STEREOSCOPIC PIV IN STEADY FLOW THROUGH A BILEAFLET MECHANICAL HEART VALVE

by

Christopher Hutchison

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Graduate Department of Mechanical and Industrial Engineering
University of Toronto

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Abstract

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The tendency of aortic bileaflet mechanical heart valves (BiMHVs) to promote thrombosis has been well documented in the literature. The relationship of thrombosis to valve fluid dynamics has prompted numerous studies of aortic BiMHV flow. In this study, steady flow was investigated downstream of a model Carbomedics No. 25 BiMHV in an axisymmetric aortic sinus using stereoscopic particle image velocimetry (SPIV). The Reynolds number based on inlet diameter was 7600, and the measurement plane was perpendicular to the leaflet axes at the centerline of the aortic sinus. The typical formation of three jets was observed: the upper and lower lateral orifice jets, and the central jet. Flow separation from the valve ring was seen, and large scale vortices were identified in both the upper and lower sinus regions. An asymmetry in the reverse flow was found, and possible causes were discussed. All three jets were seen to decay similarly to free rectangular jets, with zero decay initially, followed by a 'linear' decay rate in which $U_{max}^2 \propto X$. The central jet was also seen to be self similar in the linear decay region. Analysis of the out-of-plane velocity yielded two alternate explanations of streamwise vortex (i.e. Ω_x) structure, with either a four-cell or an eight-cell streamwise vortex structure being present in the mean velocity field. Organization of large scale three dimensional flow structures was thus apparent. Calculation of in-plane Reynolds stresses showed that values were highest in the outer shear layers of the lateral orifice jets. Elevated Reynolds shear stress values were also found in the leaflet wake regions, and the shear layers of the central jet.

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List of Symbols

b	local weighted mean smoothing parameter
C	lens radius
d	inlet and outlet diameter
dx	X direction displacement
dy	Y direction displacement
dz	Z direction displacement
d_i	lens image distance
d_o	lens object distance
d_p	particle diameter
d_s	aortic sinus diameter
f	lens focal length
$f(x,y)$	local weighted mean mapping function
$f\#$	camera aperture setting
H_i	contraction inlet radius
H_o	contraction outlet radius
h_c	contraction radius
h_2	He-Ne laser beam diameter
l_c	contraction length
M	nominal image magnification
N	number of samples
N_{cp}	number of control points
n	index of refraction
n_{vec}	number of vectors
n_2, n_3	lens 2 and lens 3 normal
P	mean pressure
p	instantaneous pressure
p_i	local weighted mean interpolating polynomial
Q	Flow rate
q, k	distorted image coordinates

R_i	local weighted mean weighting function
r_i	local weighted mean ratio function
Re	Reynolds number
$RMSD$	root mean square deviation
St	particle Stokes number
s	particle/fluid density ratio
t	time
Δt	laser pulse time separation
U	mean X direction, axial, velocity
U_0	bulk inlet velocity
u	instantaneous X direction, axial, velocity
u'	fluctuating X direction, axial, velocity
V	mean Y direction, transverse, velocity
v	instantaneous Y direction, transverse, velocity
v'	fluctuating Y direction, transverse, velocity
W	mean Z direction, out-of-plane, velocity
w	instantaneous Z direction, out-of-plane, velocity
w'	fluctuating Z direction, out-of-plane, velocity
X	axial coordinate
ΔX	axial vector spacing
x, y	undistorted image coordinates
Y	transverse coordinate
ΔY	transverse vector spacing
Z	out-of-plane coordinate

Tensor Notation

U_i, U_j	mean velocity in i and j directions (tensor notation)
u_i, u_j	instantaneous velocity in i and j directions (tensor notation)
u_i', u_j'	fluctuating velocity in i and j directions (tensor notation)
x_i, x_j	cartesian coordinate in i and j directions (tensor notation)
δ_{ij}	Kronecker delta

Greek Symbols

α	angle between XZ plane particle rays and laser sheet normal
β	angle between YZ plane particle rays and laser sheet normal
Δ_v	vortex identification threshold
∂	denotes partial differentiation
ϕ	Scheimpflug angle
η	particle/fluid amplitude ratio
φ	angle between lens normal and laser beam ray
λ	laser light wavelength
ν	kinematic viscosity
θ	diffuser angle
θ_2	laser beam divergence after lens 1
θ_3	laser beam divergence after lens 3
ω	turbulent fluctuation frequency
ρ	fluid density
ρ_p	particle density
ψ	particle/fluid phase angle lag
Ω	mean vorticity
ζ	laser sheet rotation angle

Chapter 1

Introduction

Cardiovascular disease is a leading cause of death around the world, and in many cases can be attributed to heart valve dysfunction (WHO 2007). In particular, aortic heart valve disease results in the valve being either stenotic and/or regurgitant, which places undue stress on the heart to maintain normal blood flow to the body (Thubrikar 1990). In this case, valve replacement is usually required, and over 180,000 heart valve replacements are made throughout the world each year (Yoganathan et al. 2004).

The bileaflet mechanical heart valve (BiMHV) has been the most successful replacement mechanical heart valve, and is currently the most commonly implanted mechanical valve (Grunkemeier et al. 2003). Although the BiMHV is an improvement over previous mechanical heart valves, there are still serious associated complications with its use that must be eliminated. Fluid mechanics plays a major role in prosthetic valve efficacy, and designs have evolved based primarily on improvement of flow characteristics.

The current in vitro study investigated the flow downstream of a model BiMHV in a model aorta. The flow through a BiMHV is highly complex and not well understood, but continued analysis of the flow may lead to improved device design, and thus a reduction in clinical complication rates.

1.1 Aortic BiMHVs

The heart, blood vessels, and blood comprise the cardiovascular system. The heart supplies the organs, tissues and cells of the body with blood. Blood flows through the blood vessels, carries oxygen and nutrients to cells, and removes waste products such as carbon dioxide. The heart is made up of four chambers, the left atrium and ventricle, and the right atrium and ventricle. The left and right heart are separated by a septum (see Figure 1.1). The right atrium and ventricle together, accept deoxygenated blood from the body and deliver it to the lungs via the pulmonary arteries. The left atrium and ventricle take oxygenated blood from the lungs via the pulmonary veins and pump it through a large blood vessel called the aorta to the rest of the body. The cardiac cycle is broken into two phases: systole, when the ventricles contract, and diastole, when the ventricles relax.

Figure 1.1 Diagram of the human heart. From <http://my.clevelandclinic.org/heart/disorders/valve/yourheartvalves.aspx>

Four valves are used in the heart to prevent regurgitation (i.e. backflow) from occurring in the atria and ventricles. On the right side of the heart, the tricuspid valve permits blood to flow from the right atrium to the right ventricle. The pulmonary valve permits blood to

flow from the right ventricle to the pulmonary arteries. On the left side of the heart, the mitral valve regulates flow between the left atrium and left ventricle, and the aortic valve allows blood to enter the aorta from the left ventricle.

Figure 1.2 Diagram showing the aortic sinus, ascending aorta, and the three leaflets of the aortic valve. From http://my.clevelandclinic.org/heart/disorders/aorta_marfan/complexaortasurgery.aspx

The aortic valve opens and closes over 100,000 times a day and is subject to the highest flow velocities of over 1 m/s at peak systole in healthy adults (Yoganathan et al. 2004). The function and design of the aortic valve and ascending aorta is guided by hydrodynamic considerations. Posterior to the aortic valve, and at the root of the aorta, is a structure called the aortic sinus which is comprised of three bulges located circumferentially about 120° apart (Thubrikar 1990). Figure 1.2 shows the aortic sinus and the aortic valve which has three leaflets. When the valve opens in systole, its three leaflets move towards the sinus walls to allow unobstructed, centralized flow. Closure of the aortic valve in diastole is aided by vortices formed in the sinus region.

Malfunction of the aortic valve occurs due to valvular disease, which results in either regurgitant flow, or obstructed flow. Flow obstruction occurs due to narrowing of the valve orifice, and is termed stenosis. Some degree of regurgitation and stenosis can be tolerated, but if patient condition deteriorates by a significant amount then valve replacement is required (Thubrikar 1990). Replacement heart valves are either prosthetic or human tissue valves. A human tissue valve can be a homograft from another human, or an autograft from the patient (Grunkemeier et al. 1992). Human tissue valves are limited by donor availability and therefore a valve prostheses must often be implanted. Prosthetic valves can be categorized into two main groups: bioprosthetic valves and mechanical heart valves (MHVs). The lifespan of a typical bioprosthetic heart valve is around 10 - 15 years and therefore these valves are often used in older patients (Puvimanasinghe et al. 2004). MHVs offer superior durability, and therefore are often used in younger patients with longer life expectancies. Bioprosthetic valves include harvested bovine and porcine valves, and pericardial valves made from bovine or porcine pericardium. MHVs consist primarily of caged-ball, tilting-disk, and bileaflet valve designs (Yoganathan et al. 2004). Most recently, hinged tri-leaflet and polymeric valves have been developed but have not yet been approved for clinical use (Brucker et al. 2002, Leo et al. 2006).

The first MHV was of a caged-ball design, and was first implanted in the 1960's. Early on it was found that hemodynamics played a primary role in valve efficiency and associated clinical complications. In an attempt to improve hemodynamics, tilting disk valves were developed in the early 1970's. Most recently, bileaflet mechanical heart valves (BiMHVs) were developed, and have been the most successful mechanical heart valve (Grunkemeier et al. 2003). The first BiMHV was designed by St. Jude Medical and implanted in 1977. Since then, several other companies have developed BiMHVs, and apart from St. Jude Medical, the most prominent is Carbomedics. The Carbomedics and St. Jude Medical valves combined account for about 85% of all implanted BiMHVs (Grunkemeier et al. 2000).

The goal of a mechanical valve is to provide centralized flow similar to a natural valve, but flow obstruction inevitably occurs due to the positioning of the valve occluder. The valve occluder decreases the cross sectional area available for blood flow, increases energy loss across the valve, and creates non-physiological turbulence in the aorta (Shahbazi 2007). Figure 1.3 shows a photograph and diagram of an aortic BiMHV. The valve occluders are two semicircular "leaflets" which are hinged at either end. The pivots are set into the valve ring which is surrounded by a sewing cuff. The leaflets rotate from the fully closed position (shown by the dashed lines) to the fully open position (blackened) in Figure 1.3(c). During systole, in the presence of a favourable pressure gradient, the leaflets open and forward flow enters the aortic sinus. When an adverse pressure gradient is applied (during diastole), the leaflets rotate back. In a BiMHV, a small amount of regurgitation occurs, which acts to wash out the hinge region (Leo et al. 2002). When the valve is open, two orifices are formed on either side of the leaflets and are called the lateral orifices. The orifice between the leaflets is called the central orifice (Yoganathan et al. 2004).

Figure 1.3 (a) Carbomedics No. 25 BiMHV with leaflets in open position (rear view). (b) Diagram of the valve showing leaflets in closed position. (c) Top view of valve leaflets in fully open position, and fully closed position (dashed lines).

BiMHV design has greatly improved over early tilting disk and caged-ball designs, but BiMHVs still have serious associated complications mainly due to thrombosis (Yoganathan et al. 2004). Hemolysis is also believed to occur from flow through a BiMHV. Thrombosis is defined as the formation of a blood clot (thrombus), and hemolysis is defined as the lysis of red blood cells. Often thrombi are found on the valve

ring and in the hinge region of explanted BiMHVs. A severe case of thrombus formation on a BiMHV is shown in Figure 1.4. The presence of thrombi can cause improper function of the valve leaflets (Shapira et al. 2000). Platelet activation is a factor in thrombosis, and along with hemolysis, has been associated with regions of high laminar shear stress (viscous shear stress) and turbulent shear stress (Reynolds shear stress) (Ge et al. 2008). However, as noted by Ge et al. (2008), these regions do not always coincide in BiMHV flow which complicates evaluation of the thrombogenic potential of BiMHVs.

Figure 1.4 Photograph of severe thrombus formation on an explanted BiMHV. From http://www.rbccv.org.br/imprimir_port.asp?id=448

Several experiments have been attempted to quantify a threshold limit for hemolysis and platelet damage with respect to shear stress. Grigioni et al. (1999) performed a 3D stress analysis of submerged impinging jet data from Sallam and Hwang (1984), and found that turbulent stress of 6000 dyne/cm^2 ($10 \text{ dyne/cm}^2 = 1 \text{ Pa}$) was required for hemolysis at an exposure time of 1 ms. Paul et al. (2003) found that hemolysis occurred at a viscous shear stress of 4500 dyne/cm^2 for an exposure time of 600 ms. However, hemolysis can occur at shear stresses an order of magnitude lower if foreign surfaces are present (Yoganathan et al. 1986). In a review article, Hellums (1994) used previous data and characterized platelet activation with serotonin release. A viscous shear stress threshold level of 1000 dyne/cm^2 at 100 ms exposure was reported. In the presence of turbulent shear stress and a smaller exposure time of 0.01 ms, platelet activation occurred at $5 \times 10^5 \text{ dyne/cm}^2$. These values demonstrate the dependence of hemolysis and platelet activation on viscous shear stress, Reynolds shear stress, and exposure time. In general, red blood

cells and platelets can be damaged with less fluid stress under longer exposure times (Ge et al. 2008). The findings have prompted numerous studies investigating the flow field downstream of a BiMHV and these are discussed in the following section.

1.2 Literature Review

Numerous experimental studies have been performed to investigate regions of high shear stress, and better understand the fluid mechanics downstream of an aortic BiMHV (Yoganathan et al. 1982, 1984, 1986, Chandran 1985, Woo and Yoganathan 1986, Hanle et al. 1988, 1989, Fatemi and Chandran 1989, Giersiepen et al. 1989, Brucker 1997, Barbaro et al. 1998, Fontaine et al. 1996, Bluestein et al. 2000, Browne et al. 2000, Ellis et al. 2000, Liu et al. 2000, Grigioni et al. 2001, Leo et al. 2002, Balducci et al. 2004, Castellini et al. 2004, Marassi et al. 2004, Ge et al. 2005, 2008, Dasi et al. 2007, Kaminsky et al. 2007a, 2007b, 2008 and others). Although in vivo techniques such as pulsed Doppler ultrasound (Travis et al. 2004) and magnetic resonance imaging (MRI) (Hasenkam 1999) show promise, spatial resolution and accuracy are still too low for detailed flow mapping (Yoganathan et al. 2005). Because of this, experimental studies have been restricted to in vitro experiments to adequately resolve flow structures and turbulent Reynolds stresses.

Yoganathan et al. (1982) initially characterized major flow structures downstream of a BiMHV in a model aorta using laser Doppler anemometry (LDA) in steady flow. The forward flow was divided into three jets: two jets, on either side of the leaflets through the lateral orifices, called the lateral orifice jets, and one jet through the central orifice, called the central jet. The lateral orifice jets separated from the valve ring and recirculation regions were created near the sinus walls. The plane perpendicular to the leaflet pivot axes and passing through the centerline of the aortic sinus has been most often measured primarily for flow structure visualization purposes. In this thesis this plane will be called the *centerline perpendicular plane*. The plane parallel to the leaflet pivoting axes and passing through the centerline of the aortic sinus will be called the *centerline parallel plane*.

It is useful to define flow structures and other regions of the flow more specifically in order to facilitate further discussion. A flow visualization image of the centerline perpendicular plane is shown in Figure 1.5, with flow structures labelled.

Figure 1.5 Flow visualization image on the centerline perpendicular plane at a peak systolic Reynolds number. Flow is from left to right. Upper and lower lateral orifice jets are 3 and 8 respectively. Approximate locations of the upper and lower lateral orifice jet shear layers are shown by dashed lines (2 and 9 respectively). The upper and lower central jet shear layers are shown by dashed lines (4 and 7 respectively). The central jet (5) and leaflet wakes (6) downstream of the leaflets are shown. The upper and lower sinus recirculation regions are 1 and 10 respectively.

The two lateral orifice jets are distinguished as the upper lateral orifice jet (3) and lower lateral orifice jet (8). The central jet (5) is shown, and the leaflets are highlighted at the left side of the image. The upper and lower sinus recirculation regions (1 and 10) are shown as the elliptical regions. Leaflet wakes (6) are shown downstream of the leaflets in the central jet. The coordinate system is shown with the Y axis at the leaflet tips, and the X axis along the aortic sinus centerline. Shear layers exterior to the lateral orifice jets are called the upper and lower lateral orifice jet shear layers, and shown as 2 and 9 respectively. The shear layers between the lateral orifice jets and central jet are called the

upper and lower central jet shear layers, and shown as 4 and 7 respectively. Dashed lines show approximate shear layer locations.

