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ORIGINAL RESEARCH

Variability of MRI Aortic Stiffness Measurements in a Multicenter Clinical Trial Setting: Intraobserver, Interobserver, and Intracenter Variability of Pulse Wave Velocity and Aortic Strain Measurement

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Conflicts of interest are listed at the end of this article.

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Purpose: To assess intraobserver, interobserver, and scan-rescan variability of MRI aortic stiffness measurements in a multicenter trial setting.

Materials and Methods: This study was a retrospective analysis of prospectively collected data in a multicenter prospective clinical trial (clinicaltrials.gov ID NCT01870739). Forty-five adult patients (31 men; mean age, 58 years ± 12 [standard deviation]; 15 patients per center; three centers) with arterial hypertension underwent standardized 3-T baseline MRI assessments between June and September 2014. Aortic strain was calculated from maximum and minimum aortic area measurements repeated three times by three readers at three aortic levels on three retrospectively gated axial gradient-echo (GRE) data sets. Pulse wave velocity (PWV) was assessed three times by five readers as $\Delta x/\Delta t$: Δx was measured on a parasagittal GRE image of the aortic arch, and Δt was extracted from ascending and descending aortic velocity curves created on three axial phase-contrast acquisitions. Intraobserver, interobserver, and scan-rescan variability was calculated using percentage coefficient of variation (COV).

Results: Aortic strain variability was lowest at the level of the distal descending aorta (DDA) with median COVs of 1.6% for intraobserver variability, 4.0% for interobserver variability, and 10.3% for scan-rescan variability. It was highest at the ascending aorta (AA) with COVs of 3.6% for intraobserver variability, 10.7% for interobserver variability, and 19.8% for scan-rescan variability. Variability of PWV was low: 0.7% for intraobserver variability, 1.5% for interobserver variability, and 8.1% for scan-rescan variability.

Conclusion: Low variability can be achieved for aortic strain and PWV measurements in a multicenter trial setting using standardized MRI protocols. Although COV was lower when measuring aortic strain at DDA compared with AA, variability was acceptable at both anatomic locations.

Supplemental material is available for this article.

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The thoracic aorta is an elastic artery that dilates in systole and recoils in diastole, buffering pulsatile blood flow ejected from the left ventricle into a steady flow to supply organs with blood. Arterial stiffening is an age-related process characterized by reduced capability of the arteries to expand and contract in response to pressure changes (1). This process can be accelerated in the presence of cardiovascular risk factors, especially arterial hypertension (2,3). Arterial stiffening primarily involves proximal segments of the aorta that contribute the most to buffering the pulsatile flow in the arterial system (4).

Aortic stiffness can be estimated either by assessing the velocity of the pulse wave propagating through the aorta, or by aortic strain or distensibility calculated from the aortic cross-sectional area in diastole and systole (5). Aortic stiffening is considered to be a potentially reversible process (6), and it is expected that effective antihypertensive treatment may reduce it (3). Therefore, reduction of aortic stiffness is one of the end points in multicenter trials on new antihypertensive drugs. However, high reproducibility is required to differentiate a true biologic change in aortic stiffness from the overall measurement error in longitudinal studies.

MRI is one method for the evaluation of regional pulse wave velocity (PWV) and cross-sectional area–derived measures of aortic stiffness, but its methodology has not yet been standardized (7). The aim of the study was to assess intraobserver, interobserver, and scan-rescan variability of PWV and aortic strain measurement using MRI in a multicenter trial setting. The hypothesis was that variability of aortic stiffness measured with MRI was low enough to detect its changes in longitudinal studies. To the best of our knowledge, this is the first multicenter investigation that evaluated variability of MRI-derived aortic stiffness.

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Abbreviations

AA = ascending aorta, bSSFP = balanced steady-state free precession, COV = coefficient of variation, DDA = distal descending aorta, ECG = electrocardiography, GRE = gradient echo, PC = phase contrast, PDA = proximal descending aorta, PWV = pulse wave velocity, TT = transit time

Summary

With the use of standardized scanning protocols, the aortic stiffness assessed with MRI had acceptable variability and can be used for scientific assessment of vascular dynamic function.

Key Points

- Aortic stiffness can be assessed using MRI by evaluation of pulse wave velocity or by calculation of aortic cross-sectional–derived parameters, including aortic strain and distensibility.
- MRI-assessed pulse wave velocity has excellent variability and can be used in longitudinal studies for follow-up of aortic stiffness.
- Variability of aortic strain using standardized MRI protocols was within acceptable limits, and its reproducibility was optimal if measured at the distal descending aorta.

