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● *Original Contribution*

AORTIC VALVE STENOSIS INCREASES HELICAL FLOW AND FLOW COMPLEXITY: A STUDY OF INTRA-OPERATIVE CARDIAC VECTOR FLOW IMAGING

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Abstract—Aortic valve stenosis alters blood flow in the ascending aorta. Using intra-operative vector flow imaging on the ascending aorta, secondary helical flow during peak systole and diastole, as well as flow complexity of primary flow during systole, were investigated in patients with normal, stenotic and replaced aortic valves. Peak systolic helical flow, diastolic helical flow and flow complexity during systole differed between the groups ($p < 0.0001$), and correlated to peak systolic velocity ($R = 0.94$, 0.87 and 0.88, respectively). The study indicates that aortic valve stenosis increases helical flow and flow complexity, which are measurable with vector flow imaging. For assessment of aortic stenosis and optimization of valve surgery, vector flow imaging may be useful. (E-mail: lindskov@gmail.com) **© 2017 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Vector flow imaging, Ascending aorta, Aortic valve stenosis, Helical flow, Flow complexity.**

INTRODUCTION

Helical flow is recognized as a normal flow pattern in the vascular system and is perceived as a secondary rotational motion of the blood normal to the mainstream of the primary flow (Bogren and Buonocore 1999; Liu et al. 2015; Markl et al. 2004). It has been observed in numerous vessel geometries, for example, in the heart (Elbaz et al. 2014), the aorta (Hansen et al. 2016a; Kilner et al. 1993), the carotid and femoral arteries (Pedersen et al. 2011; Sarrami-Foroushani et al. 2015) and the veins of the lower extremities (Lurie and Kistner 2013), and has been explained by several theories. It has been suggested that helical flow stabilizes flow, preserves energy and protects against atherosclerosis (Kilner et al. 1993; Liu et al. 2009b; Morbiducci et al. 2011). Studies have indicated that the helical flow pattern facilitates blood flow transport to vessel branches, thereby optimizing organ perfusion and oxygen delivery, and is associated with lower lipid concentration along the inner vessel wall (Liu et al. 2009a, 2009b; Stonebridge and Brophy 1991).

Disease in the cardiovascular system is often accompanied by altered flow patterns; for example, aortic valve stenosis can be assessed with echocardiography as an increase in systolic velocities, pressure gradients and flow complexity (Nishimura et al. 2014; Simpson et al. 1988), where flow complexity can be evaluated by spectral broadening, power intensity and mosaic patterns using spectral, power and color Doppler ultrasound (US), respectively (Cloutier et al. 1995; Hutchison et al. 1996; Stringer et al. 1989). Helical flow is also affected by cardiovascular disease. Studies of blood flow in the ascending aorta in patients with bicuspid aortic valve and aortic valve stenosis have reported increased helical flow, which has been linked to development of aortic aneurysm (Hope et al. 2010; Meierhofer et al. 2013; von Knobelsdorff-Brenkenhoff et al. 2016).

The majority of studies of helical blood flow have been conducted with magnetic resonance imaging (MRI) and, to a lesser extent, conventional Doppler US (Bogren and Buonocore 1999; Frazin et al. 1996; Hope et al. 2010; Kilner et al. 1993; Koh et al. 2001; Liu et al. 2015; Markl et al. 2004; Meierhofer et al. 2013;

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Sarrami-Foroushani et al. 2015; Segadal and Matre 1987; von Knobelsdorff-Brenkenhoff et al. 2016; von Spiczak et al. 2015). However, recent studies have indicated that vector flow imaging (VFI) using US also is a useful modality for helical flow imaging (Hansen et al. 2015, 2016a, 2016b). A study of the helical flow in the ascending aorta during late systole and diastole in patients with normal or stenotic aortic valves did not find any correlation to aortic valve stenosis (Hansen et al. 2016b). It was, however, indicated that there is a short rapid vortical motion in the ascending aorta during peak systole in some patients (Hansen et al. 2016a, 2016b). A measure of flow complexity, where the averaged flow angle is found, has likewise been introduced recently with VFI (Pedersen et al. 2014). Studies of flow in the carotid artery and the ascending aorta have indicated that the measure can distinguish between complex and laminar flow (Hansen et al. 2015, 2016b; Pedersen et al. 2014).