In vitro experiments differ by measurement technique, aortic sinus geometry, and upstream conditions. Early studies used one, two, and three component laser Doppler anemometry (1C-LDA, 2C-LDA and 3C-LDA) to measure single points within the flow with high temporal resolution. Later, two component particle image velocimetry (2C-PIV) allowed multi-point planar measurements and quantitative visualization of spatial flow structures, helpful in describing BiMHV flow dynamics. Most recently, stereoscopic PIV (SPIV) has been used to measure all three velocity components on a plane in the flow.

Generally either a rigid three sinus chamber, or an axisymmetric sinus chamber is used to simulate the aortic sinus. A three sinus design better reproduces in vivo conditions, but good optical access for measurements is more difficult to achieve (Lim et al. 1994). An axisymmetric sinus design shows similar flow features, creates less optical distortion, and has therefore been used extensively (Yoganathan et al. 1984, Ge et al. 2005, Fontaine et al. 1996, Liu et al. 2000, Fatemi and Chandran 1989). Furthermore, axisymmetric sinus designs facilitate computational fluid dynamics (CFD) validation studies (Ge et al. 2005, Shahbazi 2007, Dasi et al. 2007). In most cases, experiments incorporate straight inlet and outlet piping. Some studies, however, have used a distensible left ventricular model in attempts to better simulate in vivo inlet conditions, though the conditions at the inlet of the aortic sinus are much less controlled in such an environment (Pierrakos et al. 2004, Giersiepen et al. 1989, Liu et al. 2000). In terms of inlet flow type, both steady and pulsatile flow have been studied.

Some steady flow studies have used dimensional similitude to match a steady flow Reynolds number to that at peak systole in pulsatile flow (Fontaine et al. 1996, Browne et al. 2000, Marassi et al. 2004, Ge et al. 2005). The Reynolds number used in this study is defined in Equation 3.12, which for the current geometry is equivalent to

$$\text{Re} = \frac{4Q}{\pi d \nu}$$

Equation 1.1

where Q is the inlet and outlet flow rate to the sinus, d is the diameter of the ascending aorta, and ν is the kinematic viscosity of the fluid. The Reynolds number at peak systole in a human aorta is between 5000 and 10,000 and typically around 7000 (Ge et al. 2005).

The first aortic BiMHV studies were performed by Yoganathan et al. (1982, 1984) in steady flow at mid- and peak systolic flow rates, and it was later shown by Hanle et al. (1988, 1989) that steady and pulsatile flow measurements corresponded best at peak systole. Yoganathan et al. (1984) used 2C-LDA in steady flow and measured the highest velocities at peak systole in the lateral orifice jets, and observed reverse flow near the sinus walls. Separated flow was seen downstream of the valve ring, which has been linked to excess tissue growth and thrombosis (Giddens et al. 1993). The axial velocity and Reynolds shear stress profiles closely resembled those found in pulsatile flow studies. Hanle et al. (1988) used 1C-LDA and showed the presence of a four cell vortex system in the cross-section of the aorta in steady flow, and that these same structures were present, in pulsatile flow. Thus, steady flow can potentially reveal flow characteristics found in more complex pulsatile flow. Velocity and Reynolds stress magnitude found in steady flow tended to be an upper bound on that found in pulsatile flow (Hanle et al. 1988). Leaflet wakes were also observed which caused a velocity defect in the central jet, and this added to an unrecoverable pressure drop across the valve. These studies illustrated the three dimensionality of the flow, and that studying steady flow at can assist in the physical understanding of pulsatile flow.

However, with the exception of Castellini et al. (2004), Browne et al. (2000), and Fontaine et al. (1996), there have been very few steady flow aortic BiMHV studies since the initial experiments noted above, as most have focused on pulsatile flow. Castellini et al. (2004) used 2C-PIV in steady flow to measure the flow in off-centerline perpendicular planes. High vorticity at the leaflet trailing edges was highlighted in the centerline plane, whereas in off-centerline planes, peak vorticity was observed near the sinus walls. Browne et al. (2000) used 2C-LDA and 2C-PIV and measured the centerline parallel

plane in steady flow and showed a multi-peaked profile of the central jet across its long axis. Fontaine et al. (1996) used 3C-LDA in steady flow and compared the use of 2D and 3D principal stress analyses to determine the maximum stress experienced by blood cells using Reynolds stresses. On the centerline perpendicular plane, it was found that the in-plane Reynolds stress only underestimated the principle shear stress by 13%. This indicated that on the centerline perpendicular plane that both the principal and in-plane Reynolds shear stresses were well aligned, and thus in-plane shear was dominant over out-of-plane shear. On the centerline perpendicular plane at $X/d \approx 0.4$, peak Reynolds shear stresses and normal stresses of 800 dyne/cm^2 and 2100 dyne/cm^2 respectively were found in the lateral orifice jet shear layers.

Pulsatile flow experiments have been performed to investigate the flow field at different times in the cardiac cycle. The studies are normally done with a pulse duplicator that creates an inlet flow waveform similar to that produced by the left ventricle. Flow is accelerated to the point of peak systole, and decelerated in diastole. Experimentally and numerically modeled pulsatile flow is important to the understanding of flow development throughout the full cardiac cycle. Woo and Yoganathan (1986) used 2C-LDA and observed that during systolic acceleration, one of the lateral orifice jets was skewed towards the sinus wall, which was attributed to asynchronous leaflet opening. Asymmetries were also seen in the recirculation regions where reverse flow was higher on one side than the other. Secondary peaks in the central jet were found when the centerline parallel plane was measured. The flow was seen to be highly turbulent at peak systole, and the central jet flow was more turbulent than the lateral orifice jets. The highest turbulent shear stresses were found in the lateral orifice jet shear layers at peak systole. On the centerline perpendicular plane, maximum Reynolds shear stress values were calculated to be 1500 dynes/cm^2 at $X/d \approx 0.3$ (Yoganathan et al. 1986). Liu et al. (2000) used 2C-LDA and related the local length and time scales of the flow to red blood cell and platelet damage. It was noted that length scales of turbulent eddies needed to be on the order of red blood cell diameter ($8 \text{ }\mu\text{m}$) or platelet size ($4 \text{ }\mu\text{m}$) to cause damage. In Liu et al. (2000), simplifying assumptions were made to calculate the smallest turbulent length scale, the Kolmogorov scale. The pulsatile flow cycle was broken into 'quasi-

steady' segments in order to apply Taylor's frozen field hypothesis. The flow was assumed isotropic and homogeneous, which was notably not the case, but was required for the calculation. The Kolmogorov scale was found to be 25 - 43 μm . In addition, integral time scales, the largest turbulent time scales, were calculated throughout the flow cycle. The smallest integral time scale was roughly 1 ms at peak systole, and largest at roughly 10 ms in early systole. It was concluded that blood cells could be damaged due to the levels of Reynolds shear stress and the size and time scales of turbulent vortices.

Measuring of the flow field in the hinge region of a BiMHV has been of recent interest and is considered one of the most important aspects of the flow due to the high velocities and shear stresses found near the hinge during regurgitation (Yoganathan et al. 2004). Leo et al. (2002) measured Reynolds shear stresses as high as 5000 dyne/cm^2 in the hinge region of a Carbomedics valve using 2C-LDA. Ellis et al. (2000) found Reynolds shear stresses of 2600 dyne/cm^2 in a new St. Jude Medical BiMHV model, though values as high as 7200 dyne/cm^2 have been measured in older St. Jude Medical models (Yoganathan et al. 2004).

In the past, PIV studies in pulsatile flow have been phase locked and have recorded selected instants in the cardiac cycle. These measurements contained cycle-to-cycle variations that may have hidden turbulent structures when ensemble averaging was used (Ge et al. 2008). A similar occurrence is found in cyclic engine flows, and techniques such as discrete wavelet transform (DWT) and proper orthogonal decomposition (POD) have been used to filter results (Ancimer et al. 2000, Suk 1999, Kostas et al. 2005). Liu et al. (2000) noted these cycle-to-cycle variations from 2C-LDA data and hypothesized that turbulence in the sinus may be affected by energy supplied from the previous cycle. Dasi et al. (2007) used 2C-PIV at 42 instances in the cardiac cycle and was able to describe pulsatile flow development in detail. In systolic acceleration, organized von Karmen vortex shedding was observed in the leaflet wakes, and it was hypothesized that a vortex ring-like structure was present in the sinus recirculation regions. At peak systole, transition to turbulence occurred rapidly and finer scale turbulent eddies were observed (Dasi et al. 2007). Ge et al. (2008) analyzed data from Dasi et al. (2007) and

found that cycle-to-cycle variations largely contaminated Reynolds stress calculations, and regions of high Reynolds stress and high viscous shear stress did not coincide. It was also found that Reynolds stresses were more than an order of magnitude larger than viscous stresses in BiMHV flow. Balducci et al. (2004) used high-speed 2C-PIV with a data acquisition rate of 1 kHz, together with particle tracking velocimetry (PTV) to describe vortices and particle residence time within the sinus. The flow was highly anisotropic and three dimensional. Vortices were found to move within the sinus during the flow cycle, and larger vortices were seen in the early systole compared to peak systole. At peak systole, particle residence time in the sinus was estimated at 30 ms.

The first SPIV measurements in prosthetic heart valve flow were done on a bioprosthesis by Marassi et al. (2004). Most recently, aortic BiMHV pulsatile flow measurements have been obtained using high-speed SPIV with an acquisition rate of 3 kHz but only for only a limited number of cycles due to memory limitations (Kaminsky et al. 2007a, 2008). Kaminsky et al. (2007a) measured three velocity components on the centerline perpendicular plane and found that the out-of-plane velocity was highest in the recirculation regions near the sinus walls. Kaminsky et al. (2008) observed a similar azimuthal vortex pattern to that seen by Hanle et al. (1988). The flow was seen to be highly three dimensional. Although high-speed PIV studies are useful for investigating detailed flow development and the source of cycle-to-cycle variations, independent sample sizes, N , on the order of $10^3 - 10^4$ are needed to obtain reliable second order turbulence statistics (i.e. Reynolds stresses) in this flow (Wernet et al. 2000, and discussed in Appendix A). In general, the independent sample size in previous aortic BiMHV experiments using PIV has been small. For example, Browne et al. (2000) had $N = 16$, Balducci et al. (2004) had $N = 90$ cycles, Ge et. al (2005) had $N = 300$, Dasi et al. (2007) had $N = 250$ cycles, and Kaminsky et al. (2008) had $N = 100$ cycles. Appendix A shows that a high statistical error in Reynolds stresses can result from using such small datasets.

Computational fluid dynamics (CFD) studies have also been of great interest in the field of BiMHV research. Initial two dimensional numerical simulations by Bluestein et al.

(2000) simulated leaflet vortices seen in experiments by Brucker et al. (1997), and it was thought that these vortices may be the sites of free thrombi formation (Bluestein et al. 2000). Recently, advanced numerical codes have been developed that may be able to accurately model the complex, turbulent, and three dimensional flow downstream of a BiMHV throughout the entire cardiac cycle (Shahbazi 2007, Ge et al. 2005, Dasi et al. 2008). Complex three dimensional vortex dynamics has been modelled by Dasi et al. (2007), and the ability to perform inexpensive parametric studies with different valve geometries using CFD has enormous potential. Grigioni et al. (2001) used 2C-LDA to compare leaflet geometry of two BiMHVs and found that leaflet curvature was an important parameter in BiMHV design. The computational resources for such simulations are significant, and only small sample sizes have been obtained ($N = 10$ cycles for Dasi et al. 2007).

If CFD code is to accurately simulate BiMHV flow, rigorous validation of CFD results is required. To validate CFD simulations, an experimental dataset is needed. Due to the three dimensional nature of this flow, the dataset must contain all three velocity components, which will enable validation of three dimensional simulations.

1.3 Objectives

The propensity of BiMHVs to promote thrombosis and the relationship of thrombosis to high fluid shear stresses have been described. Previous PIV studies have described the flow field and identified regions of high shear, but often with small sample sizes which may be inadequate to accurately resolve turbulent Reynolds stresses. Furthermore, in pulsatile flow, cycle-to-cycle variations contaminate Reynolds stress calculations (Ge et al. 2008). Hanle et al. (1988) showed that steady and pulsatile flow results correspond at peak systole, and that analyzing a simpler steady flow regime can identify flow structures sometimes hidden in more complex pulsatile flow. In addition, recent computational advances may make accurate modelling of BiMHV flow possible. The flow has been described as highly three dimensional, and therefore to gain more insight into three dimensional flow structures, and validate three dimensional flow simulations, an experimental dataset containing spatial data in all three velocity components is required. Notably, CFD methods have been seen to break down at peak systole (Dasi et al. 2007). If CFD code is to model the entire cardiac cycle, it should be first validated in steady flow at peak systole.

The objectives for this thesis are:

1. Design and build a recirculating flow loop to provide steady flow to the experimental test section.
2. Obtain a three velocity component dataset using SPIV to measure steady flow downstream of a BiMHV at a peak systolic Reynolds number. The dataset will be used to investigate three dimensional flow structures, and for CFD code validation purposes.
3. Obtain a large independent measurement sample size for the above dataset to adequately resolve second order turbulence statistics (i.e. Reynolds stresses).

The study had three phases:

1. Flow loop design, construction, and testing
2. Flow visualization experiments
3. PIV experiments

Phase 1 ensured proper functioning of the constructed flow loop. The flow visualization performed in phase 2 provided a qualitative view of the flow at several different steady flow rates. Phase 3 was performed for quantitative analysis of the flow field. Inlet conditions to the test section were assessed using 2C-PIV, and conditions within the test section were assessed using SPIV. In total, three datasets were obtained in the PIV experiments:

1. Inlet Conditions Dataset (2C-PIV)
2. Full Aortic Sinus Dataset (SPIV)
3. Near Wall Sinus Dataset (SPIV)

The thesis is structured as follows. Chapter 2 describes the experimental apparatus built, and the in-house SPIV system used to obtain the measurements. Chapter 3 describes the methodology used to obtain the measurements. Chapter 4 contains results and discussion on flow visualization, inlet conditions, and SPIV data. Chapter 5 summarizes the conclusions of the study, and makes recommendations for future work.

Chapter 2

Experimental Apparatus

This chapter describes the experimental apparatus required to complete the three phases of the study and obtain the three PIV datasets.

2.1 Flow Loop

A recirculating flow loop was designed and built for the study. The primary in-line components were:

1. filling tank (T)
2. centrifugal pump (P)
3. two flowmeters (FM1, FM2)
4. settling chamber
5. test section
6. control valves (CV1, CV2)
7. air separator (ASP)

A diagram of the flow loop is shown in Figure 2.1. Components are identified in Table 2.1. The pump, flowmeter, and air separator manufacturer information is listed in Table 2.2.

Flow Loop Components	
Label	Component
T	Filling Tank
P	Centrifugal Pump
FM1	Flow Meter (high flow rate)
FM2	Flow Meter (low flow rate)
D1	Inlet Diffuser
HC	Honeycomb
SC1	Screen 1 (coarse)
SC2	Screen 2 (fine)
C	Contraction
IS	Inlet Section (test section)
AS	Aortic Section (test section)
D2	Outlet Diffuser
ASP	Air Separator
VJ1, VJ2	Vibration Joints
VM	Vibration Mounts
3V	3 Way Ball Valve
NV	Check Valve
CV1	Control Valve 1
CV2	Control Valve 2

Table 2.1 Flow loop components as labelled in Figure 2.1.

Component	Manufacturer / Supplier	Model
Centrifugal Pump	Iwaki-Walchem (MA)	MC-100R(T)
Flow Meter (high flow rate)	Sea Metrics (WA)	33100
Flow Meter (low flow rate)	McMillan (TX)	G111-8
Air Separator	Stourflex (West Midlands, UK)	JP501-40

Table 2.2 Manufacturers of key purchased components.

A centrifugal pump was used to circulate fluid to and from a 4 L filling tank. Clear PVC piping was used throughout the system. The pump was vibration-isolated from the rest of the flow loop by flexible vibration joints (VJ1, VJ2) and vibration mounts (VM). A check valve (NV) immediately downstream of the pump prevented backflow during system filling and shutdown.

