Accelerating Cine Phase-Contrast Flow Measurements Using *k-t* BLAST and *k-t* SENSE

Christof Baltes,[1] Sebastian Kozerke,[1] Michael S. Hansen,[2] Klaas P. Pruessmann,[1] Jeffrey Tsao,[3] and Peter Boesiger[1]*

Conventional phase-contrast velocity mapping in the ascending aorta was combined with *k-t* BLAST and *k-t* SENSE. Up to 5.3-fold net acceleration was achieved, enabling single breath-hold acquisitions. A standard phase-contrast (PC) sequence with interleaved acquisition of the velocity-encoded segments was modified to collect data in 2 stages, a high-resolution undersampled and a low-resolution fully sampled training stage. In addition, a modification of the *k-t* reconstruction strategy was tested. This strategy, denoted as "plug-in," incorporates data acquired in the training stage into the final reconstruction for improved data consistency, similar to conventional keyhole. "*k-t* SENSE plug-in" was found to provide best image quality and most accurate flow quantification. For this strategy, at least 10 training profiles are required to yield accurate stroke volumes (relative deviation <5%) and good image quality. In vivo 2D cine velocity mapping was performed in 6 healthy volunteers with 30–32 cardiac phases (spatial resolution 1.3 × 1.3 × 8–10 mm^3, temporal resolution of 18–38 ms), yielding relative stroke volumes of 106 ± 18% (mean ± 2*SD) and 112 ± 15% for 3.8× and 5.3× net accelerations, respectively. In summary, *k-t* BLAST and *k-t* SENSE are promising approaches that permit significant scan-time reduction in PC velocity mapping, thus making high-resolution breath-held flow quantification possible. Magn Reson Med 54:1430–1438, 2005. © 2005 Wiley-Liss, Inc.

Key words: *k-t* BLAST; *k-t* SENSE; cine imaging; flow quantification

Magnetic resonance phase contrast (PC) velocity mapping (1) is a powerful tool to study flow-related physiology and pathophysiology. It is a non-invasive technique that resolves 3-dimensional flow fields at relatively high spatial and temporal resolutions. A key disadvantage of the PC approach is its long scan duration. To quantify velocities in 1 spatial direction, at least 2 images have to be acquired to be able to separate flow-induced phase changes from background phases caused by susceptibility-induced inhomogeneities and coil sensitivity changes. For the acquisition of 3-dimensional velocity patterns, at least 4 velocity encoded images are required, leading to significantly prolonged scan times.

In several reports, PC velocity mapping has been used for blood flow quantification in the great vessels, such as the ascending aorta or the pulmonary artery. In order to perform PC sequences in cardiac applications without compromising spatial or temporal resolution, either navigator gating (2–4) or signal averaging (5) is needed to compensate for respiratory motion. Both approaches lead to acquisition times on the order of minutes. For this reason, a number of approaches to shorten scan times have been proposed, resulting in reduced susceptibility of the scan to bulk motion and consequently in improved accuracy of flow quantification. In several studies, PC sequences were accelerated by the parallel imaging method SENSitivity Encoding (SENSE) (6–8). Furthermore, the combination of the UNFOLD method (9) with PC velocity mapping was proposed to reduce acquisition times (10). In another approach, only a single velocity-encoding segment was acquired and background phase errors were corrected using filter operations (11). Still, scan time reductions beyond a factor of 2–3 are difficult to achieve. Consequently, spatial and temporal resolutions have to be compromised to enable single breath-hold acquisitions.

Recently, the *k-t* BLAST/*k-t* SENSE approach has been presented (12), which allows significantly accelerated dynamic imaging. *k-t* BLAST and *k-t* SENSE differ in terms of the reconstruction strategy used when data from multiple receiver coils are available. In *k-t* BLAST, the reconstruction does not incorporate information from sensitivity encoding, and reconstructed images from multiple receiver coils are combined after reconstruction by root-mean-square (13). In contrast, coil sensitivity information is incorporated directly in the *k-t* SENSE reconstruction to aid the unaliasing process (12). Both methods are based on the observation that dynamic data sets exhibit considerable correlation in space and time. By taking advantage of this correlation, only a subset of the data needs to be acquired and the missing data points can be recovered in the subsequent reconstruction process. To achieve this, additional prior knowledge on the signal distribution is required, which is obtained from low-resolution training data.

For cine cardiac imaging, the influence of the training data quality has already been investigated (14), but the impact on the accuracy of flow quantification has not yet been studied.

The aim of this work was to assess the feasibility of 5- and 8-fold accelerated *k-t* BLAST/*k-t* SENSE cine velocity mapping and to investigate the effect of different reconstruction parameters, such as the amount of training data

