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Aortic Pulse Wave Velocities Using Real-Time Phase-Contrast MRI

Arun A. Joseph[a,b], Martin Fasshauser[c], Klaus-Dietmar Merboldt[a] and Jens Frahm[a,b,*]

[a]*Biomedizinische NMR Forschungs GmbH am Max-Planck-Institut für biophysikalische Chemie, Göttingen, Germany*

[b]*DZHK, German Center for Cardiovascular Research, partner site Göttingen, Germany*

[c]*Abteilung Diagnostische Radiologie, Universitätsmedizin, Göttingen, Germany*

Abstract: *Purpose:* To evaluate aortic pulse wave velocities obtained by real-time phase-contrast (PC) MRI in comparison to cine PC MRI.

Methods: Real-time PC MRI of eight healthy volunteers employed highly undersampled radial FLASH sequences and phase-sensitive image reconstructions by regularized nonlinear inversion (NLINV) at 40 ms temporal resolution and 1.3 mm in-plane resolution. Pulse wave velocities were analyzed for combinations of 2, 3 and 4 locations of aortic flow using time-to-upslope and cross-correlation methods.

Results: For the time-to-upslope analysis mean pulse wave velocities ranged from 3.5 to 3.9 m s^{-1} for real-time PC MRI and from 3.5 to 3.8 m s^{-1} for cine PC MRI. A cross-correlation analysis of the same data resulted in 2.9 to 3.3 m s^{-1} and 3.3 to 3.7 m s^{-1}, respectively.

Conclusion: Real-time PC MRI determined aortic pulse wave velocities from single cardiac cycles in close correspondence to values obtained by cine PC MRI.

Keywords: Real-time MRI, Phase-contrast MRI, Pulse wave velocity, Blood flow.

INTRODUCTION

The pulse wave velocity (PWV) describes the pulse wave of blood flow through the aorta and reflects its elastic properties [1, 2]. It is considered as a biomarker or indicator of aortic stiffness [3] which is an important sequela of diseases such as artherosclerosis [4], stroke [5], and hypertension [6]. PWV is usually calculated from the distance travelled by the pulse wave between at least two locations along the aorta divided by the time needed. This transit time may be obtained from respective flow curves using different proposed analysis methods (see below). A pressure catheter is considered as gold standard for aortic PWV determination, but is not frequently applied due to its invasive nature [7]. Alternative methods determine peripheral PWV by a variety of tools such as, for example, sphygmomanometers in order to derive aortic PWV with the use of invasively validated algorithms [8-10]. Instead of these approaches, however, the focus has shifted to the use of cine phase-contrast (PC) MRI where the acquisition extends over multiple heartbeats with synchronization to the electrocardiogram (ECG), but allows for noninvasive flow velocity measurements from arbitrary positions along the aorta [11-13]. The method determines the velocity of through-plane flow in a single averaged cardiac cycle which is retrospectively reconstructed from multiple heartbeats. It may be extended to multi-dimensional PC MRI which encodes velocity in three dimensions at the expense of prolonged measuring time [14, 15]. In fact, cine 2D PC MRI and 4D PC MRI methods under free breathing conditions have typical measuring times of about 3.5 min and at least 10 min, respectively. Therefore, real-time MRI techniques using echo-planar [16], spiral [17-20] or radial encoding strategies [21, 22] in combination with data undersampling and parallel imaging [23-25] gained increasing interest for flow assessments. However, only few studies using one-dimensional MRI techniques have attempted to analyze PWV in real time [26, 27]. This situation may now be overcome by recent advances in real-time MRI which combine highly undersampled radial fast low-angle shot (FLASH) acquisitions with image reconstructions by regularized nonlinear inversion (NLINV) [28-32]. This technique has been adapted to PC MRI to obtain flow information in real time [33-36]. The aim of this study was to evaluate the performance and potential of PWV determinations based on real-time PC MRI in comparison to conventional cine PC MRI.

METHODS

Subjects

Nine young volunteers (7 male, 2 female, mean age 26.8 ± 3.3 years) without known cardiovascular illness were

*Address correspondence to this author at the Biomedizinische NMR Forschungs GmbH am Max-Planck-Institut für biophysikalische Chemie, 37070 Göttingen, Germany; E-Mail: jfrahm@gwdg.de

1874-3471/15 2015 Bentham Open

Table 2. Mean aortic pulse wave velocities using real-time and cine phase-contrast MRI.