Downstream of the pump, a 3-way ball valve (3V) directed flow through high flow (FM1) and low flow (FM2) turbine impeller flowmeters. Downstream of the flowmeters, a 1.5" globe valve (CV1) was used as the first flow control valve. A large radius elbow preceded the settling chamber.

2.1.1 Settling Chamber

An axisymmetric settling chamber was designed to reduce turbulence levels and provide a uniform velocity profile flow upstream of the test section. The settling chamber was machined from cast acrylic and consisted of four parts:

1. inlet diffuser
2. honeycomb
3. two turbulence damping screens
4. contraction

Figure 2.2 shows an exploded view of the settling chamber assembly with major dimensions included. Figure 2.3 shows a photograph of the assembled components.

Figure 2.2 Exploded view of settling chamber assembly. The drawing is not to scale.

Figure 2.3 Photograph of settling chamber assembly.

The inlet diffuser had a small included angle of $2\theta = 5^\circ$ (Figure 2.2) to reduce the possibility of boundary layer separation. A 16 mm straight section led to the honeycomb to reduce the chance of honeycomb stall.

Honeycomb, in conjunction with two turbulence reduction screens, were used to condition the flow upstream of the test section (Loehrke and Nagib 1976, Mehta 1979). Aluminum hexagonal honeycomb (supplied by Aerolab, MD) with a cell length of 25.4 mm and diameter of 3.2 mm giving a cell-length-to-diameter ratio of 8 was used. A coarse screen (screen 1) with mesh spacing 1.2 mm, and a fine screen (screen 2) with mesh spacing 0.9 mm were used downstream of the honeycomb to attenuate turbulent fluctuations. Design recommendations by Groth and Johansson (1988) and Loehrke and Nagib (1976) were employed for honeycomb and screen spacing, which called for the separation between screen 1 and the honeycomb to be less than 5 times the honeycomb diameter, and for the separation between the two screens to be 20 times the screen 1 mesh spacing. In addition, a 2 mm diameter radial hole was drilled in the settling chamber between the 2 screens to allow air venting during system filling.

An axisymmetric contraction section with contraction ratio of 4.5 was designed to produce a steady, uniform velocity profile to the test section. The contraction profile was a 5th order polynomial employed successfully in low speed wind and water tunnel applications (Brassard and Ferchichi 2005, Wetzel and Arndt 1994, Bell and Mehta 1988). The equation for the profile was (Brassard and Ferchichi 2005)

$$h_c = \left[-10 \left(\frac{x}{l_c} \right)^3 + 15 \left(\frac{x}{l_c} \right)^4 - 6 \left(\frac{x}{l_c} \right)^5 \right] \left[1 - \frac{H_o}{H_i} \right] + 1 \quad \text{Equation 2.1}$$

where h_c is the contraction radius, x is the axial coordinate, l_c is the total contraction length, H_i is the inlet radius, and H_o is the outlet radius. The contraction had $H_i = 28.6$ mm, $H_o = 13.4$ mm and $l_c = 100$ mm. Downstream of the contraction, straight cast acrylic piping of diameter $d = 26.8$ mm and length 322 mm ($12d$) preceded the test section.

2.1.2 Test Section

The test section was machined from cast acrylic block and consisted of two mating parts:

1. inlet section
2. aortic sinus section

Making the test section from two parts enabled insertion and removal of the BiMHV and calibration grid during image calibration. Figure 2.4 shows an exploded view of the two mating test section components, the inlet section, and the aortic sinus section. The BiMHV was placed between the two components similar to the design of Fontaine et al. (1996). The inlet section inserted into the aortic sinus section, and two gland seal o-rings provided sealing. In addition, the inlet section incorporated a viewing window at the upstream end for PIV measurement of inlet conditions.

The coordinate system used for the measurements is shown in Figure 2.5. The aortic sinus geometry was axisymmetric which has proved useful in CFD validation studies (Ge et al. 2003, Dasi et al. 2007, Shahbazi 2007). The sinus profile was a b-spline curve generated by Solid Edge V18 and defined by the points given in Table 2.3. The axisymmetric sinus had a diameter $d_s = 32.0$ mm, which reduced to the aortic diameter, downstream of the sinus. The reduction in diameter in the sinus was termed the aortic contraction region. The inlet diameter was the same as the aortic diameter at $d = 26.8$ mm (see Figure 2.5).

Figure 2.4 Diagram of test section used. The test section was designed in 2 parts to facilitate calibration grid and BiMHV insertion and removal during the image calibration process. The drawing is not to scale.

Figure 2.5 Axisymmetric aortic sinus detail drawing (not to scale).

Aortic Sinus Profile	
x (mm)	y (mm)
-4.30	16.00
13.80	16.00
14.80	15.96
15.80	15.94
16.80	15.92
17.80	15.88
18.80	15.81
19.80	15.66
20.80	15.38
21.80	14.89
22.80	13.54
23.50	13.40

Table 2.3 Points defining the axisymmetric aortic sinus. The coordinate system is defined in Figure 2.5.

Figure 2.6 Photograph of test section assembly.

The inlet section and aortic sinus section were bolted to an aluminium support frame at upstream and downstream flanges. Additional rigidity was provided by supports at the upstream end of the aortic sinus section (labelled in Figure 2.4 and Figure 2.6 as mid-support) which minimized test section movement during the image calibration process.

2.1.3 BiMHV Model

To eliminate reflections and laser sheet blockage during the flow visualization and PIV experiments, an acrylic BiMHV model was used. The BiMHV was modeled after a Carbomedics No. 25 aortic BiMHV. To reduce the possibility of fluid structure interaction effects in the turbulent flow, the leaflets were fixed in the fully opened position. The valve ring was machined from cast acrylic and the leaflets were made from

0.76 mm thick polycarbonate sheet. For the leaflets, polycarbonate sheet was used instead of acrylic to reduce the chance of cracking during machining. Leaflet and valve ring designs are shown in Figure 2.7 and Figure 2.8 and photographs are shown in Figure 2.9.

Figure 2.7 Drawing of BiMHV model prior to assembly.

Figure 2.8 Drawing of assembled BiMHV model.

Figure 2.9 Photographs of acrylic MHV modeled after a Carbomedics No. 25 aortic BiMHV.

2.1.4 Additional Components

Outlet piping of length 268 mm ($10d$) ran from the test section to diffuser with an included angle of $2\theta = 5^\circ$. Downstream of the diffuser, a second flow control valve (CV2) was used (Figure 2.1).

Air bubble recirculation was a problem in the flow loop. The small filling tank size meant that little time was given for bubbles to rise to the surface before being recirculated. To eliminate this problem, an air separator was installed just upstream of the filling tank and was effective at removing recirculating bubbles. In addition, the air separator was used as a make-shift heat exchanger during the PIV experiments to minimize the effect of pump heat input. Ice was packed around the air separator to maintain the temperature increase at 8°C/hr during operation.

2.2 Flow Visualization Setup

2.2.1 Flow Illumination

Flow visualization experiments were performed and included both a particle streak photography study and a particle streak video study. The flow visualization location is shown in Figure 2.10. A 15 mW Melles-Griot helium-neon (He-Ne) CW laser with beam diameter of $h_2 = 0.65$ mm was used in the flow visualization experiments. The laser was mounted to give X, Y, Z, and rotation alignment capability. The laser beam passed through three cylindrical lenses as recommended by Raffel et al. (1998) to give independent tuning of laser sheet width and thickness.

Figure 2.10 Schematic of setup for flow visualization.

Figure 2.11 Diagram of laser sheet path used for flow visualization. Labels are described in the text.

The first lens had a focal length of -13.7 mm and spread the beam into a sheet. The second and third lenses controlled laser sheet thickness and had focal lengths 25.4 mm and 100 mm, respectively. Lenses 1, 2 and 3 were positioned 1144 mm, 702 mm and 544 mm from the test section respectively. The laser sheet thickness was 1 mm across the measurement region and Gaussian thin lens approximations were used to estimate the laser sheet divergence at the measurement location. Thin lens formulae are only valid if (Tipler 1990)

$$\sin \varphi \approx \varphi \quad \text{Equation 2.2}$$

where φ is the angle between the lens face normal and the incident ray (Figure 2.11).

The Gaussian thin lens equation is (Tipler 1990)

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \quad \text{Equation 2.3}$$

where d_o is the distance from the point being imaged to the lens, d_i is distance from the image formed to the lens, and f is the lens focal length. The radii of the lenses were defined as C_2 and C_3 . Thin lens approximations were verified for lens 2 by noting that, the half thickness of the laser sheet, $h_2/2 = 0.325$ mm, and $C_2 = 13.1$ mm. Using $\sin(\varphi_1) = 0.325/13.1$ gave $\sin(0.025) \approx 0.025$ radians, and therefore Equation 2.2 was satisfied for

lens 2 so that using Equation 2.3 with lens 2 was justified. For lens 3, φ_2 was equal to the half angle $\theta_2/2 = 0.01$ radians plus the angle between n_2 and the optical axis. Using Equation 2.3 for lens 2, d_{o2} was calculated to be 133 mm. Using this and known $C_3 = 51.7$ mm, the angle between n_2 and the optical axis was calculated at 0.041 radians. For $\sin(0.041) \approx 0.041$ radians, Equation 2.2 is satisfied for lens 3. The thin lens equation, Equation 2.3, was therefore suitable for determining the sheet thickness divergence.

Referring to Figure 2.11, the sheet thickness was $h_2 = 0.65$ mm to the left of lens 2. With negligible beam divergence (less than 0.07° , Melles-Griot laser specifications) to the left of lens 2, Equation 2.3 gave $d_{i1} = 25.4$ mm, $d_{o2} = 133$ mm, $d_{i2} = 893$ mm. The laser sheet thickness divergence was then calculated to be $\theta_3 = 0.18^\circ$ at the measurement location. This divergence can be considered negligible, and the sheet thickness was therefore considered constant across the measurement region for the flow visualization.

The laser mount and lens assembly were set on a large XYZ stage previously used for LDA studies. Mounting on the stage allowed the light sheet to be accurately positioned once sheet width and thickness were set. This stage was later used to mount the PIV laser head. The orientation of the flow visualization measurement plane was identical to that used in the SPIV study. A diagram of the setup is shown in **Error! Reference source not found.**, and a photograph is shown in Figure 2.12.

2.2.2 Particle Streak Photography

A 6 megapixel (3008 x 2000 pixels) Nikon D70s digital SLR camera was used to capture images. The camera was mounted on a small XYZ stage to allow positioning and focus. A 55 mm micro-Nikkor lens was used with the aperture set at the maximum $f_\# = 2.8$ because of the low power He-Ne laser and the short exposure times needed. The camera was controlled with a remote shutter and images were stored on-camera.

2.2.3 Particle Streak Video

A particle streak flow visualization study was also performed using video at a 15 Hz frame rate. A Pulnix TM-1010 digital camera was used with the same laser sheet setup as the particle streak photography study. Camera connections, framegrabber and image acquisition software were the same as outlined for PIV, and will be discussed in Section 2.3. The camera triggering sequence detailed in Section 2.3 did not have to be used, as the camera was set in "free-run" mode and collected video at 15 Hz. A photograph of the setup is shown in Figure 2.12.

Figure 2.12 Flow visualization setup showing the test section, camera, and He-Ne laser. The Pulnix TM-1010 camera used for flow visualization videos is shown. For the particle streak photography, a Nikon D70s camera was used.

2.3 SPIV Setup

As noted previously, three PIV datasets were obtained:

1. Inlet Conditions Dataset (2C-PIV)
2. Full Aortic Sinus Dataset (SPIV)
3. Near Wall Sinus Dataset (SPIV)

This section describes the experimental setup for the SPIV experiments. The setup for the 2C-PIV Inlet Conditions Dataset is discussed in Section 2.4.

The coordinate system used for all measurements is found in Figure 2.13 along with the Full Aortic Sinus Dataset measurement location which was 20.1 mm in the X direction starting from $X = 1.4$ mm downstream of the leaflet tips, to $X = 21.5$. It spanned $Y = \pm 15.2$ mm on either side of the X axis which was 0.8 mm from either sinus wall.

The Near Wall Sinus Dataset was acquired separately due to low velocities observed in the areas near the sinus walls. These low velocities were more difficult to resolve when the full aortic sinus was studied because they were of comparatively low magnitude for the system dynamic range. In order to investigate these regions more closely, a larger time separation between laser pulses was used (see Table 2.5), which increased measurement sensitivity in the low velocity regions. There were two separate measurement regions for the Near Wall Sinus Dataset as shown in Figure 2.14. For the upper sinus region, the measurement region spanned from $Y = 12$ mm to $Y = 15.2$ mm, and for the lower sinus region it spanned from $Y = -12$ mm to $Y = -15.2$ mm. Both upper sinus and lower sinus measurement regions of the Near Wall Sinus Dataset were from $X = 1.4$ mm to $X = 13.4$ mm.

Figure 2.13 Diagram showing coordinate system and test section orientation. The boxed region indicates the measurement location for the Full Aortic Sinus Dataset. (Drawing not to scale)

Figure 2.14 Diagram showing the measurement location for the Near Wall Sinus Dataset as the boxed area. (Drawing not to scale)

Primary components used for SPIV image acquisition were:

1. dual-head Nd:YAG laser
2. two digital cameras
3. PC controlled image acquisition software
4. two frame grabber boards
5. function generator
6. logic box
7. delay generator

These, along with labelled signalling (A to J) are shown in Figure 2.15 and Table 2.4. The components and PIV triggering method are detailed in the following sections.

Figure 2.15 Experimental setup for SPIV image acquisition. Labels are described in the text.

Component	Manufacturer / Supplier	Model
Dual-head Nd:YAG laser	New Wave (CA)	SOLO PIV 120
Cameras	Pulnix (CA)	TM-1010
Image Acquisition Software	IO Industries (ON, Canada)	Video Savant 3.0
Frame grabbers	BitFlow (MA)	Roadrunner V12
Delay Generator	Stanford Research (CA)	DG535

Table 2.4 SPIV setup component manufacturers.

2.3.1 Flow Illumination

Flow was illuminated with a New Wave SOLO PIV 120 dual-head Q-switched Nd:YAG laser emitting $\lambda = 532$ nm wavelength light. Each laser pulse was 3 - 5 ns in duration. Peak laser power was 120 mJ/pulse although power was attenuated to provide necessary illumination of the flow field. A New Wave 80x70 Light Sheet Series light sheet generator was used to produce a 1 mm thick laser sheet at the measurement location.

The laser was triggered by a Stanford Research DG535 delay generator. The laser was pulsed twice to create two consecutive laser sheets with a fixed time separation. The delay generator was also used to control the Q-switch delay of the laser pulses which is outlined below.

To ensure both laser pulses were of the same intensity, Q-switch delay time was adjusted and grey level values from particle images were compared. The average difference between image gray level values of pulse 1 and pulse 2 was 2.3 / 256 gray levels for a Q-switch delay of 195 μ s for laser head 1, and Q-switch delay of 175 μ s for laser head 2. This indicated that the pulse intensities were well matched.

Background reflections caused imaging problems. To minimize this, piping upstream and downstream of the measurement location was covered with black cloth. In addition, a framed black cloth enclosure was built around the cameras and test section to isolate the measurement location from external reflections.

2.3.2 Image Acquisition Components

Images were acquired by two 1008 x 1018 pixel Pulnix TM-1010 progressive scanning CCD cameras positioned at an angle to the light sheet plane as described in Section 3.5. The cameras are referred to as camera 0 and camera 1. Computar TEC-M55 telecentric lenses with object space telecentricity and focal length, $f = 55$ mm, were used. Image capture software, Video Savant 3.0, was used to relay signals from the cameras to the delay generator which in turn triggered the laser. A diagram showing signals used to synchronize the camera frames and laser pulses is shown in Figure 2.15 and described below.