[1]Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland.
[2]MR-Centre, Skejby Hospital, Aarhus University Hospital, Aarhus, Denmark.
[3]Novartis Institutes for BioMedical Research, Inc., Cambridge, MA, USA.
Grant Sponsor: ETH Zurich; Grant Number: SEP Life Sciences TH7/02–2. Grant Sponsor: Philips Medical Systems, Best, the Netherlands.
*Correspondence to: Peter Boesiger, PhD, University and ETH Zurich, Institute for Biomedical Engineering, Gloriastrasse 35, CH-8092 Zurich, Switzerland. E-mail: boesiger@biomed.ee.ethz.ch
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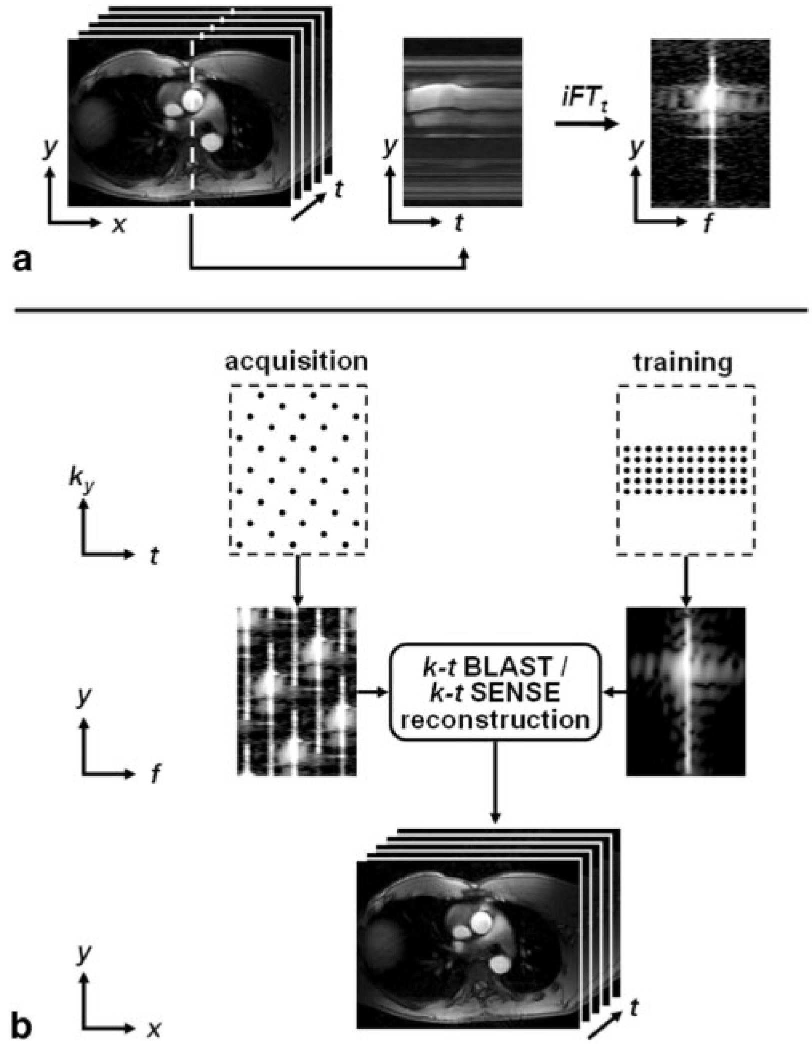

FIG. 1. (**a**) Left panel: cine image series containing the ascending aorta; middle panel: one pixel column (white dashed line) over time denoted as *y-t* space; right panel: temporal frequency components of *y-t* space denoted as *y-f* space. (**b**) Schematic of the *k-t* BLAST/*k-t* SENSE reconstruction framework: sampling pattern and resulting *y-f* space of the high-resolution undersampled acquisition and the low-resolution fully sampled training stage (left and right columns), processing of acquisition and training data according to the *k-t* reconstruction approach, and the resulting artifact-free cine image series (middle column) .

and acceleration factor, on the accuracy of flow quantification.

MATERIALS AND METHODS

Theory

The *k-t* approach takes advantage of the observation that signals from a natural image series can be represented in a compact fashion in *x-f* space, where *x* and *f* denote space and temporal frequency, respectively. Most of the signal is concentrated in a small portion of *x-f* space, while large areas contain little to no signal. Exploiting this fact, data collection can be accelerated without losing significant signal information.

This concept is illustrated in Fig. 1a showing a cine data set of the heart containing the ascending aorta (left). In the middle panel, the magnitude distribution of one column is shown over time, where *y* and *t* represent space and time, respectively. Static areas, like the chest wall, and moving areas, like the aorta, can be easily identified as regions that remain unchanged from left to right (i.e., along the time axis). Applying an inverse Fourier transform over time yields the corresponding *y-f* space (denoted as *x-f* space in the original description of the *k-t* approach (12)). The signal distribution in *y-t* space is represented in a more compact format in *y-f* space.

Data acquisition is accelerated by taking advantage of this compact data representation. Skipping certain *k*-space lines in *k-t* space accelerates the data acquisition, but can lead to overlapping of the signal replicas in *y-f* space (Fig. 1b, left column). The *k-t* reconstruction approach resolves potential aliasing by using prior knowledge about the expected signal distribution in *y-f* space. A detailed description of the *k-t* BLAST/*k-t* SENSE procedure can be found in (12). The a priori information is obtained from a fully sampled, but low-resolution training scan, which can be acquired in a very short time period for all cardiac phases (Fig. 1b, right column). In the *k-t* SENSE reconstruction, the knowledge about coil sensitivities from multiple receiver coils is additionally taken into account to improve the reconstruction result. Time-invariant coil sensitivities are estimated from the temporally averaged undersampled data (12), i.e., no additional calibration scan is required to obtain the coil sensitivity maps.

Since the *k-t* reconstruction is linear, PC velocity mapping can be combined with *k-t* BLAST and *k-t* SENSE (15), respectively. For this purpose, each velocity encoded segment is acquired according to the *k-t* sampling pattern

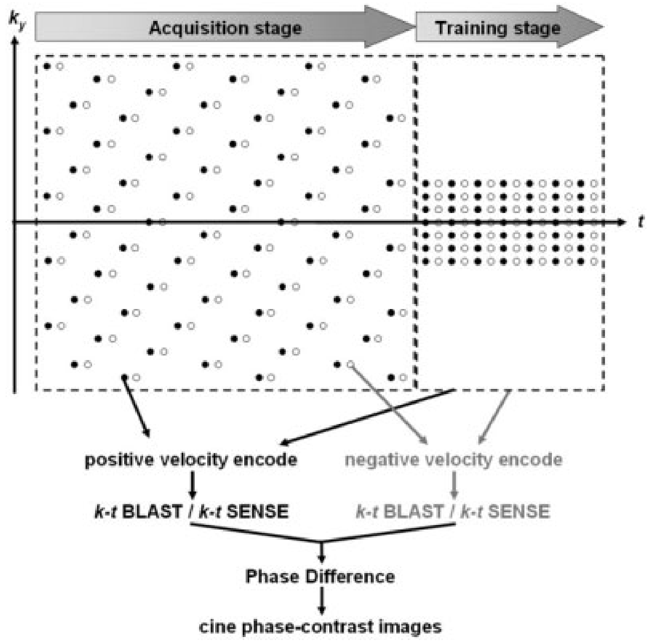

FIG. 2. Sampling pattern of PC velocity mapping accelerated by *k-t* BLAST/*k-t* SENSE. Positive and negative velocity encodes are acquired in an interleaved fashion. In post processing, each velocity encode is reconstructed separately before the phase difference is calculated to achieve the desired cine PC image series.

