European Journal of Radiology 81 (2012) 2203–2207

Contents lists available at ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Flow and peak velocity measurements in patients with aortic valve stenosis using phase contrast MR accelerated with k-t BLAST

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ARTICLE INFO

Article history:
Received 15 March 2011
Accepted 7 June 2011

Keywords:
Aortic valve
Stenosis
k-t BLAST
SENSE
Phase contrast imaging

ABSTRACT

Objective: To investigate the accuracy of velocity measurements in patients with aortic valve stenosis using phase contrast (PC) imaging accelerated with SENSE (Sensitivity Encoding) and k-t BLAST (Broad-use Linear Acquisition Speed-up Technique).
Methods: Accelerated quantitative breath hold PC measurements, using SENSE and k-t BLAST, were performed in twelve patients whose aortic valve stenosis had been initially diagnosed using echocardiography. Stroke volume (SV) and peak velocity measurements were performed on each subject in three adjacent slices using both accelerating methods.
Results: The peak velocities measured with PC MRI using SENSE were $-8.0 \pm 9.5\%$ lower ($p < 0.01$) compared to the peak velocities measured with k-t BLAST and the correlation was $r = 0.83$. The stroke volumes when using SENSE were slightly higher 0.4 ± 17.1 ml compared to the SV obtained using k-t BLAST but the difference was not significant ($p > 0.05$).
Conclusions: In this study higher peak velocities were measured in patients with aortic stenosis when combining k-t BLAST with PC MRI compared to PC MRI using SENSE. A probable explanation of this difference is the higher temporal resolution achieved in the k-t BLAST measurement. There was, however, no significant difference between calculated SV based on PC MRI using SENSE and k-t BLAST, respectively.

1. Introduction

Different parameters are of interest when determining the severity of aortic valve diseases. Two of these are the peak velocity and stroke volume (SV). From the peak velocity the pressure difference over the aortic valve can be calculated using the simplified Bernoulli equation [1] and from the stroke volume curve the regurgitant fraction can be determined [2]. These sources of information are clinically important since the pressure difference over the valve reflects a degree of resistance experienced by the heart when pumping blood to the ascending aorta while the regurgitant fraction is needful for assessing the degree of valve insufficiency.

Patients suffering from aortic valve stenosis are usually followed up on a regular basis using echocardiography to examine how the severity of the aortic valve stenosis advances. In some cases, for example when a limited acoustic window restricts the echocardiographic examination, magnetic resonance imaging (MRI) is used as an alternative for the assessment of the aortic valve stenosis. The MRI examination includes flow measurements using phase contrast (PC) [3] from which the regurgitant fraction and peak velocity can be calculated.

The peak velocity in a blood flow jet is localized downstream from the constriction. It is recommended that velocity measurements are performed at several adjacent slice locations downstream from the orifice of the constriction when using MRI in order to ensure that the peak velocity is found [4]. A velocity measurement in one image plane is usually acquired during a breath hold. When searching for the peak velocity in multiple image planes this implies, therefore, a repeated number of breath holds for the patient.

The introduction of parallel imaging [5,6] made it feasible to perform PC measurements within reasonable breath hold times. Quantitative flow measurements in combination with Sensitivity Encoding (SENSE) have shown good accuracy [7,8] and can now be considered as standard in routine clinical cardiac MR.

The fast acquisition technique termed Broad-use Linear Acquisition Speed-up Technique (k-t BLAST) enables velocity measurements in multiple slices during one breath-hold [9]. It has been demonstrated that whole-heart 3D cine imaging is feasible within

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doi:10.1016/j.ejrad.2011.06.034

Table 1
Some basic characteristics of the patients included in the study.

	Mean (±SD)	Range
Age (years)	68 ± 11	41–80
Peak stenotic jet velocity (cm/s) (measured with echocardiography)	375 ± 44	320–460
Aortic valve orifice[a] (cm^2)	1.0 ± 0.3	0.7–1.6

[a] The aortic valve orifice was determined by using echocardiography and the continuity equation.

one breath-hold using k-t BLAST while a comparable conventional acquisition is performed using multislice, multibreathhold acquisitions [10]. Another advantage using k-t BLAST is the avoidance of potential misregistrations that might occur in multiple slices acquired during separate breath holds [11]. These favourable features of k-t BLAST are also feasible to exploit in quantitative PC MRI.

Several studies have validated accelerated PC MRI in combination with k-t BLAST [12–15]. These studies have shown that accurate flow measurements can be obtained at very high acceleration factors. The validations of PC using k-t BLAST have, however, mainly been conducted in the aorta in healthy subjects.

The purpose of this study was to compare measured stroke volumes and peak velocities using SENSE and k-t BLAST accelerated PC MRI in patients with aortic valve stenosis.

2. Materials and methods

2.1. Subjects

Twelve patients (7 females and 5 males) with aortic valve stenosis were included in this study. The patients, who are all on regular follow-up echocardiography examinations of their aortic valve stenosis, were examined with MR immediately after the echocardiography. In Table 1, some basic characteristics are listed of the patients included in the study. All patients gave their written informed consent. The local ethical committee approved this study.