The cameras were set in "asynchronous reset" mode and triggered by a 3 Hz TTL pulse (shown as signal A in Figure 2.15) from an external function generator. Signal A was used as the VINIT (vertical scan initialization) pulse and reset both camera frames. Each camera was connected to a separate Bitflow Roadrunner V12 frame grabber board in the PC via a 10 bit digital cable connector. The frame grabbers used a custom camera file PnTm1010T1AsyncResetTwoFrames.cam to capture the images. The frame grabbers were controlled by the image capture software, Video Savant 3.0, which was set in dual board, and software triggering modes to control outgoing signals. At the start of each frame the cameras sent vertical drive (VD) signals B and C to the frame grabbers. Video Savant sent two outgoing TTL signals D and E corresponding to the two incoming signals B and C. Signals D and E were sent via a PC parallel port to a "logic-box". The logic-box sent a single TTL pulse, shown as signal F, to the delay generator.

The logic-box was required because the internal horizontal line scan drives (HD) in camera 0 and camera 1 could not be synchronized. This resulted in signals B and C being randomly offset by a maximum of 1H (1 horizontal line scan), of $63.75 \mu\text{s}$. This caused two offset signals (D and E) to leave the PC parallel port. The logic-box contained "OR" logic and allowed only the first incoming signal (D or E) to reach the delay generator. A timing diagram showing all signals is found in Figure 2.16.

Figure 2.16 Signal timing diagram for PIV image acquisition. Cameras were asynchronously reset but had a random offset of 1 HD which required the use of the logic box. Q-switch delay for laser pulse 1 is the time G to H. Q-switch delay for laser pulse 2 is the time I to J. The laser pulse time separation was thus the time H to J.

The laser was placed in “external trigger” mode and laser trigger signals G, H, I, J were timed by the delay generator with respect to signal F. Laser head 1 flashlamp and Q-switch triggers were signals G and H respectively. Laser head 2 flashlamp and Q-switch

triggers were signals I and J respectively. Laser signal and camera frame timing is shown in the timing diagram in Figure 2.16.

A camera frame straddling technique was used to capture the images, and is illustrated in Figure 2.16. Laser pulse 1 occurred just before the end of the first camera frame and laser pulse 2 occurred at the beginning of the second camera frame which enabled image capture with a small fixed time separation. The delay generator was set such that the time delay between signal F and signal G, Δt_{F-G} , was 67 ms, which allowed the first laser pulse to occur just before the end of the first camera frame. The delay between signals G and H, the laser 1 Q-switch delay, was set to $\Delta t_{G-H} = 195 \mu\text{s}$. The delay between signals I and J, the laser 2 Q-switch delay, was set to $\Delta t_{I-J} = 175 \mu\text{s}$. By adjusting the delay between the laser 1 flashlamp and laser 2 flashlamp, Δt_{G-I} , the total time separation Δt could be changed. The time separation between laser pulses is found by

$$\Delta t = \Delta t_{G-I} - \Delta t_{G-H} + \Delta t_{I-J} \quad \text{Equation 2.4}$$

Images were taken with various time separations to optimize the dynamic range of the system. The images were cross correlated and pixel displacement histograms were compared. In addition, a dataset was obtained at an increased time separation to resolve low velocity regions with higher precision. This is discussed in greater detail in Section 3.8. Table 2.5 shows Δt for each PIV dataset obtained.

Dataset	$\Delta t \ (\mu\text{s})$
Full Aortic Sinus Dataset (SPIV)	400
Near Wall Sinus Dataset (SPIV)	800
Inlet Conditions Dataset (2C-PIV)	400

Table 2.5 Time separations used for each PIV dataset.

By using this setup, two images from each camera could be obtained with a fixed time separation Δt at a sampling frequency of 3 Hz controlled by the function generator. This resulted in four images taken for each sample.

2.4 Inlet Conditions Setup (2C-PIV)

The Inlet Conditions Dataset was obtained with 2C-PIV upstream of the BiMHV to provide well-defined inlet velocity profiles for use in CFD validations, and to evaluate the quality of upstream flow. 2C-PIV was obtained with a single camera and therefore was able to resolve only the in-plane velocity components u and v . The measurement region for the Inlet Conditions Dataset is shown in Figure 2.17, and extended from $X = -89.4$ mm to $X = -79.0$ mm. It spanned $Y = \pm 12.9$ mm on either side of the X axis which was 0.5 mm from the inlet piping walls (where inlet diameter $d = 26.8$ mm as shown in Figure 2.5). The laser sheet passed through the centerline of the inlet piping, as shown in Figure 2.13, but at the upstream location noted above.

Figure 2.17 Inlet Conditions Dataset measurement location (shown in the boxed area).

Flow illumination was provided by the same Nd:YAG laser used in the SPIV studies and was triggered in the same manner. Images were acquired with a single Pulnix TM-1010 camera placed at directly above the measurement location. Signalling and other hardware was identical to that used for SPIV as discussed in Section 2.3.

2.5 Working Fluid

Matching the index of refraction, n , of the working fluid and that of the test section greatly reduces optical distortions and reflections in optical measurements (Budwig 1994, Nguyn et al. 2004), and this is particularly important when the inner walls of the test section are curved, as in the current case. Because of the accuracy required in PIV studies, an index matched fluid was used for the PIV studies. For the flow visualization study a non-index matched fluid, water, was used. These are described below.

2.5.1 Flow Visualization Fluid

In the flow visualization studies, deionized water was used as the working fluid. Water has an index of refraction of $n = 1.33$ at 20°C , and the acrylic test section had $n = 1.49$ (Budwig 1994). During the flow visualization experiments, the temperature ranged from $23 - 27^{\circ}\text{C}$. The increase in fluid temperature was due to pump heat and was approximately 8°C/hr . Water viscosity and density data was used from Munson et al. (2002) as a function of temperature. The flow rate was adjusted based on temperature at the time images were taken in order to maintain the required Reynolds number.

2.5.2 PIV Fluid

The reflection that occurred due to this index of refraction mismatch between the fluid and test section in the flow visualization experiments prevented good PIV measurements near the sinus walls in the upper and lower sinus regions.

A commonly used fluid that matches index of refraction with an acrylic test section is a mixture of aqueous sodium iodide, NaI, and was used in the PIV experiments. Refractive index testing was done on varying concentrations of aqueous NaI solutions in order to determine the solution concentration with an index of refraction of $n = 1.49$. Refractive index testing experiments were performed at 21.5°C and used an AFAB HR-090 refractometer. The results are shown in Figure 2.18.

Figure 2.18 Plot of refractive index versus concentration of NaI

Figure 2.18 shows that an index matched solution of NaI is reached at 60 - 61% NaI by weight. Based on this, and data in Narrow et al. (2000), which discusses the variation of n with illumination wavelength for NaI solutions, a solution of 61% NaI was chosen as the working fluid. During data collection, pump heat caused fluid temperature to rise and therefore viscosity to drop. A thermometer was placed in the filling tank and monitored periodically. The flow rate was adjusted and kept steady for every 1°C increase in temperature, to maintain a constant Reynolds number throughout the PIV experiments. Between $20 - 26^{\circ}\text{C}$ the required change in flow rate was $0.38 \text{ L/min}/^{\circ}\text{C}$, and between $26 - 30.5^{\circ}\text{C}$ the change in flow rate was $0.26 \text{ L/min}/^{\circ}\text{C}$. The adjustment was dictated by the change in kinematic viscosity of the fluid described below.

To predict the viscosity at varying temperatures, kinematic viscosity, ν , measurements with a Cannon-Fenske capillary viscometer were performed. The results are shown in Figure 2.19 and tabulated in Table 2.6. Figure 2.20 shows agreement between the viscosity measurement results compared to data from other researchers including Abdulagatov et al. (2006), International Critical Tables (ICT) (1930), Lobo (1989), and Aseyev (1992).

Figure 2.19 Kinematic viscosity measurements for 61 % NaI at 20, 26 and 30.5°C.

T (°C)	v (m ² /s)
20	1.87E-06
26	1.58E-06
30.5	1.43E-06

Table 2.6 Kinematic viscosity data for 61 % NaI at 20, 26 and 30.5°C.

Figure 2.20 Plot of kinematic viscosity versus concentration of NaI from this work in addition to data from other researchers.

2.6 Particle Response

Silver coated hollow glass spheres with diameter $d_p = 15 \mu\text{m}$ and density $\rho_p = 1650 \text{ kg/m}^3$ were used in both the flow visualization and PIV experiments. Particle specifications are given in Table 2.7.

Particle Specifications	
Manufacturer	Potters Industries (PA)
Product No.	SH400S33
Product Name	Spherichel
Core	hollow glass
Shape	spherical
Silver by Weight	33% (silver coated)
Typ. Particle Dia.	10-30 μm
Mean Dia.	15 μm
Density	1.65 g/cc
Colour	light gray
Bulk Powder Resistivity	0.0017 ohm/cm

Table 2.7 Specifications given by Potters Industries for particles used in flow visualization and SPIV.

Due to differences between fluid and particle density, once the pump was turned off, particles settling occurred after some time. This affected the seeding density on subsequent start-ups. To seed the flow a dense particle mixture was made, and injected by a syringe at the filling tank. The injection rate was timed such that uniform particle density was achieved. This was done at the start of each experiment.

To ensure flow measurement accuracy, particle response to flow disturbances must be evaluated. Hjermfelt and Mockros (1966) discussed relative motion of particles in a fluid, and results are well summarized by Gunther (2001). Three parameters are used to describe the relative motion of the fluid and particles: the particle-to-fluid density ratio s , the particle-to-fluid motion amplitude ratio, η , and the particle-to-fluid motion phase

angle lag, ψ . Gunther plotted η and ψ at density ratios $s = 1.05, 1.1, 1.2, 1.5, 2$ and 3 , versus Stokes number, St , where

$$St = \sqrt{\frac{\nu}{\omega d_p^2}} \quad \text{Equation 2.5}$$

with ω being the frequency of turbulent fluctuations. Liu et al. (2000) measured turbulence downstream of a Carbomedics BiMHV using LDA and considered a maximum turbulent fluctuation frequency of $\omega = 5 \times 10^3$ Hz.

During the flow visualization experiments, water temperature was not constant, but the sample average kinematic viscosity was calculated as $\langle \nu \rangle = 0.90 \times 10^{-6} \text{ m}^2/\text{s}$ and the sample average density, $\langle \rho \rangle$, was 997 kg/m^3 . This gave $s = 1.65$ and $St = 0.89$. Using Gunther's plots, values of $\eta > 0.95$ and $\psi < -0.05$ radians were obtained, which can be considered negligible.

During the PIV experiments the viscosity of NaI ranged between $\nu = 1.43 \times 10^{-6} \text{ m}^2/\text{s}$ and $1.77 \times 10^{-6} \text{ m}^2/\text{s}$ as fluid properties changed with increasing temperature (see Section 2.5). Likewise the density ranged between $\rho = 1793 \text{ kg/m}^3$ and 1801 kg/m^3 (Sohnel 1985). Calculating the sample average kinematic viscosity and density gave $\langle \nu \rangle = 1.57 \times 10^{-6} \text{ m}^2/\text{s}$ and $\langle \rho \rangle = 1796 \text{ kg/m}^3$. This gave $s = 0.92$ and $St = 1.18$. Gunther's plots for these values give $\eta > 0.99$ and $\psi < 0.01$ radians. Because η and ψ can be considered negligible, it can be concluded that the particles faithfully followed the flow in both the flow visualization and PIV experiments.

Chapter 3

Experimental Methodology

3.1 Flow Visualization

The flow visualization study using particle streak photography and particle streak video, was carried out prior to the PIV experiments to help identify regions of interest and provide length scale estimates of flow structures. The experiments were performed at different Reynolds numbers of $Re = 2200, 2600, 3800, 5500, 6600$, and 7600 . Results for $Re = 2200, 3800$ and 7600 are shown in Section 4.1.

3.1.1 Particle Streak Photographs

A Nikon D70s camera was used to take images at various exposures to test particle streak length and image brightness. Exposures ranging from $1/200$ s (5 ms) to $1/30$ s (33 ms) were attempted. For $Re = 7600, 5500$ and 3800 , a shutter speed of $1/80$ s (12.5 ms) yielded sufficiently bright and detailed images. For $Re = 2200$ and 2600 , a slower shutter speed of $1/60$ s (17 ms) gave good results. Focusing gave a field of view that allowed imaging of the entire aortic sinus measurement region. Approximately 500 images at each Reynolds number were acquired to capture the general characteristics of the flow.

Image dewarping of flow visualization images was performed because of the distortions due to refraction at the water and acrylic test section interfaces. The local weighted mean transformation was chosen for dewarping. The procedure was similar to that done in SPIV discussed in Section 3.2 but control points were chosen at spacings of 2 mm x 2 mm. The warped and dewarped calibration grid images are shown in Figure 3.1. The warped image in Figure 3.1 (a) shows that the calibration grid is relatively uniform near the centerline (area c), but becomes distorted vertically near the walls (area d), and distorted horizontally near the aortic sinus contraction region (area e). After dewarping, the distortions were reduced and an overall uniform grid resulted, (f), (g), (h).

Figure 3.1 a) Warped calibration image. b) Dewarped image after local weighted mean transformation. c), d), e) show distortions due to fluid index of refraction mismatch in the raw warped image. c) Grid squares near centerline; d) grid squares near top edge; e) grid squares in aortic sinus contraction region. f), g), h) show the same grid squares after dewarping.

3.1.2 Particle Streak Video

The Pulnix TM-1010 camera was operated in "free-run" mode for the particle streak video flow visualization study. Because the camera frame rate was 15 Hz, the integration time for the particle streaks was 67 ms. Quality video images could not be obtained at shorter exposures such as those used in streak photography, due to the comparatively lower light sensitivity of the Pulnix CCD. The length of the video was limited to 11 s due to limited video buffer space on the PC. For the videos, the field of view was approximately 10 x 10 mm. This therefore did not span the entire test section as the particle streak photography did, but allowed viewing of small areas within the aortic

sinus. Dewarping was not performed on the video images because the field of view was small. Video was obtained in the lateral orifice jet shear layers, upper and lower sinus recirculation regions, and in the leaflet wakes at Reynolds numbers of 2200, 3800 and 7600.

3.2 SPIV Image Calibration

Image calibration was carried out for flow visualization experiments, 2C-PIV inlet conditions experiments and the SPIV experiments. The methodology presented in this section describes the procedure specifically used for SPIV image calibration. The procedure used in the flow visualization and 2C-PIV inlet conditions experiments is similar but less involved, and the differences are noted in Sections 3.1 and 3.7.

SPIV calibration requires that either a vector or image dewarping strategy is employed before final particle displacements are calculated. In this work, an image dewarping method was used to accurately map pixel locations to their back-projected locations.

The need for image dewarping was two-fold. First, due to Scheimpflug angle tilting of the CCD image plane, SPIV images exhibited projective distortion. Second, when viewing the measurement plane through the curved contraction portion of the axisymmetric aortic sinus, non-linear image distortions resulted which was due to a slight difference in refractive index between the fluid, NaI, and acrylic test section.

The calibration procedure consisted of seven steps:

1. Calibration grid insertion
2. Calibration grid imaging
3. Laser sheet alignment
4. Image registration
5. Image dewarping to determine an image mapping function
6. Calibration grid removal and BiMHV insertion
7. Landmark imaging

These steps are discussed below.

3.2.1 Calibration Grid Insertion

A calibration grid with 1x1 mm grid squares was cut to the dimensions of the aortic sinus and printed on transparency film. The film was placed between two 1 mm thick acrylic plates cut to the same dimensions. The plates and grid were sandwiched between two semicircular rings machined to the same dimensions as the BiMHV ring. Locating pins were used between the rings and plates to ensure proper alignment. The assembly was placed on the inlet section with locating pins, and then inserted into the aortic sinus section (see Section 2.1.2) in the same manner as the BiMHV. A photograph of the calibration grid assembly is shown in Figure 3.2. Locating pins between the inlet section and ring ensured the grid was positioned at the center-plane of the aorta.

Figure 3.2 Photograph of calibration grid assembly prior to insertion into test section.

The inlet section and aortic sinus section were bolted together, and the test section was filled with NaI solution and plugged on both ends. The grid was ready for imaging once the test section was secured to the support frames and the mid-support (see Section 2.1.2).

3.2.2 Calibration Grid Imaging

Both cameras were carefully positioned and focused to have the same field of view and image magnification. Images were taken of the calibration grid by both cameras using an incandescent lamp for illumination. A variable resistance switch was used on the lamp to adjust image brightness without changing camera aperture settings. The distorted calibration grid images are shown in Figure 3.3.

Figure 3.3 Distorted grid images used for SPIV calibration. Left: camera 0 calibration grid image, Right: camera 1 calibration grid image. The dots (1 - 8) indicate the corner control points.