Materials and Methods

The study was conducted in compliance with the ethical principles specified in the Declaration of Helsinki. It was a retrospective analysis of prospectively collected data in a multicenter prospective clinical trial (clinicaltrials.gov ID NCT01870739) (8). Study protocol and informed consent from the main study were approved by relevant authorities and the institutional review board and ethics committees, and as a retrospective analysis of prospectively collected data, the study was performed under a waiver for the requirement for informed consent. From this randomized, multicenter prospective clinical trial, 45 patients (31 men; mean age, 58 years ± 12 [standard deviation]) were randomly selected for evaluation of PWV and aortic strain variability on the baseline MRI examination performed between June and September 2014 (15 patients per center). The number of patients was selected using an exploratory approach because variation was not known prior to the study. Patients underwent cardiovascular MRI using a 3-T scanner (MAGNETOM Verio at center 1, MAGNETOM Skyra at center 2, and MAGNETOM Prisma at center 3; Siemens Healthcare, Erlangen, Germany) with standardized imaging protocol, acquisition parameters, and three repetitions of the breath-hold sequences (Fig 1).

After localizer and axial half-Fourier acquisition single-shot turbo spin-echo images, three prospectively electrocardiographically (ECG) gated parasagittal (candy-cane) gradient-echo (GRE) images (repetition time, 363 msec; echo time, 1.4 msec; slice thickness, 6 mm; interslice gap, 0 mm) of the aortic arch were obtained for measurement of the aortic length between flow measurement sites at the ascending aorta (AA) and descending aorta (Δx). Subsequently, acquisition of two axial retrospectively ECG-gated aortic spoiled GRE cine images (repetition time, 50.8 msec; echo time, 4.2 msec; slice thickness, 6 mm; flip angle, 12°; 50 images per R-R interval; field of view, 341 × 287 mm; matrix 320 × 216; in-plane resolution, 1.07 × 1.33 mm) was repeated three times without patient repositioning: proximal at the level of the right pulmonary artery, and distal at the level of the diaphragmatic dome (Fig 2a). Acquisition of an additional set of retrospectively ECG-gated cine axial through-plane velocity-encoded phase-contrast (PC) images (repetition time, 17.6 msec; echo time, 2.3 msec; slice thickness, 6 mm; velocity encoding, 150 cm/sec; flip angle, 20°; reconstructed frames per R-R interval, 100; field of view, 341 × 234 mm; matrix, 128 × 79; in-plane resolution, 2.66 × 2.96 mm) was repeated three times at the level of the right pulmonary artery to assess transit time (TT) between the AA and descending aorta (Δt).

Cine GRE data sets for aortic strain measurement were assessed by three readers, whereas PC and prospectively gated candy-cane images for PWV measurement were analyzed by five readers. All readers were board-certified radiologists (M.H.P., A.K., S.A.S., S.K., T.H.) with at least 2 years of experience in cardiovascular MRI, all coming from center 3.

Each of three readers measured the maximum (A_{max}) and minimum (A_{min}) cross-sectional aortic area with respect to the cardiac cycle three times on each of three cine GRE data sets at three different aortic levels: AA and proximal descending aorta (PDA) on the proximal scan, and distal descending aorta (DDA) on the distal scan using a validated automated software ARTerial-FUNction (9). The contours of the aorta were semiautomatically traced for all 50 phases of the cardiac cycle (Fig 2b) by manual contouring of a rectangular region of interest around the aorta on a single image averaging all phases over the cardiac cycle. If the contour was dragged by adjacent structures or shrunk inside the lumen, segmentation was improved by identification of the center of the aorta and the vessel wall, with subsequent border detection and tracking for the cardiac cycle, as previously described (10). The lumen area variation during the cardiac cycle was graphically presented, and A_{max} and A_{min} were extracted as the maximum and the minimum of the curve (11). For each A_{max} and A_{min} measurement, aortic strain was calculated as a relative change in the aortic area:

$$\text{aortic strain}\,[\%] = \frac{A_{max} - A_{min}}{A_{min}} \times 100 \quad (12).$$

PWV Calculation

PWV was calculated using semiautomatic analysis software (Syngo.via; Siemens Healthcare, Erlangen, Germany) as Δx/Δt. Δx was measured three times by each reader on one of three candy-cane images that optimally depicted the aortic arch. Cross sections between the reference line of the PC image with the luminal center of the AA and descending aorta were marked by arrows, and the distance between the arrows was measured along the aortic centerline by manual tracing of six to 15 markers creating a curved polygonal line (Fig 3a). For Δt measurement, mean velocity curves were created three times for each of three axial PC images using semiautomatic one-click vessel segmentation of the AA and descending aorta (Fig 3b). Δt was calculated using the TT-upslope method by minimizing the area delimited by two normalized sigmoid curves fitted to the systolic upslope of the AA and descending aorta velocity curves (13).

