Role of Sinus in Prosthetic Venous Valve

W.-H. Tien [a], H.Y. Chen [b,c,d], Z.C. Berwick [b,c], J. Krieger [e], S. Chambers [e], D. Dabiri [a], G.S. Kassab [c,d,f,*]

[a] Department of Aeronautics and Astronautics, University of Washington, Seattle, WA, USA
[b] Research and Development, 3DT Holdings, LLC, Indianapolis, IN, USA
[c] Department of Cellular and Integrative Physiology, Indiana University School of Medicine, Indianapolis, IN, USA
[d] Department of Biomedical Engineering, IUPUI, Indianapolis, IN, USA
[e] Research Engineering, COOK® Medical, Bloomington, IN, USA
[f] Department of Surgery, Indiana University School of Medicine, Indianapolis, IN, USA

WHAT THIS PAPER ADDS
This study determines the contribution of the venous valve sinus to valve fluid dynamics and, hence, greatly extends our understanding of venous valve mechanics and the potential for prosthetic interventions.

Background: The majority of bioprosthetic venous valves do not have a sinus pocket and, in practice, they are often placed in non-sinus segments of the veins. The aim of this study is to investigate the effect of the sinus pocket on the flow dynamics in a prosthetic valve.
Methods: A bench top in vitro experiment was set up at physiological flow conditions to simulate the flow inside a venous system. Bicuspid bioprosthetic valves with different leaflet lengths (5 and 10 mm) were tested in tubes with and without a sinus pocket and the flows around the valve were visualized by particle image velocimetry (PIV). Velocity data measurements were made and the vorticity was calculated in the with- and without-sinus set-ups.
Results: PIV measurements showed that vortex structure was maintained by the sinus. For the 10-mm leaflet length design with sinus, the jet width at the exit of the valve was 59% of that without sinus. For the 5-mm design with sinus, the jet width was 73% of the valve without sinus. Flow from the sinus region was entrained into the main jet observed near the exit of the sinus and altered the flow at the near wall region.
Conclusions: The sinus pocket alters the flow around the valve and functions as flow regulator to smooth the flow pattern around the valve. The vortical structure inside the sinus is maintained at the valve leaflet tip during the valve cycle. For the prosthetic valve designated to be placed without a sinus, a shorter leaflet length is preferable and performs more closely to the valve with sinus.

Article history: Received 18 December 2013, Accepted 25 March 2014, Available online XXX
Keywords: Bioprosthetic valve, Flow dynamics, Pulse duplicator, Particle image velocimetry, Vortex

INTRODUCTION

The valves in the venous system play an important role in the regulation of the flow pattern of the lower extremities. The valve functions as a passive flow regulator that reacts to the pressure change[1,2] in the venous system. When the valve closes, it prevents reflux and provides a one-way flow to direct the blood back to the heart. The incompetence of the venous valve is a major cause of chronic venous insufficiency (CVI) of the lower extremities. This disease affects 10% to 35% of adults in the USA, and it is the seventh most common chronic debilitating disease.[3] A prosthetic valve to replace an incompetent venous valve has been proposed to treat venous reflux associated with CVI. In the last decade, several valve designs had been proposed[4–6] without incorporation of the sinus that normally exists in native venous valves.

The vein vessel is dilated at the valve region and creates a sinus pocket. While the dynamics of the valve itself have been studied extensively, the role of the sinus pocket in the venous system remains unclear. In the arterial system, the sinus pockets of the aortic valve are known to play a positive role in reducing the solid stress to the valve leaflet[7–9] and to prevent the leaflet from touching the vessel wall during systole.[10] For the venous valve, it is speculated that the sinus has the following functions: (a) avoid flow stasis by generation of a vortical flow behind the valve leaflet, and (b) assist valve closure by increasing the pressure inside the sinus pocket during the valve closing phase.[2,11]

The implant location of a prosthetic valve is not likely to be at the same site as the native valve. Hence, prosthetic valves must function without the sinus pocket. This raises the question of the efficiency of a prosthetic valve without a sinus. The aim of this study is try to address this question

* Corresponding author. G.S. Kassab, Department of Biomedical Engineering, IUPUI, Indianapolis, IN, USA.
E-mail address: gkassab@iupui.edu (G.S. Kassab).
1078-5884/$ — see front matter © 2014 European Society for Vascular Surgery. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ejvs.2014.03.041

from a flow dynamics point of view. An in vitro bench study was used to test prosthetic valve performance with and without the sinus pocket. The flow patterns were obtained by particle imaging velocimetry (PIV) to provide detailed velocity data in the valve. The hypothesis is that the disadvantage of a prosthetic valve without a sinus pocket can be compensated for by certain design characteristics, and the prosthetic valve performance can be improved to more closely mimic a native valve with a sinus.

