

Improving Dynamic MR Angiography: Iterative TWIST

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Introduction

Nowadays, many vascular territories are explored non-invasively for the purpose of diagnosis, therapy planning and surveillance of vascular disease. Invasive catheter angiography is almost exclusively being used during therapy and intervention. However, the benefits of invasive approaches include the ability to visualize dynamics of applied dye and may therefore provide additional information on the potential hemodynamic relevance of vascular disease or stenosis.

In recent years, magnetic resonance angiography (MRA) has become a dominant tool of non-invasive high-resolution delineation of body and peripheral vasculature. With

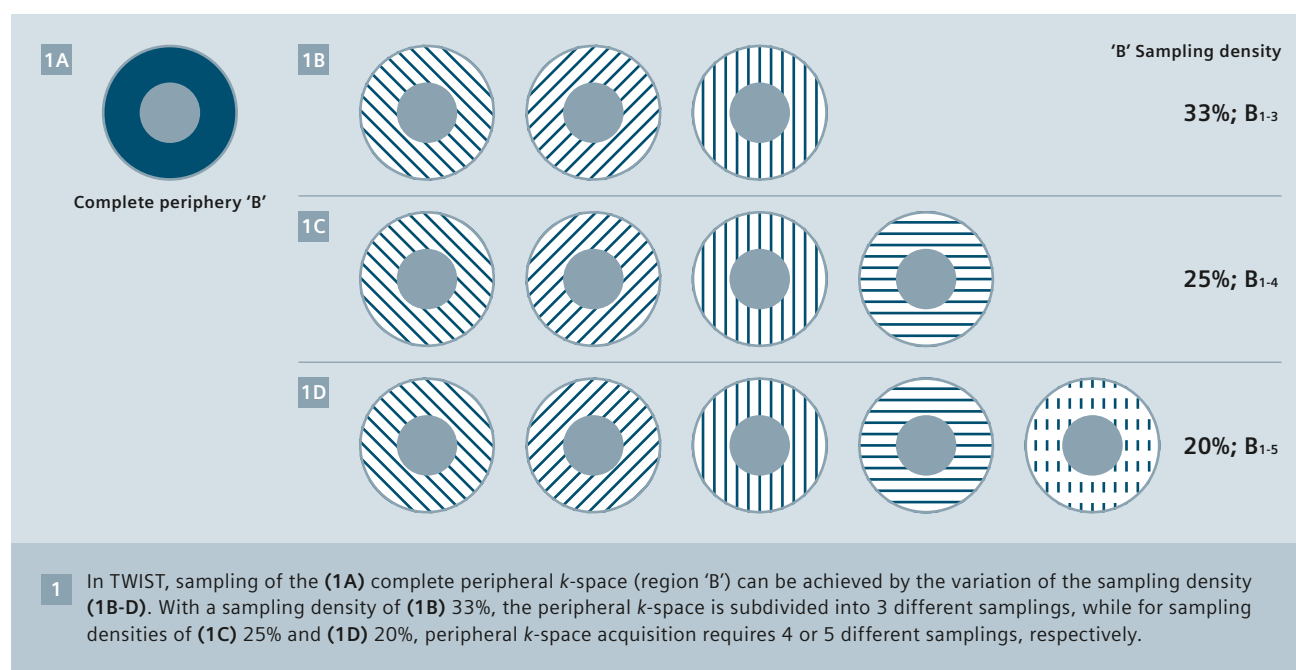
the ever increasing importance of continuous surveillance in genetic aortic disease (e.g. Marfan's, Ehlers-Danlos, Loeys-Dietz, etc.), the role of MRA developed beyond atherosclerotic disease and focuses more often on a younger population.

Most commonly, outside the brain, contrast-enhanced MRA (CE-MRA) techniques are being employed sampling a high-resolution data set after a contrast agent timing bolus.