3.2.3 Laser Sheet Alignment

To provide fine scale translation of the Nd:YAG laser it was mounted an XYZ stage. The laser power level was set to low and internally triggered at 15 Hz during alignment. The laser sheet was positioned such that the middle of the sheet painted the edge of the calibration grid transparency film.

3.2.4 Image Registration

Because the two calibration grid images were distorted, the images were first registered and then dewarped. The result was two images with uniformly spaced grid nodes which corresponded to the back-projection of the measurement plane.

In the process of image registration, distorted calibration grid image nodes were matched to uniformly spaced grid nodes. The corresponding node points are referred to as *control points*, and their relative locations were used to determine coefficients for the image mapping function. The corner control points in the distorted calibration images are shown as the dots labelled 1 - 8 in Figure 3.3.

Initially, a Matlab 6.5 program (*cpselect.m*) was used to manually choose $N_{CP} = 651$ node points on the distorted calibration grid image and the locations were recorded in a text file. The locations of the nodes were then refined by cross correlation of a 21 x 21 pixel area surrounding the nodes with a “+” shaped mask similar to that used by Willert (1997) and Brucker (1997). The mask and the cross correlated region from the distorted calibration grid image (see Figure 3.3) are shown in Figure 3.4

Figure 3.4 Calibration grid node from the distorted calibration grid image, and the cross correlation mask used to fine tune control points.

The position of the cross correlation peak was used to determine the required pixel shift of the calibration image node points, and a new node location was calculated. A Matlab program, *pixcoordsprgm.m*, was written that performed the cross correlation and recorded the refined node points. In order to ensure high quality correlation, the correlation coefficient was required to be at least 0.75 and the maximum change in node location was set at 2 pixels.

In the warped calibration image, it was found that on average the calibration grid image node points were spaced 27 pixels/mm in the X direction, and 30 pixels/mm in the Y direction. To reduce image artifacts due to resampling after dewarping, the uniformly spaced node points were positioned at this spacing. This therefore resulted in a dewarped image with a uniform image magnification of 27 pixels/mm in X and 30 pixels/mm in Y .

3.2.5 Image Dewarping

Once the distorted calibration grid image was registered it was then dewarped and a image mapping function was determined. A standard 2nd order polynomial dewarping algorithm used by Suk (1999) and Willert (1997), and a local weighted mean approximation dewarping method were tested and compared. The polynomial dewarping did not yield satisfactory results, and errors are discussed below. The local weighted mean method provided very good results, however. The local weighted mean method is described in Appendix D, and is well suited to deal with varying non-linear image distortions that cannot be handled by standard polynomial mapping methods such as those used in previous studies, e.g. Brucker (1997), Marassi et al. (2004), and Lim et al. (1994).

The local weighted mean approximation method was applied to the warped calibration grid image node points and the uniformly spaced node points. This was done separately for each camera, and therefore two unique mapping functions determined. These mapping functions were then used to dewarp the distorted SPIV images. A program called *imgtransform_loop.m* was written that read in the two text files containing: 1. the

distorted calibration grid image node point locations, and 2. uniformly spaced node point locations. The *cp2tform.m* program in Matlab 6.5 implemented the local weighted mean transformation.

The dewarped calibration images are shown in Figure 3.5. Some grid waviness was seen outside of the control point area, and therefore SPIV images were cropped to only include regions inside the corner control points (shown as the dots at the image corners in Figure 3.5).

Figure 3.5 Dewarped image after local weighted mean transformation. Left: Camera 0 image, Right: camera 1 image. The dots at the image corners show the locations of the dewarped corner control points. The calibration landmarks are shown as the black triangles.

The error in dewarping is defined as the difference between the control point locations of the dewarped calibration grid image, and the corresponding uniformly spaced control point locations. This was computed by inputting the uniformly spaced control point locations (x,y) into the mapping function and comparing the output (q,k) (see Appendix D), to that of the distorted calibration grid image control point locations. A dewarping error histogram is shown in Figure 3.6 and illustrates that transformation error was at most 0.8 pixels with the majority of displacements being 0.1 pixel. This is comparable to the sub-pixel errors quoted by Willert (1997) and others using other dewarping schemes in geometrically simpler test sections. Figure 3.6 also shows that the transformation error

for the 2nd order polynomial mapping is much larger, with a maximum error of 5.5 pixels and about 50% of the distribution having more than 1 pixel error. It is clear that the non-linear image distortions present in the current study resulted in unacceptable errors using a 2nd order polynomial transformation. In contrast, the quality of image dewarping using the local weighted mean transformation was acceptable.

Figure 3.6 Image transformation error histograms for the local weighted mean approximation method and 2nd order polynomial method.

The results show that good image dewarping can be obtained with the fairly complex test section geometry when non-linear optical distortions are present by using a local weighted mean method. For this reason, the local weighted mean transformation was used in the SPIV study for image dewarping.

3.2.6 Calibration Grid Removal & BiMHV Insertion

After calibration grid imaging and dewarping, the calibration grid was removed from the test section. This required that the inlet section was disconnected from the aortic sinus section. The BiMHV was then positioned in the inlet section with locating pins and carefully inserted into the aortic sinus section. The inlet section and aortic sinus section were bolted together and adjacent piping was connected to the test section flanges. The piping was then filled with the NaI solution. This required a great deal of care to minimize test section movement during the process.

3.2.7 Landmark Imaging

To account for small movements of the test section that occurred during calibration grid removal and BiMHV insertion, special calibration landmarks were used. The landmarks consisted of 4 small triangles printed on transparency film and were fixed on the top and bottom exterior surfaces of the test section. When the calibration images were taken, the landmarks were visible (see Figure 3.3). Once the calibration grid was removed and the BiMHV inserted, images were taken again with the landmarks visible. By accounting for translation of the landmarks (and therefore the translation of the test section), the previously determined calibration image mapping function could be used. For all datasets obtained, test section translation was no more than 11 pixels (about 0.3 mm) in the *X* or *Y* directions, and usually around 5 pixels. This translation was accounted for by shifting the SPIV images by the required amount during image pre-processing prior to dewarping.

3.3 SPIV Image Acquisition

After calibration was completed, SPIV images were obtained at a Reynolds number corresponding to peak systole. As discussed in Chapter 1, the Reynolds number corresponding to peak systole is around 7000. A Reynolds number of $Re = 7600$ was used in the SPIV experiments. Images were acquired in sets of 40 samples due to limited buffer space on the PC. In total there were two image pairs taken by each of the two cameras, i.e. four images per sample. The images were saved to the PC hard disk and another set was taken. The flow was seeded as mentioned in Section 2.6, and the steady flow rate was adjusted for small changes in fluid viscosity as mentioned in Section 2.5. In total, $N = 1105$ samples were obtained for the Full Aortic Sinus Dataset, and $N = 718$ for the Near Wall Sinus Dataset.

3.4 SPIV Image Pre-Processing & Interrogation

After images were obtained they were processed by a series of Matlab 6.5 based programs. The sequence of programs and their primary functions is shown in Table 3.1.

Program Name	Description
<i>p1_namcnv.m</i>	rename files for sequential processing
<i>p2_imgcut.m</i>	cut single .tif file into four 1008 x 1018 pixel images
<i>p3_lisqCN_LWM_1.m</i>	perform dewarping
<i>p3_lisqCN_LWM_2.m</i>	perform brightness and contrast adjustment
<i>p4_pivrun.m</i>	perform cross correlation interrogation
<i>p5_f2to3_Norm.m</i>	perform 3 component velocity vector reconstruction
<i>spivens.m</i>	calculated ensemble averaged statistics

Table 3.1 Matlab 6.5 based image pre-processing and interrogation programs used.

Initially, all four images were contained in a single .tif file and had to be re-named by *p1_namcnv.m* and cut by *p2_imgcut.m* to give four individual 1008 x 1018 pixel images. Images were dewarped by *p3_lisqCN_LWM_1.m* using the procedure discussed in Section 3.2. After dewarping, image brightness was adjusted by *p3_lisqCN_LWM_2.m* to improve cross correlation. *p3_lisqCN_LWM_2.m* adjusted images for contrast such that image intensities spanned the entire 0 - 255 gray level range. Images were thresholded such that all gray level values less than the mean image intensity plus 10, were set to 0, which significantly cut down on image noise. Images were then cropped such that an equal number of data points lay above and below the test section centerline (i.e. the X-axis). The test section centerline was calculated based on the aortic sinus wall locations which could be determined within 1 - 2 pixels.

Images pairs taken at laser pulse 1 and laser pulse 2 were cross correlated using an adaptive cross correlation (ACC) algorithm developed by Usera (1999). An example image pair is shown in Figure 3.7. Note the black regions in the upper and lower right hand corners of the images which corresponded to the contraction of the aortic sinus.

Figure 3.7 Example SIV image pair from camera 1. Left: laser pulse 1, Right: laser pulse 2.

The ACC algorithm was implemented in *p4_pivrun.m*. The algorithm was a multi-pass algorithm in which particle displacement estimates on the first pass were made using large 64 x 64 pixel interrogation areas. These estimates were then used to locate second pass interrogation areas of 32 x 32 pixels. By doing this, the dynamic range of the system was determined by the first pass interrogation area size, and the spatial resolution was determined by the second pass interrogation area size (Usera 1999 and Westerweel et al. 1997b). A 50% interrogation area overlap was used for both the first and second passes. The resulting spatial resolution based on the 27 pixel/mm in X and 30 pixel/mm in Y image magnification (see Section 3.2.4) was $\Delta X = 0.59$ mm, and $\Delta Y = 0.53$ mm. The total number of vectors, n_{vec} , was 1982. Further details of the ACC algorithm are found in Usera (1999) and Suk (1999).

3.5 SPIV Velocity Reconstruction

Cross correlation data from both cameras was combined to yield the third fluid velocity component normal to the laser sheet plane. This was called the out-of-plane velocity component, and was in the Z direction. The reconstruction was implemented by Matlab 6.5 program *p5_f2to3_Norm.m*, which also normalized vectors by the bulk inlet velocity, U_0 , prior to ensemble averaging. The following describes the methodology used to construct the three component velocity vector field.

To resolve the fluid velocity component normal to the laser sheet plane, two cameras were positioned using the angular displacement method (Prasad 1993, 2000) in a configuration developed by Willert (1997). Camera locations and angles are shown in Figure 3.8. In this configuration, two cameras were used and positioned on either side of the laser sheet. The advantages of this configuration were two-fold. First, both cameras were able to collect images of the same scattering intensity. Second, both camera images were warped identically from one side to the other, rather than opposite warping that results from cameras positioned on the same side of the laser sheet. First, camera positioning will be discussed, followed by the velocity reconstruction equations.

3.5.1 Camera Positioning

The angular displacement method was accomplished by tilting the CCD array at an angle to the lens axis. By doing this, the image can be focused over the entire field of view when the image plane is at angle $(\alpha + \phi)$ to the object plane. The Scheimpflug condition, in which the entire image is in focus, is satisfied when (Walker 2002)

$$\frac{\tan(\phi)}{\tan(\alpha)} = M \quad \text{Equation 3.1}$$

where ϕ is the angle between the lens plane and image plane, α is the angle between the laser sheet plane and lens plane, and M is the nominal image magnification factor.

Figure 3.8 Camera positioning in the XZ plane showing Scheimpflug angles.

The Scheimpflug condition was satisfied when uniform focus was obtained over the entire image, with angles $\alpha_1 = \alpha_2 = 30^\circ$ and $\phi_1 = \phi_2 = 5^\circ$, and was accomplished with two Dantec Dynamics Scheimpflug mounts set on XYZ stages (Figure 3.9).

Figure 3.9 Photograph of Scheimpflug mount for camera 0.

3.5.2 Velocity Reconstruction Geometry

The in-plane, u and v , and out-of-plane, w , velocity components were calculated using the equations developed by Willert (1997). A Cartesian coordinate system was used with the location of the origin shown in Figure 2.5. The u velocity was aligned with the X -axis, v velocity with the Y -axis and w velocity with the Z -axis. The XY plane consisted of the laser sheet plane with the Z -axis normal to it. Figure 3.10 shows measured displacements, dx_1 , dx_2 , which were pixel displacements calculated after image interrogation. For brevity, only X -direction displacements are shown in the figures since Y -direction displacements, dy_1 , dy_2 , were analogous. Because object space telecentric lenses were used, all particle rays were paraxial, and therefore angles α_1 and α_2 were the same for all particles imaged in the field of view. This eliminated the need for additional ray tracing equations (Prasad and Jensen 1995) as fluid filled prisms were not used. It should be mentioned, however, that because fluid filled prisms were not used, radial blurring of particles likely occurred, which affected cross correlation (Prasad and Jensen 1995). Even though the index of refraction of the fluid and acrylic test section closely

matched, this effect was likely increased where particles were imaged through the sinus contraction at $X > 17$ mm. Figure 3.10 shows the angles α_1 and α_2 as the angles between the particle rays in the XZ plane and the laser sheet normal. Similarly, angles β_1 and β_2 were the angles between the particle rays in the YZ plane and the laser sheet normal.

Figure 3.10 Reconstruction geometry in the XZ plane. Geometry in the YZ plane is analogous.

Figure 3.10 (b) gives a close up view of Figure 3.10 (a). A particle traveled from point P to point Q within the laser sheet in time separation Δt . Using the geometry shown, and assuming a zero-thickness light sheet, Willert (1997) expressed the true particle displacements, dx , dy , and dz as

$$dx = \frac{dx_2 \tan(\alpha_1) - dx_1 \tan(\alpha_2)}{\tan(\alpha_1) - \tan(\alpha_2)} \quad \text{Equation 3.2}$$

$$dy = \frac{dy_2 + dy_1}{2} \quad \text{Equation 3.3}$$

$$dz = \frac{dx_1 - dx_2}{\tan(\alpha_2) - \tan(\alpha_1)} \quad \text{Equation 3.4}$$

Camera 0 imaged a particle travelling from P to R and recorded dx_1 . Camera 1 imaged the particle travelling from P to S and recorded dx_2 . The equation for dy is independent of setup angles because the cameras were placed at the same Y positions. This makes β_1 and β_2 very small and thus their tangents also very small. Velocity components u , v and w were found by accounting for image magnification applied in the image dewarping, and then dividing the displacements dx , dy , dz , by the laser pulse time separation Δt .

3.6 SPIV Experimental Setup Parameters

A table summarizing the SPIV experimental setup parameters is shown below.

Test Section		Illumination	
material	acrylic	laser type	dual-head Nd:YAG
inlet/outlet diameter, d	26.8 mm	λ	532 nm
aortic geometry	axisymmetric sinus	sampling rate	3 Hz
		sheet thickness	1 mm
BiMHV		Interrogation	
material	acrylic	type	adaptive cross-correlation
type	model Carbomedics 25		
leaflets	fixed	interrogation area	64x64 to 32x32 (with 50% overlap)
Flow			
type	steady	magnification	27 pixel/mm in X 30 pixel/mm in Y
Re	7600		
fluid	64% w/w NaI(aq)	XY resolution	0.59 mm in X 0.53 mm in Y
Seeding		Cameras	
type	silver coated hollow glass spheres	type	progressive scan CCD
diameter	15 μm		
density	1650 kg/m^3	resolution	1008x1018 pixel
SPIV		pixel depth	8 bit
α	30°	lens	telecentric, $f=55$ mm
ϕ	5°		
Δt	400 μs (Full Aortic Sinus Dataset) 800 μs (Near Wall Sinus Dataset)		

Table 3.2 Summary of experimental parameters for SPIV.

3.7 Inlet Conditions Image Acquisition (2C-PIV)

The Inlet Conditions Dataset was collected with 2C-PIV at the same peak systolic Reynolds number as the SPIV experiments of $Re = 7600$. Image dewarping is usually not required for 2C-PIV studies unless perspective distortions, lens distortions, or refractive distortions are present. Because a telecentric lens was used, perspective distortions were eliminated. It was found that other non-linear distortions were not present, as the single camera was positioned directly in front of the measurement location, and imaging through the curved aortic sinus contraction was not required. The calibration grid image is shown in Figure 3.11 and had uniform grid spacing in both the X and Y directions due to the matched refractive indices of the fluid (NaI) and test section (acrylic). Image magnification was 34 pixel/mm with a grid spacing standard deviation of 0.8 pixels. Because the standard deviation was in the sub-pixel range, image dewarping was not necessary. Image rotation of 0.37° counter-clockwise was required to align the image centerline with the X axis. With 50% interrogation area overlap, the spatial resolution was 0.47 mm in X and Y . During data acquisition, images were obtained using the same triggering sequence as the SPIV images discussed in Section 3.3. In total $N = 1080$ samples were obtained for the Inlet Conditions Dataset.

