. In another study by Ekaterinanis et al. [24] computational investigation of

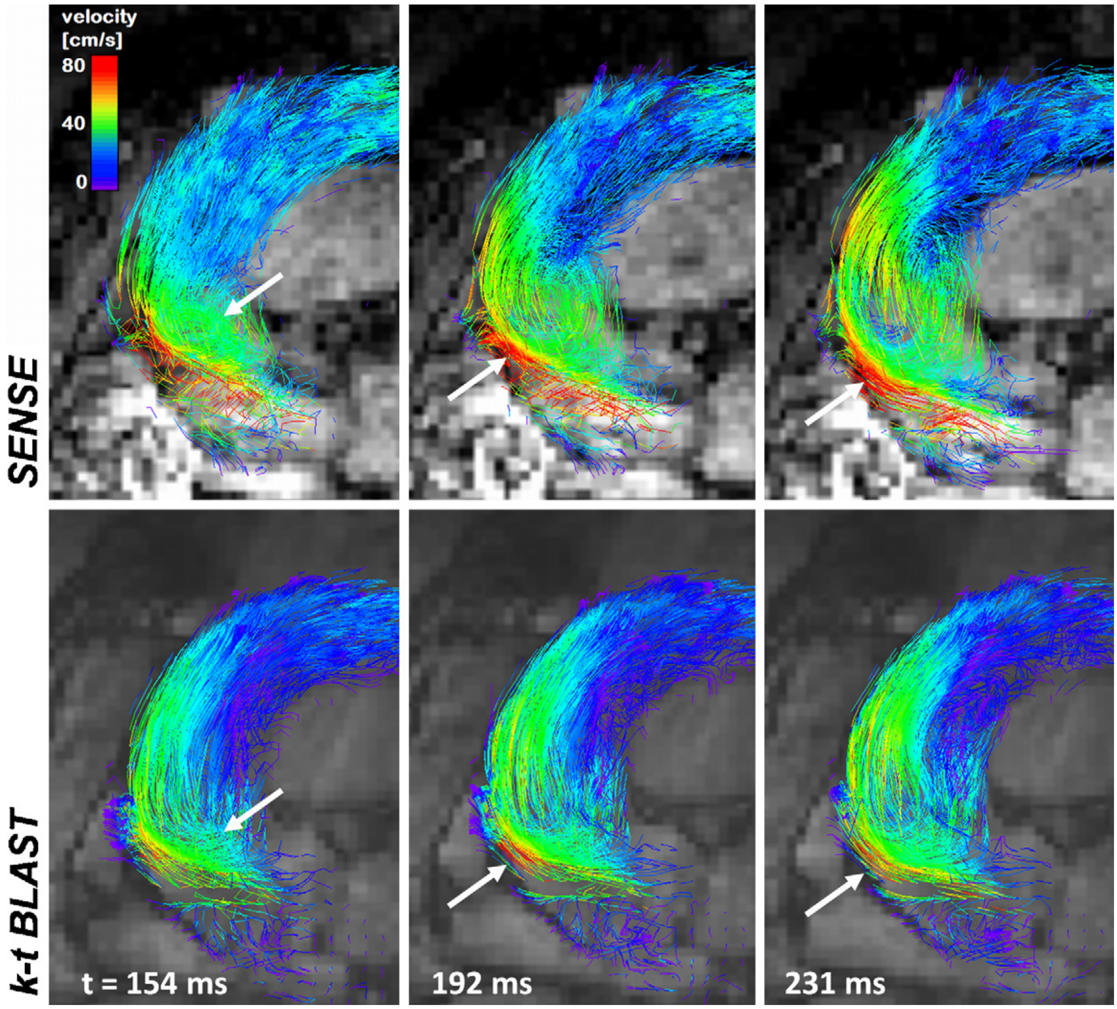

Fig. 5. Temporal evolution of blood flow in the aorta of a 73-year-old female patient with an ectasia of the ascending aorta: 3D streamlines for three successive early systolic time frames measured with PC-MRI in combination with SENSE ($R = 2$) (upper row) and k-t BLAST 6 (lower row). The color code is overlaid in the upper left image. The white arrows point to the most distinct differences between the SENSE and the k-t BLAST experiment.

flow in AAA models demonstrated recirculating flow regions in the expanded part of the AAAs which is accompanied by a minor increase in pressure but a significant increase in wall shear stress. The authors conclude that the levels of wall shear stress reached in turbulent blood flow may cause lesions of an aneurysmal wall. Information about the fluid dynamics of aortic blood flow from time-resolved 3D MR velocity mapping in combination with these novel computational analysis and simulation methods may help to obtain data on wall stress distribution and aortic wall tissue yield stress, which are required to estimate the aortic aneurysm rupture risk [27].

Our study was limited by the fact that we used retrospective triggering for SENSE and prospective triggering for k-t BLAST. Prospective triggering does not permit complete acquisition of the cardiac cycle, but the combination of k-t BLAST with the more favourable retrospective triggering was not feasible. However, we used the shortest possible trigger delay while discrepancy between retrospective and prospective triggering was just 11–15 ms. Furthermore, Seitz et al. [28] showed no significant differences between these two triggering methods for blood flow measurements at the carotid arteries. A further limitation was that we used not the recently developed k-t training plug-in, because this option was not available on the MR scanner at the time the experiments were performed. The advantages of this plug-in, which incorporates information about coil sensitivity in the reconstruction to aid the unaliasing process, have been demonstrated recently [11,13]. Hansen et al. [29] investigated the influence of the quality of the training stage data on the k-t BLAST reconstruction for cardiac MRI and concluded that the training data sets should be limited to 10–20 profiles. We used 11 profiles for our experiments.

5. Conclusions

The present study is the first in which time-resolved 3D MR velocity mapping from accelerated PC-MRI using k-t BLAST was qualitatively and quantitatively compared with PC-MRI using SENSE. We demonstrated the feasibility of SENSE and detected potential limitations of k-t BLAST when used for time-resolved 3D velocity mapping. The effects of higher k-t BLAST acceleration factors have to be considered for use in 3D MR velocity mapping. However, further studies using the k-t training plug-in or the k-t SENSE approach are necessary. The detected flow patterns in the patients with aortic diseases, especially for the time-resolved 3D MR velocity mapping results obtained in combination with SENSE, are encouraging to develop a fast and reliable method useful as additional screening tool for AAA and TAA high risk patients.

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