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Hansen, Kristoffer Lindskov; Møller-Sørensen, Hasse; Kjaergaard, Jesper; Nguyen, Tin Quoc; Jensen, Jørgen Arendt; Nielsen, Michael Bachmann

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Flow changes after biological and mechanical aortic valve implantation measured with VFI

Kristoffer Lindskov Hansen
Dept. of Diagnostic Radiology
University Hospital of Copenhagen
Copenhagen, Denmark
lindskov@gmail.com

Hasse Möller-Sørensen
Dept. of Cardiothoracic Anesthesiology
University Hospital of Copenhagen
Copenhagen, Denmark
hassedk@gmail.com

Jesper Kjaergaard
Dept. of Cardiology
University Hospital of Copenhagen
Copenhagen, Denmark
jesper.kjaergaard@dadlnet.dk

Tin-Quoc Nguyen
Dept. of Diagnostic Radiology
University Hospital of Copenhagen
Copenhagen, Denmark
tinnguyen@gmail.com

Jørgen Arendt Jensen
Center for Fast Ultrasound
Technical University of Denmark
Kgs. Lyngby, Denmark
jaj@elektro.dtu.dk

Michael Bachmann Nielsen
Dept. of Diagnostic Radiology
University Hospital of Copenhagen
Copenhagen, Denmark
mbn@dadlnet.dk

Abstract—Aortic valve stenosis increases peak systolic velocity (PSV) and flow complexity in the ascending aorta, and is treated with either biological or mechanical implants. Vector flow imaging (VFI) is an angle independent ultrasound method for flow assessment. In contrast to conventional ultrasound, VFI can quantify complex flow patterns, e.g. the flow complexity called vector concentration (VC) in long axis and the secondary rotation (SR) in short axis view. Study aim was to evaluate flow changes only visible with VFI before and after valve implantation in patients with aortic valve stenosis. VFI on a commercial scanner (Pro Focus 2202 UltraView, BK Medical) with a linear transducer (8670, BK Medical) was applied intraoperatively on the ascending aorta. Four patients scheduled for biological valve implants and 4 patients for mechanical valve implants were scanned before and after surgery. Four patients with normal aortic valve were scanned for comparison. VFI data of the ascending aorta were obtained in long and short axis view during the systolic phase for assessment of VC and SR. VC ranges from 0 to 1 (complex to laminar flow), and SR is measured in Hz. PSV was obtained with conventional spectral Doppler. Before surgery, patients with aortic valve stenosis scheduled for mechanical (PSV: 356.3 (64.3) cm/s; SR: 15.3 (7.8) Hz; VC: 0.18 (0.03)) and biological implants (PSV: 350.0 (80.8) cm/s; SR: 17.9 (2.6) Hz; VC: 0.26 (0.07)) had more complex flow with higher velocities compared with patients with normal aortic valve (PSV: 124.8 (16.7) cm/s; SR: 2.9 (1.1) Hz; VC: 0.83 (0.09)). After surgery, velocities were lower for mechanical (PSV: 214.5 (47.5) cm/s; SR: 5.6 (3.0) Hz) compared with biological implants (PSV: 241.5 (39.1) cm/s; SR: 13.2 (1.8) Hz). However, VC was higher for biological (0.68 (0.05)) compared with mechanical implants (0.56 (0.09)) indicating a more laminar and less complex flow despite higher systolic velocities in patients treated with biological implants. The mechanical valve has a larger opening with cusps attached centrally in the lumen opposed to the biological valve, which may explain the differences found. Normal flow was neither found for biological nor mechanical implants. VFI can provide new parameters for flow evaluation and be useful for aortic flow assessment before and after valve implantation and in the development of mechanical valves.

Keywords—ultrasound; vector flow imaging; ascending aorta; aortic valve stenosis; aortic valve implantation

I. INTRODUCTION

One of the most common valvular heart diseases is stenosis of the aortic valve. Aortic valve stenosis is a degenerative process with a prevalence of 4.6% in persons older than 75 [1]. The only effective treatment for aortic valve stenosis is implantation of a valvular prosthesis, which can be surgically or percutaneously done, while medical treatment only is used to alleviate symptoms temporarily [2].

