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● *Original Contribution*

COMPARISON OF VORTICAL STRUCTURES INDUCED BY ARTERIOVENOUS GRAFTS USING VECTOR DOPPLER ULTRASOUND

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Abstract—Arteriovenous prosthetic grafts are used in hemodialysis. Stenosis in the venous anastomosis is the main cause of occlusion and the role of local hemodynamics in this is considered significant. A new spiral graft design has been proposed to stabilize the flow phenomena in the host vein. Cross-flow vortical structures in the outflow of this graft were compared with those from a control device. Both grafts were integrated in identical in-house ultrasound-compatible flow phantoms with realistic surgical configurations. Constant flow rates were applied. In-plane 2-D velocity and vorticity mapping was developed using a vector Doppler technique. One or two vortices were detected for the spiral graft and two to four for the control, along with reduced stagnation points for the former. The in-plane peak velocity and circulation were calculated and found to be greater for the spiral device, implying increased in-plane mixing, which is believed to inhibit thrombosis and neo-intimal hyperplasia. (E-mail: E.Kokkalis@dundee.ac.uk or Kokkalis.s@gmail.com) © 2015 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Color Doppler, Vector Doppler ultrasound, Velocity, Vorticity, Circulation, Flow phantom, Arteriovenous prosthetic grafts, Vortical structures, Spiral flow, Flow mixing and stagnation.**

INTRODUCTION

Color Doppler ultrasound has been found to be of great value in clinical diagnosis where blood flow can be visualized and quantified to assess cardiovascular complications. However, conventional color Doppler imaging is limited to displaying two spatial components and one velocity component. The velocity measurements are vulnerable to errors mainly because of the angle dependency between the ultrasound beam and the direction of the target (Evans et al. 2011; Hoskins 2010). In addition, the complex vortical structures that occur in the cardiovascular system increase the angle dependency and cannot be quantified. These structures can be intense in bifurcations (Udesen et al. 2007), post-stenotic regions (Hoskins 1997), the heart (Garcia et al. 2010) and graft anastomoses (Doorly et al. 2002; Lee et al. 2005). The display of vortical phenomena requires at least two components of velocity. The evolving understanding of the role of local hemodynamics in endothelial function and the proliferation of vascular smooth muscle (Caro 2009; Malek et al. 2013; Slager et al. 2005a, 2005b) serves to increase the interest in more detailed velocity profiles and fluid dynamic assessments. During the last few decades, a number of vector Doppler approaches have been proposed (Fei et al. 1994; Garcia et al. 2010; Hoskins et al. 1994; Jensen and Munk 1998; Maniatis et al. 1994), and recently, a real-time technique was integrated into a conventional system (Pedersen et al. 2012).

The rotational nature of blood flow in vessels is widely accepted. In 1990, Frazin et al. detected spiral flow in the thoracic aorta using color Doppler. Stonebridge and Brophy (1991) were the first to suggest the blood flow in arteries is spiral in nature. Subsequent ultrasound studies confirmed the presence of spiral flow in arteries (Frazin et al. 1996; Hoskins et al. 1994; Tanaka et al. 2010; Udesen et al. 2007), veins (Marie

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et al. 2014; Rosenthal et al. 1995) and the heart (Garcia et al. 2010; Mehregan et al. 2014). It has also been verified with magnetic resonance imaging (Kilner et al. 1993; Markl et al. 2005) and computational modeling (Gallo et al. 2012; Hardman et al. 2013).

The formation of vortical structures in blood originates from the rotational compression of the heart (Jung et al. 2006) and is propagated because of the curvature, branching, non-planarity and spiral folds in the arteries (Caro et al. 1996; Stonebridge 2011; Stonebridge and Brophy 1991). Caro et al. (1996, 2005) hypothesized that helical flow in arteries supports in-plane mixing and uniform distribution of wall shear and inhibits blood stagnation, separation and instability. Similarly Stonebridge et al. (2004) maintained that single-spiral induces flow stability and coherence, and Cookson et al. (2009) verified and explained an increase of in-plane mixing as a result of helical flow. Recently, Marie et al. (2014) reported single-spiral flow as a predictor of successful arteriovenous (AV) fistula maturation.