Figure 3.11 Calibration grid image used in Inlet Conditions Dataset.

3.8 System Dynamic Range

For the Full Aortic Sinus Dataset, the SPIV system was optimized for the entire available dynamic range. Adrian (1991) suggested that particle displacements less than 1/4 of the interrogation area size will improve correlation. Particle image testing at various time separations were done to ensure that total particle displacement did not exceed 16 pixels which is 1/4 of the 64 pixel first pass interrogation area size. Testing was done at $\Delta t = 125, 300, 400, 800$ and $1600 \mu\text{s}$.

For the Full Aortic Sinus Dataset (see Table 2.5) an optimal time separation of $\Delta t = 400 \mu\text{s}$ was used. Figure 3.12 indicates that the full dynamic range was used as displacements taper at ± 16 pixels.

Figure 3.12 X and Y displacement histograms for the Full Aortic Sinus Dataset.

For the Near Wall Sinus Dataset a $\Delta t = 800 \mu s$ was used and images were taken of the full aortic sinus. The images were then cropped to the measurement locations of upper and lower sinus regions (see Section 2.4), and displacements were found to be below 16 pixels.

For the Inlet Conditions Dataset $\Delta t = 400 \mu\text{s}$. The velocity range was smaller in the inlet piping, which resulted in about 75% of the of the X -displacements being between 6 - 7 pixels, and the remaining 25% were in the 1 - 6 pixel range. The entire system dynamic range of 16 pixels was therefore not utilized for the Inlet Conditions Dataset, but the ACC algorithm has been shown to perform well in the 1 - 7 pixel range (Tang 2002). All Y displacements were found to be less than 1 pixel. Good performance of the ACC algorithm was further confirmed with close agreement to flow meter readings as discussed in Section 4.2.

3.9 Governing Equations and Derived Quantities

In this study, ensemble averaging of velocity over N samples was performed to decompose the velocity into mean and fluctuating components. The governing equations of motion for an incompressible fluid of constant dynamic viscosity are the continuity and Navier-Stokes equations, given in tensor notation as (Tennekes and Lumley 1972)

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{Equation 3.5}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad \text{Equation 3.6}$$

with Cartesian coordinate x , and fluid velocity, u , in the i direction. In Equation 3.5 and Equation 3.6, gravitational effects are neglected, p is fluid pressure, t is time, ρ , is the fluid density, and ν is the fluid kinematic viscosity.

Reynolds decomposition breaks velocity into mean and fluctuating components as (Tennekes and Lumley 1972)

$$u_i = U_i + u'_i \quad \text{Equation 3.7}$$

Here the mean velocity, U_i , is given as the sample average velocity

$$U_i = \langle u_i \rangle = \frac{1}{N} \sum_{k=1}^N u_{ik} \quad \text{Equation 3.8}$$

where $\langle \rangle$ denotes a sample averaged quantity. The fluctuating velocity in direction 1 for sample k , is then calculated as $u'_{1k} = u_{1k} - U_1$.

Applying Reynolds decomposition to the continuity equation, we obtain for the mean velocity field

$$\frac{\partial U_i}{\partial x_i} = 0 \quad \text{Equation 3.9}$$

and applying the decomposition to the Navier-Stokes equations we obtain the mean momentum transport equation

$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} \delta_{ij} + \frac{\partial}{\partial x_j} \left(\nu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \langle u_i' u_j' \rangle \right) \quad \text{Equation 3.10}$$

where P is the mean pressure and δ_{ij} is the Kronecker delta. There is no temporal term in the above equations due to the decomposition, and the sample average was considered as the time average.

The term on the left hand side represents the transport of mean momentum by the mean velocity field. The first term on the right hand side is the effect on momentum of the mean pressure. The second term on the right hand side accounts for momentum transfer by viscous shear, and the last term, when multiplied by ρ , is the turbulent Reynolds stress. The Reynolds stress is the result of Reynolds averaging the convective acceleration term (the second term on the left hand side of Equation 3.6), and represents the mean transport of turbulent momentum by turbulent velocity (Tennekes and Lumley 1972).

In this study, the three velocity components were referred to as u , v , and w in the X , Y and Z directions respectively. The mean velocity field had velocity components U , V and W , and the turbulent fluctuating velocities were u' , v' , w' . The orientation of the coordinate system is shown in Figure 2.5, and therefore U was axial velocity, V was transverse velocity, and W was the out-of-plane velocity.

All velocities were normalized by the bulk inlet velocity U_0 where,

$$U_0 = \frac{4Q}{\pi d^2} \quad \text{Equation 3.11}$$

The quantity, $d = 26.8$ mm, is the inlet piping diameter (which is the same as the outlet piping diameter), and Q is the steady flow rate. The mean velocity field was therefore described in terms of variables U/U_0 , V/U_0 , W/U_0 .

The Reynolds number given in Equation 1.1 is related to U_0 as

$$\text{Re} = \frac{U_0 d}{\nu} \quad \text{Equation 3.12}$$

Mean vorticity, Ω_z , was normalized by d and U_0 to give

$$\frac{\Omega_z d}{U_0} = d \left(\frac{\partial V / U_0}{\partial x} - \frac{\partial U / U_0}{\partial y} \right) \quad \text{Equation 3.13}$$

Vortex detection is discussed in relation to the vortex identification threshold, Δ_v , where

$$\Delta_v = 4 \left(\frac{\partial U / U_0}{\partial x} \frac{\partial V / U_0}{\partial y} - \frac{\partial U / U_0}{\partial y} \frac{\partial V / U_0}{\partial x} \right) - \left(\frac{\partial U / U_0}{\partial x} + \frac{\partial V / U_0}{\partial y} \right)^2 \quad \text{Equation 3.14}$$

The vortex identifier was derived by Balducci et al. (2004), and based on eigenvalues of the velocity gradient tensor. The criterion for vortex detection was $\Delta_v > 0$ (Balducci et al. 2004).

Reynolds stress components in the XY plane were normalized by U_0^2 . In-plane Reynolds normal stress components $\langle u'u' \rangle / U_0^2$ and $\langle v'v' \rangle / U_0^2$, and the in-plane Reynolds shear stress component $\langle u'v' \rangle / U_0^2$ are reported.

If we assume that the Reynolds stresses scale linearly with U_0^2 then a corresponding "physiological" stress can be calculated using the bulk velocity at peak systole in a human aorta, $U_{0blood} = Re \ v_{blood} / d$. Using $Re = 7600$, $v_{blood} = 3.5 \times 10^{-6} \text{ m}^2/\text{s}$, gives $U_{0blood} = 1.00 \text{ m/s}$. The Reynolds stress components were converted to N/m^2 by multiplying by $\rho_{blood} = 1050 \text{ kg/m}^3$ (Fontaine et al. 1996).

The Reynolds shear stress was thus presented as

$$\rho_{blood} U_{0blood}^2 \left(\frac{\langle u'v' \rangle}{U_0^2} \right) \quad \text{Equation 3.15}$$

This quantity is converted to the dynes/cm^2 ($1 \text{ N/m}^2 = 10 \text{ dyne/cm}^2$) for comparison with previous studies.

Chapter 4

Results and Discussion

This chapter is divided into three sections: Section 4.1 Flow Visualization, Section 4.2 Inlet Conditions (2C-PIV), and Section 4.3 SPIV.

Initially, it is useful to refer to Figure 1.5 which shows primary in-plane flow structures:

1. Upper and lower lateral orifice jets
2. Upper and lower lateral orifice jet shear layers
3. Central jet
4. Upper and lower central jet shear layers
5. Upper and lower sinus recirculation regions
6. Leaflet wakes

which will facilitate discussion in the following sections.

4.1 Flow Visualization

Particle streak photography at Reynolds numbers of $Re = 2200, 2650, 3800, 5500, 6600$ and 7600 was performed. Images at $Re = 2200, 3800$ and 7600 are presented in the following sections as they best demonstrate the major flow characteristics seen in the flow visualization experiments. It is important to note that in pulsatile flow, the leaflets reach the fully open position at around 30% of the peak systolic flow rate, which in this case corresponds to about $Re = 2300$ (Dasi et al. 2007). Therefore, the fully open leaflet angle used in the model BiMHV is suitable for the steady flow rates studied. It was noted in Section 3.3 that the SPIV experiments were performed at a peak systolic Reynolds number of 7600 , but flow visualization at lower flow rates was beneficial, and

comparisons between Reynolds numbers are used to highlight differences between flow states.

For presentation of the flow visualization results, it is convenient to divide the aortic sinus into sections in order to better describe flow structures in specific areas, as shown in Figure 4.1. In the images, flow is from left to right, and the leaflets are highlighted to the left of the Y axis.

Figure 4.1 Division of aortic sinus into areas to facilitate discussion of flow visualization results.

4.1.1 $Re = 2200$

Four dewarped images taken at $Re = 2200$ are shown in Figure 4.2 to Figure 4.5. All four images show the formation of the central jet in A3 and A4, the upper lateral orifice jet at A2, and the lower lateral orifice jet at A5. Flow separation occurred as the lateral orifice jets expanded past the valve ring. Recirculation bubbles were formed in regions B1 and B6, and large scale vortices near the sinus walls were observed. In the remainder of this thesis, these large scale vortices will be referred to as *sinus vortices*. Figure 4.5 shows a total of four sinus vortices, two in the upper sinus recirculation region and two in the lower sinus recirculation region. The undulating shape of the lateral orifice jet shear layers at $Re = 2200$ was influenced by the size, shape and location of the sinus vortices.

Figure 4.2 Flow visualization at $Re = 2200$ showing asymmetric flow detachment from the lower leaflet.

Figure 4.3 Flow visualization at $Re = 2200$ showing asymmetric flow detachment from the lower leaflet and multiple sinus vortices.

Figure 4.4 Flow visualization at $Re = 2200$ showing a vortex about to be shed from the lower leaflet.

Figure 4.5 Flow visualization at $Re = 2200$ showing a leaflet vortex (in region B3) after it is shed downstream, and well defined multiple sinus vortices.

The presence of separated flow on the interior of the lower leaflet is shown by shorter particle streaks in regions A4 and B4 in Figure 4.2 to Figure 4.5 indicating a large leaflet wake from the lower leaflet. The spread of the wake was confined by the high velocity lower lateral orifice jet and the central jet. The absence of a similar wake on the upper leaflet in A3 and B3 is interesting. On the upper side of the leaflet, the central orifice jet remained attached until the leaflet trailing edge, and thus a large wake did not develop on the upper side. This led to an asymmetrical flow pattern in the leaflet wakes.

This asymmetry is likely due to a Coanda-type effect. At this Reynolds number, the central orifice jet was seen to be unstable. Flow either remained centralized, or it consistently detached from the lower leaflet. The central jet remained in the detached

state until the Reynolds number was increased to around $Re = 3300$, after which symmetric separated flow was observed on both leaflets. Symmetric separated flow at $Re > 3300$ was observed when the inlet piping was clean, and there were no upstream transient flow rate disturbances. However, if inlet piping was not clean, or the flow was rapidly accelerated or decelerated, asymmetrical central jet flow could be induced at higher Reynolds numbers. Also, a small geometric imperfection in the valve model, such as slightly differing leaflet angle, may have been a factor in this flow asymmetry. This indicated that leaflet wake flow symmetry was Reynolds number dependant, sensitive to inlet conditions, and may have been affected by small geometrical asymmetries.

The separated flow over the lower leaflet also showed evidence of vortex shedding. Figure 4.2 and Figure 4.3 show a vortex prior to shedding in region A4. Figure 4.4 shows the formation of a smaller leaflet vortex at a slightly upstream location. Figure 4.5 displays a vortex after it was shed and convected downstream in region B4.

4.1.2 $Re = 3800$

Four images taken at $Re = 3800$ are shown in Figure 4.6 to Figure 4.9. In all four images the formation of the central orifice jet and two lateral orifice jets is visible, and Figure 4.7 and Figure 4.8 show large scale vortices in both upper and lower recirculation regions. Generally only a single large sinus vortex could be seen in the upper and lower recirculation regions, but Figure 4.9 shows an atypical case where two counter-rotating sinus vortices are seen in the upper sinus region.

Figure 4.6 Flow visualization at $Re = 3800$ showing a symmetric central jet in contrast to $Re = 2200$. The central jet is contracted by separated flow from both leaflets.

Figure 4.7 Flow visualization at $Re = 3800$ showing large vortices in the sinus recirculation regions and contraction of the central jet from leaflet separated flow.

Figure 4.8 Flow visualization at $Re = 3800$ showing symmetrical central jet flow and well defined sinus vortices on both upper and lower sides. For $Re = 3800$ typically only 2 well defined sinus vortices were observed, but this was not always the case as seen in Figure 4.9.

Figure 4.9 Flow visualization at $Re = 3800$ showing an atypical case of multiple wall vortices in the upper sinus recirculation region.

In contrast to $Re = 2200$, at $Re = 3800$ there was symmetrical separated flow on the interiors of both of the leaflets (in regions A3 and A4) which acted to center the central jet. The central jet, driven by higher inertia, was more stable than at $Re = 2200$?, and detached symmetrically from both leaflets. As the Reynolds number was increased, this symmetrical flow pattern commenced at around $Re = 3300$. Figure 4.6 and Figure 4.7 shows that the separation bubbles on the leaflet surfaces also acted to contract the central jet. Once the flow moved past the leaflets, jet expansion occurred, and the central orifice jet interacted with the lateral orifice jets on either side.

4.1.3 $Re = 7600$

Four images showing flow at $Re = 7600$ are shown in Figure 4.10 to Figure 4.13. As seen at $Re = 2200$ and $Re = 3800$, the three jet formation was seen, though flow at $Re = 7600$ was visibly more disturbed than at the lower Reynolds numbers. Figure 4.10 to Figure 4.13 show that the central jet flow was highly chaotic, which has been observed previously by Woo and Yoganathan (1986). Similar to the flow at $Re = 3800$, symmetric separation bubbles are seen on the interior sides of both leaflets (in regions A3 and A4), and the central jet remains relatively centered. Also similar to $Re = 3800$, central jet compression due to leaflet separated flow, and the subsequent jet expansion just downstream of the leaflet trailing edges, were observed.

Figure 4.10 Flow visualization for $Re = 7600$ showing symmetry of the central jet similar to that observed at $Re = 3800$. Sinus vortices are visible in both upper and lower sinus recirculation regions.

Figure 4.11 Flow visualization for $Re = 7600$ showing central jet symmetry and a large vortex in the upper sinus. Relatively low speed flow is found in the upper and lower sinus recirculation regions.

Figure 4.12 Flow visualization for $Re = 7600$ showing expanded vortices shed from the leaflets in regions C2 and C5.

Figure 4.13 Flow visualization for $Re = 7600$ showing a wall vortex on the right side, and a shed vortex in region C2.

Vortices in the central jet region are visible at $Re = 7600$. These are found in C4/5 in Figure 4.10, C2 and C5 in Figure 4.12 and C2 in Figure 4.13. These vortices were likely due to leaflet vortex shedding, and expanded as they were convected downstream. The lateral orifice jets were seen to bow outwards as a shed vortex passed, which can be seen in Figure 4.10 in region C5.

It appeared that the increased streamwise momentum carried by the lateral orifice jets at $Re = 7600$ suppressed interaction with the near-wall fluid and inhibited the formation of multiple large counter-rotating sinus vortices seen at lower Reynolds numbers. Figure 4.10 shows large scale sinus vortices in both upper and lower sinus recirculation regions (B1 and B6). Figure 4.11, Figure 4.12 and Figure 4.13 show the lower sinus vortex was consistently not as distinct as the upper sinus vortex, however. This is also apparent in

Figure 4.14 where 50 images at $Re = 7600$ were averaged. The upper sinus recirculation region shows evidence of a single large scale sinus vortex indicating that its location was relatively steady. A large vortex in the lower sinus recirculation was not as apparent, however.