(Fig. 2). The negative and positive velocity encodes are interleaved in order to minimize the delay between corresponding profiles (i.e., corresponding phase-encode lines). Furthermore, data collection is split into 2 stages: acquisition of high-resolution undersampled data (first stage) and of low-resolution training data (second stage). The two velocity-encoding segments are reconstructed separately using *k-t* BLAST or *k-t* SENSE. Subsequently, cine PC velocity maps are obtained by calculating the phase difference of the positive and negative velocity-encoded segments.

This work tested the *k-t* reconstruction strategy described in (12), as well as the strategy described in (16). In the latter strategy, denoted as "plug-in" hereafter, the profiles acquired in the training stage are plugged into *k-t* space to replace the corresponding profiles reconstructed from undersampled data, in a similar fashion to conventional keyhole imaging (17,18) (Fig. 3). In the case of *k-t* SENSE, the plug-in strategy requires the following additional steps, which are necessary because the reconstructed image is coil-combined whereas the raw data are separate for each coil. The reconstructed image is multiplied with the sensitivity maps to generate the reconstructed images from individual coils. Data plug-in takes place in the *k*-space of these coil images. For profiles that were acquired in both the undersampled and training stages, only the training profiles were retained since these are expected to be more consistent with the neighboring profiles. In general, the corresponding profiles can also be averaged to improve SNR, but the improvement is expected to be small, since very few profiles are acquired in both stages. After data replacement, the coil images are combined using Roemer's optimal combination method (13). The plug-in strategy assumes that training and undersampled data were collected in a consistent manner (i.e., the same breath-hold or in an interleaved manner) such that the two data sets match (14).

Computer Simulations

In computer simulations, the performance of the standard *k-t* reconstruction and *k-t* BLAST/*k-t* SENSE plug-in was compared. Furthermore, simulations were used to find the amount of training data required for reliable flow quantification. For this purpose, a cine 2D PC fast gradient field echo (FFE) sequence was used to acquire a fully sampled data set during free-breathing in the ascending aorta of a healthy volunteer with the following scan parameters: field-of-view (FOV): 217 mm × 330 mm, spatial resolution: 1.3 mm × 1.3 mm × 10 mm, echo/repetition time (TE/TR): 3.0 ms/6.3 ms, flip angle: 15°, number of cardiac phases: 30, encoding velocity (venc): 150 cm/s, and 3 signal averages to reduce respiratory motion artifacts. Free-breathing

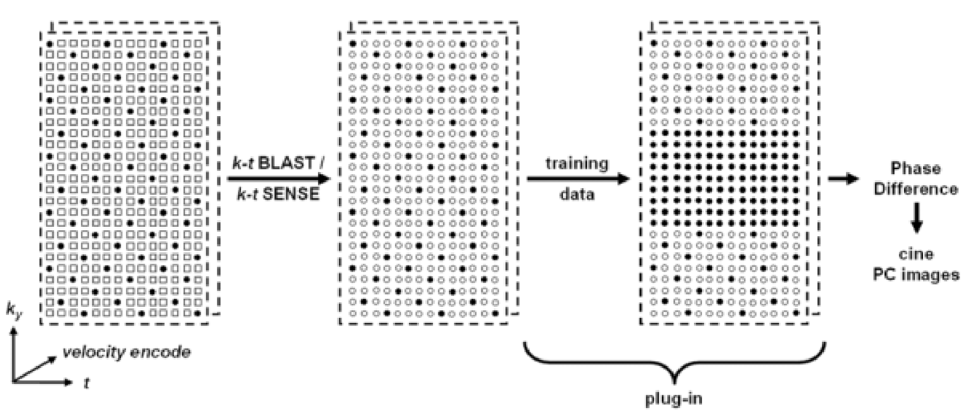

FIG. 3. *k-t* reconstruction framework incorporating replacement with training data, denoted as *k-t* BLAST/*k-t* SENSE plug-in. □ denotes an unacquired data point in k_y-*t* space; ○ denotes a recovered data point using *k-t* BLAST/*k-t* SENSE; ●denotes an acquired data point. After reconstructing the data points in k_y-*t* space using *k-t* BLAST/*k-t* SENSE, the profiles sampled in the training stage (●) are plugged into k_y-*t* space (plug-in) .

and subsequent averaging was necessary in practice for the conventional fully sampled PC acquisition due to the long scan time. During data collection, cardiac gating was performed prospectively. A 5-element phased-array coil was used for signal reception. In the subsequent image reconstruction, coil combination was performed by calculating the root-mean-square (RMS) (13) to obtain magnitude information and using the squared magnitude-weighted sum of phase differences (19) to derive phase-contrast maps. In *k-t* SENSE, coil sensitivities (6,20) were derived directly from the time average of the undersampled data, making a separate scan for coil calibration unnecessary.

A subset of the reference data was used to simulate 5-fold accelerated *k-t* BLAST/*k-t* SENSE with the amount of training data ranging from 1 to 51 out of a total of 168 profiles. For comparison, sliding window reconstruction (21) was performed using 5 consecutive time frames. The cardiac cycle was repeated in time (i.e., wrapped) in order to reconstruct images at initial and final cardiac phases, where the sliding window would otherwise extend beyond the cardiac cycle.

Velocity maps were corrected for phase errors caused by eddy current effects. For this purpose, image pixels containing only static tissue, e.g., the chest wall, were selected for each time frame. A 2D plane was fitted through the phase values of the selected pixels and subsequently subtracted from the phase maps. Phase errors due to concomitant gradient fields were not corrected because these errors were expected to be negligible in aortic flow measurements where the imaging slice was close to the iso-center of the magnet.