Acquisition	Analysis	2 Positions	3 Positions	4 Positions
Real-time	TTU	3.9 ± 0.6 3.6 ± 0.5 3.5 ± 0.5	3.9 ± 0.4	3.8 ± 0.4
	XCor	3.1 ± 0.5 3.0 ± 0.5 2.9 ± 0.5	3.3 ± 0.4	3.2 ± 0.4
Cine	TTU	3.5 ± 0.5	3.8 ± 0.6	3.7 ± 0.5
	XCor	3.3 ± 0.5	3.7 ± 0.7	3.6 ± 0.6

Values are given in m s^{-1} (mean ± SD) for 8 subjects and 10 cardiac cycles (real-time data). The real-time data for 2 positions represent 3 repetitions (compare Table **1**).

between repetitive measurements as well as breathing-induced changes between inspiration and expiration. This underlying sensitivity of real-time PC MRI to respiration is demonstrated in Fig. (**3**) for a single subject (single section) and 10 consecutive cardiac cycles. The traces represent mean velocities in the ascending and descending aorta together with the resulting PWV values as a function of time for a period covering about two respiratory cycles. Quantitative differences (i.e., maximum to minimum PWV values) are on the order of 1 m s^{-1}.

DISCUSSION

As shown in Table **1** individual real-time PWV values for our group of healthy young volunteers are highly reproducible on an individual basis and regardless of the analysis method. Beat-to-beat variations suggest a pronounced sensitivity to physiological alterations. The resulting aortic PWW values compare well with literature data which nevertheless are rather diverse and cover a broad range, also because PWV values tend to increase linearly with age even in healthy subjects [1, 2]. For example, while early cine PC MRI studies [15, 33, 39] mainly used the time-to-foot method abandoned here, a more recent cine PC MRI study [42] introduced TTU and XCor analyses and reported 5.1 to 5.3 m s^{-1} for 2D PC MRI as well as 3.8 to 4.8 m s^{-1} for 4D PC MRI and middle-aged subjects.

Here, consistent PWV values in the range from 3.5 to 3.9 m s^{-1} were obtained for both real-time and cine PC MRI in conjunction with a TTU analysis. For the XCor method, the PWV values for real-time PC MRI are up to 10% lower than for cine PC MRI. However, in the absence of a true gold standard, it seems impossible to decide about the “best” or most reliable analysis technique. Moreover, this discussion is outside the scope of the present study which emphasizes real-time vs cine PC MRI.

Previous PWV work [15] suggested the measurement of flow velocities from multiple locations along the aorta for a more accurate analysis which, for example, minimizes the putative influence of turbulent blood flow close to the aortic arch. Most remarkably, however, for any chosen acquisition and analysis technique the PWV values obtained in the present study for 2, 3 or 4 positions were very consistent and comparable. This also includes a very reproducible determination of mean PWV values from real-time PC MRI measurements of only a single slice covering the ascending and descending aorta. While such a strategy might also be preferable because the data for the two analyzed positions stem from the same cardiac cycles, its successfulness depends on the shape of the aorta and the ability to place a section for measuring through-plane flow in both locations within the acceptable limits of 10 to 15º angulation [43].

A limitation of the present and previous 2D PC MRI studies is the manual determination of aortic distances from a single sagittal plane. Although simple and performed with consensus, the approach may be prone to errors because of the complex anatomy of the aorta and variations during breathing. However, when analyzing the distance for specific breathing conditions (i.e., during breathhold after inhalation or exhalation), the differences between two locations in the ascending and descending aorta (same section) turned out to be surprisingly small (about 3%, data not shown) and unable to account for the PWV modulations during free breathing. The latter effect has to be ascribed to the lowered intrathoracic pressure during inspiration which causes increased flow velocities in the ascending aorta [35].

CONCLUSION

Aortic PWV values may be obtained for single cardiac cycles by real-time PC MRI with sufficiently high spatial and temporal resolution. Respective analyses were performed for two different analysis methods and up to 4 locations along the aorta. While mean PWV values averaged across multiple cardiac cycles were found to be reproducible and consistent for 2, 3 and 4 locations, the beat-to-beat variability of PWV values from individual cardiac cycles revealed a remarkable sensitivity to breathing with highest values during inspiration, i.e. lowest intrathoracic pressure. In future, real-time PC MRI determinations of PWV are expected to markedly reduce examination times. Moreover,

Fig. (3). Mean blood flow velocities obtained from real-time phase-contrast MRI (single subject, single section) in the ascending (Asc) and descending aorta (Dsc) as well as resulting pulse wave velocities (PWV) as a function of time for 10 cardiac cycles.

real-time PC MRI will allow for studying PWV variations in response to breathing maneuvers [27, 35, 36] or protocols of physical exercise which may aid in the diagnosis of patients with suspected aortic stiffness.

CONFLICT OF INTEREST

JF holds a patent on the NLINV reconstruction method.

ACKNOWLEDGEMENTS

We are grateful for financial support (A.A.J.) by the DZHK (German Centre for Cardiovascular Research) and BMBF (German Ministry of Education and Research).