In order to overcome the limitations of purely static MRA, various techniques such as time-resolved imaging of contrast kinetics (TRICKS) and time-resolved angiography with stochastic trajectories (TWIST) are being employed [1, 2]. The predominant underlying principle of these

approaches relates to keyhole imaging with more frequent sampling of central k -space data vs. peripheral k -space data. In addition to commonly applied acceleration techniques (e.g. partial Fourier, parallel imaging, etc.), dynamic CE-MRA also relies on view-sharing for peripheral k -space coverage in order to improve temporal resolution (Figs. 1-2).

Dynamic CE-MRA using TWIST has proven beneficial and successful in the diagnosis of disease across vessel territories from head to toe [3-5]. Besides a direct vascular focus, the relatively high temporal resolution 3D coverage, combined with prominent T1-weighting and background tissue suppression, has been applied to tissue perfusion studies.



Dynamic contrast-enhanced MRA with iterative TWIST

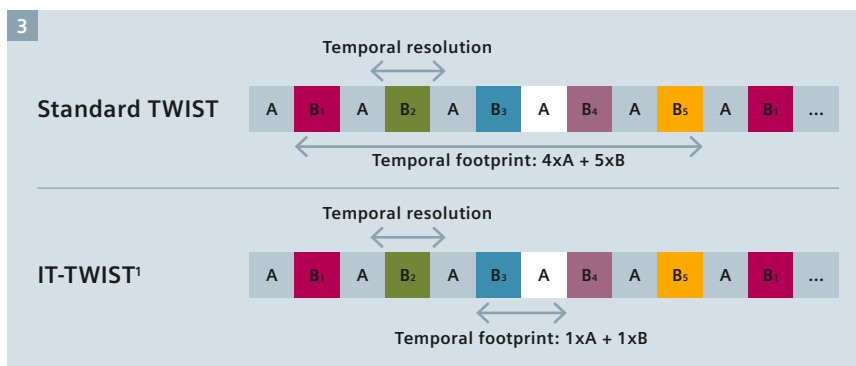
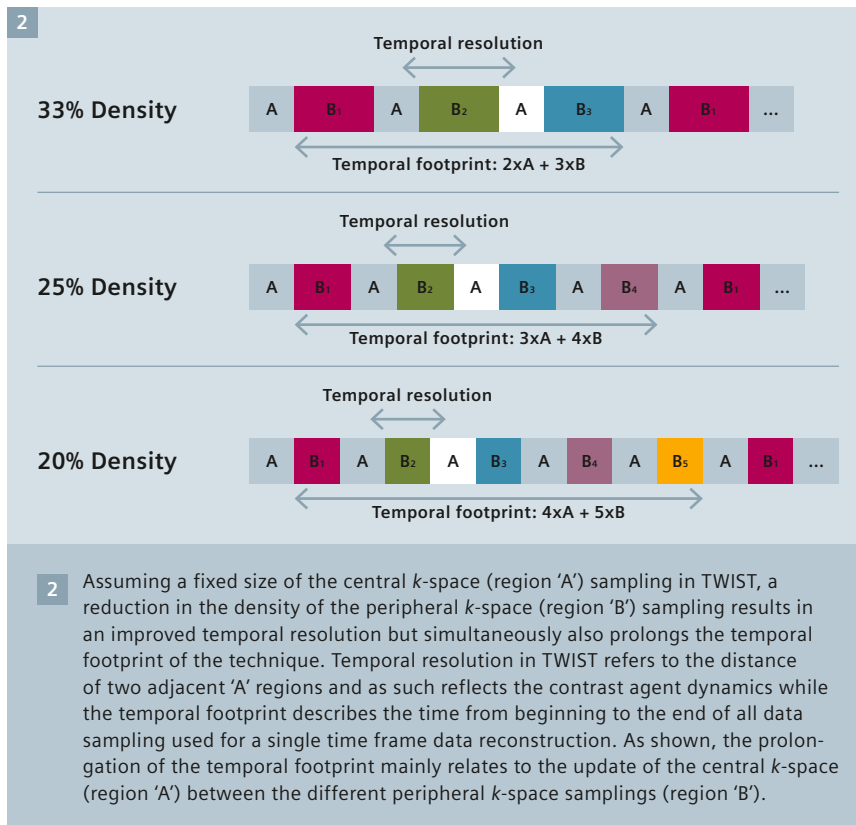
With repeated updates of the central k -space data, the dynamic pass of a Gadolinium-based contrast agent (GBCA) can be followed through the vasculature of interest without the need for a timed bolus. However, while the sharing of peripheral k -space data across multiple time points

