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Institutional report - Valves

Non-invasive assessment of differences between bileaflet and tilting-disc aortic valve prostheses by 3D-Doppler profiles[☆]

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Abstract

The aim of this study was to analyse flow characteristics of two different prosthetic valves by means of a non-invasive 3D Doppler technique. As previously demonstrated, negative velocity peaks within a 3D-Doppler profile significantly correlate with the severity of aortic stenosis. Transesophageal echocardiography was performed in 42 patients with normal aortic valves and in 35 patients after aortic valve replacement (bileaflet $n=23$, tilting-disc $n=12$). Three-dimensional reconstruction of color Doppler data was performed by the EchoAnalyzer software developed at our institution. Cross-section velocity distribution in the ascending aorta was analysed 2 cm distal to the aortic valve in 3 different sectors (non-coronary (NC), left-coronary (LC) or right-coronary (RC)). The percentages of negative velocity values (PNVV) in native aortic valves (6.8±6.4%, range: 0–21.8%) were significantly lower ($P<0.0001$) than in prosthetic valves (bileaflet: 38.5±18.5%, range: 13.2–71%; tilting-disc: 47.2±17.6%, range: 21.7–78.1%). Significant differences between normal and prosthetic valves were found in all different sectors. Furthermore, Medtronic Hall showed significantly higher PNVV than St. Jude Medical within the LC sector ($P=0.03$). This method, which allows non-invasive analysis of 3D flow distributions in patients, revealed significant differences between prosthetic valves and native valves as well as among different prosthetic types.

Keywords: Prosthetic heart valves; Turbulent flow; Doppler; 3-Dimensional echocardiography

1. Introduction

Fluid dynamic characteristics downstream of aortic valve prostheses account for events such as haemolysis, thromboembolism, calcification, tissue overgrowth, mechanical failure and prosthetic valve endocarditis [1,2]. Most comparisons of artificial valves have been evaluated in standardized in-vitro models which only poorly reflect the circumstances in-vivo [3]. In patients, velocity profiles may be obtained by invasive techniques, such as hot-film anemometry [4], perivascular [5,6], intraluminal Doppler ultrasound [7] or by MRI [8]. However, none of these techniques is suitable for daily clinical routine and long-term follow-up.

By Doppler echocardiography, clinical assessment of prosthetic valves was mainly based on velocity measurements to estimate transvalvular pressure gradients with the Bernoulli equation, and the valve effective orifice area by means of the continuity equation [9]. However, those two parameters proved to be insufficient for the evaluation of prosthetic valve function in vivo [9]. The advent of 3D-echocardiography has opened new perspectives for the non-invasive assessment of intracardiac flow in patients [10,11].

Angle dependency of the Doppler method resulted in the inability to accurately evaluate the flow downstream of artificial aortic valves by transesophageal or parasternal transthoracic echocardiography. A novel non-invasive method for the estimation of aortic flow profiles by angle corrected 3D-Doppler based on transesophageal echocardiography was developed at our institution. In contrast to former Doppler methods [5,6] our method enables measurement in more than 400 points within the cross sectional area of the ascending aorta. Additionally, it does not require thoracotomy and is also suitable for out-patient follow-up. We previously demonstrated that the occurrence of negative velocity values within an angle-corrected 3D-Doppler flow profile significantly correlates with the severity of aortic stenosis.

The aim of the present study was to analyse the flow characteristics of two different prosthetic valves in patients by means of non-invasive 3D Doppler technique.

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2. Materials and methods

Multiplanar three-dimensional transesophageal echocardiography with HP SONOS 5500 and 7500 (Philips Medical Systems, Hamburg, Germany) was performed in 35 patients (23 men and 12 women, mean age 69.2±9.1 years) after aortic valve replacement. Twenty-three St. Jude Medical (Standard 101 $n = 20$, HP-Series 105 $n = 3$) and 12 Medtronic Hall (A/M7700) were implanted. The positioning of artificial valves was performed as follows: The large orifice of Medtronic Hall was oriented towards the former non-coronary cusp, whereas the two orifices of St. Jude Medical were oriented towards the former right- and left-coronary cusps. The sizes of prostheses were 23.1±2.5 cm (range: 19–25 cm) for St. Jude Medical and 23.8±2.5 cm (range: 21–29) for Medtronic Hall. Although no patient had to be re-operated due to suspected prosthesis dysfunction or malposition, one patient had to be re-operated 2 months after implantation because of endocarditis.

For comparison, a control group of 42 patients (37 men and 5 women, mean age 63.8±9.5 years) with normal aortic valves was included. Patients with severe reduction of left ventricular function (ejection fraction lower than 25% estimated by echocardiography and angiography) were excluded. The diameters of the normal aortas were 22.7±2 cm (range: 18–26 cm). The study was approved by the independent institutional ethics committee on human research (date of approval 11/19/2002).