MATERIAL AND METHODS

Pulse duplicator flow loop and particle image velocimetry set-up

An in vitro bench top experimental set-up was utilized to create and image the venous flow with prosthetic valves. A pulse duplicator flow loop was constructed to generate pulsatile flow to mimic the physiological conditions of the venous system, and PIV was set up in conjunction with the PD flow loop platform to perform the velocity measurements. The mean flow rate was set at 0.35 L/min at a rate of 15 BPM (beats per minute). These parameters were chosen based on previous studies on the lower extremity pressures[12] and the physiological conditions of the blood flow inside a normal adult common femoral vein,[13] as well as other sources.[14] The peak inflow pressure was set to 40 mmHg and the peak pressure difference under diastolic phase was adjusted to 2 mmHg. Additional detail on the experimental set-up can be found in a recent study.[15]

Prosthetic valves

The bioprosthetic valves used were provided by Cook Biotech Inc (West Lafayette, IN, USA). The valves were the third generation bioprosthetic venous valve (BVV3) frame with a 12 mm nominal diameter. The inner diameter of the glass tube is slightly smaller than the valve frame to ensure a tight fit between the valve and the vessel to prevent slippage or migration of the valve. Detailed information on the valve can be found in Pavcnik et al.[6] The proximal and distal sides refer to the leaflet surfaces that face the venous flow proximal or distal to the heart, respectively. Two different valve leaflet designs were tested in the current study. Fig. 1A,B shows the side views of the 5- and 10-mm-long valve designs. The main difference between these two valve designs is the length of the leaflet (10 mm long in one and 5 mm in the other). For the 10-mm-long valve, the leaflet was sutured all the way to the start of the frame, while for the 5-mm valve the leaflet edge was shortened to be roughly half of the valve frame.

Working fluid

The working fluid was a solution of glycerol and water at a volume ratio of 2:3 with a resultant viscosity of 3.6 cP (25 °C). This mixture approximates the viscosity of blood which is 3–4 cP at 37 °C. A transparent solution is necessary for the PIV technique discussed in the next section. The refraction index of the fluid is 1.4 to minimize the image distortion effect from the cylindrical tube. Under the