provides an improved update rate of images (apparent 'temporal resolution'), it also results in a prolongation of the 'temporal footprint' of TWIST (Fig. 2). Especially in areas of possible motion and fast blood circulation (e.g. chest, pulmonary vasculature), this may result in inconsistencies, temporal blurring and subsequent image degradation, specifically of small vasculature.

Recent interest in Compressed Sensing approaches successfully demonstrated benefits of these techniques in various MR applications including CE-MRA [6] and dynamic CE-MRA [7, 8]. The potential benefits of such iterative reconstruction approaches have recently been explored in clinical scenarios [8, 9].

Iterative TWIST (IT-TWIST)¹ uses the sampling pattern of a regular TWIST acquisition, but does not rely on view sharing during image reconstruction. Instead, the implemented iterative reconstruction algorithm relies on the intrinsic incoherent sampling pattern of the peripheral k -space data and uses a Compressed Sensing approach with spatial and temporal regularization to suppress artifacts arising from k -space undersampling.

More in detail, the TWIST acquisition consists of interleaved acquisitions of central k -space (region 'A') and different incoherent sub-samplings of peripheral k -space (region 'B'). Regular TWIST reconstruction then combines multiple 'B' regions (view sharing) with one 'A' region to form a coherently subsampled k -space suitable for parallel imaging reconstruction (see Figures 1, 2). In contrast, the iterative TWIST reconstruction uses a single region 'A' and region 'B' pair per time frame, thus decreasing the 'temporal footprint' to be identical to the 'image update rate' (apparent 'temporal resolution') (Fig. 3). To recover the individual time frames despite the higher undersampling, a non-linear iterative SENSE reconstruction is being used. The iterative reconstruction uses spatio-temporal regularization based on Haar wavelets [8, 10]. This reconstruction process results in a considerable computational burden and therefore is carried out on the Graphics Processing Unit (GPU) of the standard image reconstruction system. Depending on detailed acquisition parameters and time frames current reconstruction times are about 20 minutes.



- 3** Iterative TWIST (IT-TWIST¹) allows a substantial shortening of the temporal footprint in data reconstruction. While in standard TWIST a complete coverage of region 'B' is required (sampling density of 20% shown), IT-TWIST reconstruction reduces the temporal footprint to a single 'B' region in addition to the respective central k -space (region 'A'). This is achieved by the incoherent sampling pattern of region 'B' in TWIST and application of a Compressed Sensing reconstruction approach with spatial and temporal regularization.

¹ WIP. IT-TWIST is work in progress and is not commercially available. Future availability cannot be guaranteed.

In order to assess the impact of such improved 'temporal footprints' and increased signal-to-noise ratio (SNR) of the CS reconstruction algorithm due to de-noising, we aimed at patients referred for the assessment of the thoracic aorta and the great thoracic vessels. The applied imaging protocol focused on high temporal and spatial resolution [8] (Table 1). All imaging was performed on a 64-channel MAGNETOM Skyra^{fit} system and contrast enhancement for TWIST was provided by automated injection of Gadobutrol (Gadavist, Bayer Pharma, Berlin, Germany) [8]. All acquired raw data sets were reconstructed twice: using the (1) standard product reconstruction as well as the above described (2) IT-TWIST reconstruction.