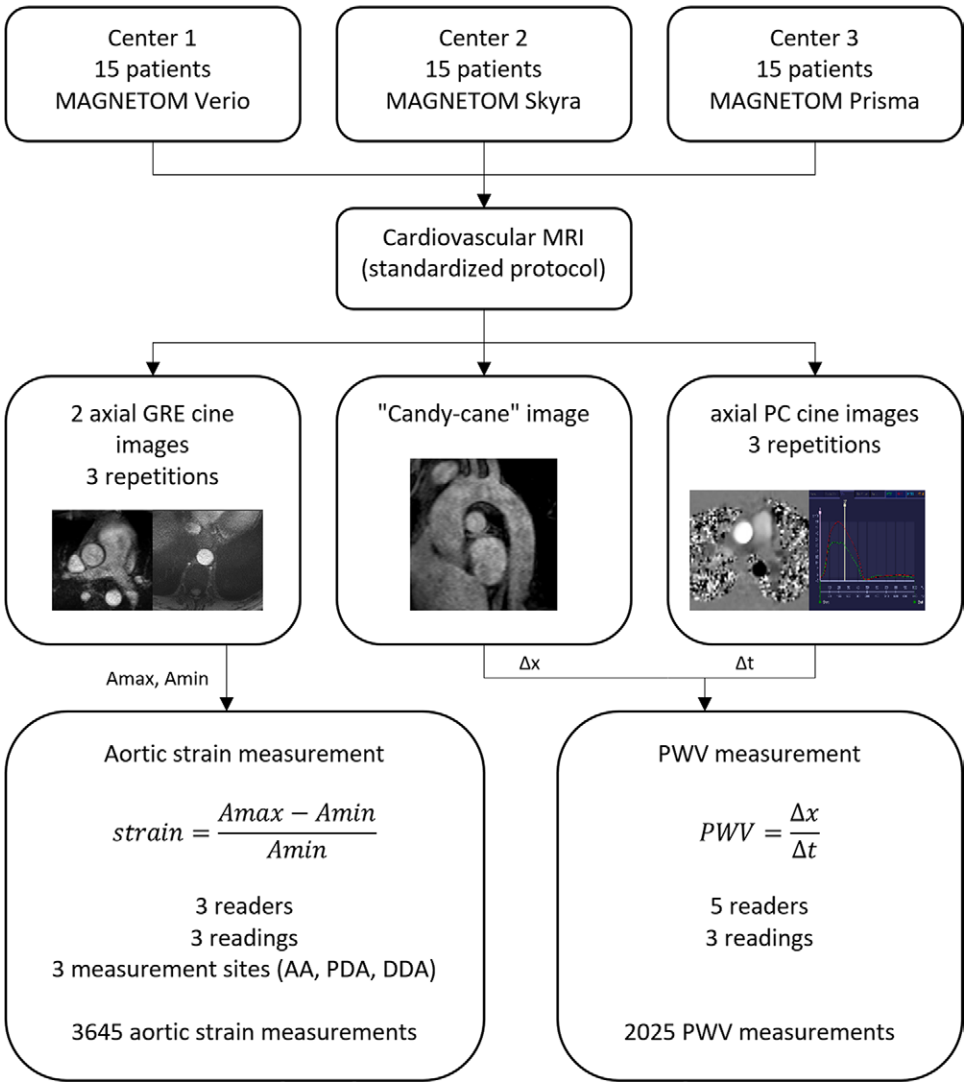


Figure 1: Flow diagram of the standardized scanning protocol used for aortic stiffness assessment. AA = ascending aorta, DDA = distal descending aorta, GRE = gradient echo, PC = phase contrast, PDA = proximal descending aorta, PWV = peak wave velocity.

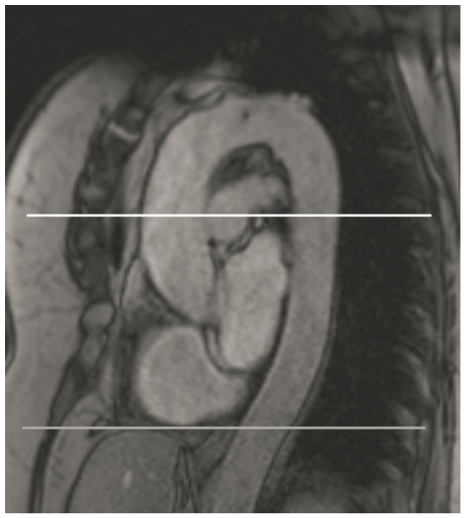
Intraobserver, interobserver, and scan-rescan variability for A_{max} and A_{min}, aortic strain, Δx, Δt, and PWV were calculated using percentage coefficient of variation (COV) (ie, the ratio of the standard deviation to the mean). A Wilcoxon signed rank test was used to compare variability of A_{max} versus A_{min}, Δx versus Δt, aortic strain versus PWV, and interobserver versus scan-rescan variability. Intraobserver COVs between the readers and scan-rescan COVs between three centers were compared using the Kruskal-Wallis H test with pairwise comparison. The Friedman test with post hoc analysis and Bonferroni adjustment for multiple testing was used to compare aortic strain variability at different aortic levels. Statistical significance was defined as $P < .05$. Statistical analysis was performed using SPSS version 22 (SPSS, Chicago, Ill).