Two main strategies are used for the valvular replacement; that is implantation of a mechanical (MP) or a biological (BP) prosthesis. The two types of implants have different benefits and limitations. While the BP made of either bovine or porcine pericardium degenerates over time with an expected lifespan of 15 years, the degeneration of MP is almost non-existent [3]. The main risk of the MP is thrombosis, as thrombogenicity of the materials used in the mechanical valve can activate the clotting pathways. Therefore, patients with implanted MP require lifelong anticoagulation therapy to avoid blood clot formation, but have with the necessary treatment, also an increased risk of spontaneous bleeding. Biological valves are not thrombogenic, and therefore, patients with implanted BP do not require anticoagulation therapy [3].

The risk and benefits of MP and BP have formed the European and American guidelines for valvular heart disease [4]. It is recommended to use MP in patients younger than 60 years of age, though other parameters such as life expectancy, bleeding risk, and comorbidities are also used to decide the final strategy.

Mechanical valves have different designs, but the most commonly used is bileaflet with the cusps centrally attached. The biological valves have an anatomically realistic trileaflet design (Fig. 1). Flow patterns through the two different prostheses are expected to be different.

Conventional imaging of aortic valve stenosis and valvular prostheses is echocardiography [4]. However, with the angle-independent Vector Flow Imaging (VFI) ultrasound method, new imaging possibilities are introduced, e.g. the

quantification of flow complexity called vector concentration (VC), and of secondary rotation (SR). Previous intraoperative VFI studies of aortic valve stenosis have indicated that insight in to the fluid dynamics of the ascending aorta can be gained with this new ultrasound tool [5-7].

The aim of this study was to quantify the blood flow of the ascending aorta with VFI in terms of VC and SR in patients with aortic valve stenosis treated with MP and BP, and compared with patients with normal aortic valves. Intraoperative recordings were obtained before and after valve implantation. Flow measurements obtained with VFI were compared with peak systolic velocity (PSV) obtained with conventional spectral Doppler ultrasound.

Fig. 1. The two main types of valvular prostheses. A shows a biological prosthesis with a trileaflet design resembling a normal aortic valve, while B shows a bileaflet mechanical prosthesis with the cusps attached centrally.

II. MATERIALS AND METHODS

A. Patients

Four patients with aortic valve stenosis scheduled for implantation of BP (mean: 69.5 years old (y.o.)), 4 patients with aortic valve stenosis scheduled for implantation of MP (mean: 62.8 y.o.), and 4 patients with normal aortic valve scheduled for coronary by-pass (57.3 y.o.) were enrolled into the study after written and informed consent. Patients with aortic valve stenosis were scanned before and after valve implantation. The study was approved by the local ethics committee (no. H-2-2012-039).

B. Vector Flow Imaging

The VFI method based on the Transverse Oscillation technique estimates both the axial and transverse velocity component by using emissions of standard pulses for conventional Doppler ultrasound. The motion in the axial direction is found as in conventional Doppler ultrasound, while the motion in the transverse direction is found by using a changed apodization function in the receive beamforming along with a special estimator [8]. Previous papers provide detailed explanations of the method [8-10].

A conventional ultrasound scanner (ProFocus 2202 UltraView, BK Medical, Herlev, Denmark) and a linear transducer (8670, BK Medical, Herlev, Denmark) were used under sterile settings to record epiaortic scan sequences in long and short axis view. The angle-independent vector velocities were displayed in real-time on the B-mode image as colored pixels given by a 2-D color bar defining both direction and velocity magnitude. Small arrows superimposed on to the color flow map were added to

facilitate flow interpretation. The temporal resolution of the VFI estimation was 16 frames/s, and the maximum scan depth was approximately 5 cm due to the transducer setup available. For each scan session, the color box was adjusted to cover the lumen, and the pulse repetition frequency, the depth setting, the gain, and the wall filtering were adjusted for vector velocity estimation. Each scan sequence corresponded to 15 s of recording.

From vector velocities, the flow complexity was assessed in long axis view during systole as an average over 4 heart cycles. The parameter VC calculates the angle spread over a region of interest (ROI) spanning the lumen of the ascending aorta downstream of the valve. VC corresponds to the distribution of vector angles found in the ROI to a certain time point, and approaches one for perfectly laminar flow decreasing towards zero for chaotic flow.