After induction of anesthesia and endotracheal intubation, the multiplanar transesophageal probe was inserted into the esophagus. The probe was placed to obtain a standard short-axis view. The 3-dimensional acquisitions were obtained by rotating the transesophageal transducer which was steered by a step motor. The acquisition was triggered to the R wave on electrocardiography. Postoperative acquisitions were performed before finishing the skin sutures.

Data stored on magneto-optical discs were transferred to an external computer for process by the software programme EchoAnalyzer™ developed at our institution [12,13]. Within the original 3D data set a position where the aorta is approximately vertical to the beam can be determined by rotation in space (s) and time (t). For angle correction the determination of the approximate flow direction and thereby of the angle α is essential. The formula for three-dimensional angle correction is:

$$v_m = \langle \vec{v}, \vec{n} \rangle = \|\vec{v}\| \|\vec{n}\| \cos \alpha$$

$$v_m = \|\vec{v}\| \cos \alpha$$

$$\|\vec{v}\| = v_m / \cos \alpha$$

(v_m: velocity measured by Doppler; $\langle .,. \rangle$: inner product; $\|\vec{v}\|$: angle corrected flow velocity, i.e. magnitude of real flow vector; $\vec{n}$: *unit vector towards ultrasound probe,* $\|\vec{n}\| = 1$; α: angle of flow to beam)

After implementation of the flow direction a cross-sectional circle with three sectors (non-coronary (NC), left- (LC) or right-coronary (RC)) can interactively be varied in size, position and orientation in order to fit in the different sizes of aortic roots. Cross-section velocity distribution in the ascending aorta was analysed 2 cm distal to the aortic valve. Percentages of negative velocity values (PNVV) were studied in early ejection in the resulting total disc and in the 3 different sectors. Early ejection was defined as the first appearance of color-Doppler signals within the original data sets after ECG R-wave.

Four typical appearances of the flow profiles were differentiated. In type A, a positive peak could be observed over the midline that was neighboured by two lateral and symmetrically positioned negative velocity peaks (Fig. 1A). In type B, negative and positive velocities were separated along the diameter of the valve (Fig. 1B). High fragmentation and a large number of positive and negative peaks were the typical characteristics of type C (Fig. 1C) normally observed in aortic stenosis. Type D consisted of one positive peak that was slightly laterally skewed (Fig. 1D).

All data are reported as mean±S.D. Differences between groups with bileaflet prosthesis, tilting-disc prosthesis and normal aortic valve were assessed by the Student's *t*-test for unpaired data. All tests were done with an alpha-level of 0.05, no alpha-adjustments were done.

3. Results

Adequate reconstructions of Doppler signals were achieved in all patients. Nyquist limits in prosthetic (60.9±7 cm/s) and normal valves (61.8±9 cm/s) did not significantly differ. Additionally, the time of measurement did not show a significant difference between normal aortic valves (174.6±35.1 ms after ECG R-wave) and prostheses (189.1±62.1 ms after ECG R-wave).

In prosthetic valves, different flow patterns could be observed in early ejection (Fig. 1 A–C). Type A was present in 78% of the patients with a bileaflet prosthesis, type B in 66.6% of the patients with a tilting-disc prosthesis. A flow profile pattern similar to aortic stenosis was observed (Fig. 1C) in patients who did not show either type A or type B. Normal aortas mainly showed type D (Fig. 1D).

There was a significant difference ($P < 0.001$) in the percentages of negative velocity values between each prosthetic valve (bileaflet: 38.5±18.5%, range: 13.2–71%; tilting disc: 47.2±17.6%, range: 21.7–78.1%) and normal (6.8±6.4%, range: 0–21.8%) in the overall cross-sectional area (Fig. 2). No significant differences were observed between bileaflet and tilting-disc in the cross-sectional area.

The analysis of the three different sectors (NC = non-coronary, LC = left-coronary and RC = right-coronary) also revealed significant (for all sectors $P < 0.001$) differences between prosthetic (bileaflet: NC: 33.6±20.6%, LC: 40.7±21.8%, RC: 41.1±21.3%; tilting-disc: NC: 38.2±22.4%, LC: 57.9±22%, RC: 48.4±22.7%) and normal valves (NC: 6.8±6.4%, LC: 5.6±8.1%, RC: 7.6±8%). Furthermore, tilting-disc valves showed higher mean values than bileaflet valves in all coronary sectors (Fig. 2) which were only significant ($P = 0.03$) for the left-coronary sector. There was no significant correlation between orifice diameters of normal and prosthetic valve and PNNV results.

