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Simultaneous Static and Cine Nonenhanced MR Angiography Using Radial Sampling and Highly Constrained Back Projection Reconstruction

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Abstract

Purpose—To describe a pulse sequence for simultaneous static and cine nonenhanced magnetic resonance angiography (NEMRA) of the peripheral arteries.

Methods—The peripheral arteries of 10 volunteers and 6 patients with peripheral arterial disease (PAD) were imaged with the proposed cine NEMRA sequence on a 1.5T system. The impact of multi-shot imaging and HYPR reconstruction was examined. The propagation rate of signal within the length of the arterial tree in the cine nonenhanced MR angiograms was quantified.

Results—The cine NEMRA sequence simultaneously provided a static MR angiogram showing vascular anatomy as well as a cine display of arterial pulse wave propagation along the entire length of the peripheral arteries. Multi-shot cine NEMRA improved temporal resolution and reduced image artifacts. HYPR reconstruction improved image quality when temporal reconstruction footprints shorter than 100 ms were used ($P < 0.001$). Pulse wave propagation within the arterial tree as displayed by cine NEMRA was slower in patients with PAD than in volunteers.

Conclusion—Simultaneous static and cine NEMRA of the peripheral arteries is feasible. Multi-shot acquisition and HYPR reconstruction can be used to improve arterial conspicuity and temporal resolution.

Keywords

angiography; time-resolved; nonenhanced; peripheral arteries; cine

INTRODUCTION

Peripheral arterial disease (PAD) is a major cause of reduced quality of life and morbidity and is associated with an increased risk of mortality (1). It is often evaluated clinically with the use of ankle brachial index and subsequent noninvasive imaging using computed tomography angiography (CTA) and contrast-enhanced magnetic resonance angiography (CEMRA). CEMRA avoids the ionizing radiation of CTA but entails the use of gadolinium-based contrast media which are associated with nephrogenic systemic fibrosis in patients with renal insufficiency (2). Due to the high prevalence of renal insufficiency in patients with PAD (3), nonenhanced magnetic resonance angiographic (NEMRA) evaluation of the peripheral arteries is helpful.

Several NEMRA techniques have been proposed for evaluating PAD, including time-of-flight MRA (4), gated subtraction (5,6), and quiescent interval single-shot (QISS) MRA (7). Time-of-flight MRA is limited by long acquisition times and poor image quality (8). Nonenhanced QISS has been proven to have high diagnostic accuracy for the morphologic depiction of PAD (9,10). However, complete characterization of PAD requires both morphologic and hemodynamic evaluation. QISS and gated subtraction methods are essentially static techniques that cannot practically be used to display the hemodynamic consequences of PAD without excessively prolonging scan times. Time-resolved CEMRA can show hemodynamic information (11,12), but is typically limited by contrast dosage limits to one station (e.g. the calves). Four dimensional phase-contrast techniques are accurate for quantifying blood flow during the cardiac cycle (13), but long acquisition times and complex post-processing preclude whole limb evaluation.

We hypothesized that a modification of the QISS MRA technique using an undersampled radial sampling trajectory can provide for simultaneous static and time-resolved NEMRA of the peripheral arteries (as a function of cardiac phase) within reasonable scan times. This method, referred to as “*cine NEMRA*” was tested in the extremities of volunteers and patients with vascular disease. The impact of multi-shot acquisition and highly constrained back projection (HYPR) reconstruction on image quality was also examined.

METHODS

Human Subjects and MR Imaging System

This study was approved by our institutional review board. After informed consent was obtained, 16 subjects (10 volunteers, 6 patients with lower extremity PAD) were imaged on a 32-channel 1.5 T MRI system (MAGNETOM Avanto, Siemens Healthcare, Erlangen, Germany). Of these subjects, 15 (10 M/5 F, age 58 ± 15 years) underwent imaging of their lower extremities and one 50-year-old male subject underwent imaging of his upper extremities; six of these subjects (6 M, age 72 ± 7 years) had a history of PAD. Lower extremities were imaged using a 24-element spine array coil, a 16-element peripheral vascular coil and a 6-element body matrix coil. Upper extremities were imaged with a 24-element spine coil, a 6-element body matrix coil and a 4-element flex coil.