REFERENCES

[1] Schlatmann TJ, Becker AE. Histologic changes in the normal aging aorta: implications for dissecting aortic aneurysm. Am J Cardiol 1977; 39: 13-20.

[2] Mohiaddin RH, Firmin DN, Longmore DB. Age-related changes of human aortic flow wave velocity measured noninvasively by magnetic resonance imaging. J Appl Physiol 1993; 74: 492-7.

[3] Hansen TW, Staessen JA, Torp-Pedersen C, *et al*. Prognostic value of aortic pulse wave velocity as index of arterial stiffness in the general population. Circulation 2006; 113: 664-70.

[4] Mohiaddin RH, Longmore DB. MRI studies of atherosclerotic vascular disease: structural evaluation and physiological measurements: Br Med Bull 1989; 45: 968-90.

[5] Laurent S, Katsahian S, Fassot C, *et al*. Aortic stiffness is an independent predictor of fatal stroke in essential hypertension. Stroke 2004; 34: 1203-6.

[6] Laurent S, Boutouyrie P, Asmar R, *et al*. Aortic stiffness is an independent predictor of all-cause and cardiovascular mortality in hypertensive patients. Hypertension 2001; 37: 1236-41.

[7] Latham RD, Westerhof N, Sipkema P, Rubal BJ, Reuderink P, Murgo JP. Regional wave travel and reflections along the human aorta – a study with six simultaneous micromanometric pressures. Circulation 1985; 72: 1257-69.

[8] Chen CH, Nevo E, Fetics B, *et al*. Estimation of central aortic pressure waveform by mathematical transformation of radial tonometry pressure: validation of generalized transfer function. Circulation 1997; 95: 1827-36.

[9] Wilkinson IB, Fuchs SA, Jansen IM, Murray GD, Cockcroft JR, Webb DJ. The reproducibility of pulse wave velocity and augmentation index measured by pulse wave analysis. J Hypertens 1998; 16: 2079-84.

[10] Katakami N, Osonoi T, Takahara M, *et al*. Clinical utility of brachial-ankle pulse wave velocity in the prediction of cardiovascular events in diabetic patients. Cardiovasc Diabetol 2014; 13: 128.

[11] Pelc NJ, Herfkens RJ, Shimakawa A, Enzmann DR. Phase contrast cine magnetic resonance imaging. Magn Reson Q 1991; 7: 229-54.

[12] Gatehouse PD, Keegan J, Crowe LA, *et al*. Applications of phase-contrast flow and velocity mapping in cardiovascular MRI. Eur Radiol 2005; 15: 2172-84.

[13] Pelc NJ, Sommer FG, Li KC, Brosnan TJ, Herfkens RJ, Enzmann DR. Quantitative magnetic resonance flow imaging. Magn Reson Q 1994; 32: 330-4.

[14] Markl M, Chan FP, Alley MT, *et al*. Time-resolved three-dimensional phase-contrast MRI. J Magn Reson Imaging 2003; 17: 499-506.

[15] Markl M, Wallis W, Brendecke S, Simon J, Frydrychowicz A, Harloff A. Estimation of global aortic pulse wave velocity by flow-sensitive 4D MRI. Magn Reson Med 2010; 63: 1575-82.

[16] Eichenberger AC, Schwitter J, McKinnon GC, Debatin JF, von Schulthess GK. Phase-contrast echo-planar MR imaging – real-time quantification of flow and velocity patterns in the thoracic vessels induced by Valsalva's maneuver. J Magn Reson Imaging 1995; 5: 648-55.

[17] Gatehouse PD, Firmin DN, Collins S, Longmore DB. Realtime blood flow imaging by spiral scan phase velocity mapping. Magn Reson Med 1994; 31(5): 504-12.

[18] Nayak KS, Pauly JM, Kerr AB, Hu BS, Nishimura DG. Real-time color flow MRI. Magn Reson Med 2000; 43: 251-8.

[19] Nezafat R, Kellman P, Derbyshire JA, Mcveigh E. Real-time blood flow imaging using autocalibrated spiral sensitivity encoding. Magn Reson Med 2005; 54: 1557-61.

[20] Steeden JA, Atkinson D, Taylor AM, Muthurangu V. Assessing vascular response to exercise using a combination of real-time spiral phase contrast MR and noninvasive blood pressure measurements. J Magn Reson Imaging 2010; 31: 997-1003.

[21] Thompson RB, Elliot RM. Flow-gated phase-contrast MRI using radial acquisitions. Magn Reson Med 2004; 52: 598-604.

[22] Johnson KM, Lum DP, Turski PA, Block WF, Mistretta CA, Wieben O. Improved 3D phase contrast MRI with off-resonance corrected dual echo VIPR. Magn Reson Med 2008; 60: 1329-36.