Results

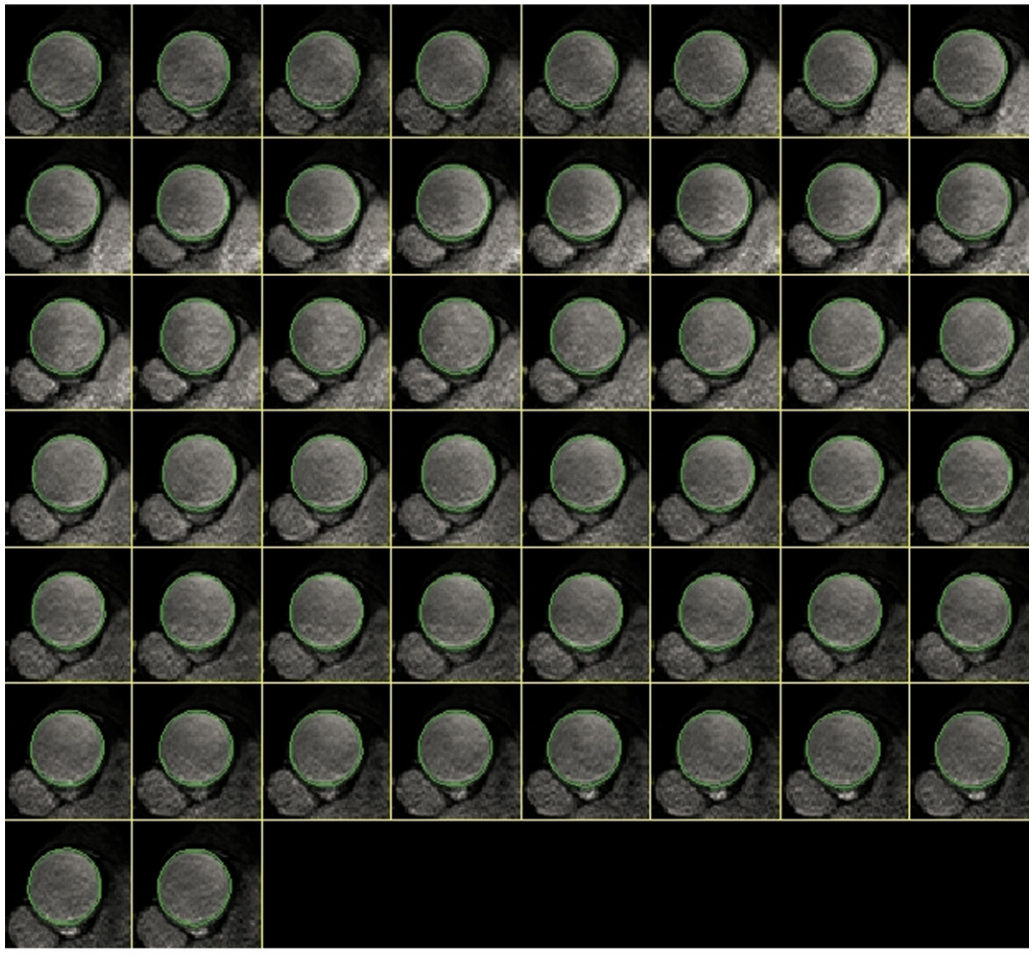
Intraobserver, interobserver, and scan-rescan variability of PWV and aortic strain measurements were assessed with MRI examinations performed in 45 adult patients (31 men; mean age, 58 years ± 12 [standard deviation]). In all patients, MRI examination results were interpretable, with A_{max}, A_{min}, and Δx measurements feasible for all patients by all readers. It was not possible to measure Δt and PWV in 22 of 2015 measurements (1.1%) because of triggering problems or the inability to fit a normalized sigmoid curve to the systolic upslope of the AA and descending aorta velocity curves. In total, 3645 aortic strain measurements (three cardiovascular imaging centers × 15 patients × three repeated scans × three aortic levels × three measurements × three readers) and 2025 PWV measurements (three cardiovascular imaging centers × 15 patients × three repeated scans × three measurements × five readers) were carried out.

Aortic Strain Variability

Variability for A_{max} and A_{min} was low with median COV of 0.3%–0.6% (intraobserver), 1.8%–3.0% (interobserver), and 1.3%–2.9% (scan-rescan) (Figure E1 [supplement]). At all aortic levels, variability for A_{min} was significantly higher than for A_{max} (all $P < .05$, Table 1). Intraobserver COVs for A_{max} and A_{min}



a.