Cine Nonenhanced MRA Sequence

The cine NEMRA imaging sequence used in this work is shown in Figure 1a. Similar to the conventional Cartesian QISS NEMRA technique (7), the cine NEMRA method is cardiac-gated, applies in-plane and tracking venous saturation RF pulses to suppress background and venous signal, and acquires groups of parallel slices at one or more locations of the patient table. Unlike conventional QISS imaging, however, the cine NEMRA method uses a minimum quiescent interval, a golden angle ($\approx 111.25^\circ$) radial instead of a Cartesian balanced steady-state free precession (bSSFP) imaging readout, and acquires data over the majority of the cardiac cycle. The use of a golden angle radial sampling enables reconstruction of nonenhanced angiograms of arbitrary temporal aperture and center within the cardiac cycle (14). A static nonenhanced MR angiogram is obtained by reconstructing all acquired radial views. Fat is suppressed based on phase differences between fat and water during bSSFP imaging at 1.5T (15).

Imaging parameters for cine NEMRA were as follows: TR/TE/flip of 4.1-4.5 ms/2.0-2.2 ms/90°, slice thickness of 2.3 mm (upper limbs) to 3.0 mm (lower limbs), in-plane spatial resolution of 1.0-1.3 mm, 192 (upper limbs) to 114-432 (lower limbs) slices acquired in 3-9 stations containing 48 slices each, 150-200 views acquired in each heartbeat (dependent on heart rate); the thickness of the in-plane saturation pulse was twice the imaging slice thickness. The relatively long bSSFP TR of approximately 4 ms was used to enable phase-based fat suppression. Single-shot imaging (i.e. 1 heartbeat/slice) and multi-shot implementations (2 heartbeats/slice) were tested for rapid and high-fidelity cine NEMRA, respectively. To optimally sample k-space over a limited temporal window, the azimuthal angle (α) for the i^{th} acquired radial view in the j^{th} shot of a multi-shot scan with n_j shots ($j < n_j$) and n_i views per shot ($0 \leq i < n_i$) followed the relation, $\alpha(i,j) = \text{mod}(g*[i*n_j + j], 360^\circ)$, where $g \approx 111.25^\circ$. In one volunteer, the impact of the presence and absence of the in-plane saturation RF pulse was investigated.

Image reconstruction was performed offline in MATLAB software (version 7.11; The Mathworks Inc., Natick, MA). A series of 40 temporal frames were created using a sliding window reconstruction scheme (16) and gridding reconstruction (17). Temporal frames were generated using the k-space weighted image contrast weighting scheme of Song et al. (18), hereafter referred to as the “standard reconstruction”, and HYPR reconstruction (19,20). The temporal footprint of each reconstructed frame was varied between 10% and 40% of the duration of the acquisition window in increments of 10%. Gradient timing errors were corrected in the manner of Speier and Trautwein (21); no additional corrections were performed during reconstruction. Typical offline reconstruction time for a 4-shot, 6-channel cine NEMRA scan (680 views per slice) using single-threaded scripted (i.e. non-compiled) MATLAB software was ≈ 0.86 s per reconstructed phase per slice for cine NEMRA with a temporal footprint of 68 views, and 3.38 s per slice for static NEMRA (including the calculation of the fat and water masks).