To estimate the performance of the different reconstruction approaches, the root-mean-square (RMS) error $E_{RMS,t}$ for each time point t was calculated relative to the fully sampled data set according to:

$$E_{RMS,t} = \sqrt{\frac{\sum_{y}^{N_y}\sum_{x}^{N_x}\left[\frac{\|r_{x,y,t}\| + \|o_{x,y,t}\|}{2} * \angle(o_{x,y,t} * conj(r_{x,y,t}))\right]^2}{\sum_{y}^{N_y}\sum_{x}^{N_x}\left[\frac{\|r_{x,y,t}\| + \|o_{x,y,t}\|}{2} * \angle(o_{x,y,t})\right]^2}} \quad [1]$$

where $o_{x,y,t}$ and $r_{x,y,t}$ denote a pixel of the original and reduced data set, respectively, at position x, y at time point t. The phase difference for each pixel was calculated by complex division to prevent wrap-around errors. Subsequently, the phase differences were weighted according to the signal magnitudes to reduce the influence of random phase from pixels with low signal. The relative errors $E_{RMS,t}$ were averaged over time to obtain a single estimate per number of training profiles. Furthermore, stroke volumes were evaluated from the reconstructed phase maps to provide a measure of accuracy in flow quantification. A region-of-interest (ROI) containing the ascending aorta was selected semi-automatically for each cardiac phase using the fully sampled reference data set. The same ROI was used to evaluate all images to avoid confounding errors in stroke volume due to changes in ROI selection.

The impact of different acceleration factors on the accuracy of flow quantification was investigated by simulating 2-fold to 10-fold accelerated *k-t* BLAST/*k-t* SENSE plug-in scans using different numbers of training profiles ranging from 1 to 51 profiles. Accordingly, the RMS error was calculated relative to the reference (i.e., fully sampled) image series.

In Vivo Validation

In vivo data were acquired in 6 healthy volunteers (3 male and 3 female) after informed consent had been obtained. All experiments were performed on a whole-body 1.5 T MR system (Philips Medical Systems, Best, The Netherlands). For optimal through-plane velocity mapping, the PC imaging plane was positioned perpendicular to the ascending aorta at the level of the pulmonary artery. Reference data were acquired during free-breathing of the subject (scan parameters: FFE sequence, FOV: 196–217 mm × 330 mm, spatial resolution: 1.3 mm × 1.3 mm × 8.0–10.0 mm, TE/TR: 2.6–3.2 ms/5.8–6.4 ms, flip angle: 15°–20°, cardiac phases: 30 and 32 (prospectively ECG-gated), venc: 120–170 cm/s). To reduce respiratory motion artifacts, 3 signal averages were acquired, resulting in scan durations between 202 s and 275 s. Furthermore, 5-fold and 8-fold accelerated scans were performed, including the acquisition of 11 training profiles per cardiac phase, resulting in net acceleration factors of 3.8 and 5.3, respectively. Scan durations between 14 s and 28 s were achieved, depending on heart rate and acceleration factor, thus allowing for single breath-hold acquisitions. To facilitate comparison, the reference and *k-t* accelerated scans were performed one after another to minimize physiologic changes of the blood flow between scans. The data were reconstructed using the *k-t* SENSE plug-in.

For comparison, flow curves over time and stroke volumes were evaluated. For this purpose, the cross-sectional area of the ascending aorta was selected separately in a semi-automatic fashion for each scan, since slight changes of the respiration curve or breath-hold position might change the position and shape of the aortic cross-section.

Exemplary Application

To demonstrate the potential benefit of *k-t* SENSE accelerated flow measurements in clinical routine, 5 low-resolution PC scans with very short scan times were performed in the aorta. After acquiring a scout image showing the ascending aorta, the aortic arch, and the thoracic descending aorta in-plane, through-plane PC velocity mapping was applied at 5 different locations (2 before and 3 after the outflow of the carotid arteries) with the following scan parameters: FFE sequence, FOV: 202 mm × 330 mm, spatial resolution: 2.3 mm × 2.3 mm × 8.0 mm, TE/TR: 2.0 ms/4.1 ms, flip angle: 10°, cardiac phases: 32 (prospectively ECG-gated), venc: 150 cm/s, scan time: 7 sec per location (including training data acquisition). These scans were executed on a Philips Achieva 3T system (Philips Medical Systems, Best, The Netherlands). Subsequently, flow curves and stroke volumes were evaluated from these PC data.

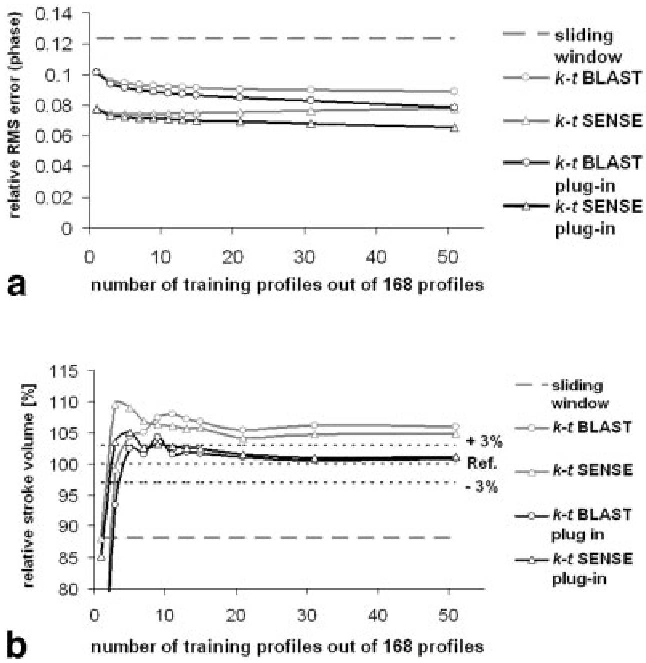

FIG. 4. Comparison of reconstruction strategies at acceleration factor 5 for an increasing number of training profiles. (**a**) RMS error relative to the unaccelerated reference data set. (**b**) Relative stroke volume evaluated from the accelerated scans and compared to the reference value.