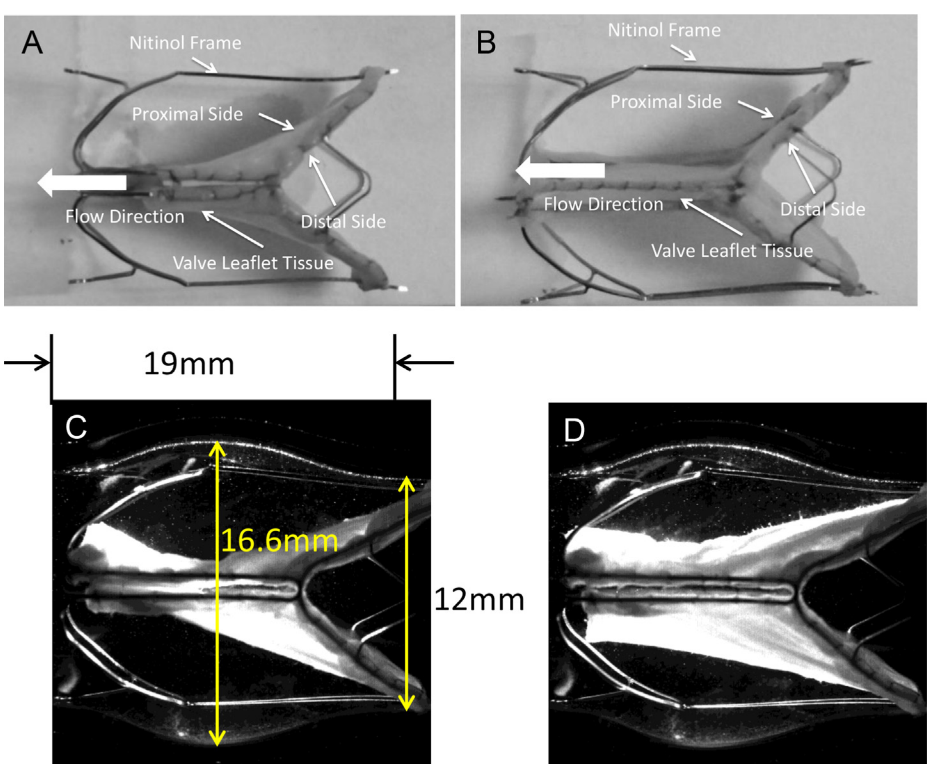

Figure 1. (A) Side view of the 5-mm prosthetic valve. (B) Side view of the 10-mm prosthetic valve. (C) Side view of the 10-mm valve fully opened, and (D) Side view of the 10-mm valve closed in the glass tube with sinus pocket. All the particle image velocimetry measurement planes were located at the center plane.

European Journal of Vascular and Endovascular Surgery Volume ■ Issue ■ p. 1—7 Month/2014

current testing conditions, the Reynolds and Womersley numbers were 358 and 4.5.

Valve testing configuration

Glass tubes of 12 mm (I.D.) with and without sinus pocket geometry were used in the test section and tested with the 5- and 10-mm-long valves. The sinus pocket dimension is shown in Fig. 1C,D. PIV images were taken at the center plane of the valve region and at the downstream region to investigate the flow field around the valve.

RESULTS

Hemodynamics

Table 1 shows the performance indices calculated from the pressure and flow data. Comparison between different valve designs also shows that the bulk flow rates of the 5-mm-long valve without the sinus were the highest. The leakage for the cases with sinus was significantly larger than those without sinus, and the 5-mm-long valve has the lowest total regurgitate volume. The closing time shows that the 5-mm valve without sinus has the fastest response, and valves without sinus responded faster than the valves with sinus. The pressure difference data were comparable for all the valves and was less than 1.5 mmHg. The effective orifice area was also comparable, but the 5-mm-long valve without sinus had the largest value.

PIV measurements

Figs. 2 and 3 show the velocity and vorticity fields measured by PIV for all four testing conditions. In general, the valve opened fully and there was less forward flow in the sinus/back of the leaflet region in the equilibrium phase. Strong jet flows were formed at the valve exit plane and hence strong vorticity was observed at the exit of the valve due to the shear flow. The shear flow layer extended in the downstream region and maintained the same width.

To further compare the differences between the four test configurations, the axial velocity profiles of all valve configurations at the exit plane of the valve were calculated and are shown in Fig. 4A. The flow jets for the cases with sinus were narrower than those without sinus. The peak velocities for the cases with sinus were also lower than those without sinus. At the wall region, valves without sinus had velocity profiles with a local minimum, while the valves with sinus had profiles that had a local maximum. In Fig. 4B, the half jet width of the 10- and 5-mm-long valves with sinus were 59% and 73%, respectively, of the valves without sinus.

The axial velocity profiles of all valve configurations at the downstream positions of the valve are shown in Fig. 5A—D. The measurement locations were normalized by the vessel diameter. In all cases, the jet flow profiles were shifted off-center, likely due to the slight asymmetry of the valve leaflet. The jet profiles were maintained in these locations, except in the 5-mm-long valve without sinus case, where the jet flow profile shifted as the flow moved downstream. Reversed flows at the wall region were found in all cases and all locations, corresponding to the shear flow structure observed in the downstream region of the valve.

DISCUSSION

The sinus functions as a flow regulator to smooth out the entrained velocity profile. The fact that the jets were narrower with the sinus than without the sinus in Fig. 4A,B shows that the flow pattern at the exit of the valves were altered by the sinus. The PIV results show the vorticity was, in general, lower for the cases with sinus than without at the shear layer region. The sinus pocket also allows the flow to turn and form a vortex structure smoothly. The vortex structure near the tip of the valve leaflets was maintained with the help of the sinus, as shown in the PIV results in Figs. 2B and 3B. This is especially true for the 5-mm-long leaflet case, since the leaflets do not extend to the end of the sinus which provides more space for the vortical structure to develop and stay. Without the sinus, the space between the leaflet and the vessel wall was limited, which can result in more sharp turns that may create local stagnation regions. During the valve-closing phase, the lasting vortical structure helps to prevent flow stasis between the leaflet and the vessel wall, which may be a potential risk factor for thrombosis.