Correlative MR Imaging

In volunteers, conventional Cartesian QISS NEMRA (7,9) was performed to assess general correspondence of anatomy. In patients with PAD, contrast-enhanced MRA was performed

using a time-resolved imaging with stochastic trajectories sequence (TWIST) (12) and bolus-chase MRA after respective injections of 0.03 mmol/kg and 0.17 mmol/kg of gadobutrol (Gadavist, Bayer Healthcare Pharmaceuticals, Montville, NJ) in an antecubital vein at a rate of 3 cc/s followed by 15 cc (3 cc/s) of saline flush. Parameters for TWIST CEMRA imaging were: TR/TE/flip of 3.1 ms/1.1 ms/25°, spatial resolution 1.2 mm × 0.9 mm × 1.5 mm (phase × read × slice), GRAPPA factor of 3, reconstructed temporal resolution of 5.8 s, temporal reconstruction footprint of 23.2 s. Imaging parameters for bolus-chase CEMRA were: TR/TE/flip of 2.9 ms/1.0 ms/25°, spatial resolutions of 1.2 mm × 1.0 mm × 1.2 mm (in calf and upper extremities) and 1.4 mm × 1.3 mm × 1.4 mm (abdomen and thighs), GRAPPA factor of 2, scan times of 15.5 s - 19.6 s.

Image and Data Analysis

Quantitative analysis of the lower extremity data was performed using ImageJ software (version 1.48b; National Institutes of Health, Bethesda, MA), where the arterial course was at first defined using the static reconstructions. Subsequently, the rate at which signal propagated within the peripheral arteries in the nonenhanced cine MR angiograms was assessed by measuring arterial signal at all acquired slices and cine NEMRA frames; axial locations containing vascular occlusions were excluded from analysis. The times (in milliseconds after the ECG R wave) at which these locations first reached six fractional percentages of their maximal signal intensity in the cine NEMRA time series (50% to 100% in 10% increments) were regressed against position within the arterial tree; exemplary regressions at one fractional percentage in one volunteer and patient are shown in Figure 1b. The slopes of the six regression lines, each representing the rate of arterial signal propagation along the arterial tree (S_p), were averaged to yield one value in each limb. The average slope of the six regression lines was used because it was a more reliable indicator of arterial filling rate than the regression line slope at only one fractional value. Robust iteratively weighted least squares regression (22) was used instead of simple linear regression because of its reduced sensitivity to outliers. The impact of the temporal reconstruction footprint and reconstruction technique (i.e. standard vs. HYPR) on S_p was quantified, and differences between S_p values in limbs of patients and healthy volunteers were evaluated.

Qualitative scoring was performed to identify image quality differences between the standard and HYPR reconstructions. Time series of coronal full thickness MIP images were displayed side by side in a randomized order at a rate of 20 frames per second, and reviewed by a board certified radiologist with 6 years of experience interpreting MRA. The radiologist identified the time series that was preferred or noted if both time series were equally preferred. Data were then tabulated according to the following scale: +1, HYPR reconstruction preferred; 0, both reconstructions equally preferred; and -1, standard reconstruction preferred.

Statistical analysis of S_p data and qualitative scores were performed in SPSS (version 17.0; SPSS Inc., Chicago, IL). Probability values less than 0.05 were considered to be statistically significant.

RESULTS

Image Appearance

The presented cine NEMRA method provided a high quality static MR angiogram and cine nonenhanced MR angiograms which displayed the propagation of through plane flow in the arteries of the lower extremities (Figure 1c-e). Due to complete arterial inflow into the slice after application of the in-plane saturation RF pulse, temporal frames reconstructed late in the cardiac cycle look similar to those reconstructed at the end of systole and are not shown. There was good correlation of the resulting static nonenhanced MR angiogram with conventional Cartesian QISS NEMRA (Figure 1f). The cine angiograms displayed the temporal propagation of arterial signal from the thighs to the calves. HYPR reconstruction improved the contrast between arteries and background tissue and the definition of small branch vessels (dashed arrows in Figure 1d). The use of HYPR reconstruction reduced streak artifacts from bright subcutaneous fat associated with radial undersampling (Figure 2). The use of in-plane saturation was critical to suppress background tissue and visualize the propagation of arterial signal centrally to peripherally throughout the cardiac cycle (Figure 3).