RESULTS

Simulations

In Fig. 4, the performance of the different reconstruction procedures is compared at an acceleration factor of 5: standard *k-t* BLAST/*k-t* SENSE, *k-t* BLAST/*k-t* SENSE plug-in, and sliding window. As measure of image quality, the relative RMS error is depicted for an increasing number of training profiles (Fig. 4a). The accuracy of standard *k-t* BLAST and *k-t* BLAST/*k-t* SENSE plug-in reconstructions continuously improves for an increasing number of training profiles, while the *k-t* SENSE reconstruction accuracy slightly decreases for a higher amount of training data. Overall, the RMS error resulting from the *k-t* reconstructions was significantly lower compared to the sliding window approach. In addition, relative stroke volumes were evaluated to estimate the reliability of flow quantification. The lowest deviation of stroke volume, relative to the reference value, was achieved with the *k-t* BLAST/*k-t* SENSE plug-in (relative deviation <3% for more than 10 training profiles out of 168 profiles). Overall, the *k-t* SENSE plug-in had the best image quality and the most accurate flow quantification.

In Fig. 5, the relative RMS error and relative stroke volume obtained by the *k-t* BLAST/*k-t* SENSE plug-in are shown for different acceleration factors and increasing number of training profiles. As expected, the RMS error decreases for an increasing amount of training data, and it increases for increasing acceleration factors. In general, the *k-t* SENSE plug-in outperforms the *k-t* BLAST plug-in for corresponding acceleration factors. Accurate flow quantification (relative deviation <5%) for all acceleration factors up to 10 is achieved, if more than 15 or 10 training profiles are acquired using the *k-t* BLAST plug-in or *k-t* SENSE plug-in, respectively.

In Vivo Results

Good image quality was achieved in all in vivo acquisitions. In Fig. 6, anatomic images and phase maps of 5 time frames evenly distributed over the cardiac cycle are shown for one representative volunteer. The 3 rows represent 3 separately acquired scans: the free-breathing reference scan and the 5-fold and 8-fold accelerated single breath-hold scans reconstructed using the *k-t* SENSE plug-in. In the column on the right side, magnitude and velocity maps of one pixel column (white dashed line) through the ascending aorta is shown over time for each of the 3 scans. A decrease in the signal-to-noise ratio (SNR) associated with the accelerated data collection is observed (not obvious from Figure). However, temporal fidelity of the aorta is

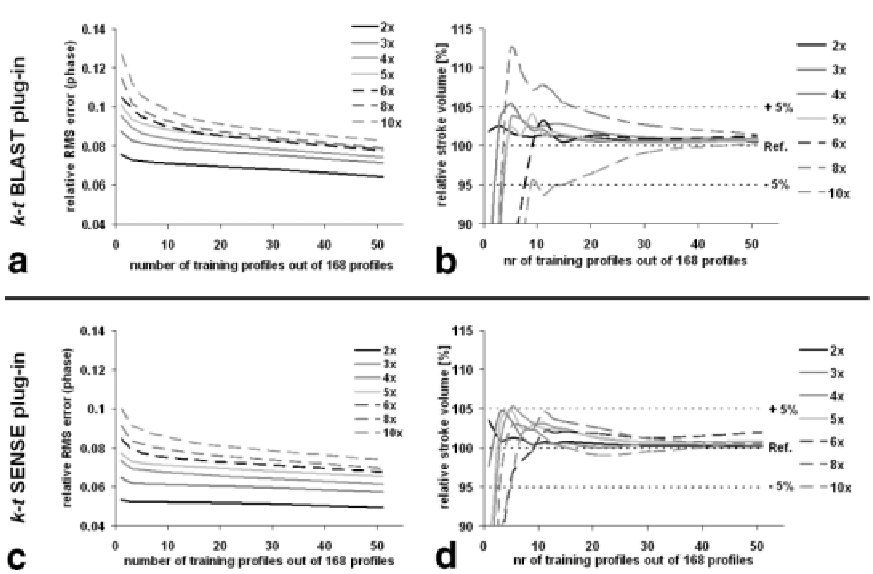

FIG. 5. Comparison of *k-t* BLAST plug-in versus *k-t* SENSE plug-in for different acceleration factors and an increasing amount of training data. (**a**), (**c**) RMS error relative to the reference data. (**b**), (**d**) Relative stroke volumes.