The sinus also creates a forward flow at the near wall region during valve opening and equilibrium phase, as seen in the velocity profile at the exit planes in Fig. 4A. This is because the fluid inside the sinus pocket is pushed out by the motion of the leaflet during valve opening to create the pressure gradient on the proximal side of the leaflets. This positive pressure gradient created the forward flow at the wall region near the exit of the valve and created a weaker shear layer. This can be seen in Fig. 5A—D, where the velocity profiles for the valve with sinus at the near wall region are smoother than those without the sinus. The positive pressure gradient formed by the sinus also causes normal stress on the leaflets to limit their opening. This effect can be seen by comparing the valve openings at equilibrium phase in Fig. 2.

Table 1. Hemodynamic performance indices of the four valve testing configurations.

	5 mm with sinus	5 mm w/o sinus	10 mm with sinus	10 mm w/o sinus
Total regurgitate volume (mL/min)	94	9.2	52	30
Closing time for valve (s)	0.62	0.2	0.37	0.30
Mean positive pressure difference (mmHg)	−1.3	−1.1	−1.2	−1.3
Effective orifice area (cm^2)	0.20	0.23	0.22	0.22
Cardiac output (mL/min)	370	354	355	358

Please cite this article in press as: Tien W-H, et al., Role of Sinus in Prosthetic Venous Valve, European Journal of Vascular and Endovascular Surgery (2014), http://dx.doi.org/10.1016/j.ejvs.2014.03.041

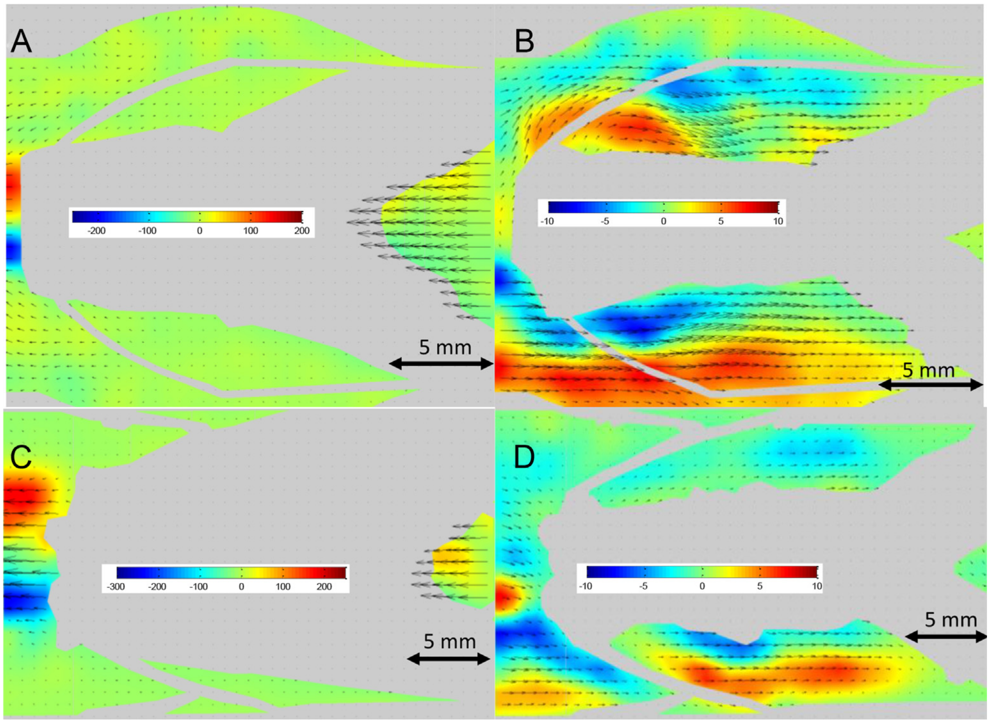

Figure 2. Particle image velocimetry (PIV) measurement results of the 10-mm valves: with sinus at the valve region for the equilibrium phase (A) and closure phase (B) of the valve cycle, and without sinus at the same location for the (C) equilibrium phase, and (D) closure phase. The vector field indicating the velocity measured by PIV and overlaid color map shows the calculated vorticity. The flow direction is from right to left. In (C), flow was formed due to the contraction region formed by the leaflet and the vessel wall. This is very different from (C), in which the leaflets and the vessel wall formed an expanding geometry and the flow was much slower. In (B) and (D), reversed flows were observed in both cases. Stronger reversed flows were found in the sinus region for (D) especially, near the back of the leaflets.