Initial results of the cine NEMRA technique in the upper extremities are shown in Figure 4. Detailed display of arterial anatomy was observed in the static nonenhanced MR angiogram. Due to the longer acquisition time, the use of a bSSFP readout and the lack of parallel imaging acceleration, the cine NEMRA images demonstrated improved contrast-to-noise ratio compared with TWIST CEMRA. Small branch arteries of the hand and of the ulnar artery at cine NEMRA showed remarkable correlation with TWIST CEMRA. With cine NEMRA, there was early enhancement of the radial and ulnar arteries 106 ms after the ECG R-wave which indicated the presence of at least 1.15 mm of forward flow soon after the application of the in-plane saturation pulse; this was due to the thinness of the in-plane saturation pulse (4.6 mm).

Initial Experience in Patients with Peripheral Arterial Disease

Patient studies revealed that cine NEMRA can demonstrate hemodynamic alterations resulting from PAD. Figure 5a-c shows results of single-shot cine NEMRA in a patient with an occlusion of the left superficial femoral artery. The nonenhanced cine MR angiogram displayed the delayed appearance of arterial signal (i.e., onset of through plane flow) distal to the occlusion, reflecting the hemodynamic effect of the occlusion. The static reconstructed MR angiogram demonstrated excellent correspondence with CEMRA. Figure 5d-g shows the results of 4-shot cine NEMRA, TWIST CEMRA, and static Cartesian QISS NEMRA in a patient with bilateral superficial femoral arterial occlusions. Bolus-chase MRA was unsuccessful in this patient due to incorrect timing and is not shown. Correspondence as to the anatomical location of disease and temporal dynamics of arterial filling with static Cartesian QISS MRA and TWIST CEMRA was observed.

Quantitative Analysis

The results of the quantitative analyses of arterial signal propagation are shown in Table 1 and Table 2. For all examined temporal footprints, the rate of arterial signal propagation

displayed by cine NEMRA slowed (i.e. improved) with the use of HYPR reconstruction ($P < 0.05$). For both standard and HYPR reconstructions, the display of arterial signal propagation improved (i.e. S_p values increased) as the temporal footprint was reduced to 10% of the acquisition window duration; this finding, however, was only significant in the standard reconstructions ($P < 0.05$). Table 2 summarizes S_p values in patients and healthy volunteers. There was a trend for S_p values to be larger in patients with peripheral vascular disease at all temporal footprints irrespective of the reconstruction technique (standard or HYPR), with statistically significant differences ($P < 0.05$) observed in 4 of 8 subgroups.

Qualitative Analysis

Table 3 summarizes the qualitative scoring of the cine NEMRA data. Standard and HYPR reconstructed cine nonenhanced MR angiograms were equally preferred when temporal footprints greater or equal than 20% of the acquisition window duration were used. HYPR reconstructions were preferred when a short temporal footprint equal to 10% of the acquisition window duration was used.

DISCUSSION

We have demonstrated the feasibility of simultaneously acquiring static and cine NEMRA of the peripheral arteries. The method, which essentially consists of a QISS sequence using an extended golden angle radial bSSFP readout and minimum quiescent interval, provided both a static anatomic image and a cine display of arterial pulse wave propagation over the entire length of the peripheral arteries. Multi-shot imaging and HYPR reconstruction enabled the use of fine reconstructed temporal resolution while preserving image quality and improving display of arterial filling dynamics.