As an alternative to AV fistulas, prosthetic grafts can be used for vascular access. The most frequent complication of AV prostheses is stenosis, which can lead to thrombosis and occlusion. Stenoses can develop in the venous or arterial anastomosis from neo-intimal hyperplasia or the mid-graft section as a result of ingrowth of fibrous tissue through puncture holes. The former is the most common incident, with disturbed hemodynamics being one of the causes (Gessaroli and Massini 2012; Manos et al. 2010; Mickley 2004; Tricht et al. 2005). An AV graft can be implanted in either the arm or the thigh, with patency depending on the location. In an AV graft review Akoh (2009) reported 1- and 2-y cumulative patency rates of 59%–90% and 47%–85% in the arm and 41%–68% and 26%–43% in the thigh, respectively, indicating the need for steady and enhanced patency.

A novel AV prosthetic graft specifically engineered to introduce a stabilized spiral flow has recently been developed and introduced for vascular access applications. Clinical data are not yet available but a similar peripheral vascular spiral graft has been compared with a control device *in vitro* exhibiting improved secondary flow phenomena (Kokkalis et al. 2013) and has been applied *in vivo* with enhanced patency rates in a 30-mo follow-up (Stonebridge et al. 2012). These promising results motivated us to investigate the hemodynamics of the AV spiral graft and the underlying mechanism.

The aim of this article is to describe and compare the rotational structures in the outflow of the spiral AV graft and a non-spiral control AV graft, using vector Doppler ultrasound. Two-dimensional velocity and vorticity maps were developed; peak velocity and circulation were identified for quantification.

METHODS

Arteriovenous access grafts

The spiral and control grafts were made of expanded polytetrafluoroethylene (ePTFE) and had a 6-mm inner diameter (ID) (Vascular Flow Technologies, Dundee, UK). The former device is supported by an injection molded polyurethane spiral flow inducer, which forms an internal non-planar helical geometry along the distal end of the graft (Fig. 1a). The control device was identical in all parameters, but with a smooth planar internal geometry along its length.

Flow phantom setup

The proximal end of each graft was connected to C-Flex (Cole–Parmer, London, UK) tubing, which simulated the arterial flow and the distal end with an in-house venous mimic with end-to-side anastomoses. The venous mimic was made of polyvinyl alcohol cryogel (PVA-c). This vascular-graft model was embedded in a liquid medium tissue mimic and housed in an acrylic tank (485 × 180 × 60 mm). The tissue mimic composition by volume was 9% glycerol and 91% distilled water. PVC tubing was used to connect the outflow of a flow pump with the C-Flex tubing (artery) and the PVA-c venous mimic with the inflow of the pump. The connections between the PVC tubing and vascular mimics on the wall of the tank were supported by straight, rigid 60-mm-long PVC screw connectors. An ultrasound Doppler test fluid (Model 707, ATS Laboratories, Bridgeport, CT, USA) was used as blood mimic. The flow pump was a UHDC computer controlled piston system (Shelley Medical Imaging Technologies, London,

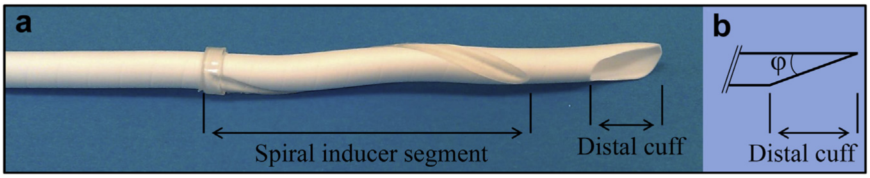

Fig. 1. (a) Distal end of the 6-mm-inner-diameter arteriovenous spiral graft. (b) Side view diagram of the distal cuff where angle $\varphi = 15°$.