Ultrasonics 56 (2015) 243–250

Contents lists available at ScienceDirect

Ultrasonics

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

First report on intraoperative vector flow imaging of the heart among patients with healthy and diseased aortic valves

Kristoffer Lindskov Hansen [a,*], Hasse Møller-Sørensen [b], Mads Møller Pedersen [a], Peter Møller Hansen [a], Jesper Kjaergaard [c], Jens Teglgaard Lund [d], Jens Christian Nilsson [d], Jørgen Arendt Jensen [e], Michael Bachmann Nielsen [a]

[a] Department of Radiology, Rigshospitalet, Copenhagen University Hospital, Denmark
[b] Department of Cardiothoracic Anesthesiology, Rigshospitalet, Copenhagen University Hospital, Denmark
[c] Department of Cardiology, Rigshospitalet, Copenhagen University Hospital, Denmark
[d] Department of Cardiothoracic Surgery, Rigshospitalet, Copenhagen University Hospital, Denmark
[e] Center for Fast Ultrasound Imaging, DTU Elektro, Technical University of Denmark, Denmark

ARTICLE INFO

Article history:
Received 29 January 2014
Received in revised form 22 July 2014
Accepted 23 July 2014
Available online 1 August 2014

Keywords:
Transverse oscillation
Vector flow imaging
Cardiac flow
Aortic valve
Stenosis

ABSTRACT

The vector velocity method Transverse Oscillation (TO) implemented on a conventional ultrasound (US) scanner (ProFocus, BK Medical, Herlev, Denmark) can provide real-time, angle-independent estimates of the cardiac blood flow. During cardiac surgery, epicardial US examination using TO was performed on (A) 3 patients with healthy aortic valve and (B) 3 patients with aortic valve stenosis. In group B, the systolic flow of the ascending aorta had higher velocities, was more aliased and chaotic. The jet narrowed to 44% of the lumen compared to 75% in group A and with a vector concentration, a measure of flow complexity, of 0.41 compared to 0.87 in group A. The two groups had similar secondary flow of the ascending aorta with an average rotation frequency of 4.8 Hz. Simultaneous measurements were obtained with spectral Doppler (SD) and a thermodilution technique (TD). The mean difference in peak systolic velocity compared to SD in group A was 22% and 45% in B, while the mean difference in volume flow compared to TD in group A was 30% and 32% in B. TO can potentially reveal new information of cardiac blood flow, and may become a valuable diagnostic tool in the evaluation of patients with cardiovascular diseases.

1. Introduction

The cardiovascular system confines a circuit for complex flow patterns with spatial and temporal velocity changes and vortex formations throughout the cardiac cycle. Using both invasive and non-invasive techniques, the cardiovascular system has been investigated to understand normal and pathological flow patterns and fluid dynamics [1]. Ultrasound (US) is the main modality for examination of the heart [2]. The epicardiac US scan approach was introduced several decades ago for evaluation of patients during cardiac surgery [3]. However, epicardiac US is today less used due to the use of transesophageal echocardiography (TEE), which has achieved a major role in perioperative echocardiographic assessment of cardiac function [4] and is recommended as a perioperative monitoring tool during cardiac surgery [5,6]. However, parts of the heart can be difficult to visualize with TEE and in some patients correct placement of the transesophageal probe is hindered; in these situations it is recommended to use epicardiac US scan approach [7]. Doppler US is used to estimate the blood flow in conventional US whether it is epicardiac, TEE or transthoracic US, but is unfortunately limited by angle-dependent and one-dimensional (1-D) velocity estimation, obscuring the complexity of cardiac blood flow [8,9].

Several authors have tried to overcome the angle dependency in conventional velocity estimation systems and efforts have been made to create a vector flow US system [10–17]. One promising method for US vector velocity estimation, Transverse Oscillation (TO), was proposed by Jensen and Munk [18,19] and has been tested in computer simulations and with flow phantoms [20]. *In-vivo* examples have been provided for blood flow in superficial vascular geometries [21,22] and TO has been validated *in vivo* against magnetic resonance imaging (MRI) angiography [23,24] and conventional spectral Doppler US [25]. Finally, as in this study, TO has been used to investigate *in vivo* cardiac blood flow intraoperatively on patients with healthy aortic valves [26].

* Corresponding author. Address: Department of Radiology, Rigshospitalet, Blegdamsvej 9, 2100 Copenhagen, Denmark. Tel.: +45 35 45 35 45; fax: +45 35 45 20 58.
E-mail address: lindskov@gmail.com (K.L. Hansen).

http://dx.doi.org/10.1016/j.ultras.2014.07.015
0041-624X/

In this preliminary study, TO, implemented on a conventional US scanner, provided real-time, angle-independent vector velocity estimates of cardiac blood flow with epicardiac examination in 6 patients undergoing cardiac surgery. The aim of the study was to investigate the feasibility of vector flow estimation using TO directly on the heart *in vivo* during surgery in a study population of patients with healthy and diseased aortic valves. Furthermore, the aim was to investigate if flow changes around the stenotic aortic valve are measurable with the TO system both qualitatively and quantitatively. Measures of angle diversity, frequency of secondary flow pattern, blood flow velocities and volume flow are obtained with TO. For comparison, blood flow velocities and volume flow estimates were compared to measurements of conventional Doppler US and pulmonary artery thermodilution technique (TD).