Previously, cine NEMRA of the lower extremities could be performed using gated subtraction techniques only by varying the onset of data acquisition relative to cardiac phase or by waiting an inversion time for labeled blood to progressively flow into the arterial anatomy of interest (23). With such methods, however, the total acquisition time is proportional to the number of desired temporal frames. Additionally, T1 relaxation and inflow constraints associated with arterial spin labeling techniques limit visualized vessel length. Compared to these approaches, the number of reconstructed temporal frames with the presented cine NEMRA sequence can theoretically be as high as the number of acquired views in the same scan time of conventional static Cartesian QISS NEMRA. Furthermore, as with conventional QISS NEMRA, arterial visualization with the presented cine NEMRA approach requires minimal inflow (on the order of a few millimeters) to refresh arterial spins after the application of the in-plane saturation pulse. Finally, the use of a golden angle radial k-space sampling trajectory allows the user to arbitrarily alter the temporal footprint and center of each reconstructed phase (14) while largely preserving spatial resolution (24).

The rate of arterial signal propagation with the cine NEMRA technique over the entire visualized vascular anatomy was objectively quantified in this work using the S_p metric which had units of time over distance. Due to the similarity in units, this metric may correlate with the inverse of the arterial pulse wave velocity. Also, although differing in time scales, it is likely that larger values of S_p during cine NEMRA generally correlate with

slower passage of the contrast bolus during time-resolved CEMRA. These suspected associations, however, remain to be tested.

One drawback of the proposed cine NEMRA method is that the high degree of radial undersampling used for generating the cine frames (as compared to the Nyquist rate) can result in streak artifacts which degrade the appearance of the cine MR angiograms. This undersampling factor is approximately 34 for a single-shot acquisition with a 352 matrix and a temporal footprint of 16 views (assuming a 10% reconstruction footprint for an acquisition containing 160 total views). Streak artifacts related to high undersampling factors, however, can be lessened with the use of multi-shot imaging (which effectively halves or quarters the undersampling factor when 2 or 4 shots are used) or HYPR reconstruction which weights the composite image by the undersampled constraining data. Future efforts will aim to incorporate a radial SENSE reconstruction (25) to reduce undersampling artifacts and ultimately facilitate single-shot imaging.

Although we compared cine NEMRA to time-resolved CEMRA, it should be noted that the two methods depend on different contrast mechanisms. Whereas time-resolved CEMRA tracks a bolus of exogenous contrast material, the cine NEMRA method tracks the arterial pulse wave. Nonetheless, the cine NEMRA technique was capable of showing differences in blood flow patterns between healthy and significantly diseased arterial segments in a small patient cohort, particularly when short temporal reconstruction footprints (equal to 10% of the acquisition window duration) were used.

CONCLUSION

We have demonstrated the feasibility of simultaneous static and cine NEMRA of the peripheral arteries. Flow abnormalities can be demonstrated by cine NEMRA that are not evident in the static NEMRA alone. Although the evaluation of flow dynamics is not nearly as quantitative as that provided by phase contrast MRI, the entire peripheral arterial tree is evaluated. This would not be practical with phase contrast MRI due to prohibitive total scan times.

For imaging of the calf region, the technique only adds a few minutes of scan time compared with standard QISS. The method supports the use of short temporal reconstruction footprints through HYPR reconstruction and multi-shot data acquisition. Future efforts will focus on further technical optimizations and clinical validation.

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Figure 1.

(a) Timing diagram of the cine NEMRA sequence; during HYPR reconstruction, the cine angiograms are used to constrain the static composite angiogram. (b) Methodology for measuring S_p (the rate of arterial signal propagation in units of ms/m) in one volunteer (left) and one patient with PAD (right). Plots show the gradual temporal propagation of flow in the healthy volunteer, and the delayed filling distal to a vascular occlusion (right). Red lines show the iteratively weighted least-squares regression lines with slopes of 117.7 ms/m (corresponding to 8.5 m/s) and 463.7 ms/m (corresponding to 2.2 m/s) in the volunteer and patient, respectively. (c-e) Representative cine and static nonenhanced MR angiograms obtained with the sequence in a 44 year old male volunteer. Standard (c) and HYPR reconstructed (d) cine NEMRA images display the propagation of through plane flow (arrows in (c)) from the thighs through the calves. Improved delineation of small branch vessels is observed with HYPR reconstruction (dashed arrows). The static nonenhanced MR angiogram (e) demonstrates good display of arterial anatomy; correlation with conventional static Cartesian QISS NEMRA (f) is observed. Imaging parameters for cine NEMRA were: 4 shots per slice, 240 slices, 72 ms temporal footprint (10% of acquisition window duration), 1.0 mm in-plane spatial resolution, 3.0 mm slice thickness, 16 min 22 sec acquisition time. Numbers indicate delay times relative to ECG R wave.