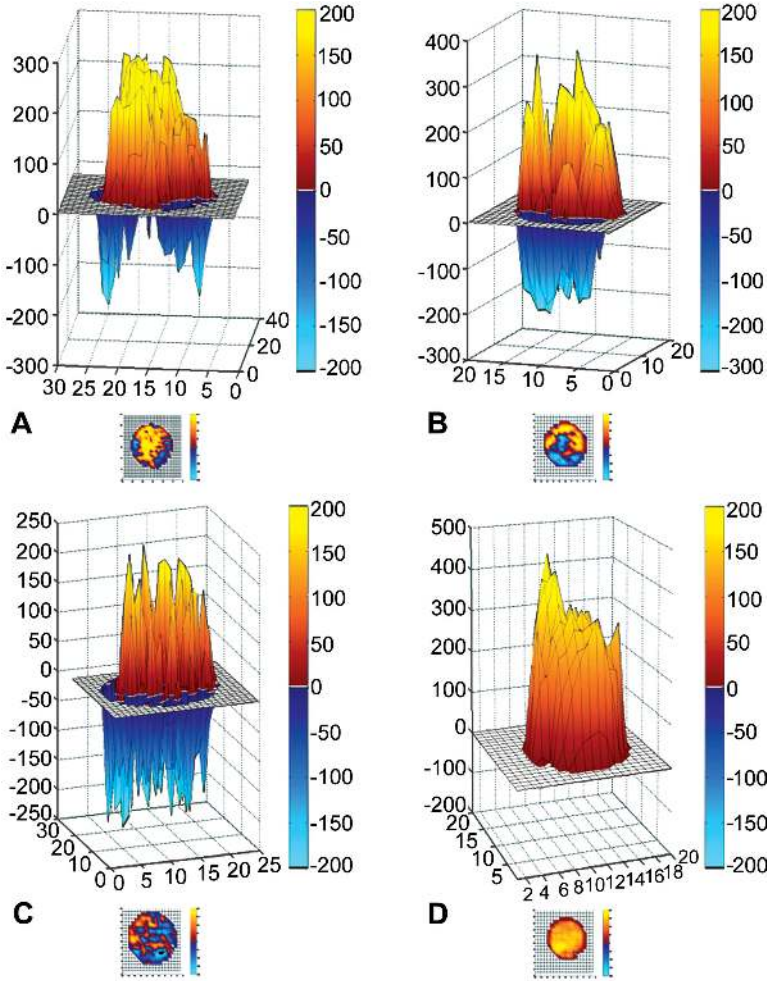

Fig. 1. A: typical 3D-Doppler profile mainly observed in bileaflet prostheses, B: typical 3D-Doppler profile mainly observed in tilting-disc prostheses, C: typical 3D-Doppler profile in severe aortic stenosis, D: typical normal 3D-Doppler profile.

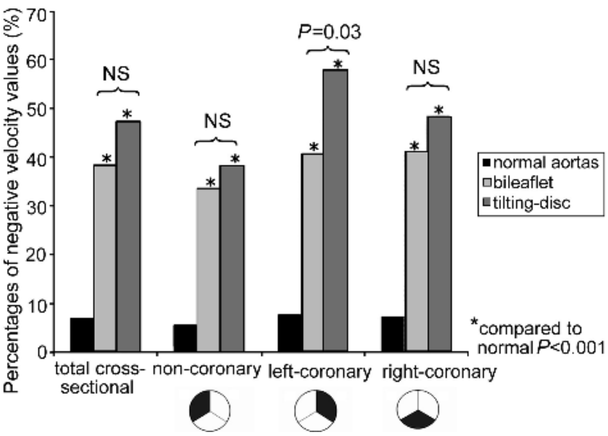

Fig. 2. Percentages of positive velocity values (%) in normal aortas, bileaflet (St. Jude Medical) and tilting-disc (Medtronic Hall) in total cross-sectional area and in different sectors (NC: non-coronary, LC: left-coronary, RC: right-coronary).

4. Discussion

Three-dimensional Color Doppler is a novel technique that offers new perspectives for the clinical management of patients with valvular disease. Percentages of negative velocity values is a novel index for the non-invasive assessment of aortic stenosis. In prosthetic valves means were higher in all coronary sectors studied for tilting-disc than for bileaflet which might lead to the hypothesis that there is more turbulence in tilting-discs than in bileaflet prostheses. However, these differences were only significant for the left coronary sector. We can only speculate that these findings are due to the fact that left coronary flow after tilting disc replacement is increased [14].

In this study, the differences of percentages of negative velocity values in prosthetic valves compared to normal valves were significant. However, it is an established truth that the flow properties of prosthetic valves do not match those of normal valves. For clinical management after valve replacement, it is highly important to distinguish between a normally-functioning prosthesis and dysfunction or malposition. It is well-known that all prosthetic valves are 'stenotic' to some extent due to the sewing ring [6].

Additionally, flow dynamics of prostheses, and especially of tilting-discs are highly dependent on the orientation [5,6,15]. The discrimination between turbulent flow in a normally functioning prosthetic valve in contrast to increased turbulence in prosthetic valve malposition or dysfunction is not trivial.