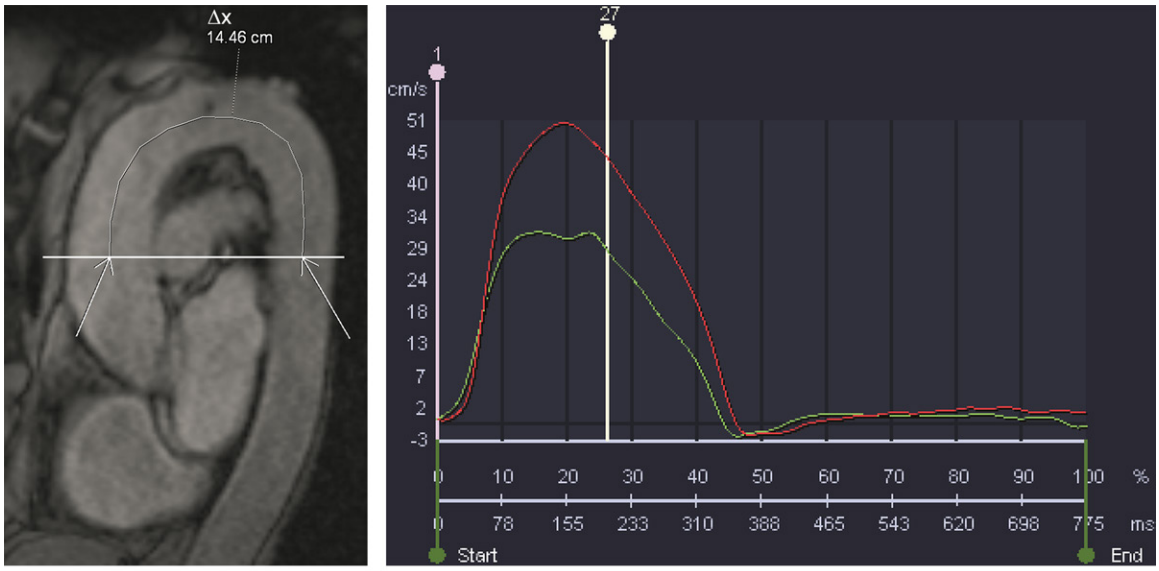


b.

Figure 2: **(a)** Parasagittal (candy-cane) gradient-echo image depicting levels of aortic strain measurement: ascending and proximal descending aorta on the axial MR image at the level of the right pulmonary artery (white line) and the distal descending aorta at the level of the diaphragm (gray line). **(b)** Aortic lumen segmentation using ARTerial-FUNction software on 50 frames throughout the cardiac cycle.

differed significantly between the readers on all aortic levels (χ^2 ranging from 83.2 to 108.3 for A_{min}, and from 89.0 to 113.6 for A_{max}, $P < .001$). Reader 1 had a higher variability for A_{max} and A_{min} at all aortic levels, whereas reader 2 had lower variability compared with other readers for A_{max} at PDA and A_{min} at PDA and DDA (Table 1). Scan-rescan variability for A_{max} did not differ between centers, except at the level of PDA where it was significantly lower in center 1 than center 2 ($\chi^2 = 6.1$, $P = .047$). Scan-rescan variability of A_{min} varied between the centers at all three levels: in center 1 it was lower at AA ($\chi^2 = 33.4$, $P < .001$) and higher at DDA ($\chi^2 = 12.4$, $P = .002$), and in center 3 it was lower at PDA than in other centers ($\chi^2 = 16.7$, $P < .001$).

Intraobserver, interobserver, and scan-rescan variability for aortic strain is presented in Table 2. Aortic strain variability



a. b.

Figure 3: **(a)** Δx measurement on the parasagittal "candy-cane" gradient-echo MR image. The white line represents the reference plane of through-plane phase-contrast images. **(b)** Ascending (green) and descending (red) aortic mean velocity curves used to fit two normalized sigmoid curves to their systolic upslope to delimit minimized area between them for Δt calculation by transit time–upslope method.

Table 1: Median Percentage Coefficients of Variation for Maximum (A_{max}) and Minimum (A_{min}) Aortic Area at Three Aortic Levels

	Ascending Aorta (%)		Proximal Descending Aorta (%)		Distal Descending Aorta (%)	
Variability	A_{max}	A_{min}	A_{max}	A_{min}	A_{max}	A_{min}
Intraobserver	0.4	0.5	0.3	0.5	0.3	0.6
Reader 1	1.1	1.8	1.1	1.5	1.1	1.4
Reader 2	0.2	0.3	0.2	0.2	0.1	0.2
Reader 3	0.2	0.3	0.3	0.5	0.3	0.7
Interobserver	2.4	3.0	1.9	2.9	1.8	2.2
Scan-rescan	1.5	1.7	1.3	1.9	1.4	2.9
Center 1	1.4	1.3	1.1	2.2	1.3	3.5
Center 2	1.6	2.2	1.6	2.1	1.6	2.7
Center 3	1.7	2.3	1.2	1.4	1.4	2.4