Figure 2.

Cine and static MR angiograms obtained in a 26 year old female volunteer using the cine NEMRA method. Due to the abundance of fat within the field of view and the high degree of angular undersampling, the standard cine NEMRA images (**a**) were corrupted by streak artifacts which degraded vascular delineation on the maximum intensity projection images. HYPR reconstructed cine NEMRA images (**b**) suppressed this artifact and resembled the image quality of the static MR angiogram (**c**) reconstructed from all acquired radial views. Imaging parameters were: 3 shots per slice, 240 slices, 64 ms temporal footprint (10% of acquisition window duration), 1.0 mm in-plane spatial resolution, 3.0 mm slice thickness, 12 min 4 sec acquisition time. Numbers indicate time delay after the ECG R-wave.

Figure 3.

Cine nonenhanced MR angiograms obtained without **(a)** and with **(b)** the use of in-plane saturation. The application of an in-plane saturation RF pulse before the golden angle radial bSSFP readout is essential for suppressing the appearance of background tissues such as muscle and venous blood, and displaying the temporal progression of contrast within the large conduit as well as the small branch arteries. Numbers denote delay times after the ECG R-wave. Standard (i.e. non-HYPR reconstructions) are shown. Imaging parameters are identical to those of Figure 1.

Figure 4.

Cine NEMRA in the upper extremity of a 50 year old healthy volunteer. Temporal propagation of through plane flow is seen in arteries of the forearm and hand in the cine NEMRA images (**a**); numbers indicate delay time relative to the ECG R wave. The early enhancement of the radial and ulnar arteries at 106 ms is due to the thinness of the in-plane saturation pulse and the presence of modest anterograde flow occurring early in the cardiac cycle. Time-resolved CEMRA of the same arteries using TWIST (**b**); numbers indicate delay after contrast injection. The static nonenhanced MR angiogram (**c**) provides excellent arterial contrast and is comparable to CEMRA (**d**). Imaging parameters for cine NEMRA were: 4 shots per slice, 192 slices, 72 ms temporal footprint (10% of acquisition window duration), 1.0 mm in-plane spatial resolution, 2.3 mm slice thickness, 11 min 8 sec acquisition time, HYPR reconstruction.

Figure 5.

Cine NEMRA in two patients with peripheral arterial disease. **(a)-(c)** Lower extremities of a 70 year old male with an occlusion (solid arrows) of the left superficial femoral artery (SFA). HYPR-reconstructed cine NEMRA **(a)** shows the delayed onset of through plane flow distal to the occlusion (dashed arrow) relative to the contralateral limb. The occlusion is demonstrated in the static nonenhanced MR angiogram **(b)** and at CEMRA **(c)**. Select cine NEMRA frames **(d)** in a 73 year old patient show asymmetric enhancement of the left and right limbs (arrowheads, image at 169 ms post ECG R-wave) and progressive filling of the collateral vessels in the left and right limbs (solid and open arrows) as well as distal vessels (double arrows). Static nonenhanced MR angiogram derived from all views of the cine NEMRA sequence **(f)** shows the bilateral SFA occlusions (dashed arrows) and demonstrates excellent correlation with Cartesian QISS NEMRA **(g)**. TWIST CEMRA **(e)** demonstrated similar enhancement patterns, albeit derived from a different contrast mechanism (exogenous contrast material). Parameters for cine NEMRA in the upper case were: 1 shot per slice, 144 slices, 207 ms temporal footprint (30% of acquisition window duration), 1.3 mm in-plane spatial resolution, 3.0 mm slice thickness, 2 min 8 sec scan time. Parameters in the lower case were: 4 shots per slice, 192 slices, 77 ms temporal footprint (10%), 1.0 mm in-plane spatial resolution, 3.0 mm slice thickness, 14 min 15 sec acquisition time, HYPR. Numbers indicate the delay time after the ECG R wave (cine NEMRA) or contrast injection (time-resolved CEMRA).