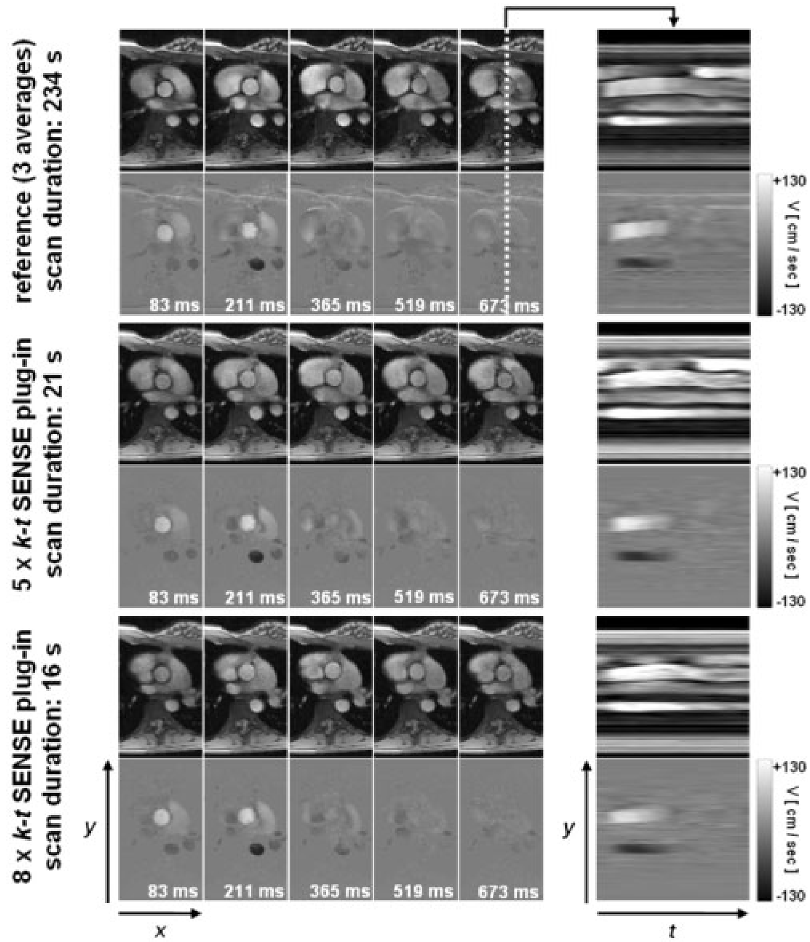

FIG. 6. Anatomic images and velocity maps acquired in one representative volunteer using conventional free-breathing (top row), 5-fold (middle row), and 8-fold (bottom row) accelerated PC sequences. For each scan, 5 time frames evenly distributed over the cardiac cycle are depicted. The images on the right represent magnitude and velocity maps of one image column (white dashed line) over time.

preserved for the 5-fold accelerated data sets, and only slight temporal low-pass filtering becomes apparent at 8-fold acceleration (Fig. 6, right column).

Results of the quantitative flow analysis are shown in Fig. 7 for the 5-fold and 8-fold accelerated *k-t* SENSE plug-in. A good agreement was found between the flow curves from the accelerated data and those from the reference data, although slight temporal low-pass filtering becomes apparent at 8-fold acceleration. For the relative stroke volumes (values evaluated from accelerated scans over reference values) (Figs. 7b and 7d), a mean value of 106 ± 18% (mean ± 2*SD) and 112 ± 15% was found for acceleration factors 5 and 8, respectively. All stroke volumes were found to be within 2 standard deviations. A Wilcoxon matched-pairs signed-ranks test was applied to estimate the difference in mean stroke volumes evaluated from unaccelerated and accelerated scans. Stroke volumes evaluated from 5-fold accelerated scans did not differ significantly from the reference values (2-tailed P-value: 0.2188), while the difference became significant at 8-fold acceleration (2-tailed P-value: 0.0313).

Exemplary Application

In Fig. 8, flow curves and corresponding stroke volumes (SV) are shown for the 5 different locations. Data were acquired using the 8-fold accelerated *k-t* SENSE plug-in. The difference of the stroke volumes calculated from the velocity maps right before and after the outflow of the carotid arteries indicates the blood volumes leaving the aorta through the carotids.

Discussion and Conclusion

In this work, the feasibility of 5-fold and 8-fold accelerated *k-t* BLAST/*k-t* SENSE has been assessed and the performance of different reconstruction approaches was investigated in terms of accurate flow quantification. Two different reconstruction strategies were compared: the standard *k-t* reconstruction as described in (12) and an extension of this approach denoted as the *k-t* BLAST/*k-t* SENSE plug-in (16). Furthermore, the impact of an increasing amount of training data and increasing acceleration factors on the reconstruction performance was studied in detail.

Computer simulations showed that the *k-t* SENSE plug-in yielded the lowest reconstruction (RMS) error and the most accurate stroke volume estimation among the studied reconstruction approaches. In this approach, it is assumed that both training and acquisition data were collected in the same breath hold to minimize spatial shifts between the two stages. Replacing profiles reconstructed from undersampled data with corresponding training profiles after *k-t* reconstruction improves the accuracy of flow quantification, since the replacement eliminates any potential reconstruction error in those profiles.

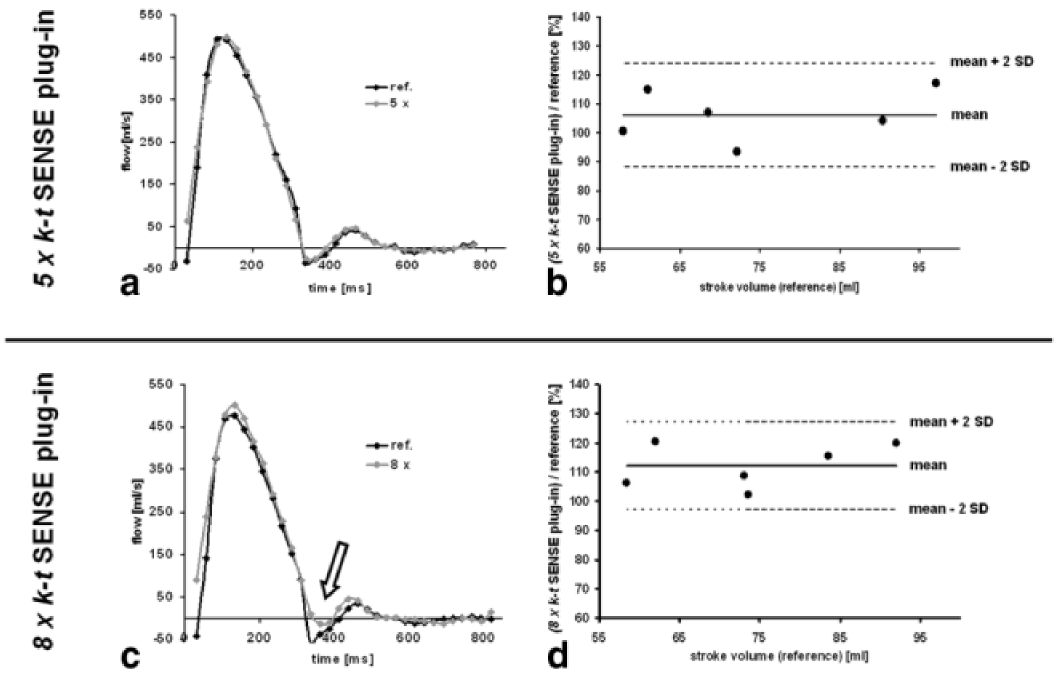

FIG. 7. In vivo results achieved with 5-fold and 8-fold accelerated *k-t* SENSE plug-in. (**a**), (**c**) Comparison of flow curves evaluated from accelerated and unaccelerated scans for one volunteer. (**b**), (**d**) Stroke volumes evaluated from the accelerated scans and compared to the reference values for all volunteers.