2.2. MRI examination

Phase contrast MR imaging was performed in a 1.5 T Achieva system (Philips Medical Systems, Best, The Netherlands) using a five channel SENSE cardiac coil. The velocimetry measurements using PC MRI consisted of two different breath-hold acquisitions. The first acquisition was a retrospectively triggered PC acquisition using SENSE and the second was a prospectively triggered acquisition accelerated using k-t BLAST. The first alternative (SENSE) has been evaluated [7,8] thoroughly and can be considered as standard in clinical practise. The parameters of the SENSE and the k-t BLAST acquisitions were set to give equal breath-holds of 13 s and the same spatial resolution. The protocol of the PC pulse sequence had the following parameters common for both SENSE and k-t BLAST; shortest TR (∼5.3 ms) and TE (∼3.2 ms), slice thickness 6 mm, pixel size 2.5 mm × 2.5 mm, flip angle 12°. The number of heart phases was 24 in the k-t BLAST measurement and 25 for the SENSE acquisition. Each method was accelerated by a factor of 8 (k-t BLAST) and 3 (SENSE), respectively. The heart phase interval was not identical between k-t BLAST and SENSE since the k-t BLAST acquisition was prospectively gated and the SENSE acquisition was retrospectively gated. In order to obtain as long interval as possible in the k-t BLAST acquisition the gate delay was set to the shortest time and the gate width to longest.

The level of velocity encoding (VENC) was adjusted for each patient to ensure there was no aliasing in the velocity measurements. The same VENC was used in the SENSE and k-t BLAST PC acquisitions using k-t BLAST. Three slices in the aortic valve plane were planned based on three different planes; (i) a coronal view of the left ventricle, the aortic root and the ascending aorta, (ii) the left ventricular outflow tract (LVOT/3-chamber view) and (iii) a basal short axis view at the level of the aortic valve. The coronal view of the left ventricle (i) was obtained from a survey stack of images obtained using a balanced turbo field echo (b-TFE) pulse sequence. The other two images that served as plane (ii) and (iii) were acquired from conventional breath-hold ECG-triggered b-TFE pulse sequences with the following typical parameters; shortest TR (∼3.5 ms) and TE (∼1.7 ms), slice thickness 8 mm, pixel size 1.2 mm × 1.2 mm, flip angle 60°, 30 reconstructed heart phases and the SENSE reduction factor set to 3.

In the k-t BLAST measurements two separate breath-holds were needed in order to acquire all data. During the first breath-hold reference data was sampled and during the second breath-hold remaining data was acquired to give the final images, both durations with a breath-hold of 13 s. For the k-t BLAST acquisitions the information was acquired from all three slices during the same breath-hold. One breath-hold of 13 s in the SENSE measurement resulted in one complete velocity acquisition of one slice. This was then repeated three times to encompass the three planned slices.

In this study the "plug-in" approach, using 11 training profiles, was used in the reconstruction of the undersampled k-t BLAST acquisition in order to improve the accuracy in the velocity measurements [14].

2.3. MR image analysis

Stroke volumes and peak velocities were measured in each slice for both the SENSE and k-t BLAST acquisition alternatives. Since measurements were performed in patients with aortic valve stenosis nonlinear phase/velocity relations due to dephasing effects could be expected in poststenotic areas [16]. These dephasing effects coincide with regions of signal void in the magnitude images. Concurrent visualization of magnitude and velocity (phase) images was used to decide whether a velocity measurement should be classified as a dephased velocity measurement and thereby excluded or included as an actual velocity, see Fig. 1. The peak velocity was, for each patient, determined as the highest measured velocity including all three imaging planes and all time frames.

The boarders of the aortic valve were manually delineated in all slices and time frames in order to enable as accurate subsequent stroke volume measurements as possible. Since the prospectively gated k-t BLAST sequence did not cover a complete RR interval the comparison of the calculated stroke volumes has to be taken into consideration. The calculated stroke volumes when using k-t BLAST ($SV_{ktBLAST}$) were compared to two different stroke volumes, which were both calculated from the SENSE acquisition. The first stroke volume encompassed velocity images from the whole RR interval ($SV_{SENSEwRR}$) while the second stroke volume covered a partial RR interval ($SV_{SENSEpRR}$) that was equivalent to the acquisition window used for the k-t BLAST acquisition. This subdivision into a whole and partial RR interval is illustrated in Fig. 2 where representative flow curves from SENSE and k-t BLAST acquisitions are shown for the same patient and slice location.

2.4. Statistical analysis

All data is presented as mean ± SD. A paired two-sided *t*-test was used to exam whether there was any significant difference in the measurements obtained from the different methods, $p < 0.05$ was considered to be statistically significant. The agreement of the data was, according to the Bland-Altman analysis, expressed as the mean difference $\bar{d}$ with the limits of agreement defined as $\pm 2\,s_{\text{diff}}$, where s_{diff} is the standard deviation of the differences. The mean