depended on the aortic location where it was measured, with the lowest median COV at the level of DDA (intraobserver 1.6%, interobserver 4.0%, scan-rescan 10.3%), and highest at the level of AA (intraobserver 3.6%, interobserver 10.7%, scan-rescan 19.8%) (Fig 4). Intraobserver variability for aortic strain varied between three readers (χ^2 = 61.3 at AA, χ^2 = 43.4 at PDA, and χ^2 = 47.9 at DDA, P = .001). Scan-rescan variability for aortic strain at PDA was significantly lower in center 3 (χ^2 = 19.15, P < .001), and at DDA higher in center 1 than in other centers (χ^2 = 10.92, P = .004), but it did not differ between the centers at the level of AA. Although scan-rescan variability of A_{max} and A_{min} was lower than interobserver variability at all levels except A_{min} at DDA (z score ranging –4.55 to –7.76, P < .001), scan-rescan variability of aortic strain at all levels was higher than interobserver variability (z score ranging –4.31 to –8.29, P < .001).

PWV Variability

Intraobserver, interobserver, and scan-rescan variability for Δx, Δt, and PWV measurement is presented in Table 3. Intraobserver variability of PWV was low with a median COV of 0.7% and was more influenced by intraobserver variability of Δx (median 0.6%) than of Δt that was negligible (z score = –8.21, P < .001). Intraobserver COV for Δx and PWV differed between the readers (χ^2 = 51.7 for Δx and 93.1 for PWV, P < .001), but for Δt there was no difference in intraobserver variability between the readers. Intraobserver variability for PWV was significantly lower for reader 2 and significantly higher for reader 5 compared with all other readers (P < .001).

Interobserver variability for Δx (median COV 1.5%) was significantly higher than interobserver variability for Δt (median COV 0; z score = –8.63, P < .001) and was the main component of interobserver PWV variability (median COV 1.5%). Although intraobserver and interobserver variability for Δt was approaching zero, scan-rescan COV for Δt was 8.3% (5.9%–16.6%), giving the median scan-rescan COV for PWV of 8.1%. Scan-rescan variability for Δt and PWV was larger in center 3 than in other centers (χ^2 = 51.76 for Δt and 56.50 for PWV, P < .001).

Intraobserver and interobserver variability for PWV was significantly lower than for aortic strain at all aortic levels (z score= –12.65 to –15.61 for intraobserver variability, and –13.87 to –16.25 for interobserver variability, P < .001). Scan-rescan variability of PWV was lower than scan-rescan variability of aortic strain at AA (z score = –9.96, P < .001) and PDA (–5.66, P < .001), but was not different from scan-rescan variability of aortic strain at DDA (Fig 4).

Discussion

To our knowledge, this study was the first multicenter investigation that evaluated intraobserver, interobserver, and scan-rescan variability of MRI-assessed aortic stiffness and confirmed its acceptable variability for differentiation of the biologic change from the measurement error.

Aortic strain and distensibility are measures of local aortic stiffness (14). In this study its variability was assessed at the level of AA, PDA, and DDA and depended on the site of measurement. Similar to previous results (12), it was lowest at the level of DDA most likely because of the absence of through-plane motion of the fixed descending aorta, in contrast to the AA that express through-plane and in-plane mobility throughout the cardiac cycle. Some authors recommend correction for through-plane motion of the aortic root during the cardiac contraction by different positioning of the acquisition plane for measurement of A_{min} and A_{max} (15). As in most other studies (10,11,16), we did not reposition the acquisition plane to keep the standardized imaging protocol more reproducible.

Aortic strain calculation requires accurate measurements of A_{min} and A_{max}. Similar to results from Alegret et al (17), intraobserver, interobserver, and scan-rescan variability for A_{max} and A_{min} in this study was excellent and lower than 3%. A_{min} had significantly higher intraobserver, interobserver, and scan-rescan variability than A_{max} that can be explained by more accurate automated segmentation of the aortic lumen on spoiled GRE images during high-velocity systolic blood flow with better intrinsic contrast between flowing blood and surrounding structures, compared with slow diastolic flow allowing blood to become saturated (18). Improved contrast between the blood pool and aortic wall should be expected on balanced steady-state free precession (bSSFP) pulse sequences in which inflow enhancement plays less of a role (18). Because this study was performed with 3-T MRI scanners that have higher magnetic field inhomogeneity compared with 1.5-T scanners, spoiled GRE imaging was used as a more robust technique with less-expressed dark band artifacts than on bSSFP images (19). It is possible that aortic strain measurement could be more reproducible if images were obtained with 1.5-T scanners using bSSFP sequence with better intrinsic contrast between the blood pool and aortic wall. However, interobserver variability of aortic cross-sectional area measurement in this study (1.8%–3.0%) was higher than in a previous study that validated automated aortic segmentation using the same software and modulus PC images (0.59%), probably because some observers in this study were not highly experienced in the use of the software (9). Differing levels of experience in the use of the software could also explain differences in intraobserver variability between the readers, stressing the importance of familiarity with the software for its proper use. Aortic strain was evaluated by three instead of five readers because the procedure was more time-consuming. Differences in scan-rescan variability between centers could be explained by different quality of images obtained with different MRI scanners, as well as by patient characteristics (eg, heart rate, rhythm, and body habitus) that most likely differed between centers.