The *k-t* SENSE reconstruction without the plug-in strategy showed an increasing RMS phase error for an increasing amount of training data. This can be explained by the fact that the training data also become increasingly noisy with a larger number of training profiles, thus offsetting the benefit of a higher spatial resolution. Nevertheless, the

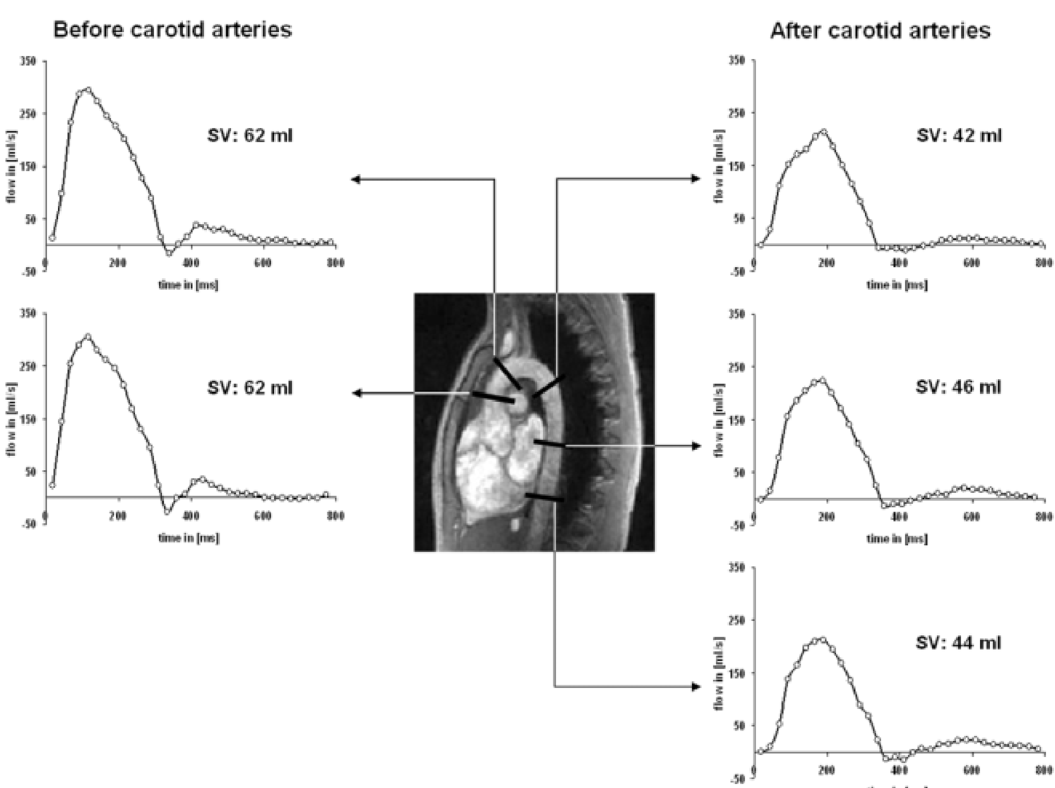

FIG. 8. Fast low resolution aortic flow measurements using 8-fold accelerated *k-t* SENSE plug-in. Flow curves and resulting stroke volume (SV) are shown for 5 different locations (2 before and 3 after the outflow of the carotid arteries) .

increased error could be overcome using the *k-t* SENSE plug-in.

The performance of the *k-t* reconstruction decreased for increasing acceleration factors. For all acceleration factors (2 to 10), the RMS error continuously decreased for an increasing number of training profiles. Using the *k-t* SENSE plug-in with more than 10 out of 168 training profiles, the stroke volume was found to deviate by less than 5% relative to the reference value. This finding is in good agreement with the results presented by Hansen et al. (14). Since patients with cardiac diseases often suffer from impaired respiratory capabilities, the breath-hold duration is a crucial parameter and needs to be as short as possible. In this respect, the smooth transition of the RMS error and of the stroke volume error at different acceleration factors allows a practical trade-off between scan duration and accuracy in flow quantification to be made in a continuous manner.

For the in vivo data collected in 6 healthy volunteers, good image quality was achieved in all cases, although a decrease in SNR was observed for the accelerated scans due to the reduced number of sampling points. In this work, the drop of SNR was not studied in detail, but the following estimation can be made. The SNR loss depends on the dynamics in the image series. The temporal bandwidth used during reconstruction is adapted according to the motion of the different regions in the FOV. Maximal loss occurs for pixels with maximal temporal bandwidth. The SNR is determined by comparing the number of sampled k_y-lines in the accelerated and non-accelerated scans: $SNR_{k-t}/SNR_{full} = 1/\sqrt{net \cdot N_a}$ with *net* and N_a denoting the net acceleration factor in the accelerated scan and the number of signal averages in the reference scan, respectively. This results in a minimum SNR of 0.3 and 0.25 for the 5-fold and 8-fold accelerated scans compared to the reference scan with 3 signal averages. In practice, the SNR is higher due to limited temporal frequency contents. A detailed analysis of the SNR loss in *k-t* BLAST/*k-t* SENSE accelerated scans is the subject of future work.

Flow curves over time evaluated from 5-fold and 8-fold accelerated scans agreed well with the reference flow curves. Only at 8-fold acceleration did slight temporal low-pass filtering become apparent. A comparison of the stroke volumes revealed a good agreement of accelerated and unaccelerated scans, although the extent of retrograde flow seems to be underestimated for acceleration factor 8 due to the temporal low-pass filtering. This leads to a slight overestimation of the stroke volumes evaluated from 8-fold accelerated scans. However, accepting slight deviations of the flow parameters, the application of high acceleration factors might allow data acquisition in patients with impaired breath-hold capacity.

The exemplary application indicated that the *k-t* approach can be applied to either accelerate the data collection or increase the spatial resolution compared to conventional PC velocity mapping. Alternatively, the gained scan time might be used to encode either more velocity directions or more imaging slices.