Figure 4.14 Averaged image at $Re=7600$ composed from 50 individual images. A sinus vortex is visible in the upper sinus recirculation region indicating that its position was relatively constant.

Video at $Re = 7600$ was used to investigate the dynamic nature of the flow. The video revealed intermittency and flapping of the central jet shear layers and lateral orifice jet shear layers. Flapping of the lateral orifice jet shear layers caused the lateral orifice jet reattachment point to oscillate in the streamwise direction. Also, small scale vortices at the edges of the lateral orifice jet shear layers were seen to be convected downstream.

4.1.4 Summary

Results for flow visualization at $Re = 2200$, 3800 and 7600 were presented. All images showed the formation of the central orifice jet and two lateral orifice jets. At $Re = 2200$, a Coanda-type effect was observed in the central orifice jet flow between the two leaflets. This caused asymmetric separation from the lower leaflet, and forced the central jet to the upper side. This had a large influence on the wake structure on both leaflets. Vortex shedding and a large wake were observed downstream of the lower leaflet. The wake generated by the upper leaflet was smaller as the flow remained attached until the trailing edge. These asymmetrical conditions were seen to be affected by upstream flow transients, the condition of inlet flow, and possibly by small geometrical imperfections in the valve model.

Flow at $Re = 2200$ and $Re = 3800$ showed the presence of multiple large scale vortices at the sinus walls. At $Re = 7600$, a single large scale sinus vortex in the upper and lower sinus regions was observed. At $Re = 7600$ this was attributed to higher streamwise momentum of the lateral orifice jets which caused lessened interaction with near-wall fluid. The averaged image in Figure 4.14 showed that the upper sinus vortex was somewhat stationary, while a lower sinus vortex was less discernable. Leaflet vortex shedding was also noted at $Re = 7600$ and expanded vortices were found downstream in the central jet. In addition, flow visualization video investigated the dynamic behaviour of the flow, which showed shear layer flapping, and downstream convection of small scale vortices in the sinus regions.

The above discussion illustrates the highly complex nature of BiMHV flow, as it combines the unsteady flow of three confined jets, leaflet wakes, and sinus recirculation regions. The flow visualization aided in defining different flow states, characteristics, and phenomena present in the flow.

4.2 Inlet Conditions (2C-PIV)

The Inlet Conditions Dataset was obtained using 2C-PIV to characterize the inlet velocity profile and facilitate the use of the SPIV datasets for CFD validation. Both the Inlet Conditions Dataset, and the SPIV datasets were obtained at a peak systolic Reynolds number of 7600 as mentioned in Section 3.3 and 3.7. In the following results, the axial coordinate, X , and the transverse coordinate, Y , were normalized by the inlet diameter, d . The inlet piping therefore spanned from $-0.5 < Y/d < 0.5$. Data was obtained 0.5 mm from the piping walls for $0.48 < Y/d < 0.48$. In the axial direction, data was obtained for $-3.34 < X/d < -2.95$ from the leaflet tips (see Section 2.4).

For the inlet conditions, the mean axial velocity, U/U_0 , was large compared to the mean transverse velocity, V/U_0 . Specifically, both V/U_0 , and transverse rms velocity, $\langle v'v' \rangle^{1/2}/U_0$, displacements were less than 0.1 pixel (corresponding to about $0.02U_0$) and therefore were considered negligible.

From the definition of U_0 (Equation 3.11), the average value of U/U_0 across the inlet diameter was expected to be approximately unity, implying correspondence with the flow meter readings. Indeed an average value of $U/U_0 = 1.03$ was found for all downstream locations, and the small deviation was within Inlet Conditions Dataset accuracy (see Appendix B).

Figure 4.15 shows mean axial velocity profiles at three downstream locations. A typical turbulent pipe flow profile was observed, and all three profiles almost completely overlapped which indicated that the inlet flow could be considered fully developed. The profiles were symmetric about the pipe centerline (X axis) within measurement accuracy.

The axial rms velocity, $\langle u'u' \rangle^{1/2}/U_0$, is shown in Figure 4.16. The profiles did not change downstream, and the shape of the profile was typical for that in turbulent pipe flow (Hinze 1959). There was less symmetry in the inlet turbulence than the mean flow, however, and an asymmetry was seen across the diameter of the inlet pipe, with greater

turbulence seen on the lower side of the pipe (negative Y values) than on the upper side (positive Y values). The peak value on the upper piping side was 33% higher than the peak value on the upper side, and this was larger than the estimated error in turbulence quantities for the Inlet Conditions Dataset of 14%. It is discussed in Section 4.3.4 that this asymmetry in inlet turbulence may have had an effect on flow in the aortic sinus.

Figure 4.15 Ensemble averaged axial velocity profiles for the Inlet Conditions Dataset. No large asymmetries were seen.

Figure 4.16 Profiles of the axial velocity fluctuating component $\langle u'u' \rangle^{1/2}/U_0$. An asymmetry is seen between the peak values.

4.3 SPIV

The SPIV experiments were performed at a peak systolic Reynolds number of 7600 as mentioned in Section 3.3. The SPIV results for the Full Aortic Sinus Dataset and Near Wall Sinus Dataset are given in the following section. In the following results, the axial coordinate, X , and the transverse coordinate, Y , were normalized by the inlet diameter, d . The aortic sinus diameter, $d_s = 32$ mm, was larger than the inlet diameter, $d = 26.8$ mm, and therefore the aortic sinus spanned from $-0.6 < Y/d < 0.6$.

For the Full Aortic Sinus Dataset, data was obtained 0.8 mm from the sinus walls, and the measurement region was $-0.57 < Y/d < 0.57$ in the transverse direction. In the axial direction, data was obtained for $0.05 < X/d < 0.80$ downstream of the leaflet tips (see Section 2.3). Convergence of mean velocity data is shown in Appendix C.

For the Near Wall Sinus Dataset, data was obtained 0.8 mm from the sinus walls, and the two measurement locations in the upper and lower sinus regions were at $0.45 < |Y/d| < 0.57$ in the transverse direction. In the axial direction, data was obtained for $0.05 < X/d < 0.5$ downstream of the leaflet tips (see Section 2.3).

4.3.1 Comparison to Previous Data

Data was collected by Fontaine et al. (1996) in steady flow at $Re = 7000$ with a similar axisymmetric aorta design as used in the current study. Fontaine et al. (1996) used a St. Jude Medical No. 27 BiMHV with an orifice diameter of $d_{valve27} = 22.3$ mm. Peak lateral orifice jet velocity of $U/U_0 \approx 1.9$ was recorded at $X/d \approx 0.4$. In the current study, steady flow at $Re = 7600$ was used with a model Carbomedics No. 25 BiMHV, which had a smaller nominal valve orifice diameter, $d_{valve25} = 20.5$ mm (see Figure 2.8) and in which we measured a peak lateral orifice jet velocity of $U/U_0 = 2.49$ at $X/d = 0.41$. Velocities are expected to be higher through a smaller orifice, and therefore we must scale our results to account for the smaller valve orifice diameter in the current study if we wish to compare to the results of Fontaine et al. Specifically, U/U_0 must be divided by $(d_{valve27})^2$

$/d_{\text{valve}25}^2) = 1.18$. Doing this gave $U/U_0 = 2.49/1.18 = 2.11$, which was within 11% of Fontaine's value of 1.9.

4.3.2 General Flow Characteristics

Figure 4.17, Figure 4.18, and Figure 4.19 are contour plots of the ensemble-averaged velocity field of the Full Aortic Sinus Dataset for U/U_0 , V/U_0 , and W/U_0 respectively. Leaflet tips were located at $Y/d \pm 0.14$ and $X/d = 0$, and are shown as the black boxes on the left of the figures. In Figure 4.17 the axial velocity, U/U_0 , in the lateral orifice jets (at roughly $0.20 < |Y/d| < 0.40$) was dominant. The highest velocities in the flow were recorded in the lateral orifice jets of roughly $U/U_0 = 2.60$ for $X/d < 0.21$. The lateral orifice jets were seen to curve towards the centerline (X axis) of the sinus around $X/d = 0.52$, which corresponded to the start of the sinus contraction at $X/d = 0.51$ (i.e. $X = 13.8$ mm, see Figure 2.5). The central orifice jet (at roughly $-0.07 < Y/d < 0.07$) had a peak velocity of roughly $U/U_0 = 2.20$ for $X/d < 0.21$.

In Figure 4.17, regions of high shear in the XY plane were indicated by the dominant gradient $\partial(U/U_0)/\partial y$, which occurred near the upper and lower lateral orifice jet shear layers around $0.40 < |Y/d| < 0.45$. The lateral orifice jet shear layers were thus sites of intense mixing and turbulence, which has been noted by Yoganathan et al. (1986, 2004), Fontaine et al. (1996) and others.

Figure 4.17 Ensemble averaged results showing contours of axial velocity, U/U_0 , for the Full Aortic Sinus Dataset. The high speed fluid in the lateral orifice jets is seen.

Figure 4.18 Ensemble averaged results showing contours of transverse velocity, V/U_0 , for the Full Aortic Sinus Dataset. The flow diverges relatively symmetrically from the centerline (X axis).

Figure 4.19 Ensemble averaged results showing contours of out-of-plane velocity, W/U_0 , for the Full Aortic Sinus Dataset. V/U_0 and W/U_0 are of similar magnitudes, and are about 4 times lower than that of U/U_0 .

Figure 4.20 Contours of normalized mean vorticity, $\Omega_z d / U_0$, for the Full Aortic Sinus Dataset. High vorticity caused by a high gradient $\partial (U/U_0) / \partial y$ is found near the lateral orifice jet shear layers ($0.40 < |Y/d| < 0.45$) and central jet shear layers ($0.16 < |Y/d| < 0.22$).

The transverse velocity, V/U_0 , in Figure 4.18 shows that the flow was relatively symmetric about the X axis. This can also be seen in the plot of normalized mean vorticity, $\Omega_z d / U_0$, in Figure 4.20. The upstream lateral orifice jet flows separated from the valve ring at $X/d = -0.16$ and expanded into the upper and lower sinus recirculation regions which caused the divergence of velocity away from the X axis. Thus high positive and negative vorticity is shown in the lateral orifice jet shear layers for $|Y/d| > 0.40$ in Figure 4.20. In Figure 4.18, regions of highest magnitude V/U_0 ended near $X/d = 0.52$ where the transverse velocity began to decrease due to the sinus contraction.

Comparing Figure 4.18 and Figure 4.19 shows that the out-of-plane velocity, W/U_0 , and transverse velocity, V/U_0 , were of similar magnitude. The highest values of V/U_0 and W/U_0 were around 0.60 which was about 4 times smaller than the highest value of U/U_0 at 2.60. It should also be noted that errors in W of $\pm 8\%$, were double the $\pm 4\%$ errors for U and V (see Appendix A). W/U_0 also had the smallest velocity range (-0.30 to 0.64), and therefore the contour levels in the above figures were chosen at $\Delta W/U_0 = 0.10$ which corresponded to the full scale error in W/U_0 of $\pm 8\% \times 0.64 = \pm 0.05$, to show significant values of all three velocity components.

Figure 4.21 shows the in-plane velocity vectors U/U_0 and V/U_0 . Every second vector in the X direction was plotted for clarity.

Figure 4.21 Ensemble averaged in-plane velocity vectors for the Full Aortic Sinus Dataset. Every second vector in the X direction is shown. Low velocity fluid is found in the upper and lower sinus regions above and below the lateral orifice jets.

Of interest was flow in the sinus recirculation regions, and enlarged views of velocities in the upper and lower sinus regions are shown in Figure 4.22 and Figure 4.23 respectively. In Figure 4.22, the flow reversed in the upper sinus and a defined recirculation was apparent. The flow observed in the upper sinus was similar to that seen in flow over a backward facing step, as flow separation occurred at the edge of the step (in this case, the valve ring at $X/d = -0.16$) due to the adverse pressure gradient caused by the sudden expansion downstream (Armaly et al. 1983). A recirculation bubble was created as the upper lateral orifice jet shear rolled up into the near-wall fluid.

Figure 4.22 Enlarged view of upper sinus region for the Full Aortic Sinus Dataset. A large scale recirculation is seen.

Figure 4.23 Enlarged view of lower sinus region for the Full Aortic Sinus Dataset. Reverse flow is difficult to see, which was the primary motivator in obtaining the Near Wall Sinus Dataset.

The lower sinus velocity field is shown in Figure 4.23, and recirculation was less apparent because velocities in the region of $Y/d < -0.50$ and $X/d < 0.20$ were at the lower limit of the system dynamic range. For this reason, the Near Wall Sinus Dataset was obtained with better resolved sinus region velocity, as discussed in Section 3.8. Results

for the mean velocity field of the Near Wall Sinus Dataset are shown for the upper sinus in Figure 4.24 and lower sinus in Figure 4.25. In Figure 4.25, recirculation was evident in the lower sinus. Comparing Figure 4.24 and Figure 4.25, the reverse flow pattern in the lower sinus was clearly different than the upper sinus. To investigate the difference in flow, recirculation bubble length was examined.

To compare the lengths of the recirculation bubbles in the upper and lower sinuses, reattachment points of the lateral orifice jets were loosely defined as the first downstream location where the axial velocity closest to the wall was positive. For the Near Wall Sinus Dataset, the point of reattachment of the upper lateral orifice jet was $X/d = 0.38$. For the lower lateral orifice jet the point of reattachment was more upstream at $X/d = 0.28$. The lower sinus recirculation bubble was therefore shorter, and the shorter recirculation bubble seemed to inhibit large scale shear layer rollup as seen in the upper sinus region. The next section describes the sinus recirculation regions in more detail with the use of a vortex detection method.

Figure 4.24 Ensemble-averaged results for the upper sinus region of the Near Wall Sinus Dataset. Due to the improved resolution of low velocities in this dataset, the reverse flow is seen to be stronger than that shown in the Full Aortic Sinus Dataset.

Figure 4.25 Ensemble-averaged results for the lower sinus region of the Near Wall Sinus Dataset. The improved resolution of low velocities shows stronger reverse flow than that seen in the Full Aortic Sinus Dataset.

4.3.3 Vortex Detection

It was difficult to identify vortices in this flow due to the dominant gradient $\partial(U/U_0)/\partial y$, especially near the lateral orifice jet shear layers. Hence, in this section, a vortex detection method was used to define large scale vortices in the sinus regions in the mean flow. Also, vortex detection was performed on instantaneous velocity fields to show that vortices were present only in specific flow regions.

A vortex identification threshold, Δ_v , (from Equation 3.14) given by Balducci et al. (2004) was used to identify locations of vortex cores in the flow. The criterion for vortex core detection in the absence of noise is $\Delta_v > 0$; however, experience shows that Δ_v should be thresholded at a level greater than zero in order to filter out noise in the plots. For example, Jeong and Hussain (1995) Thresholded Δ_v in their work. For the instantaneous velocity fields, we used a threshold value of 0.1. For the mean velocity field a threshold value of 0.005 was used.

Plots of vortex core detection in the instantaneous velocity fields of the Full Aortic Sinus Dataset are shown in Figure 4.26 (a), (b) and (c). Overlaid streamlines show the separated flow regions in the sinuses, and that the largest vortical structures in the flow were present in these regions. Smaller vortices were seen in the central jet. It is possible that these vortices were shed from the leaflets as was seen previously in the flow visualization images. It is interesting to note that vortices were identified in the central jet, but are not in the lateral orifice jets. This indicated that central jet flow was more disturbed than the lateral orifice jet flow, as has been noted by Yoganathan et al. (1986).

Figure 4.26 (a) Instantaneous velocity field contours of Δv , showing the locations of vortex cores. Streamlines are overlaid showing the location of the recirculation bubbles in the upper and lower sinus regions.

Figure 4.26 (b) Instantaneous velocity field contours of Δv , showing the locations of vortex cores. Streamlines are overlaid. Vortices were identified in the central jet but not in the lateral orifice jets.

Figure 4.26 (c) Instantaneous velocity field contours of Δv , showing the locations of vortex cores. Streamlines are overlaid, and the largest vortices are found in the upper and lower sinus regions.