Table 2: Percentage Coefficients of Variation for Aortic Strain at Three Aortic Levels

	Ascending Aorta (%)		Proximal Descending Aorta (%)		Distal Descending Aorta (%)	
Variability	Median	IQR	Median	IQR	Median	IQR
Intraobserver	3.6	1.4–15.5	3.0	1.3–6.4	1.6	0.9–4.0
Reader 1	13.4	3.3–33.7	4.3	2.3–10.7	2.4	1.2–5.4
Reader 2	2.8	1.2–8.2	1.7	0.2–4.1	1.0	0.6–1.8
Reader 3	1.9	1.1–6.8	2.9	1.5–5.7	2.3	1.3–3.7
Interobserver	10.7	4.1–32.2	7.6	3.8–15.6	4.0	2.1–11.0
Scan-rescan	19.8	14.0–34.5	15.1	8.3–22.8	10.3	6.0–17.0
Center 1	18.7	12.1–32.8	16.2	8.8–28.8	13.7	6.3–21.3
Center 2	23.5	14.1–42.6	17.2	8.3–27.6	9.4	4.7–17.0
Center 3	19.3	14.5–26.4	12.7	7.3–18.3	9.4	6.6–13.3

Note.—IQR = interquartile range.

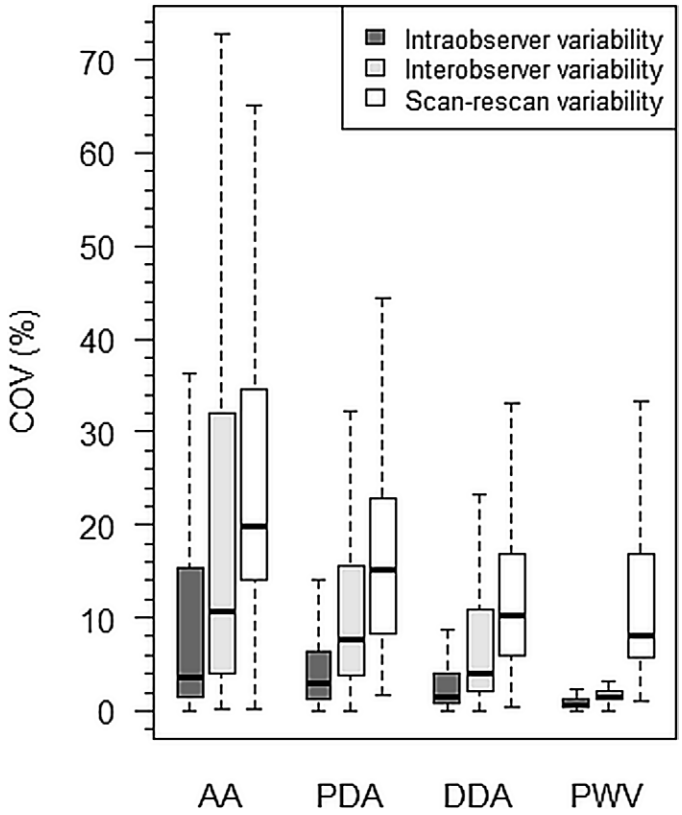


Figure 4: Tukey box plots represent intraobserver, interobserver, and scan-rescan variability for aortic strain at the level of ascending aorta (AA), proximal descending aorta (PDA), and distal descending aorta (DDA) and for pulse-wave velocity (PWV). COV = coefficient of variation.

Table 3: Percentage Coefficients of Variation for Δt, Δx, and Pulse Wave Velocity

	Δt		Δx		PWV	
Variability	Median	IQR	Median	IQR	Median	IQR
Intraobserver	0	0–0	0.6	0.4–1.1	0.7	0.4–1.2
Reader 1	0	0–0.2	0.7	0.4–1.0	0.7	0.4–1.1
Reader 2	0	0–0.2	0.4	0.2–0.5	0.5	0.3–0.8
Reader 3	0	0–0.4	0.5	0.3–0.8	0.6	0.4–1.4
Reader 4	0	0–0	0.7	0.5–1.1	0.7	0.5–1.1
Reader 5	0	0–0.4	1.2	0.6–1.9	1.2	0.6–2.00
Interobserver	0	0–0.35	1.5	1.2–1.8	1.5	1.2–2.0
Scan-rescan	8.3	5.9–16.6	NA	NA	8.1	5.8–16.8
Center 1	7.1	5.9–16.6	NA	NA	7.4	5.7–17.8
Center 2	7.4	4.9–15.3	NA	NA	7.2	4.8–15.2
Center 3	11.0	7.8–18.2	NA	NA	11.5	7.8–20.2

