International Journal of Heat and Fluid Flow 67 (2017) 59–68

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Stereoscopic particle image velocimetry of the impinging venous needle jet during hemodialysis

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ARTICLE INFO

Article history:
Received 4 August 2016
Revised 10 July 2017
Accepted 11 July 2017

Keywords:
Stereo particle image velocimetry
Impinging jet
Venous needle
Hemodialysis

ABSTRACT

Stereoscopic particle image velocimetry (S-PIV) was used to quantify the dynamic flow field caused by the venous needle jet (VNJ) in an idealised model of hemodialysis cannulation. Scaling based on Reynolds number ensured dynamic similarity with physiological conditions. Measurements taken along the center plane indicate the presence of a steady secondary flow region, which develops downstream of the impingement region. Upon impingement, a wall jet forms on the floor of the vein and spreads along the curvature of the vessel. Circulating flow forms due to the interaction between the jet spreading and the wall jet. This secondary flow region represents a potential site of stenosis on the roof of the vein where flow is reversed. The effects of the circulating flows can be minimized by using shallow needle angles, low needle flow rates and placement of the needle away from the walls of the vein.

1. Introduction

An arteriovenous fistula (AVF) is the surgical connection between an artery and a vein and forms a crucial component in renal replacement therapy by providing vascular access for hemodialysis. However, AVFs have a high predisposition to pathological narrowing of the access which leads to poor long term success. If untreated, the formation of a clinical stenosis can result in thrombosis, which may leave the access unusable for dialysis (Salahi et al., 2006).

Stenosis can develop rapidly upon injury to the endothelial layer, where the blood vessel responds through intimal expansion in a process called intimal hyperplasia (IH). This usually occurs in the anastomosis and the draining vein of AVFs (Bilgic et al., 2015; Sivanesan et al., 1999; Turmel Rodrigues et al., 2000). Stenosis in the drainage vein can have severe implications as it is a vital component of the hemodialysis circuit, providing the site where hemodialysis cannulation is conducted.

The venous needle jet (VNJ) has been reported as one potential source of IH formation in the draining vein due to high levels of turbulence (Huynh et al., 2007; Unnikrishnan et al., 2005) and high shear forces (Fulker et al., 2013). Unnikrishnan et al. (2005) employed a bench top flow rig and measured turbulent fluctuations produced by the VNJ up to 8 cm downstream using laser Doppler anemometry. Huynh et al. (2007) extended the bench top flow rig by incorporating endothelial cells. Turbulent fluctuations significantly altered the function of the blood vessel wall, which is a precursor event in stenosis formation.

Previous computational studies have identified secondary flow structures downstream of the VN which may contribute to IH (Fulker et al., 2013; Fulker et al., 2015). Secondary flows affect vascular function and have also been correlated with IH in the anastomosis of AVFs (Bassiouny et al., 1992; Keynton et al., 2001). Visualisation of the flow structures produced by the VNJ will elucidate the impact of the VN on potential intimal thickening in the draining vein of AVFs.

The aim of this study is to investigate the nature of the VNJ under normal hemodialysis conditions using stereoscopic particle image velocimetry (S-PIV). An idealised model of hemodialysis cannulation with constant flow conditions is utilised with a blood analog. In particular, the regions of interest include the free stream jet, impingement zone, wall jet and the extent of secondary flow within the vein itself. Different needle flow rates, needle positions and insertion angles are tested to cover the range of normal hemodialysis conditions. Examining the flow field downstream of the VN will elucidate if the VNJ contributes to stenosis formation, which have been shown to form within the draining vein of AVFs.

2. Materials and methods

2.1. Experimental setup

An idealised model of hemodialysis cannulation was constructed from rigid acrylic (PMMA). The outflow vein was modelled as a simple cylinder with the VN placed within, to investigate

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.07.005
0142-727X/

Table 1
Summary of flow rates and Reynolds numbers after dimensional analysis.

Inlet Type	Physiological Flow Rate (ml/min)	Scaled Flow Rate (ml/min)	Reynolds Number
Vein	654	666	740
Needle	200	291	924
Needle	300	436	1385
Needle	400	581	1847

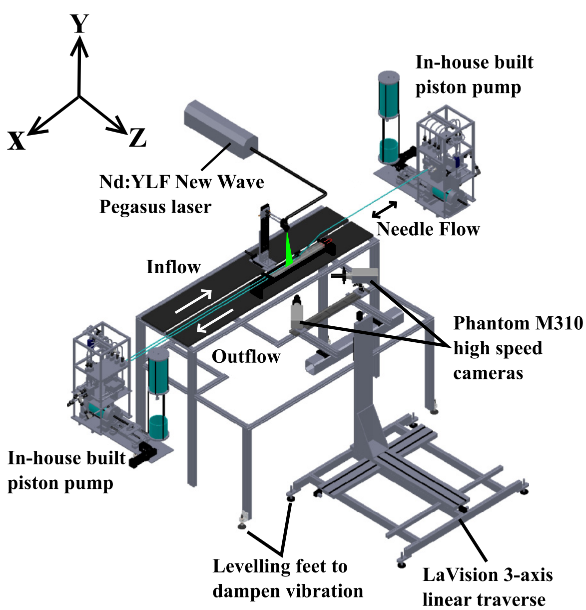

Fig. 1. Experimental Setup.