The data presented in this work were all collected using prospective cardiac gating because the current implementation of the *k-t* methods requires the data points to be equidistantly sampled in time. Non-regular sampling would result in more complex aliasing patterns in *y-f* space, which requires a more elaborate numerical approach to resolve the aliasing, as presented recently in (22).

In this work, the coil configuration was not optimized. Further investigations are envisaged to determine the optimal number of receive coils and their positioning for accurate flow quantification. The temporal low-pass filtering occurring at acceleration factor 8 might be addressed by shifting the balance between prior information provided by the training data toward coil encoding when using a larger number of receive coils (23).

In conclusion, the results suggest that *k-t* BLAST and *k-t* SENSE are promising methods for accelerating PC velocity mapping. With these methods, single breath-hold flow quantification becomes possible with high spatial and temporal resolutions.

REFERENCES

1. Bryant DJ, Payne JA, Firmin DN, Longmore DB. Measurement of flow with NMR imaging using a gradient pulse and phase difference technique. J Comput Assist Tomogr 1984;8:588–593.
2. Nagel E, Bornstedt A, Hug J, Schnackenburg B, Wellnhofer E, Fleck E. Noninvasive determination of coronary blood flow velocity with magnetic resonance imaging: comparison of breath-hold and navigator techniques with intravascular ultrasound. Magn Reson Med 1999;41: 544–549.
3. Keegan J, Gatehouse PD, Yang GZ, Firmin DN. Spiral phase velocity mapping of left and right coronary artery blood flow: correction for through-plane motion using selective fat-only excitation. J Magn Reson Imaging 2004;20:953–960.
4. Keegan J, Gatehouse PD, Mohiaddin RH, Yang GZ, Firmin DN. Comparison of spiral and FLASH phase velocity mapping, with and without breath-holding, for the assessment of left and right coronary artery blood flow velocity. J Magn Reson Imaging 2004;19:40–49.
5. Caruthers SD, Lin SJ, Brown P, Watkins MP, Williams TA, Lehr KA, Wickline SA. Practical value of cardiac magnetic resonance imaging for clinical quantification of aortic valve stenosis: comparison with echocardiography. Circulation 2003;108:2236–2243.
6. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. Magn Reson Med 1999;42:952–962.
7. Thunberg P, Karlsson M, Wigstrom L. Accuracy and reproducibility in phase contrast imaging using SENSE. Magn Reson Med 2003;50:1061–1068.
8. Beerbaum P, Korperich H, Gieseke J, Barth P, Peuster M, Meyer H. Rapid left-to-right shunt quantification in children by phase-contrast magnetic resonance imaging combined with sensitivity encoding (SENSE). Circulation 2003;108:1355–1361.
9. Madore B, Glover GH, Pelc NJ. Unaliasing by fourier-encoding the overlaps using the temporal dimension (UNFOLD), applied to cardiac imaging and fMRI. Magn Reson Med 1999;42:813–828.
10. Kerwin WS. High-pass-low-pass (HP-LP) reconstruction of CINE phase-contrast MRI. Magn Reson Med 2004;52:566–574.
11. Man LC, Pauly JM, Nishimura DG, Macovski A. Nonsubtractive spiral phase contrast velocity imaging. Magn Reson Med 1999;42:704–713.
12. Tsao J, Boesiger P, Pruessmann KP. k-t BLAST and k-t SENSE: dynamic MRI with high frame rate exploiting spatiotemporal correlations. Magn Reson Med 2003;50:1031–1042.
13. Roemer PB, Edelstein WA, Hayes CE, Souza SP, Mueller OM. The NMR phased array. Magn Reson Med 1990;16:192–225.
14. Hansen MS, Kozerke S, Pruessmann KP, Boesiger P, Pedersen EM, Tsao J. On the influence of training data quality in k-t BLAST reconstruction. Magn Reson Med 2004;52:1175–1183.
15. Baltes C, Kozerke S, Tsao J, Pruessmann KP, Boesiger P. Eight-fold acceleration of PC-SSFP velocity mapping using k-t BLAST. In: Proceedings of 12th Annual Meeting ISMRM, Kyoto, Japan, 2004; Abstract: 1858.
16. Kozerke S, Tsao J, Razavi R, Boesiger P. Accelerating cardiac cine 3D imaging using k-t BLAST. Magn Reson Med 2004;52:19–26.
17. Jones RA, Haraldseth O, Muller TB, Rinck PA, Oksendal AN. K-space substitution: a novel dynamic imaging technique. Magn Reson Med 1993;29:830–834.

18. van Vaals JJ, Brummer ME, Dixon WT, Tuithof HH, Engels H, Nelson RC, Gerety BM, Chezmar JL, den Boer JA. "Keyhole" method for accelerating imaging of contrast agent uptake. J Magn Reson Imaging 1993; 3:671–675.
19. Bernstein MA, Grgic M, Brosnan TJ, Pelc NJ. Reconstructions of phase contrast, phased array multicoil data. Magn Reson Med 1994;32:330–334.
20. Kellman P, Epstein FH, McVeigh ER. Adaptive sensitivity encoding incorporating temporal filtering (TSENSE). Magn Reson Med 2001;45: 846–852.
21. Riederer SJ, Tasciyan T, Farzaneh F, Lee JN, Wright RC, Herfkens RJ. MR fluoroscopy: technical feasibility. Magn Reson Med 1988;8:1–15.
22. Hansen MS, Tsao J, Kozerke S, Eggers H. *k-t* BLAST reconstruction from arbitrary *k-t* space sampling: application to dynamic radial imaging. In: Proceedings of 13th Annual Meeting ISMRM, Miami, USA, 2005. Abstract: 684.
23. Kozerke S, Baltes C, Tsao J, Hansen MS, Pruessmann KP, Boesiger P. Comparison of SENSE and *k-t* SENSE in dynamic imaging. In: Proceedings of 13th Annual Meeting ISMRM, Miami, USA, 2005. Abstract: 2452.