

VELOCITY MAPPING

Measurement of Left Ventricular Velocities: Phase Contrast MRI Velocity Mapping Versus Tissue-Doppler-Ultrasound in Healthy Volunteers

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ABSTRACT

The aim of this study was the comparison of phase contrast magnetic resonance imaging (PCMRI) measurements of left ventricular velocities in a physiological in vivo setting with tissue-Doppler-ultrasound (tissue Doppler imaging: TDI) data in healthy volunteers. Images were acquired in short axis view using a flow compensated black blood k-space segmented gradient echo sequence. Velocity encoding was performed by adding a bipolar gradient after each rf-pulse to the otherwise identical pulse sequences. Full in-plane velocity information of the moving heart was obtained in 16 heartbeats within one breath-hold measurement. Twenty-nine healthy volunteers (mean age=25 years) were examined with both imaging modalities. Both PCMRI and TDI demonstrate a biphasic profile of radial velocities over the cardiac cycle. Intraindividual comparison of left ventricular velocity data acquired using PCMRI and TDI show a very good correspondence with r-values of 0.97. The in vivo study in 29 healthy volunteers demonstrates a high validity of time-resolved phase contrast measurements for the analysis of left ventricular myocardial velocities.

Key Words: Cardiac MRI; Phase contrast; Tissue Doppler imaging; Heart.

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INTRODUCTION

Magnetic resonance imaging (MRI) offers the possibility to study and quantify left ventricular function using techniques such as spatial tagging or velocity encoding by phase contrast methods. In tagging, the displacement of saturation grid points over the cardiac cycle is primarily used to calculate stress and strain rates but can also be used to calculate left ventricular velocities (McVeigh, 1996).

Magnetic resonance phase contrast (PCMRI) methods are based on the sensitivity of the phase of the MR signal to motion. The change of the phase of the MR signal is proportional to the velocity of tissue motion and can be used to measure tissue velocities directly. Therefore, phase contrast velocity mapping has recently gained increasing importance for the analysis of intravascular flow and left ventricular performance (Arai et al., 1999; Bryant et al., 1984; Drangova et al., 1998; Firmin et al., 1987; Hennig et al., 1998; Kaiser et al., 2000; Markl et al., 1999, 2002; McVeigh, 1996; Pelc et al., 1991, 1995; Schneider et al., 2001; Wedeen, 1992). Previously, PCMRI measurements of myocardial velocities were validated using a phantom with a predefined velocity profile (Arai et al., 1999; Drangova et al., 1998; Hennig et al., 1998). Due to the complexity of left ventricular motion, however, we studied whether PCMRI is also able to provide valid velocity data for in vivo settings in the case of complex three-dimensional (3D) left ventricular motion. In order to validate our PCMRI velocity data, we chose to compare our data with velocity data provided by TDI. A major advantage of MR measurements is the

ability to see the entire heart without restrictions of interference from bone or lung as encountered in ultrasound.

METHODS

All magnetic resonance phase contrast (PCMRI) measurements were performed on a 1.5 T scanner (Sonata, Siemens, Erlangen, Germany) using a high-power gradient system (40 mT/m, 0.2 ms rise time). Images (slice thickness=8 mm, 300×400 mm rectangular field of view (FOV), matrix 80×256) were acquired in short-axis view using a four-segment phased-array body coil. The pulse sequence used for data acquisition was a black blood k-space segmented gradient echo sequence (TR=6.2 ms, TE=4.6 ms, $\alpha=15^\circ$) with first-order flow compensation in read and phase direction for suppression of motion artifacts. Velocity encoding was performed by adding a bipolar gradient ($v_{enc}=20$ cm/s) after each rf-pulse to the otherwise identical pulse sequences.