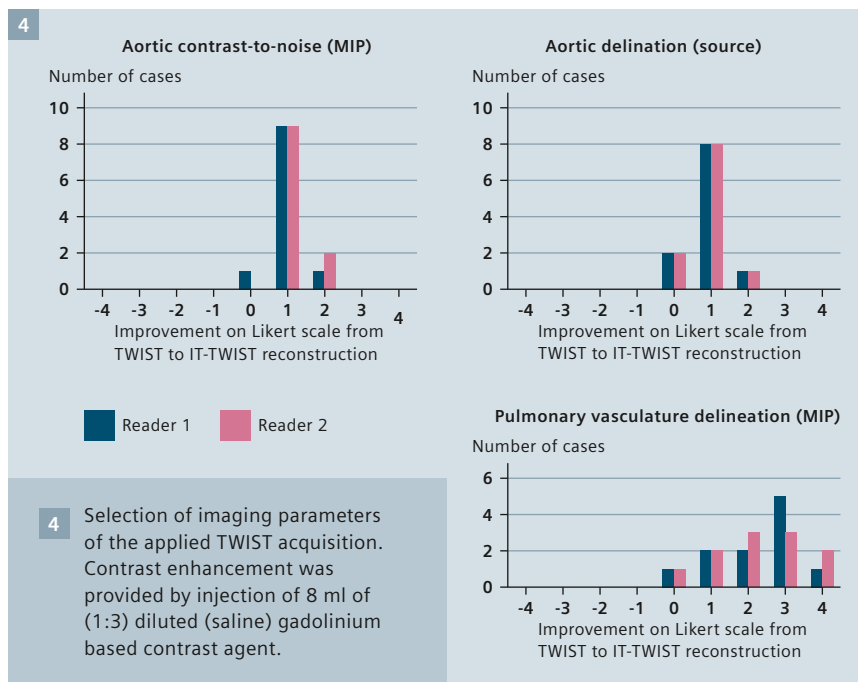
In all patients, IT-TWIST was equal or superior to TWIST reconstruction; in fact, in the vast majority of cases, image quality as assessed by two readers with respect to aortic contrast-to-noise (CNR), aortic delineation and medium-to-small vessel (pulmonary vasculature) delineation improved by at least 1 point on the Likert scale (0 = non-diagnostic; 1 = poor; 2 = fair; 3 = good; 4 = excellent) [9] (Figs. 4-6). The most prominent improvement with IT-TWIST was seen in the area of medium-to-small vessels of the pulmonary vasculature, which also demonstrated an improvement in the signal response amplitude as compared to TWIST [8] (Figs. 4-6).

Conclusion

Initial experiences of IT-TWIST in clinical thoracic imaging with dynamic CE-MRA demonstrate extremely promising results, especially when focusing on the medium-to-small sized pulmonary vasculature. The specific improvement within the pulmonary vasculature most likely relates to the substantially shortened 'temporal footprint' with IT-TWIST. This approach allows to further push temporal resolution by lowering sampling density of the peripheral *k*-space. As the principles of Compressed Sensing maintain a reasonable SNR and CNR level, a further push of spatial resolution by using higher parallel imaging

FOV	333 x 380 x 88 mm ³
Voxel size (measured)	1.2 x 1.0 x 1.2 mm ³
Voxel size (interpolated)	1.0 x 1.0 x 1.0 mm ³
iPAT	4 x 2
TR / TE / Flip angle	2.89 ms / 1.05 ms / 17°
'A' region (sampling density)	15%
'B' region (sampling density)	20%
Temporal resolution (apparent)	2.4 s