Note.—IQR = interquartile range, NA = not applicable, PWV = pulse wave velocity

Unlike aortic strain, MRI-assessed PWV is a measure of regional rather than of local aortic stiffness. Intraobserver and interobserver variability for PWV was very low (0.7% and 1.5%, respectively), and for Δt it was negligible, with lower values than previously described (11). Although there was no repositioning of the patient between the scans, there was relevant, but still low (8.3%), scan-rescan variability of Δt measurement that was sometimes related to difficulties in fitting of the sigmoid curve to the flow velocity waveform. Δt was calculated from flow velocity curves using the TT-upslope method that was previously found to be more sensitive to characterize aging and global aortic stiffness in older individuals compared with other methods (12). Using TT-upslope method in our study, it was not possible to determine TT in only approximately 1% of measurements.

MRI, compared with standard of reference applanation tonometry–derived carotid-femoral PWV, allows accurate measurement of the distance traveled by the pulse wave (11). We measured the aortic arch length on two-dimensional images that sometimes results in underestimation of the distance because of three-dimensional geometry of the aortic arch. In our study, the two-dimensional image of the thoracic aorta was planned using a three-point technique so that it followed the geometry and the major curves of the aortic arch, most likely giving similar values of the distance as a three-dimensional measurement. Measurement of this distance on a single double-oblique view of the thoracic aorta has also been suggested in two previously published review articles (14,20). However, by using two-dimensional measurement of the aortic arch length in this study, lower interobserver variability of Δx (1.5%) and PWV (1.5%) was observed than by three-dimensional measurement in a study by Dogui et al with COVs of 4% and 6%, respectively (13). One of the main disadvantages of MRI-assessed PWV is the relatively low temporal resolution of MRI compared with echocardiography and applanation tonometry (14). Real temporal resolution of PC sequence in our study was equal to repetition time of 17.6 msec.

Results of our study suggest that MRI could be used for longitudinal follow-up of aortic stiffness in clinical studies and could detect biologic changes in larger cohorts of patients. For example, in a previous study, a 5.3% reduction of the aortic strain for each decade of age has been shown (10). Similarly, in the multiethnic study of atherosclerosis a 5% decrease of the aortic distensibility and an 18% increase of PWV was evidenced over a 10-year period (16). Even more relevant, longitudinal changes were observed for MRI-assessed PWV in a study by Musa et al; there was an increase in PWV by 73% (from 6.38 m/sec ± 4.47 to 11.01 m/sec ± 5.75, P = .001) 6 months after surgical valve replacement that was not present in patients after transcatheter aortic valve implantation (21).

This study had a few limitations. None of our patients were scanned using different MRI scanners, but as other studies suggest, differences in MRI scanner models should not result in substantial variability (9). Furthermore, scan-rescan variability was evaluated without repositioning of the patient between the scans because this study was a substudy of a pharmaceutical study with added elements of reproducibility, and it was not practical to reposition patients between the sequences. Evaluation of scan-rescan variability without repositioning of the patient almost certainly resulted in underestimation of real scan-rescan variability. The difference between this "pure" scan-rescan variability without repositioning of the patient and "real" scan-rescan variability with repositioning still has to be tested, but in our opinion pure variability represents a significant proportion of real variability as long as the standard scanning protocol is adhered to consistently. In that case, pure scan-rescan variability could be used for power analysis to estimate the lower bound on number of patients in future studies, or for detecting target variation in studies with more complex protocols and additional sources of variation. In a previously published study that included repositioning of patients between the scans, slightly higher scan-rescan variability of PWV in the aortic arch with a COV of 13% was described (22). Another possible limitation was that the variability could be different if the commonly used bSSFP sequence is used for aortic strain measurement instead of the spoiled GRE sequence used in this study. In this study, variability of the aortic distensibility was not evaluated, but its previously reported intraobserver and interobserver variability of 1% and 2% (23) is similar to variability of aortic strain in this study. Aortic distensibility calculation requires measurement of central pulse pressure and is therefore a better indicator of the aortic stiffness than aortic strain. In our study, reproducibility of the aortic strain was tested within a single MRI examination, so we believe that there has not been relevant change of the blood and pulse pressure during the examination, and that we should measure similar scan-rescan variability if we calculated aortic distensibility instead of strain.

MRI-assessed PWV measurement with a median COV of 8.1% has excellent variability and can be used in longitudinal studies for follow-up of aortic stiffness. Variability of aortic strain using standardized protocols is lower than 20% and within acceptable limits (24), and its reproducibility is optimal if measured at DDA.

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