Sequence design and the use of high-power gradients permitted reference scans and motion-sensitized scans to be performed consecutively, and thus multiphase images providing full in-plane velocity information of the moving heart were obtained within one breath-hold period over 16 heartbeats (Markl et al., 2002). View sharing was used to accelerate the temporal resolution of data acquisition from 99 ms to 62 ms. It was shown that velocity-induced phase shifts in PCMRI are mainly encoded in the central sections of k-space, which makes view sharing very suitable for velocity mapping (Markl and Hennig, 2001). A

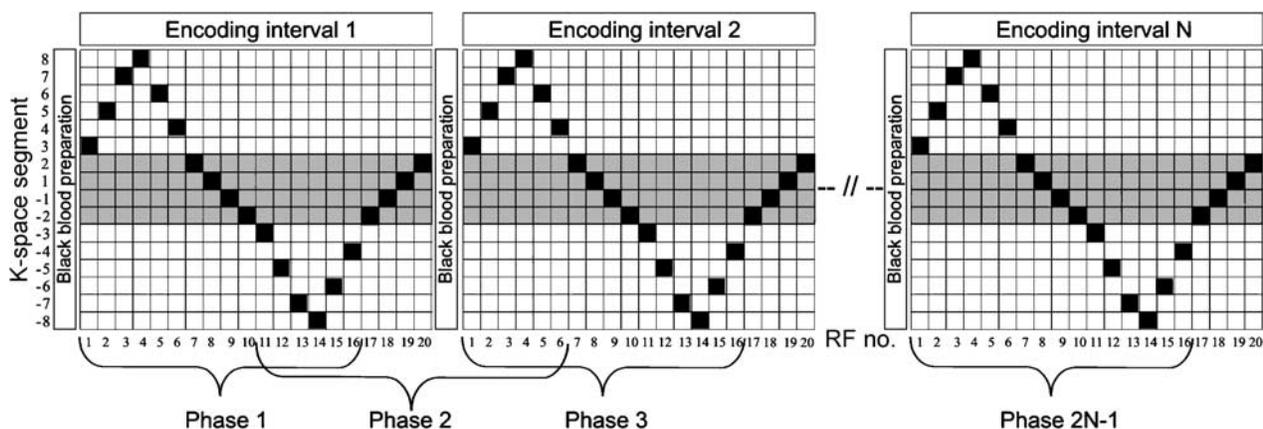


Figure 1. Schematic representation of the k-space segmentation with view sharing. The black squares depict the k-space segment as a function of the RF excitation. With the acquisition on N encoding intervals (with a double acquisition of the central k-space, gray area) $2N-1$ cardiac phases are reconstructed. The k-space parts for the image reconstruction are shown by the block arrows.

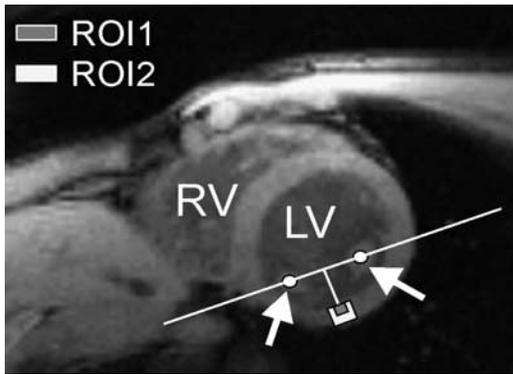


Figure 2. Position of the regions of interest (ROIs) at the posterior wall of the left ventricle just below the AV valve (ROI 1=5 × 5 mm, ROI 2=10 × 10 mm). The arrows indicate the papillary muscles, which had to be identified and marked by every observer during postprocessing.

schematic representation of the k-space segmentation is shown in Fig. 1. Twenty-five percent of the central k-space is acquired twice to provide a reasonable value of the maximum of shared echo lines without adulterating the velocity information (Markl and Hennig, 2001). The acquisition of more than one view per cine time frame per cardiac cycle in a segmental manner results in low-pass filtering of the measured velocities. Thus, the acquisition strategy is based on an interleaved segmented view ordering in which the phase-encoding steps acquired within a single cine time frame are evenly distributed over k-space (Fig. 1). This results in reduced low-pass filtering effects, since the data for the central part of k-space (or any other k-space region) for

each cine time frame are always sampled at a consistent time point within each cardiac cycle.