Table 1: Imaging protocol

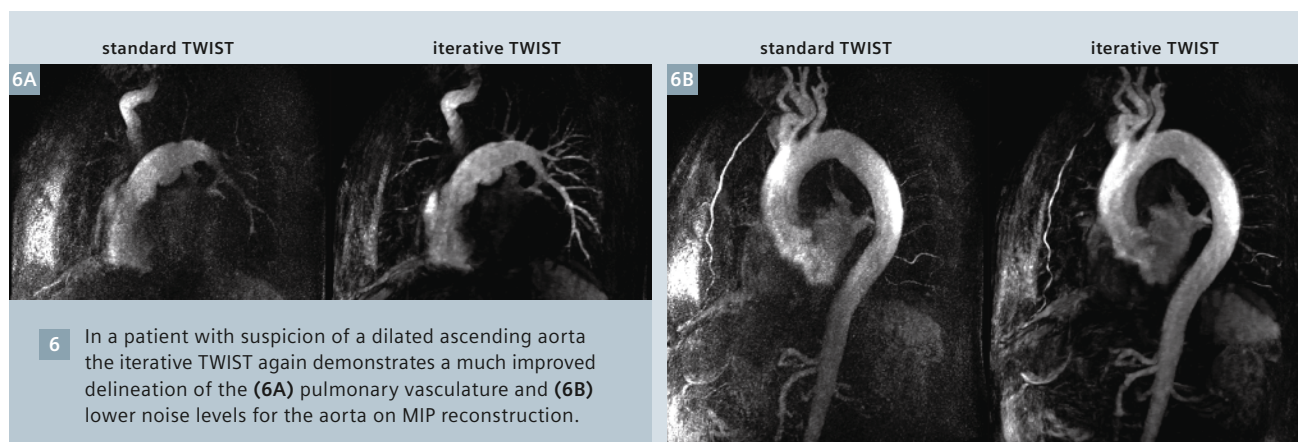
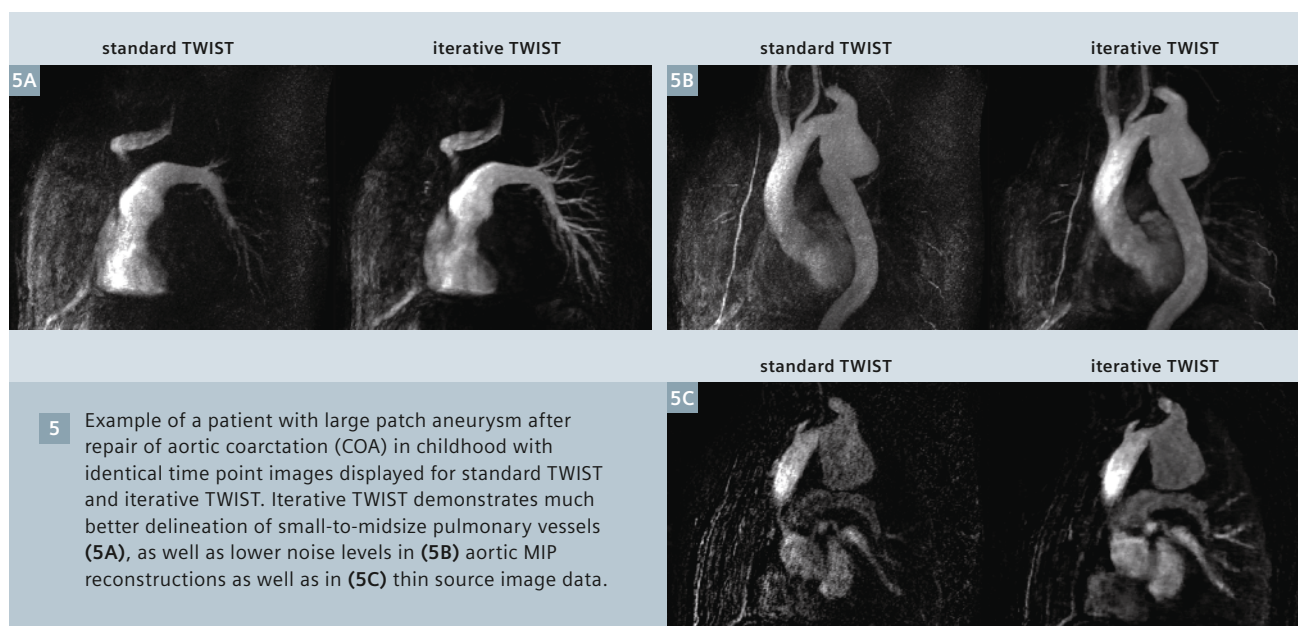