[23] Shankaranarayanan A, Simonetti OP, Laub G, Lewin JS, Duerk JL. Segmented k-space and real-time cardiac cine MR imaging with radial trajectories. Radiology 2001; 221: 827-36.

[24] Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. Magn Reson Med 1999; 42: 952-62.

[25] Griswold MA, Jakob PM, Heidemann RM, *et al*. Generalized autocalibrating partially parallel acquisitions (GRAPPA). Magn Reson Med 2002; 47: 1202-10.

[26] Bock M, Schad LR, Mueller E, Lorenz WJ. Pulsewave velocity measurement using a new real-time MR method. Magn Reson Imaging 1995; 13: 21-9.

[27] Gaddum NR, Schaeffter T, Buehrer M, *et al*. Beat to beat variation in pulse wave velocity during breathing maneuvers. Magn Reson Med 2014; 72: 202-10.

[28] Uecker M, Hohage T, Block KT, Frahm J. Image reconstruction by regularized nonlinear inversion – joint estimation of coil sensitivities and image content. Magn Reson Med 2008; 60: 674-82.

[29] Uecker M, Zhang S, Voit D, Karaus A, Merboldt KD, Frahm J. Real-time MRI at a resolution of 20 ms. NMR Biomed 2010; 23: 986-94.

[30] Zhang S, Uecker M, Voit D, Merboldt KD, Frahm J. Real-time cardiovascular magnetic resonance at high temporal resolution – radial FLASH with nonlinear inverse reconstruction. J Cardiovasc Magn Reson 2010; 12: 39-46.

[31] Voit D, Zhang S, Unterberg-Buchwald C, Sohns JM, Lotz J, Frahm J. Real-time cardiovascular magnetic resonance at 1.5 T using balanced SSFP and 40 ms resolution. J Cardiovasc Magn Reson 2013; 15: 79.

[32] Zhang S, Joseph AA, Voit D, *et al*. Real-time MRI of cardiac function and flow – recent progress. Quant Imaging Med Surg 2014; 4: 313-29.

[33] Joseph AA, Merboldt KD, Voit D, *et al*. Real-time phase-contrast MRI of cardiovascular blood flow using undersampled radial fast low-angle shot and nonlinear inverse reconstruction. NMR Biomed 2012; 25: 917-24.

[34] Joseph AA, Kowallick JT, Merboldt KD, *et al*. Real-time flow MRI of the aorta at a resolution of 40 ms. J Magn Reson Imaging 2014; 40: 206-13.

[35] Fasshauer M, Joseph AA, Kowallick JT, *et al*. Real-time phase-contrast flow MRI of hemodynamic changes in the ascending aorta and superior vena cava during Mueller maneuver. Clin Radiol 2014; 69: 1066-71.

[36] Kowallick JT, Joseph AA, Unterberg-Buchwald C, *et al*. Real-time phase-contrast flow MRI of the ascending aorta and superior vena cava as a function of intrathoracic pressure (Valsalva manoeuvre). Br J Radiol 2014; 87(1042): 10.1259/bjr.20140401.

[37] Frahm J, Schaetz S, Untenberger M, *et al*. On the temporal fidelity of nonlinear inverse reconstructions for real-time MRI – The motion challenge. Open Med Imaging J 2014; 8: 1-7.

[38] Schaetz S, Uecker M. A multi-GPU programming library for real-time applications. In: Xiang Y, Stojmenovic I, Apduhan B, Wang G, Nakano K, Zomaya A, Eds. Algorithms and Architectures for Parallel Processing; Lecture Notes in Computer Science. Springer: Berlin Heidelberg 2012; 7439: pp. 114-128.

[39] Vulliemoz S, Stergiopulos N, Meuli R. Estimation of local aortic elastic properties with MRI. Magn Reson Med 2002; 47: 649-54.

[40] Fielden SW, Fornwalt BK, Jerosch-Herold M, Eisner RL, Stillman AE, Oshinski JN. A new method for the determination of aortic pulse wave velocity using cross-correlation on 2D PCMR velocity data. J Magn Reson Imaging 2008; 27: 1382-7.

[41] Grotenhuis HB, Westenberg JJM, Steendijk P, *et al*. Validation and reproducibility of aortic pulse wave velocity as assessed with velocity-encoded MRI. J Magn Reson Imaging 2009; 30: 521-6.

[42] Wentland AL, Wieben O, Francois CJ, *et al*. Aortic pulse wave velocity measurements with undersampled 4D flow-sensitive MRI – comparison with 2D and algorithm determination. J Magn Reson Imaging 2013; 37: 853-9.

[43] Lotz J, Meier C, Leppert A, Galanski M. Cardiovascular flow measurement with phase-contrast MR imaging – Basic facts and implementation. Radiographics 2002, 22: 651–71.

Received: January 23, 2015 Revised: April 17, 2015 Accepted: April 20, 2015

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