An additional advantage of the sinus may be to reduce the solid stress on the leaflet. In a finite element analysis, Grande-Allen et al.[7] showed that the leaflet stress was increased without the sinus on the spared aortic valve. Katayama et al.[9] showed that the sinus of Valsalva results in a lower solid stress to the aortic valve leaflet and facilitates the gradual but smooth closure of the valve. In their simulations, deformations of the leaflet were reduced by the sinus. This is because the sinus pocket accommodates the retrograde flow and prevents the retrograde flow to split from the axial direction to the backside of the leaflets to form a torque to bend the leaflet tip. For the prosthetic valves, the effect of the solid stress may be less important than for native venous valves, because the valve is connected to the rigid valve frame. For the fluid stress, the effect can be reduced by decreasing the leaflet length so the retrograde flow does not split up to form the bending torque. A summary of the potential venous sinus functions found in this and other studies is included in Table 2.

For the current prosthetic valve design, it appears advantageous to have a valve with a shorter leaflet. PIV results from Fig. 3A,B show that the flow structure of the 5-mm-long valve without a sinus was closer to the one with sinus than the 10-mm-long valve (Fig. 2A,B). For 5-mm valves without a sinus (Fig. 3C,D), a vortical flow structure was present near the tip of the leaflet during the closed phase, similar to the one located inside the sinus pocket for the 5-mm-long valve. In the case of 10-mm valve without a sinus (Fig. 2C,D), because the leaflet length is long, the region behind the leaflets is not enough to maintain the vortical structure. Therefore a decrease in leaflet length can provide a similar effect to the sinus pocket for maintaining the vortical flow pattern near the leaflet tip. The vertical structure only occurred at the tip of the leaflets and it may be harder to reach the root of the leaflet when the leaflet is longer. Karino and Motomiya[11] showed that, although the vortex structure near the tip of the leaflet can induce a counter-rotating vortex inside the pocket region, the flow velocity was extremely low. Flow can still be stagnant at the root of the leaflet and become a source of thrombosis. Hence, shorter leaflets reduce the size of this stagnant region, may reduce the chance of thrombosis, and have a similar performance to the valve with a sinus.

The leaflet length also has an influence on the hemodynamic performance. The 5-mm-long valve responded faster (shorter valve closing time) and had less regurgitation. This is because the short leaflet has less inertia to move, and the reduced number of suture points in the shorter leaflet length also ensures better valve quality and symmetry of the leaflets. In practice, it is hard to implant the prosthetic valve in a working sinus pocket unless a graft or stent are used to create the pseudo sinus region. Therefore, it is more desirable to design a valve that can function with the straight vessel wall but still have some of the benefits provided by the sinus.

Please cite this article in press as: Tien W-H, et al., Role of Sinus in Prosthetic Venous Valve, European Journal of Vascular and Endovascular Surgery (2014), http://dx.doi.org/10.1016/j.ejvs.2014.03.041

European Journal of Vascular and Endovascular Surgery Volume ■ Issue ■ p. 1–7 Month/2014