Table 1

Rate of Arterial Signal Propagation (Sp): Impact of Reconstruction Method

	TF = 10%	TF = 20%	TF = 30%	TF = 40%	P-value^a
Standard	86.9 ± 121.6 (11.5 m/s)	73.6 ± 91.8 (13.6 m/s)	72.7 ± 107.8 (13.8 m/s)	72.5 ± 107.2 (13.8 m/s)	0.035
HYPR	107.0 ± 114.1 (9.3 m/s)	94.5 ± 99.1 (10.6 m/s)	93.2 ± 121.8 (10.7 m/s)	96.7 ± 125.8 (10.3 m/s)	0.315
P-value^b	0.038	<0.001	0.002	0.003	

Data have units of ms/m and are given as mean ± standard deviation. Values in parentheses are group mean velocity values in meters per second.

^aRepeated measures one way analysis of variance of Sp values across TF groups.

^bPaired t-tests comparing Sp values obtained with standard and HYPR reconstruction.

TF: temporal footprint; values given as percentages of total acquisition window duration.

Table 2

Rate of Arterial Signal Propagation (Sp): Impact of Reconstruction Method and Disease

Standard	TF = 10%	TF = 20%	TF = 30%	TF = 40%	P-value^a
Volunteers	59.2 ± 28.3 (16.9 m/s)	48.1 ± 23.8 (20.8 m/s)	41.2 ± 25.1 (24.3 m/s)	40.2 ± 28.5 (24.9 m/s)	0.023
Patients	128.4 ± 186.1 (7.8 m/s)	111.9 ± 136.6 (8.9 m/s)	120.0 ± 159.9 (8.3 m/s)	121.1 ± 157.4 (8.3 m/s)	0.369
P-value^b	0.129	0.061	0.048	0.041	
HYP	TF = 10%	TF = 20%	TF = 30%	TF = 40%	P-value^a
Volunteers	71.5 ± 37.9 (14.0 m/s)	65.7 ± 26.8 (15.2 m/s)	60.5 ± 20.8 (16.5 m/s)	61.4 ± 20.0 (16.3 m/s)	0.100
Patients	160.3 ± 164.2 (6.2 m/s)	137.7 ± 146.2 (7.3 m/s)	142.2 ± 184.5 (7.0 m/s)	149.7 ± 189.7 (6.7 m/s)	0.560
P-value^b	0.034	0.049	0.071	0.058	

Data have units of ms/m and are given as mean ± standard deviation. Values in parentheses are group mean velocity values in meters per second.

^a Repeated measures one way analysis of variance of Sp values across TF groups.

^b Paired t-tests comparing Sp values in healthy volunteer and patient limbs.

TF: temporal footprint; values given as percentages of total acquisition window duration.

Table 3

Qualitative Scoring

	TF = 10%	TF = 20%	TF = 30%	TF = 40%
Score ^a	0.63 ± 0.62	0.19 ± 0.55	0.13 ± 0.50	0.19 ± 0.55
P-value ^b	<0.001	0.188	0.333	0.188

^a Scoring system: +1, HYPR reconstruction preferred; 0, neither reconstruction preferred; -1, standard reconstruction preferred.

^b One sample t-test with comparison value of zero.

TF: temporal footprint; values given as percentages of total acquisition window duration.