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● *Original Contribution*

ANALYSIS OF SYSTOLIC BACKFLOW AND SECONDARY HELICAL BLOOD FLOW IN THE ASCENDING AORTA USING VECTOR FLOW IMAGING

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Abstract—Secondary rotational flow and systolic backflow are seen in the ascending aorta and, in this study, were analyzed with the vector velocity method transverse oscillation. Twenty-five patients were scanned intra-operatively, and the vector velocities were related to estimates of transesophageal echocardiography and pulmonary artery catheter thermodilution, and associated with gender, age, aortic diameter, atherosclerotic plaques, left ventricular ejection fraction and previous myocardial infarctions. Secondary flow was present for all patients. The duration and rotational frequency ($p < 0.001$) and the duration and flow direction of the secondary flow ($p < 0.002$) were associated. Systolic backflow was present in 40% of the patients and associated with systolic velocities ($p < 0.002$) and the presence of atherosclerotic plaques ($p < 0.001$). No other significant associations were observed. The study indicates that backflow is injurious and that secondary flow is a normal flow phenomenon. The study also shows that transverse oscillation can provide new information on blood flow in the ascending aorta. (E-mail: lindskov@gmail.com)

Key Words: **Ultrasound, Transverse oscillation, Vector flow Imaging, Ascending aorta, Systolic backflow, Secondary rotational flow, Atherosclerotic plaque.**

INTRODUCTION

The aorta plays a crucial role in the human body. Blood exits the left ventricle and curls in a non-planar route in the aortic arch to the systemic circulation, with the highest velocities within the cardiovascular system and with a highly complex flow pattern (Kvitting et al. 2004). An understanding of blood flow in the ascending aorta is important as pathologic conditions in the aortic arch such as aneurysms, dissections, valve pathologies and atherosclerosis are all connected to the blood flow, and the prognosis and timing for intervention are built on knowledge of the aortic flow (Burris and Hope 2015).

The two main modalities used for imaging aortic flow are magnetic resonance and ultrasound. Ultrasound is a real-time method for cardiac blood flow visualization, which can be performed bedside, but provides only 1-D velocity estimation (Jensen 1996). Magnetic resonance imaging of aortic flow is available in both 2-D and 3-D, but is not a bedside or real-time modality, as the estimates are calculated as averages of several heartbeats (Markl et al. 2011).

To improve our understanding of the complex aortic flow, a 2-D, real-time method is warranted. Several authors have, over the decades, provided possible solutions for 2-D vector flow imaging using ultrasound (Bohs et al. 2000; Bonnefous 1988; Daigle et al. 1975; Fox 1978; Newhouse et al. 1987; Nygaard et al. 1994; Overbeck et al. 1992; Trahey et al. 1987), and a recent study of two different real-time vector flow methods using transmission of focused beams and plane waves, respectively, indicated the vector methods performed better than the conventional spectral Doppler method (Tortoli et al. 2015).

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The ultrasound vector velocity method called transverse oscillation, which estimates 2-D blood flow angle-independently and in real time, was introduced by Jensen and Munk (Jensen 2001; Jensen and Munk 1998), and has recently been implemented on a commercial scanner (ProFocus 2202 UltraView, BK Medical, Herlev, Denmark). Transverse oscillation has been tested in computer simulations and validated in flow phantoms (Udesen and Jensen 2006) and *in vivo* against magnetic resonance angiography (Hansen et al. 2009a, 2009b). The transverse oscillation method implemented on the commercial scanner has been validated against conventional spectral Doppler ultrasound (Pedersen et al. 2012), and preliminary studies have been published on cardiac vector flow estimation proving the feasibility of the method for cardiac flow imaging (Hansen et al. 2013, 2015b).

The previous cardiac studies with transverse oscillation have indicated that complex flow patterns are present in the ascending aorta (Hansen et al. 2013, 2015b). The main focus of the present study is assessment of secondary helical flow and systolic backflow in the ascending aorta. These flow patterns have previously been studied with magnetic resonance imaging (Bensalah et al. 2014; Bogren and Buonocore 1999; Hope et al. 2007; Kilner et al. 1993, 2000; Markl et al. 2011). However, magnetic resonance imaging for flow characterization is hampered by a reduced temporal resolution affecting flow estimation (Markl et al. 2011). With the vector velocity method transverse oscillation, a real-time tool for analyses of complex blood flow patterns is proposed.

METHODS

In this study, 25 patients with healthy aortic valves were scanned with transverse oscillation intra-operatively to estimate the blood flow of the ascending aorta. Flow was visualized in short- and long-axis views, with the main focus on secondary helical flow and systolic backflow. The aim of the study was to better understand aortic flow and to investigate possible explanations for flow differences among the 25 patients.

In a recent paper, the data of the included 25 patients have been analyzed quantitatively in terms of blood flow velocity and volume flow (Hansen et al. 2015a). However, the complex flow patterns in the ascending aorta, e.g. secondary helical flow and systolic backflow, have not been assessed before.

The study was approved by the local ethics committee (No. H-2-2012-039). Twenty-five patients (20 males, 5 females, mean age: 65.6, range: 41–80 y) without any history of valvular disease, undergoing coronary bypass surgery, entered the study after written informed consent. Epi-aortic scan sequences of blood flow in the ascending aorta were recorded with transverse oscillation after standard sternotomy and opening of the pericardium and before cannulation for extracorporeal circulation. Standard spectral Doppler measurements of blood flow in the ascending aorta were obtained with transesophageal echocardiography, and cardiac output measurements were obtained with pulmonary artery catheter thermodilution.

Transverse oscillation and pulmonary artery catheter thermodilution measurements were performed simultaneously, whereas transverse oscillation and transesophageal echocardiography measurements were performed within 5 min, as simultaneous ultrasound emissions from the probes placed on the ascending aorta and in the esophagus create unwanted signal interference. For each patient, the medical record was consulted to obtain information on previous myocardial infarctions as well as left ventricular ejection fraction, which was obtained before the cardiac surgery with conventional echocardiography.

Transverse oscillation

The transverse oscillation method emits a conventional pulse for Doppler ultrasound, but estimates both the axial and transverse velocities. The axial velocity is found exactly as in conventional Doppler ultrasound, whereas the transverse velocity is found with a changed sensitivity of the receiving elements and a special estimator (Fig. 1) (Jensen 2001). Previous articles provide more detailed explanations of the method (Jensen 2001; Jensen and Munk 1998; Udesen and Jensen 2006).

Epi-aortic vector flow imaging

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

The ascending aorta was scanned in both long- and short-axis views for each patient (Fig. 2). The temporal resolution of the transverse oscillation estimation is 16 frames/s, and the maximum scan depth is approximately 5 cm because of the transducer setup available. For each scan session, the color box was adjusted to cover the lumen, and the pulse repetition frequency, depth setting,