The rotation of the secondary flow was assessed from a ROI encompassing the lumen of the ascending aorta downstream of the valve in short axis view. SR was obtained during systole and calculated as an average over 4 heart cycles. The vortex formation was identified by inspecting the vector map with overlaid streamlines. Within a grid adjusted to encompass the vortical flow, SR was calculated from the recorded vector velocities. SR gives the rotational frequency in Hz, i.e. rotations per second, with the sign indicating the rotational direction, i.e. a negative sign corresponding to a clockwise rotation (Fig. 2).

VC and SR have been used in previous papers for assessment of the aortic flow, where also the calculations behind the VFI parameters are described in details [5-7].

Fig. 2. Short axis view of blood flow in the ascending aorta during systole of a patient with aortic valve stenosis before surgery. A shows the VFI image, where velocity and direction of the flow are shown with the color display and the overlaid vector arrows. B shows the corresponding streamline map after calculation of the counter-clockwise secondary vortical flow.

C. Conventional Doppler Ultrasound

A Philips iE33 scanner equipped with a Philips X7-2t transducer (Philips Healthcare, Eindhoven, The Netherlands) using continuous wave ultrasound was used for transesophageal echocardiography. The scan parameters were adjusted for flow imaging, and the scan sequences were obtained through the aortic valve aperture in the deep transgastric long axis view with the line of interrogation placed along the left ventricular outlet tract and the ascending aorta. PSV was reported for each patient as an average of three

Fig. 3. The systolic flow in the ascending aorta in three patients with normal aortic valve, biological and mechanical implants visualized with VFI in long axis view. The illustration indicates that the flow complexity is higher for the mechanical than the biological implant as the color blend is more pronounced in the patient with an implanted mechanical valve, and that both implants produce more complex flow than the normal aortic valve.

heart cycles and obtained just prior to each VFI examination. For patients with aortic valve stenosis, the PSV was measured twice, both before and after aortic valve replacement.

D. Statistics

The obtained measurements were treated with descriptive statistics, and comparisons were done with one-way ANOVA using turkey post Hoc test for three group analyses and independent t-test for two group analyses. Significance level was set to 0.05, and statistical analyses were performed with IBM SPSS Statistics v. 22 (SPSS Inc., Chicago, IL, USA).

III. RESULTS

Descriptive statistics on obtained data with VFI and spectral Doppler ultrasound are given in Table 1 with standard deviation in parentheses. The direction of the SR was counter-clockwise for all patients with normal aortic valves (4/4) and for 75% (6/8) of the patients with aortic valve stenosis before implantation. After implantation, 2 patients treated with MP changed direction to clockwise, resulting in 75% (3/4) of the patients with MP presenting clockwise rotations, while 75% (3/4) of the patients with BP presented counter-clockwise rotations as before treatment.

TABLE I. DESCRIPTIVE STATISTICS

	Before implantation of prosthesis			After implantation of prosthesis		
	PSV [cm/s]	VC	SR [Hz]	PSV [cm/s]	VC	SR [Hz]
Normal valve	124.8 (16.7)	0.83 (0.09)	2.9 (1.1)	N/A	N/A	N/A
Biological valve	350.0 (80.8)	0.26 (0.07)	17.9 (2.6)	241.5 (39.1)	0.68 (0.05)	13.2 (1.8)
Mechanical valve	356.3 (64.3)	0.18 (0.03)	15.3 (7.8)	214.5 (47.5)	0.56 (0.09)	5.6 (3.0)

Patients with aortic valve stenosis, whether scheduled for BP or MP, differed significantly from patients with normal aortic valve for both PSV (BP and MP: $p < 0.001$), VC (BP and MP: $p < 0.0001$) and SR (BP: $p < 0.004$; MP: $p < 0.013$). PSV, VC and SR were not different between the two patient groups with aortic valve stenosis before valve replacement (PSV: $p = 0.99$; VC: $p = 0.26$; SR: $p = 0.74$). After aortic valve implantation, VC ($p < 0.05$) and SR ($p < 0.005$) differed significantly between patients implanted with BP and MP, but not PSV ($p = 0.41$) as indicated in Fig. 3.

The flow was not normalized after valve replacement when compared with patients with normal aortic valve for neither PSV (BP: $p < 0.004$; MP: $p < 0.02$), VC (BP: $p < 0.05$; MP: $p < 0.002$) nor SR (BP: $p < 0.0001$), except for SR in patients with MP ($p < 0.22$).