Semiautomatic analysis of left ventricular velocities was performed on an external workstation (Sun Sparc 20, Sun Microsystems, Mountain View, CA) with a custom-made software package based on Matlab (The Mathworks Inc., Natick, MA). In order to remove bulk motion from the velocity field, a correction based on subtraction of global translation velocities from the local velocity components was performed (Hennig et al., 1998). The calculation of radial velocities was based on an internal polar coordinate system with the center of gravity of the left ventricle as midpoint. For statistical calculations, Microcal Origin (Microcal Software Inc., Northampton, MA, USA) was used.

Echocardiographic examinations were performed with a current standard ultrasound machine (Toshiba Power Vision 6000) with a 2.5 to 3.5 MHz ultrasound transducer according to the guidelines of the American Society of Echocardiography. Digital data (Quant modus, Toshiba) of regional myocardial velocity profiles were acquired in cine loops of color and pulse-wave Doppler format at the posterior wall of the left ventricle as described for the PCMRI examination. Before calculating the regional time velocity curve with a temporal resolution of 40 ms, postprocessing with a new off-line workstation (Toshiba, UIWS 300) was performed to eliminate cardiac through-plane and rotational motion mathematically. The regions of interest were manually positioned in each frame at the inner part of the posterior myocardial wall close to the endocardium.

For both PCMRI and TDI we defined a region of interest (ROI) at the posterior wall of the left

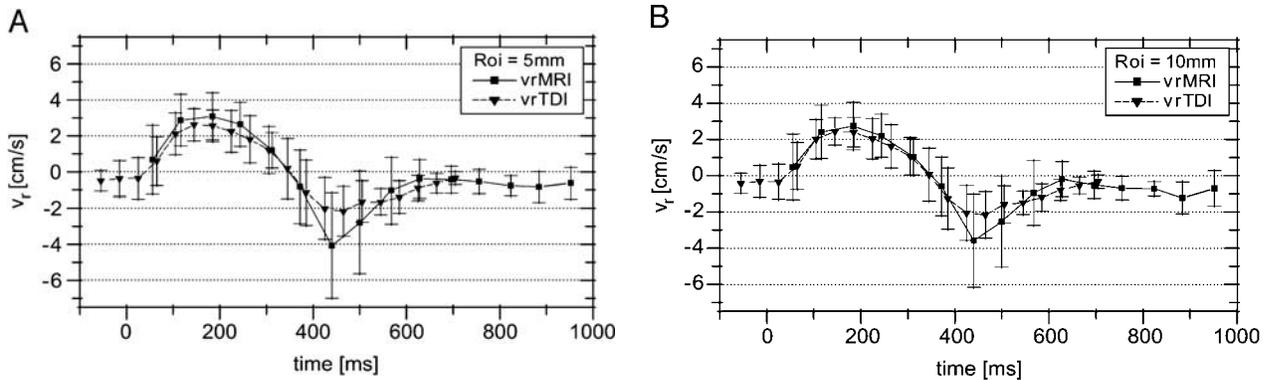


Figure 3. (A) Time courses of averaged radial velocities over the cardiac cycle for the 5 mm ROI for TDI (triangles) and PCMRI (rectangles). The standard deviations represent the interindividual standard deviations of the measured velocities. (B) Time course of radial velocities over the cardiac cycle for the 10 mm ROI.