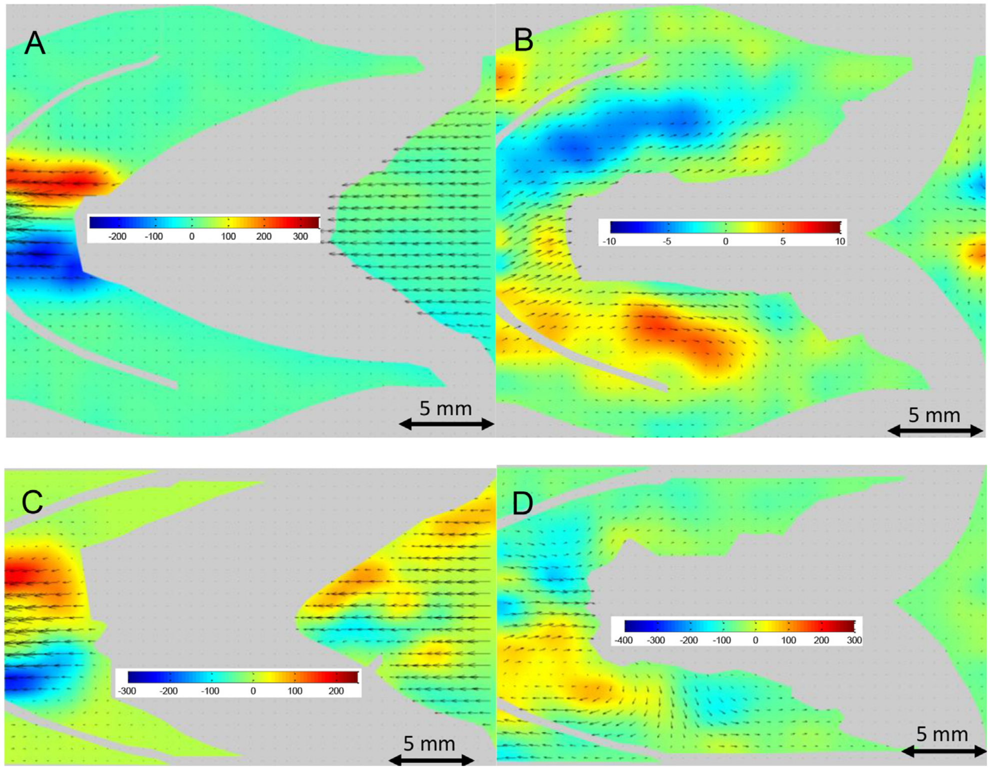

Figure 3. Particle image velocimetry measurement results of the 5-mm valves: with sinus at the valve region for the equilibrium phase (A) and closure phase (B) of the valve cycle, and without sinus at the same location for the (C) equilibrium phase and (D) closure phase. The vector field indicating the velocity measured by PIV and overlaid color map shows the calculated vorticity. The flow direction is from right to left. Higher vorticity was observed in both (A) and (C) than in the 10-mm valve cases (Fig. 2A,C). Vorticity inside the sinus pocket was low at (A) and (C), but vortical flow patterns were observed in both the (B) and (D) cases. The flow was reversed for the cases with sinus (A) but more random for the cases without sinus (D).

Some limitations of this study warrant discussion. First, the vessel is rigid and has no compliance. This is likely to be the cause of the higher leakage for the valves with sinus because the rigid valve frame and the rigid vessel cannot provide a good seal at the side of the valve. Second, the leakage from the valve with sinus was significantly larger than that without sinus. The main reason is that the valve frame was designed for the vessel without the sinus. The suturing points of the valve leaflet to the frame did not extend to the sinus region, as shown in Fig. 1A,B. This results in leakage from the side of the valve when the valve is fully closed. During the opening and equilibrium phases, the opening of the valve provides a path of lower resistance, so flow across the leaking region is expected to be minimal. Additionally, the PIV measurement plane is located at the center of the vessel and is away from the leaking region. As a result the impact on the measured flow structure during opening phases is expected to be minimal. The valve with sinus did respond more slowly. The closing time was three times slower for the 5-mm-long valve and

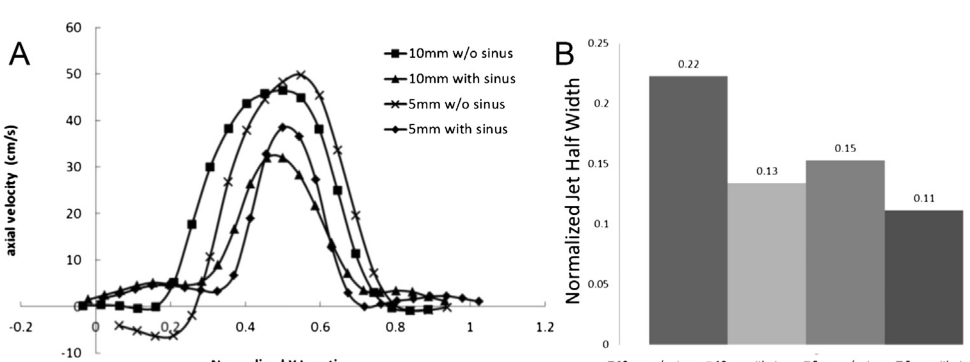

Figure 4. (A) Velocity profiles of the equilibrium phase at the exit of the four valve test configurations. The profiles are shifted to align to the center, and the location is normalized by the tube diameter D. (B) Jet half width of the four valve test configurations calculated from Fig. 3A. The half jet width is defined as the distance measured from the centerline of the jet where the velocity is equal to half of the centerline velocity and was normalized by the tube diameter D.