2. Materials and methods

2.1. Patients and setup

The Danish National Committee on Biomedical Research Ethics approved the study (project-ID H-2-2012-039). Three patients (group A) with no history of valvular disease undergoing coronary bypass surgery (female: 68 years (y), male: 62 y, male: 76 y) and 3 patients (group B) with aortic valve stenosis undergoing valve replacement surgery (male: 62 y, male: 82 y, female: 78 y) entered the study after written informed consent.

After standard sternotomy and before cannulation for extracorporeal circulation, epicardiac scan sequences were recorded with TO. Additional standard Doppler measurements of blood flow in the ascending aorta were obtained with TEE, and cardiac output measurements were obtained with pulmonary artery TD measurements. All measurements were performed within 10 min.

2.2. Transverse oscillation

The basis for estimation of the vector velocities with TO has been described previously [18–20]. A conventional pulse for Doppler US is emitted and the scatterer motion is tracked along two orthogonal axes to achieve the 2-D vector velocity estimate. The motion in the axial direction is found exactly as in conventional Doppler US by using a bell-shaped receiving apodization function, while the motion in the lateral direction is found by using a receiving apodization function resembling a two-point source, and a special estimator [18].

A conventional US scanner (ProFocus 2202 UltraView, BK Medical, Herlev, Denmark) and a linear transducer (8670, BK Medical, Herlev, Denmark) under sterile settings were used to record epicardiac scan sequences (Fig. 1). The TO method is implemented so real-time estimation of vector flow is achieved with a temporal resolution of 67 ms i.e. 16 frames/s. The angle-independent vector velocities are displayed real-time on the B-mode image as colored pixels given by a 2-D color bar defining both flow direction and velocity magnitude. To facilitate interpretation of the vector velocity estimations, small arrows are superimposed on to the color flow map. The error of transverse velocity estimate increases with scan depth and is mainly governed by the distance between the peaks of the two-point source, thus the dimension of the transducer array. Maximum scan depth for vector flow in this setup is approximately 5 cm due to the transducer setup available. In this study, the aortic valve and the ascending aorta were examined. For each scan sequence, Doppler gain, pulse repetition frequency (PRF), and wall filtering were optimized for flow imaging.

Vector flow estimation is achieved and displayed in real-time, but no quantification of velocities is available on the scanner, therefore, scan sequences were analyzed off-line using Matlab (Mathworks, Natick, MA, USA). Details about the measurement setup and post processing are described by Pedersen et al. [25]. Vector estimates of peak systolic velocities are found of blood flow in the ascending aorta as an average over five heart cycles from scan sequences in long axis view. A region of interest (ROI) is defined so the vessel of interest i.e. ascending aorta is included. In this ROI, 15% of the central lines corresponding to 4 mm in the transverse direction and an axial height depending on the aortic width are used for velocity estimation. Volume flow calculation (Q) from vector velocities as a mean over five heart cycles is calculated using two different approaches:

$$Q = 0.5 * V_{max} * A \tag{1}$$

$$Q = V_{mean} * A \tag{2}$$

where A is cross sectional area of the ascending aorta and calculated from perpendicular diameters of the vessel measured in short axis view. V_{max} is the maximum velocity and V_{mean} is the mean velocity averaged over all included lines of the ROI to each frame. Q is calculated to every frame and given as a mean over each sequence of five

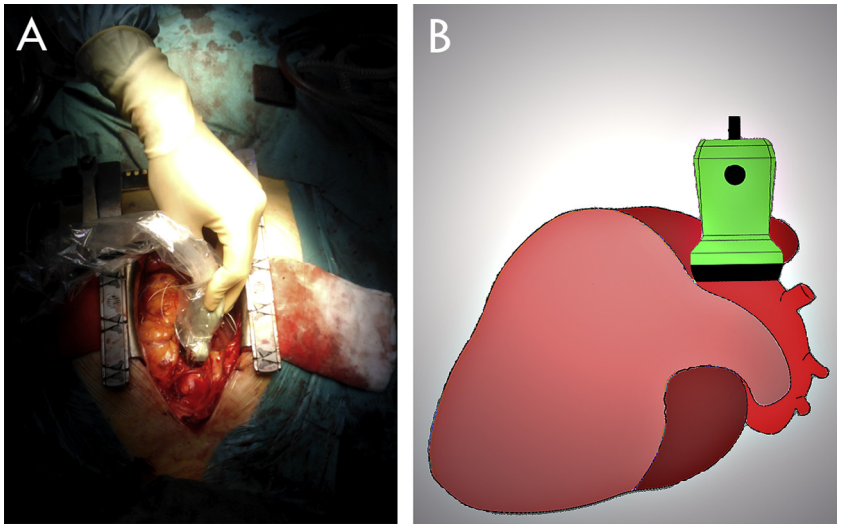

Fig. 1. Intraoperative *in vivo* TO measurement performed on the heart during surgery under sterile settings as shown in (A). In (B) an illustration is given of the orientation of the transducer when placed directly on the ascending aorta in the longitudinal scan plane.