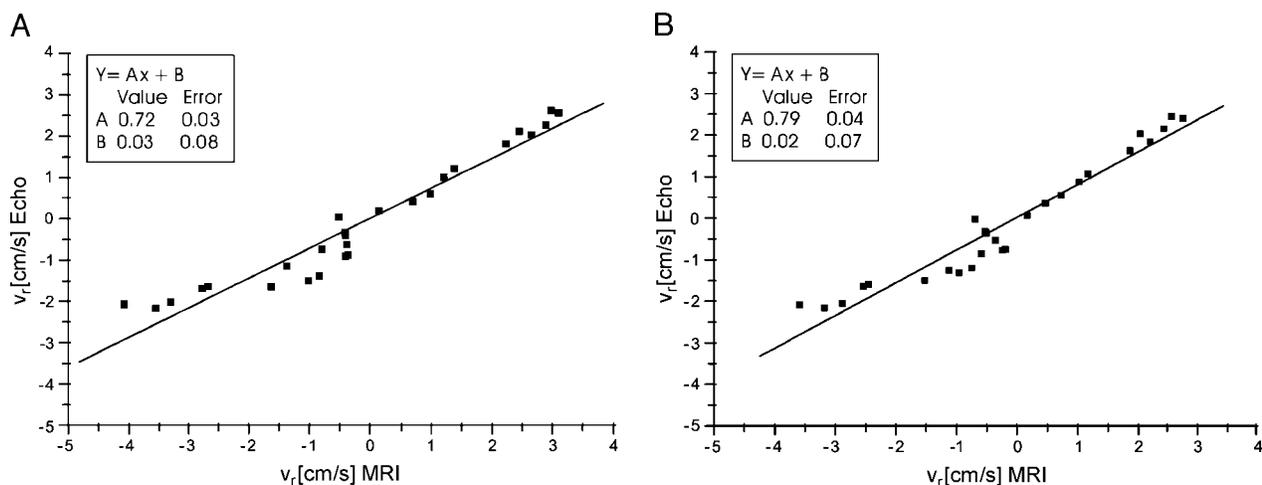


Figure 4. (A) Linear regression analysis of radial velocities (5-mm ROI) measured by tissue Doppler echocardiography (Echo) and phase contrast MRI (MRI). Correlation coefficient $r=0.97$. (B) Linear regression analysis of radial velocities (10-mm ROI) measured by tissue Doppler echocardiography (Echo) and phase contrast MRI (MRI). Correlation coefficient $r=0.97$.

ventricle directly below the level of the mitral valve with respect to the position of the papillary muscles (Fig. 2). The ROIs were always positioned at the inner part of the myocardium close to the endocardium. The only observer interaction required for PCMRI post-processing was the identification of the papillary muscles. The ROIs were positioned at the intersection of the endocardial border with the bisector of the side

of the line connecting the two papillary muscles (Fig. 2).

Twenty-nine healthy volunteers with a mean age of 25 years were examined with both imaging modalities within one week. Approval of the local ethics committee was obtained in advance. The evaluation of both PCMRI and Doppler-ultrasound data was performed in a blind test by three independent readers.