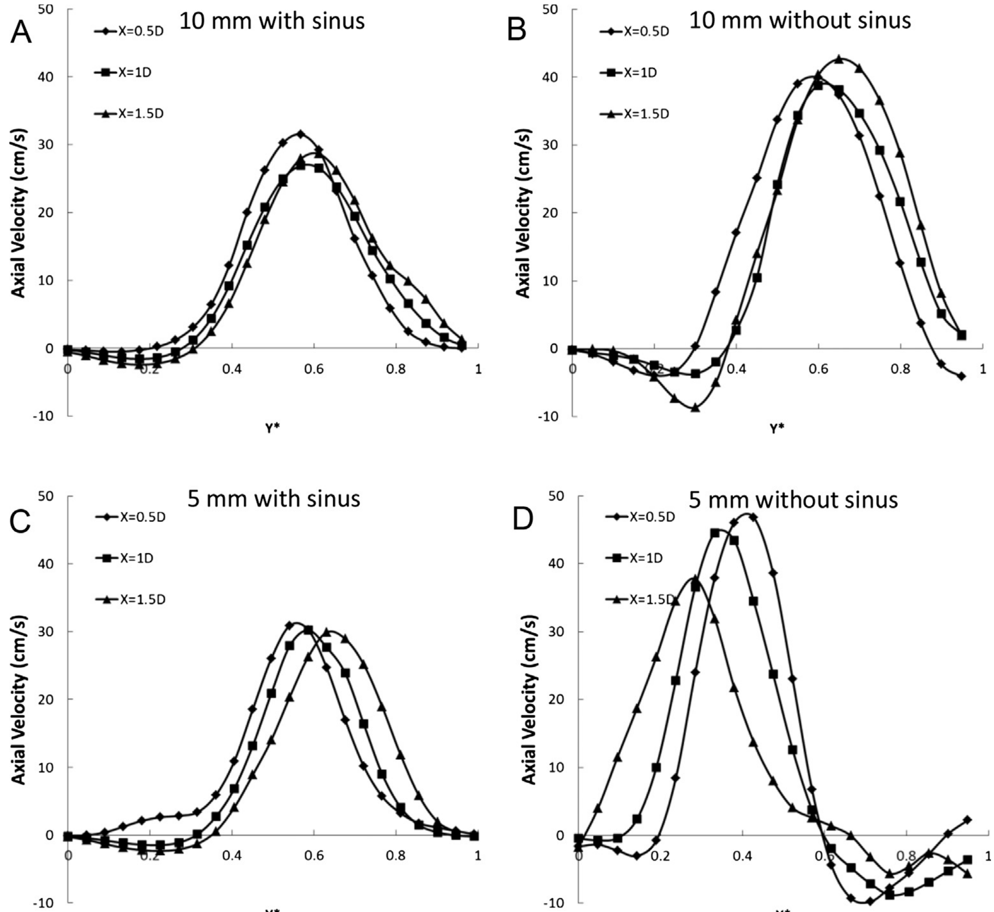

Figure 5. (A—D) Velocity profiles of the equilibrium phase at different downstream locations for the four valve test configurations. The X locations were normalized by the diameter of the vessel. Y* was normalized by the diameter of the vessel, Y* = Y/D.

23% slower for the 10-mm valve. The effective orifice area (EOA) (a measure of the valve performance and flow resistance) was found to be at the same level for all valve configurations. This suggests that although the flow inside the sinus pocket created slightly more resistance to the valve motion, it provided similar flow resistance to the flow system.

CONCLUSION

In summary, the flow dynamic effect of a sinus pocket around a venous valve was investigated using bicuspid bioprosthetic valves with an in vitro PIV set-up. The sinus significantly altered the flow around the valve and helped to maintain the vortex structure during the valve cycle. For the prosthetic valve design, it was found that a shorter leaflet length can create an effect similar to the sinus pocket to provide fluid dynamic advantages.