For the first time, analysis of typical patterns (Fig. 1) obtained by non-invasive 3D-Doppler has the potential to solve this problem.

It has to be emphasized that 3D-Doppler profiles do only reflect actual flow profiles when applied in normal aortas. Strictly speaking, in prostheses and aortic stenosis 3D-Doppler profiles do not reflect actual flow but provide a tool for the assessment of turbulence. Turbulence consists of high velocity flow and retrograde flow. Both, true retrograde flow as well as abnormally high velocities, will appear negative in 3D-Doppler profiles. The reason why abnormally high velocities will appear negative is aliasing. In aliasing, all velocities higher than the Nyquist limit or lower than twice the Nyquist limit will appear negative. Provided that Nyquist limits are constant, aliasing which was the former 'limitation' of the pulsed Doppler method can now be utilized to quantify turbulence.

Typical flow profile patterns were observed in most patients with prosthetic valves (Fig. 1A, B). However, the parameter of PNVV (percentages of negative velocity values) can be misleading in prosthetic valves since flow patterns can have similar values as in severe aortic stenosis (Fig. 1C), although differing in the amount of peaks. Various small turbulences in aortic stenosis result in a higher number of peaks than in prosthetic valves. In normally-functioning prosthetic valves, areas of abnormally high velocities [8] produce cohesive negative areas with fewer peaks due to less swirling. Therefore, the spatial distribution, not the absolute PNVV (percentages of negative velocity values), is fundamental for diagnosis of increased turbulence. An additional peak count parameter defined as the number of connected components with positive values will have to be introduced in order to distinguish between fractionated stenotic and cohesive prosthetic flow distribution. Further studies will have to investigate the influence of this additional parameter on valve orientation and long-term left ventricular remodelling after aortic valve replacement.

Three-dimensional Color Doppler is suited for the non-invasive assessment of pathologic flow areas downstream of artificial valves. This new non-invasive technique is ideally suited for the evaluation of different prosthetic valve designs, intraoperative diagnosis of prosthetic malposition and diagnosis of dysfunction of artificial valves in long-term follow-up.

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Appendix. Conference discussion

Mr D. Wheatley (*Glasgow, UK*): Are you now at the stage where you are using this to define abnormalities in prosthetic valves, and have you looked, for instance, at bioprosthetic valves where you might expect change?

Dr Mottl-Link: Well, indeed, this was the very first study where we used the 3D Doppler, and indeed, we did have two prosthetic bioprotheses, and in these bioprostheses, we had a similar pattern as in mild stenosis, but with two cases I think it is too early to say something about that.

Mr J. Pepper (*London, UK*): Two short questions. One, what happens when you have septal hypertrophy in association with aortic stenosis, how easy is it to analyze, and secondly, have you looked at what happens on simulated exercise?

Dr Mottl-Link: Well, we didn't look at what happens in exercise. This is the very first application of this method, but indeed, we will have to evaluate that.

The second question was the hypertrophy. We did not yet look at these conditions, but indeed, we will have to look at them in further studies.

Dr J. Hasenkam (*Aarhus, Denmark*): Were you able to compensate for the fact that the heart was moving and the transducer was fixated in the esophagus?

Dr Mottl-Link: Yes, indeed. We tried to hold the position very still, and when the probe is rotating, you can see by comparing the first picture and the last whether you moved or not.

Dr Hasenkam: But with the movements when the diaphragm is moving up and down and the heart is moving up and down relative to the transducer.

Dr Mottl-Link: Well, of course you can't totally exclude this, and this may be a limitation, of course.

Dr M. Antunes (*Coimbra, Portugal*): Will this method eventually be applicable to the mitral valve as well?

Dr Mottl-Link: Yes, of course.

Dr Antunes: And is it time-consuming, is it a method that can be applied routinely to all patients?

Dr Mottl-Link: Hopefully, because the acquisition time is very low, about one minute, and for reconstruction you need three minutes. So I think this will be a technique which can really be applied in clinical circumstances.

Dr S. Takamoto (*Tokyo, Japan*): I would like to ask about the differentiation between the aliasing and very severe aortic stenosis or the turbulent flow. Usually aliasing has a negative flow, in color Dopplers very severe aortic stenosis displayed as a mosaic pattern. So how do you differentiate aliasing with regular turbulent flow?

Dr Mottl-Link: This indeed is the key question, because the major issue of Doppler methods is that we do have the limitation of aliasing. In this case both retrograde flow as well as very high velocities are displaced negatively, and we can't discriminate between those two. But with our method, for the first time we do have such a high resolution that you can measure 400 points, and this gives you the ability of looking at the fragmentation, and the fragmentation will be the parameter which enables you to differentiate between severe aortic stenosis or mainly aliasing in prostheses.