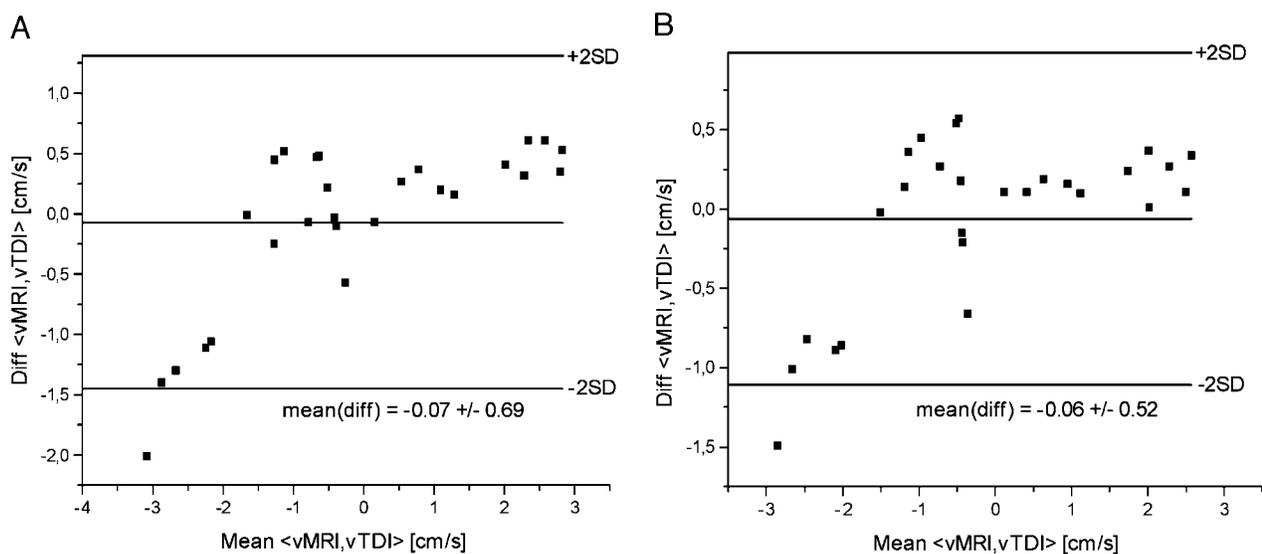


Figure 5. (A) Bland-Altman agreement of the velocity values plotted in Fig. 4A. (B) Bland-Altman agreement of the velocity values plotted in Fig. 4B.

Table 1. Intra- and interobserver variabilities for phase contrast MRI (PCMRI) and tissue Doppler ultrasound (TDI) in cm/s.

	PCMRI		TDI	
	Mean	std	Mean	std
<i>Intraobserver variability (cm/s)</i>				
obs 1	0.23	0.21	0.04	0.07
obs 2	0.11	0.16	0.03	0.04
obs 3	0.11	0.18	0.04	0.08
<i>Interobserver variability (cm/s)</i>				
3 obs	0.16	0.23	0.09	0.10

RESULTS

Figure 2 displays the average radial velocities \pm SD of all healthy volunteers for both PCMRI and TDI over the cardiac cycle (Fig. 3A=5 mm ROI, Fig. 3B=10 mm ROI). Positive velocity values indicate contraction, negative values indicate relaxation of the left ventricular myocardium. The measured radial velocities demonstrate a biphasic behavior for both techniques and demonstrate consistent temporal evolution over the cardiac cycle with higher standard deviations for MRI especially in early diastole. Additionally, MRI measurement provides higher velocities in early diastole for both the 5 mm ROI and the 10 mm ROI. Figures 4A and 4B shows the correlation of velocity data measured by TDI and PCMRI with a correlation coefficient (R) of 0.97 for both the 5 mm ROI and the 10 mm ROI. Figures 5A and 5B show a Bland-Altman agreement of the velocity values plotted in Figs. 4A and 4B, respectively. Intra- and interobserver variabilities for both MRI and Doppler-ultrasound are listed in Table 1. Since in PCMRI postprocessing is automated, the variabilities given below reflect the differences in the identification of the papillary muscles (see Fig. 2).

DISCUSSION

In previous applications, left ventricular velocity measurements using PCMRI were validated using a rotating and oscillating phantom with a predefined velocity profile (Arai et al., 1999; Drangova et al., 1998; Hennig et al., 1998). Left ventricular motion, however, is a complex 3D process including contraction and relaxation as well as rotation around the z-axis (long axis) of the heart and also movement perpendicular to the z-axis of the heart. In our study, we examined if PCMRI provides reliable data in the in

vivo setting. We compared PCMRI data with results obtained by another in vivo method: tissue Doppler ultrasound. In order to provide a high degree of comparability, we defined a distinct region of interest (ROI) at the posterior wall of the left ventricle for both PCMRI and TDI.