accelerations is possible. While experience in other vascular territories is currently limited at our site, further exploration will determine the possible benefit across the body vasculature and also the impact of IT-TWIST on detailed parameters of vessel boundaries and vessel size. Furthermore, it will provide insights into the possibly required adaptation of specific factors of the reconstruction based on territory, image quality need and acceleration.

Nevertheless, IT-TWIST represents an important step ahead towards high spatial/high temporal resolution dynamic CE-MRA of the future. This will provide a straightforward inject-and-shoot CE-MRA protocol without the need for any bolus timing and quite possibly also result in changes of the required contrast agent volumes.

References

- Korosec FR, Frayne R, Grist TM, Mistretta CA (1996) Time-resolved contrast-enhanced 3D MR angiography. *Magn Reson Med* 36:345-351.
- Song T, Laine AF, Chen Q, Rusinek H, Bokacheva L, Lim RP, Laub G, Kroeker R, Lee VS (2009) Optimal *k*-space sampling for dynamic contrast-enhanced MRI with an application to MR renography. *Magn Reson Med* 61:1242-1248.
- Jeong HJ, Vakil P, Sheehan JJ, Shah SJ, Cuttica M, Carr JC, Carroll TJ, Davarpanah A (2011) Time-resolved magnetic resonance angiography: evaluation of intrapulmonary circulation parameters in pulmonary arterial hypertension. *J Magn Reson Imaging* 33:225-231.
- Kinner S, Quick HH, Maderwald S, Hunold P, Barkhausen J, Vogt FM (2013) Triple-TWIST MRA: high spatial and temporal resolution MR angiography of the entire peripheral vascular system using a time-resolved 4D MRA technique. *Eur Radiol* 23:298-306.



- 5 Lohan DG, Tomasian A, Saleh RS, Singhal A, Krishnam MS, Finn JP (2009) Ultra-low-dose, time-resolved contrast-enhanced magnetic resonance angiography of the carotid arteries at 3.0 tesla. *Invest Radiol* 44:207-217.
- 6 Stalder AF, Schmidt M, Quick HH, Schlamann M, Maderwald S, Schmitt P, Wang Q, Nadar MS, Zenge MO (2015) Highly undersampled contrast-enhanced MRA with iterative reconstruction: Integration in a clinical setting. *Magn Reson Med* 74:1652-1660.
- 7 Rapacchi S, Natsuaki Y, Plotnik A, Gabriel S, Laub G, Finn JP, Hu P (2015) Reducing view-sharing using compressed sensing in time-resolved contrast-enhanced magnetic resonance angiography. *Magn Reson Med* 74:474-481.
- 8 Wetzl J, Forman C, Wintersperger BJ, D'Errico L, Schmidt M, Mailhe B, Maier A, Stalder AF (2016) High-resolution dynamic CE-MRA of the thorax enabled by iterative TWIST reconstruction. *Magn Reson Med*. 10.1002/mrm.26146.
- 9 D'Errico L, Schmidt M, Wetzl J, Forman C, Stalder AF, Wintersperger BJ (2016) Improved Dynamic Contrast-Enhanced Magnetic Resonance Angiography (CE-MRA) using Iterative Data Reconstruction. *Journal of Cardiovascular Magnetic Resonance* 18:O112.
- 10 Forman C, Piccini D, Grimm R, Hutter J, Hornegger J, Zenge MO (2015) Reduction of respiratory motion artifacts for free-breathing whole-heart coronary MRA by weighted iterative reconstruction. *Magn Reson Med* 73:1885-1895.



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