The primary aim of this study was to examine the influence of aortic valve stenosis on secondary helical blood flow in the ascending aorta during peak systole and diastole by comparing blood flow in 10 patients with normal aortic valves to that of 10 patients with aortic valve stenosis before and after valve replacement. Also, the flow complexity of the primary blood flow during systole was estimated with VFI and correlated to peak systolic velocities. The hypothesis was that helical flow and flow complexity in the ascending aorta, when estimated with VFI, can be correlated to aortic valve stenosis in a study of patients with normal, stenotic and replaced aortic valves.

METHODS

After approval by the local ethics committee (No. H-16024707), 20 patients entered the study after giving written informed consent. The 10 patients in group I (6 males, 4 females, mean age: 63.9 y, range: 53–78 y) had no history of valvular disease and were scheduled for coronary bypass surgery, and the 10 patients in group II (9 males, 1 females, mean age: 70.7 y, range: 62–80 y) had aortic valve stenosis and were scheduled for valve replacement with a biologic valve prosthesis.

Blood flow in the ascending aorta was measured with epi-aortic VFI scans in long-axis (LAX) and short-axis (SAX) views after standard sternotomy and opening of the pericardium, but before cannulation for cardiopulmonary bypass. For the patients with aortic valve stenosis in group II, the epi-aortic VFI scans were repeated after implantation of the biologic prosthetic valve, weaning of bypass and decannulation. Thus, patient group II was scanned twice, over a stenotic aortic valve (group IIa) and over a replaced aortic valve (group IIb). Standard spectral Doppler measurements of blood flow in the ascending aorta were obtained with transesophageal echocardiography (TEE) before each VFI scan in the LAX view.

Vector flow imaging

The VFI method transverse oscillation, proposed by Jensen and Munk (1998), is an angle-independent vector velocity method, which estimates both the axial and transverse velocity components from each received echo using conventional Doppler pulse emission. The axial velocity component v_z is found as in conventional Doppler US with a conventional bell-shaped apodization function in receive, whereas the transverse velocity component v_x is found by changing the apodization function in receive to resemble a two-point source and with the use of a special estimator (Fig. 1) (Jensen 2001). Combining the axial and the transverse velocity components for each point within a region of interest (ROI) provides a 2-D vector velocity map of angle-independent blood velocities in the measurement plane. VFI is described in detail in previous articles (Jensen 2001; Jensen and Munk 1998; Udesen and Jensen 2006).

A conventional US scanner (ProFocus 2202 UltraView, BK Medical, Herlev, Denmark) with a linear transducer (8670, BK Medical, Herlev, Denmark) under sterile settings was used to record the epi-aortic scan sequences. Sterile saline was poured into the mediastinal cavity before each epi-aortic scan to enhance the acoustic transmission from the probe to the aortic surface (American Society of Anesthesiologists and Society of Cardiovascular Anesthesiologists Task Force on Transesophageal Echocardiography 2010).

The ascending aorta was scanned in LAX and SAX views 1–2 cm downstream of the aortic valve for each patient. In SAX view, the secondary helical motion was recorded. To capture both the slow and fast rotational motion of the blood in the diastolic and systolic phases, the blood flow in the ascending aorta in SAX view was measured with both a low and a high pulse repetition frequency (PRF). In LAX view, each patient was only scanned with a high PRF to capture the blood flow during systole for assessment of flow complexity.

For each scan, the color box was adjusted to cover the lumen, in either the longitudinal or transverse direction, and depth setting, gain and wall filtering were adjusted for vector velocity estimation. The averaged applied parameter setting for each patient group is provided in Table 1. For all measurements, the center frequency for B-mode imaging was 9 MHz, and that for VFI, 5 MHz.

The temporal resolution of the VFI estimation was 16 frames/s, and the maximum scan depth was approximately 5 cm because of the transducer setup available.