Table 2
Parameters and variables of all test cases.

Parameter	Variable	Constants
Needle Flow Rate	200 ml/min 300 ml/min 400 ml/min	20° Middle
Needle Angle	10° 20° 30°	300 ml/min Middle
Needle Position	Top Middle Bottom	300 ml/min 20°

the nature of the impinging jet and subsequent mixing with the core flow. An idealised model is preferred to examine the general flow features produced by the VN, as opposed to patient specific cases which may not be translatable. Two in-house designed piston pumps were used to deliver continuous constant flow through four solenoid valves. The flow and pressure produced by the pump were monitored using an Atrato Ultrasonic flow meter (Titan Enterprise Ltd, Dorset, United Kingdom) and an MRC22 PT100 pressure transducer (MeasureX Pty Ltd, Melbourne, Australia). The flow remained within 1.16% of the set value whilst the pressure varied less than 13.95% of the mean. A stepper motor was used to drive the pump and an encoder was used to control the position of the piston. The laser was mounted on a single axis micrometre traverse system whilst the cameras were mounted on a three axis motorised traverse (LaVision GmbH, Goettingen, Germany) with a precision up to 0.1 mm. The experimental flow rig, laser system and cameras were mounted on self-levelling feet which also dampened the vibrations produced by the pump as displayed in Fig. 1.

Dynamic similarity was achieved by scaling the diameters of the circuit and needle by a factor of two whilst maintaining Reynolds number. The resultant scaled flow rates are displayed in Table 1 with their associated Reynolds numbers.

The diameter of the vein is 20 mm (D), with the downstream portion extended 20D to prevent any back pressure from affecting the flow around the needle and the upstream portion is extended 50D to ensure fully developed flow before the needle. The arterial needle was removed from the circuit so that a single needle could be examined in isolation. The scaled needles were manufactured from 8G stainless steel tubing with an inner diameter of 2.692 mm (d), which equates to standard 15 G needles commonly used in clinical practice. The dimensions were taken from measurements of a real scale needle using a keyence digital microscope (Keyence Corporation of America., New Jersey, USA)). The rig was designed in modular blocks and sealed with o-rings to test a range of parameters. Needle angles of 10°, 20° and 30° were tested whilst the position of the needle bore was also shifted to sit within the center and in the upper and lower thirds of the vein. Standard hemodialysis blood flow rates of 200 ml/min, 300 ml/min, 400 ml/min were forced through the needle whilst a constant flow rate of 666 ml/min was pumped through the venous circuit, providing the core flow. Fistula flows commonly range between 600–1200 ml/min, with the arterial needle extracting a portion of this after the anastomosis (Konner, 1999). For the three tested parameters (needle flow rate, needle angle, needle position), there were three separate variables, which constituted nine different cases as displayed in Table 2.

2.2. Test fluid

A blood analog fluid was used which contained a mixture of aqueous sodium iodide (76.5%) and glycerol (23.5%). Sodium thiosulfate (0.1% w/w) was added to minimize the effects of discoloration which occurs when the test fluid contacts UV light. The ratio of this mixture was controlled to match the refractive index of the PMMA (1.49), which minimized any light distortion occurring at the fluid-solid interface. A Cannon-Fenske viscometer (Cannon Instrument Company, Pennsylvania, USA) was used to monitor the viscosity of the blood analog during mixing. The subsequent test fluid has a dynamic viscosity of 0.00706 Pa s, which is similar to that of blood (0.0035 Pa s), and a density of 1652 kg/m^3 at 20 °C. The test fluid was seeded with spherical fluorescent polymer particles made from poly methyl methacrylate labelled with Rhodium B. The particles were seeded at a concentration of approximately 5 mg/L based on the work by Melling (Melling, 1997). The largest particle diameter required for optimal flow tracking was calculated using Stokes number. Subsequently, particles with a mean diameter of 10 μm (range: 1–20 μm) were used to obtain optimum light scattering and particle tracking. All experiments were conducted in a controlled environment at 20 °C to maintain constant viscosity across measurements. A Monel Thermowell PT100 temperature transducer (Pyrosales Pty Ltd, Sydney, Australia) was placed at the inlet and outlet of the pump system and confirmed that the temperature remained constant over a 4 h operating period.