IV. DISCUSSION

Stenosis of the aortic valve increased the PSV, and replacement with a valve prosthesis reduced the velocity as expected from previous studies and guidelines [2-4]. This study showed additionally that VC and SR, which only are quantifiable with VFI, are changed in patient with aortic valve stenosis compared with normal aortic flow, as a more complex primary flow and a faster secondary rotational flow were seen in patients with aortic valve stenosis. These findings are comparable with findings of previous VFI studies [5-7].

However, it was also shown that flow through BP and MP were different. After surgery, the flow velocities in terms of PSV (not significant) and SR (significant) were lower in patients implanted with MP compared with patients treated with BP, while flow complexity was significantly higher. Previous VFI studies of patients with normal aortic valve and with aortic valve stenosis before and after implantation of BP have shown that VC correlates strongly with PSV, i.e. that higher antegrade velocities produce more complex flow [5,7]. The present study indicates that this relationship apparently is not valid in patients with MP as higher flow complexity was found despite lower flow velocities compared with patients with BP. The explanation could be the non-anatomical design of MP, where the attachment for two cusps are placed centrally in the lumen (Fig. 1). This geometry is not found in normal vessel and valve anatomy, and while systolic flow through the normal aortic valve and the anatomical realistic

BP is formed by one jet through the orifice, MP creates two jets from each orifice confined by the vessel wall and the central attachment along with a small third jet between the two leaflets [11].

A VFI study of blood flow in the ascending aorta showed that flow disturbances were correlated to atherosclerotic plaque formation along the vessel wall, probably as a consequence of lowered wall shear stress [6]. Therefore, more anatomical realistic designs of MP could reduce flow complexity in the ascending aorta and, thereby, lower the thrombogenicity of mechanical valves by reducing flow disturbances. Ultimately, this could affect the recommendations provided in the guidelines for valvular heart disease.

Secondary flow is a normal flow pattern seen in all larger vessels, and has been connected to energy preservation and protection of atherosclerosis [12]. In studies with VFI and MRI, it has been observed that SR in the ascending aorta is increased in patients with aortic valve stenosis and with implanted aortic BP when compared with patients with normal aortic valve, which probably is a consequence of the higher velocities of the primary antegrade flow found in these patient groups [5,13,14]. In this study, it was observed that SR was lower in patients with MP compared patients with BP. This has been shown previously with MRI-based CFD data [11] and could be explained by the lower velocities of the primary flow, the larger orifice compared with BP and non-anatomical design of MP as proposed by others [11]. For 2 patients treated with MP, the direction of SR changed from counter-clockwise to clockwise after surgery. This has been shown previously with VFI for patients with implanted BP for aortic valve stenosis, and underlines that the aortic valve shapes the helical flow in the ascending aorta [5,7].

Compared with patients with normal aortic valves, none of the patients with implanted prostheses had normalized flow. This has previously been shown in VFI studies of patients with aortic valve stenosis treated with BP, when compared with patients having normal aortic valves [5,7], and indicates that flow changes in patients with aortic valve stenosis not only are shaped by the stenosed leaflets, but also by an altered function of the left ventricle.

Some limitations of this preliminary study should be acknowledged. The study had a small study population. Conventional spectral Doppler and VFI were not measured simultaneously, and as both methods acquired data in 2D, alignment of compared scan planes was not perfect. Also, the reduced temporal resolution and scan depth of VFI could have affected the results.

V. CONCLUSION

VFI and conventional spectral Doppler were used to investigate flow changes in the ascending aorta in patients with aortic valve stenosis treated with either BP or MP and compared with patients with normal aortic valve.

The study showed that patients with aortic valve stenosis had more complex flow with higher systolic velocities and faster systolic secondary rotations compared with patients with normal aortic valve. After implantation of valvular prostheses, reduced flow complexity and velocities were observed for both BP and MP. However, despite lower systolic velocities in both the primary and secondary direction,

the flow complexity was significantly higher for MP compared with BP, which could be explained by differences in design of the implanted prostheses.

With these preliminary results, the study indicates that VFI can be a useful tool for complex flow assessment and may be used for advanced flow analyses in patients with valvular disease and in the development of valvular prostheses.

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