In contrast to earlier validation studies, which relied on different types of phantom measurements, we could demonstrate that PCMRI provides valid velocity data also in the in vivo setting of complex 3D left-ventricular movement. Comparison with tissue Doppler ultrasound showed an excellent correlation of left-ventricular velocity data for the biphasic character of the velocity profile over the cardiac cycle (Fig. 3) as well as for the magnitude of left ventricular velocities with a correlation coefficient of 0.97 (Fig. 4).

Comparison of data sets shows two major differences between PCMRI and TDI: First, intraobserver variabilities and interobserver variabilities are higher for PCMRI (Table 1). This finding might reflect the fact that no filter or smoothing algorithm was used in the postprocessing of the PCMRI data and, as a result, variations in the spatial location of the ROIs may result in stronger changes in the velocity time curves if compared to TDI.

Second, PCMRI yields higher velocities in early diastole compared to systole for both the 5-mm and the 10-mm ROI. TDI, in contrast, shows slightly higher velocities in systole than in diastole (Fig. 3). However, marked differences between systolic and early diastolic velocities with higher velocities in early diastole are also known from open chest tissue Doppler studies in pigs and dogs (Derumeaux et al., 1998, 2000). Arai et al. (1999) performed PCMRI in healthy dogs and analyzed phase contrast data in strict mechanical terms as the strain rate. Corresponding with our PCMRI results, radial strain rates were higher in early diastole than in systole.

Early diastolic (Fig. 3) velocities measured by PCMRI are markedly higher than the velocities measured using TDI. The Bland-Altman agreement (Fig. 5) shows relatively high standard deviations of the difference between the PCMRI and the TDI velocities due to the higher values of MR data in the diastolic velocities. This finding applies for both the 5-mm and the 10-mm ROI but is more pronounced in the subendocardial region (5-mm ROI). However, the interindividual variability with respect to diastolic velocities has to be taken into account since for both the 10-mm ROI and the 5-mm ROI the standard deviations of PCMRI measurements were highest in early diastole. Higher standard deviations might be caused by changes of heart rate during long breath-hold

periods, which primarily affect the duration of diastole while leaving the extent of systole mostly unchanged. In systole, PCMRI provides slightly higher velocities, especially in the subendocardial region (5-mm ROI). This finding is remarkable with respect to the lower temporal resolution of the PCMRI approach (62-ms PCMRI vs. 40-ms TDI), since lower temporal resolutions tends to result in an underestimation of velocities (low pass filter effect).

There is a small shift visible in Figs. 3A and 3B between the curves of TDI and PCMRI measurements. While the cardiac cycle in MR measurements started with the detection of the R-wave, it started somewhat earlier in TDI measurements.

As mentioned above, the intramyocardial velocities are quite complex and translational effects are more than simple bulk translation and are not accounted for the 2D in-plane acquisition. Thus, a 3D PCMRI measurement would be the most accurate. While not available for a strict comparison with Doppler, a 3D PCMRI measurement may provide substantially more accurate and robust assessment of cardiac function.

In summary, our in vivo study of 29 healthy volunteers demonstrates a high validity of time-resolved phase contrast MRI for the analysis of left ventricular myocardial velocities. Comparison of left ventricular velocity data acquired using PCMRI and TDI show a very good correspondence with r-values of 0.97 in healthy volunteers. These findings apply for a precisely defined region of interest (ROI) at the posterior wall of the left ventricle just below the AV valve. It is thus not obvious if this high degree of correlation between PCMRI and TDI also applies for the rest of the left ventricle. Moreover, further studies with patients are required in order to find out if this high degree of correlation can also be demonstrated in pathological patterns of left ventricular motion.