Table 2. Summary of venous sinus functions determined in this and other studies.

Function(s) of sinus	References
Avoids flow stasis (generates vortical flow structure behind leaflets)	Karino and Motomiya,[11] Lurie et al.,[2] Current study
Reduces solid stress on valve leaflets (accommodates the retrograde flow and reduces bending torque to the leaflets)	Grande-Allen et al.,[7] Katayama et al.[9]
Assists valve closure	Lurie et al.[2]
Lowers wall shear stress (reduces vorticity around the wall region)	Current study

ACKNOWLEDGEMENTS

This research was supported by 3DT Holdings, LLC, and COOK® Medical.

We wish to acknowledge the excellent technical expertise of Dr. Chad Johnson and Mrs. Martha Spicer for their excellent technical expertise.

CONFLICT OF INTEREST

None.

REFERENCES

1 Qui Y, Quijano RC, Wang SK, Hwang NH. Fluid dynamics of venous valve closure. *Ann Biomed Eng* 1995;**23**(6):750—9.
2 Lurie F, Kistner RL, Eklof B, Kessler D. Mechanism of venous valve closure and role of the valve in circulation: a new concept. *J Vasc Surg* 2003;**38**:955—61.

3 Criqui MH, Jamosmos M, Fronek A, Denenberg JO, Langer RD, Bergan J, et al. Chronic venous disease in an ethnically diverse population: the San Diego Population Study. *Am J Epidemiol* 2003;**158**(5):448—56.

4 de Borst GJ, Moll FL. Percutaneous venous valve designs for treatment of deep venous insufficiency. *J Endovasc Ther* 2012;**19**(2):291—302.

5 Zervides C, Giannoukas AD. Historical overview of venous valve prostheses for the treatment of deep venous valve insufficiency. *J Endovasc Ther* 2012;**19**(2):281—90.

6 Pavcnik D, Uchida B, Kaufman J, Hinds M, Keller FS, Rösch J. Percutaneous management of chronic deep venous reflux: review of experimental work and early clinical experience with bioprosthetic valve. *Vasc Med* 2008;**13**(1):75—84.

7 Grande-Allen KJ, Cochran RP, Reinhall PG, Kunzelman KS. Recreation of sinuses is important for sparing the aortic valve: a finite element study. *J Thorac Cardiovasc Surg* 2000;**119**(4 Pt 1):753—63.

8 Beck A, Thubrikar MJ, Robicsek F. Stress analysis of the aortic valve with and without the sinuses of Valsalva. *J Heart Valve Dis* 2001;**10**(1):1—11.

9 Katayama S, Umetani N, Sugiura S, Hisada T. The sinus of Valsalva relieves abnormal stress on aortic valve leaflets by facilitating smooth closure. *J Thorac Cardiovasc Surg* 2008;**136**(6). 1528—1535.e1.

10 Fries R, Graeter T, Aicher D, Reul H, Schmitz C, Böhm M, et al. In vitro comparison of aortic valve movement after valve-preserving aortic replacement. *J Thorac Cardiovasc Surg* 2006;**132**(1):32—7.

11 Karino T, Motomiya M. Flow through a venous valve and its implication for thrombus formation. *Thromb Res* 1984;**36**(3):245—57.

12 Meissner MH, Moneta G, Burnand K, Gloviczki P, Lohr JM, Lurie F, et al. The hemodynamics and diagnosis of venous disease. *J Vasc Surg* 2007;**46**(6):S4—24.

13 Fronek A, Criqui MH, Denenberg J, Langer RD. Common femoral vein dimensions and hemodynamics including Valsalva response as a function of sex, age, and ethnicity in a population study. *J Vasc Surg* 2001;**33**(5):1050—6.

14 Rittgers SE, Oberdier MT, Pottala S. Physiologically-based testing system for the mechanical characterization of prosthetic vein valves. *Biomed Eng Online* 2007;**6**:29.

15 Tien WH, Chen HY, Berwick ZC, Krieger J, Chambers S, Dabiri D, et al. Hemodynamic coupling of a pair of venous valves. *J Vasc Surg Venous Lymphatic Disord*; 2014. http://dx.doi.org/10.1016/j.jvsv.2013.09.008.