REFERENCES

- Arai, A. E., Gaither, C. C., Epstein, F. H., Balaban, R. S., Wolff, S. D. (1999). Myocardial velocity gradient imaging by phase contrast MRI with application to regional function in myocardial ischemia. *Magn. Reson. Med.* 42:98–109.
- Bryant, D. J., Payne, J. A., Firmin, D. N., Longmore, D. B. (1984). Measurement of flow with NMR imaging using a gradient pulse and phase difference technique. *J. Comput. Assist. Tomogr.* 8(4): 588–593.
- Derumeaux, G., Ovize, M., Loufoua, J., Andre-Fouet, X., Minaire, Y., Cribier, A., Letac, B. (1998). Doppler tissue imaging quantitates regional wall motion during myocardial ischemia and reperfusion. *Circulation* 97:1970–1977.
- Derumeaux, G., Ovize, M., Loufoua, J., Pontier, G., Andre-Fouet, X., Cribier, A. (2000). Assessment of nonuniformity of transmural myocardial velocities by color-coded tissue Doppler imaging. *Circulation* 10:1390–1395.
- Drangova, M., Zhu, Y., Bowman, B., Pelc, N. J. (1998). In vitro verification of myocardial motion tracking from phase-contrast velocity data. *Magn. Reson. Imaging* 16(8):863–870.
- Firmin, D. N., Nayler, G. L., Klipstein, R. H., Underwood, S. R., Rees, R. S., Longmore, D. B. (1987). In vivo validation of MR velocity imaging. *J. Comput. Assist. Tomogr.* 11(5):751–756.
- Hennig, J., Schneider, B., Peschl, S., Markl, M., Krause, T., Laubenberger, J. (1998). Analysis of myocardial motion based on velocity measurements with a black blood prepared segmented gradient-echo sequence: methodology and applications to normal volunteers and patients. *J. Magn. Reson. Imaging* 8:868–877.
- Kaiser, H. W., van der Geest, R. J., van der Wall, E. E., Duchateau, C., de Roos, A. (2000). Right ventricular function in patients after acute myocardial infarction assessed with phase contrast MR velocity mapping encoded in three directions. *J. Magn. Reson. Imaging* 11(5):471–475.
- Markl, M., Hennig, J. (2001). Phase contrast MRI with improved temporal resolution by view sharing: k-space related velocity mapping properties. *Magn. Reson. Imaging* 19(5):669–676.
- Markl, M., Schneider, B., Hennig, J., Peschl, S., Winterer, J., Krause, T., Laubenberger, J. (1999). Cardiac phase contrast gradient echo MRI: measurement of myocardial wall motion in healthy volunteers and patients. *Int. J. Card. Imaging* 15(6):441–452.
- Markl, M., Schneider, B., Hennig, J. (2002). Fast phase contrast cardiac magnetic resonance imaging: improved assessment and analysis of left ventricular wall motion. *J. Magn. Reson. Imaging* 15(6): 642–653.
- McVeigh, E. R. (1996). MRI of myocardial function: motion tracking techniques. *Magn. Reson. Imaging* 14:137–150.
- Pelc, N. J., Herfkens, R. J., Shimakawa, A., Enzmann, D. R. (1991). Phase contrast cine magnetic resonance imaging. *Magn. Reson. Q.* 7(4):229–254.

- Pelc, N. J., Drangova, M., Pelc, L. R., Zhu, Y., Noll, D. C., Bowman, B. S., Herfkens, R. J. (1995). Tracking of cyclic motion with phase-contrast cine MR velocity data. *J. Magn. Reson. Imaging* 5:339–345.
- Schneider, B., Markl, M., Geiges, C., Winterer, J. T., Hennig, J., Langer, M. (2001). Cardiac phase contrast gradient echo MRI: characterization of abnormal ventricular wall motion in patients with ischaemic heart disease. *JCAT* 25(4):550–557.
- Wedeen, V. J. (1992). Magnetic resonance imaging of myocardial kinematics. Technique to detect, localize, and quantify the strain rates of the active human myocardium. *Magn. Reson. Med.* 27(1): 52–67.

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