Vortex detection was also performed on the mean velocity field of the Near Wall Sinus Dataset which had improved velocity resolution in the sinus regions. Figure 4.27 and Figure 4.28 show the upper and lower sinus regions respectively. These figures show that, as expected, large scale vortices were present in both the upper and lower sinus regions, and indicated that the basic structure of the flow in the sinuses was similar. However, Figure 4.27 and Figure 4.28 indicate that the shape and extent of the vortex cores are different, though this may have been due to the limited measurement location size in the Near Wall Sinus Dataset. It was discussed in Section 4.3.2 that the upper sinus

recirculation bubble was longer than the lower sinus recirculation bubble, and possible factors contributing to this asymmetry are discussed Section 4.3.4 below.

Figure 4.27 Vortex core detection for upper sinus from the Near Wall Sinus Dataset. A large scale sinus vortex was identified.

Figure 4.28 Vortex core detection in the lower sinus for the Near Wall Sinus Dataset. A sinus vortex was identified, but was different from that seen in the upper sinus.

4.3.4 Sinus Region Asymmetry

Large vortices were identified in both the upper and lower sinuses and therefore the basic structure of the flow was similar in these two locations. However, differences in flow pattern and recirculation bubble size were observed. Here, possible factors contributing to the observed asymmetry are explored.

For steady flow, detailed spatial data showing the full aortic sinus are unfortunately not available from previous studies. Ge et al. (2005) used a similar axisymmetric model as the current study, and performed a 2C-PIV study at $Re = 6000$, but results were presented at only at three downstream locations. However, Ge et al. (2005) noted that small asymmetries in the model had a large effect on the flow near peak systole. Fontaine et al. (1996) used LDA with the same axisymmetric aortic sinus geometry as Ge et al. (2005), though only one downstream location was measured. In the current study, it was therefore difficult to compare the specifics of the observed recirculation bubble asymmetry to data from previous steady flow studies with similar axisymmetric sinus geometry.

Recent pulsatile studies show that large scale vortex rollup, similar to that seen in the upper sinus of the current study, is typically found in both upper and lower sinuses (Dasi et al. 2007). However, differences between pulsatile flow studies and steady flow studies should be mentioned. Hanle et al. (1988) compared steady and pulsatile flow and noted that steady flow was more asymmetric than pulsatile flow, and Chandran (1985) observed that reverse flow in the sinus region was weaker in steady flow.

The exact reason for the observed asymmetry in the upper and lower sinus regions is difficult to determine, but several hypotheses are presented below. It was initially thought that the flow asymmetry was due to a geometrical imperfection in the model BiMHV. In order to investigate this, another dataset was obtained after the valve was rotated 180° about the X axis. The results showed no change in flow structure in the upper and lower sinuses, and therefore a valve geometry effect was unlikely. However, a small geometric asymmetry in the valve cannot be definitively ruled out as a possible contributing factor.

Another possibility was the asymmetry in inlet turbulence across the inlet piping discussed in Section 4.2. It was found that the mean inlet velocity profiles were approximately symmetric about the X axis, but higher inlet turbulence was present in on the lower side of the inlet piping than on the upper side. It is possible that higher

turbulence on the lower side caused the atypical recirculation region in the lower sinus, as upstream turbulence has been shown to influence backward facing step-type flow (Le et al. 1997).

In addition, the presence of asymmetrical recirculation regions in a symmetrical sudden expansion is not unusual. Fearn et al. (1990) conducted a steady flow study specifically designed to investigate instabilities responsible for causing such asymmetries. They concluded that initially symmetric recirculation regions became unstable at a Reynolds number of $Re = 60$, which was the result of a symmetry breaking bifurcation and was therefore intrinsic to the flow.

In the flow visualization, it was also noted that the large scale vortex in the lower sinus recirculation was consistently less distinct than the upper vortex. With the complex test section geometry, noted asymmetries in steady flow, and sensitivity to upstream turbulence, it can be postulated that, in steady flow, the occurrence of flow symmetry is difficult to achieve.

4.3.5 Velocity Profile and Self-Similarity

Axial velocity profiles, U/U_0 , are shown in Figure 4.29 at six downstream locations. The spread of the all three jets was apparent as the three peaks flattened and widened. The lateral orifice jets consistently had greater axial velocities than the central jet, and this has been observed in previous studies (Yoganathan et al. 1984, Liu et al. 2000).

Both lateral orifice jets (at roughly $Y/d = \pm 0.30$) had flat-topped profiles for the $X/d = 0.08$ and 0.23 locations shown, which were similar to that of an under-developed free turbulent jet (Tennekes and Lumley 1972). The central jet (at roughly $Y/d = 0$) did not exhibit a flat-topped profile at any downstream location, however. The flow visualization experiments revealed the presence of separated flow and wake regions on the interiors of the leaflets. The lack of a flat-topped profile in the central jet indicated that the interior shear layers of the leaflet wakes merged upstream of the leaflet tips.

The leaflet wakes were apparent from velocity defects seen near the central jet shear layers between the lateral orifice jets and the central jet, and have been described in previous studies (Hanle et al. 1988, Yoganathan et al. 2004). Higher axial velocity was observed in the velocity defect near the lower central jet shear layer (negative Y values) than that near the upper central jet shear layer (positive Y values). Asymmetries in velocity defects seen in previous steady flow studies, however, tend to be larger than that seen here (Yoganathan et al. 1982, Fontaine et al. 1996, Ge et al. 2005). In these previous studies, actual BiMHVs were used with moving leaflets. Larger wake asymmetry in previous studies may have been due to fluid structure interaction from leaflet movement. This was eliminated in the current study by using fixed leaflets. Also, flow visualization revealed a Coanda effect between the leaflets at $Re = 2200$, and a similar effect may have been present in previous studies. Indeed, in pulsatile studies, leaflet wake asymmetries have been attributed to asymmetrical leaflet opening (Brucker 1997, Marassi et al. 2004). The comparatively small leaflet wake asymmetry seen in the current study indicated central jet stability at $Re = 7600$, and that any geometrical asymmetry in the leaflets was small.

The peak lateral orifice jet velocities differed by less than 2% between the upper and lower jets. Also the distance from the aortic centerline to the peak velocities differed by only $\Delta Y/d = 0.02$ for all downstream locations. This implied that the core flow of the lateral orifice jets was highly symmetric. However, asymmetry was seen in the lateral orifice jet shear layers for $|Y/d| > 0.4$ due to the differing recirculation bubble flow. A higher gradient, $\partial(U/U_0)/\partial y$, was observed in the upper lateral orifice jet shear layer than the lower lateral orifice jet shear layer, which can also be observed in the axial velocity contour plot shown in Figure 4.17. Because of the longer recirculation bubble in the upper sinus, the upper lateral orifice jet was confined for a greater downstream distance, and the flow remained more centralized than in the lower lateral orifice jet. Although extrapolations to in vivo should be made with caution, it can be argued that the confinement provided by the upper sinus recirculation is advantageous, as more centralized flow is beneficial in prosthetic heart valves (Yoganathan et al. 1982).

It should also be noted that the spread of the central jet and curvature of the sinus contraction altered the transverse location of the peak lateral orifice jet velocity. The transverse location of peak velocity in the lateral orifice jets upstream at $X/d = 0.08$ was $Y/d = \pm 0.30$, but downstream at $X/d = 0.67$ the peak velocity location had moved to $Y/d = \pm 0.41$.

Figure 4.29 Axial velocity profiles at different downstream locations.

The decay of peak jet velocity with downstream distance for all three jets is shown in Figure 4.30. In Figure 4.30, note the regular vertical fluctuations in the plots that occurred in all three jets at the same downstream locations. These regular fluctuations were found to be due to the interrogation area overlap used in SPIV data processing, and therefore were not an actual feature of the flow. The amplitude of the fluctuations was found to be only 3%, however, and is discussed in Appendix A.2.4.

The central jet is rectangular in shape due to flats on the top and bottom of the valve ring, and the flat leaflet surfaces (see Figure 2.8). The lateral orifice jets are elliptical on the exterior side, but flat on the leaflet interior side (see Figure 2.8). Krothapalli et al. (1981) obtained measurements in a single free rectangular jet and found that the rate of decay of the square of peak jet velocity was initially zero, followed by a region of decay rate proportional to the downstream coordinate as seen in a free plane jet (Tennekes and Lumley 1972). Figure 4.30 compares $(U_{max}/U_0)^2$ versus X/d . Because of the vertical fluctuations in the data, the decay not as apparent, but fitting an expected linear relationship to the velocity data, the lateral orifice jets showed little decay for approximately $X/d < 0.2$. Beyond $X/h \approx 0.2$, a linear decay was observed to the end of the measurement plane. For the central jet, the same trend was seen with essentially no decay for approximately $X/d < 0.2$, and a linear decay afterwards. All three jets therefore exhibited a decay rate similar to that seen in free rectangular jets. Fabris and Fejer (1974) found that single jet analysis could be applied to confined multiple jet configurations. It is interesting that a similar situation arises here, especially noting the difference in geometry of the lateral orifices, the contraction of the sinus, and the presence of leaflet wakes.

Figure 4.30 Peak jet velocity decay with downstream distance. All three jets exhibit a decay rate not unlike that seen in free rectangular jets with a region of zero decay followed by a decay rate of a planar jet. Dashed lines show the decay rate trends found in the data.

Free rectangular jets have also been shown to be self similar when the axial velocity is normalized with the peak velocity (Krothapalli et al. 1981). Figure 4.31 shows normalized axial velocity profiles for the central jet plotted versus non-dimensional transverse coordinate Y/X . Normalizing the central jet profiles versus Y/X thus assumed a constant jet spreading rate. Apart from classical free jet studies, this assumption has also been employed in confined multiple jet studies (Fabris and Fejer 1974), and single free rectangular jet studies (Krothapalli et al. 1981). The lateral orifice jets were not tested for self similarity.

It can be seen in Figure 4.31 that for $X/d \geq 0.14$ that the velocity profiles of the central jet collapsed well for positive values of Y/X , and that the profiles were reasonably self similar. $X/d \geq 0.14$ was close to the approximate location of start of linear decay of $X/d \approx$

0.2, and therefore the central jet profile became self similar near the start of the linear decay range. The upstream profile at $X/d = 0.08$, is seen to appreciably deviate from the other profiles, and was not self similar. It appears that at this downstream location the central jet was not fully developed. It is difficult to say if a true potential core of the central jet existed, as simultaneous mixing of leaflet wakes and jet shear layers complicated flow dynamics. It is clear, however, that the zero-decay region corresponded to a transition region, the end of which was near to commencement of self similarity and linear decay.

In Figure 4.31, the profiles were reasonably self similar for $Y/X > -0.3$ but did not collapse well for $Y/X < -0.3$. This was due to the asymmetry in the leaflet wake velocity defects, where consistently higher axial velocities were observed for negative Y values, than for positive Y values (see Figure 4.29).

Figure 4.31 Normalized axial velocity profiles of the central jet. The jet is shown to be reasonably self similar for $X/d \geq 0.14$ and $Y/X > -0.3$.

A proposed diagram of the in-plane development of the central jet is shown in Figure 4.32. Near zero decay was observed in the upstream portion of the central jet. At downstream locations, decay was similar to a planar jet where $(U_{max}/U_0)^2 \propto X/d$ and the axial velocity profiles were self similar. The decay rate and onset of self similarity has been observed in free rectangular jets (Krothapalli et al. 1981). This finding has important implications in the context of flow modelling. Free jet theory is well established and can perhaps assist in understanding BiMHV flow models. In addition, self similarity of the central jet can be used as a criterion for validating CFD simulations.

Figure 4.32 Diagram of central jet velocity profile development. Near zero decay of peak velocity is expected at upstream locations, but a planar jet decay rate is expected afterwards and axial velocity profiles are self similar.

4.3.6 Continuity and 3D Flow Structure

To validate mean flow continuity of the measurements, the variation of total in-plane flow with downstream location shown in Figure 4.33 was examined. The total in-plane flow was calculated by integrating U/U_0 across the entire aortic sinus using the rectangle rule, where U/U_0 values were multiplied by the transverse vector spacing, ΔY , and then summed over the sinus diameter, d_s . Vertical fluctuations in the data can be seen and are similar to those noted in Section 4.3.5. The fluctuations were attributed to interrogation area overlap and are discussed in Appendix A. Using standard error propagation with the error estimate of $\pm 4\%$ in U/U_0 given in Appendix A, the estimated error in the axial flow rate was approximately $\pm 5\%$. The slight increase in axial flow seen in Figure 4.33 was within roughly $\pm 5\%$, and therefore it was considered not statistically significant. The axial flow rate was therefore considered approximately constant downstream, which was an acceptable validation of mean flow continuity.

Figure 4.33 Axial flow rate variation with downstream distance. The variation is within uncertainty estimates and therefore the flow rate can be considered constant downstream.

It was a goal of the study to obtain measurements as close to the XY plane as possible, but finite laser sheet thickness, and inevitable laser sheet positioning errors caused non- XY plane particles to be recorded. Therefore, it was important to distinguish between the geometric XY plane (or $Z = 0$ plane), and the actual measurement plane. If a measurement plane located slightly above the XY plane is considered, there is an expected net W flow through the measurement plane. In Figure 4.34, the measurement plane, denoted as MP , is located slightly above the XY plane. As the jet flow expands past the valve ring, a net positive W flow occurs through the measurement plane because of its positioning slightly above the XY plane. This explanation therefore assumes that expansion past the valve ring is symmetric about the XY plane. However, the same effect of net W flow through the measurement plane would be seen if the measurement plane was coincident with the XY plane, but the flow was asymmetric about the XY plane. This was an equally probable scenario, since symmetry breaking about the XZ plane was noted in Section 4.3.4 with respect to recirculation bubble flow. In either case, it was clear that a net W flow occurred through the measurement plane.

Figure 4.34 Diagram showing the possible positioning of the measurement plane (designated as *MP*) above the *XY* plane. This allowed a net flow of out-of-plane velocity, *W*, through the measurement plane. Net *W* flow through the measurement plane could also have occurred if the measurement plane was positioned coincident with the *XY* plane but the flow was asymmetric about the *XY* plane.

Figure 4.35 Contours of W/U_0 with overlaid streamlines to show the locations of the sinus recirculation regions. Large streamwise vortices are identified by the corresponding positive and negative W found in the lateral orifice jets. Dashed lines show the locations of positive velocity contained in two smaller streamwise vortices found in the central jet.

Figure 4.35 shows a contour plot of W/U_0 velocity with overlaid streamlines. For $X/d < 0.65$, larger regions of positive W/U_0 velocity can be seen relative to regions of negative W/U_0 . This was attributed to the net positive flow W expected through the measurement plane which caused W/U_0 to be positively biased. For $X/d > 0.65$, however, Figure 4.35 shows a region of negative W velocity spanning almost the entire sinus for $-0.25 < Y/d < 0.25$. Particles in this region were imaged through the curved sinus contraction, which likely led to an increase in error. This was due to possible radial blurring of particle images (Section 3.5.2). Because of this, and the increased errors in the W/U_0 discussed in

Appendix A, it was concluded that the region of negative velocity for $-0.25 < Y/d < 0.25$ and $X/d > 0.65$ was due to measurement uncertainty in W/U_0 .

Figure 4.36 Diagram of 3D vortex structure in the cross section of the axisymmetric aorta sinus. (a) A four-cell structure was possible with four large counter-rotating streamwise vortices in the lateral orifice jets. (b) An alternate scenario was an eight-cell streamwise vortex structure with a second set of four smaller counter-rotating vortices in the central jet. (c) Downstream of the aortic sinus a four-cell vortex structure has been observed by previous researchers.

In previous BiMHV studies investigating the cross section of the aorta, three dimensionality of the flow has been observed. In both steady and pulsatile flow studies, it has been shown that four large streamwise vortices, two above and two below the XY plane are formed (Hanle et al. 1988) as shown in Figure 4.36(c). However, it should be noted that these measurements were made downstream of the aortic sinus, and beyond the current measurement plane at $X/d \approx 1.0$.

Further examination of the contour plot in Figure 4.35 reveals the presence of similar counter-rotating streamwise (i.e. Ω_x) vortices that extended longitudinally along the aortic sinus. Positive W/U_0 velocity occurred at the sinus walls at $Y/d = \pm 0.60$ which then fed negative W/U_0 velocity into regions which, at the upstream side, are shown at $Y/d = \pm 0.22$ and $X/d = 0.05$. The axes of these streamwise vortices closely followed the leaflet angle and the axes of the lateral orifice jets, and are therefore referred to as the lateral orifice jet vortices. The presence of positive W velocity in the central jet region for $-0.15 < Y/d < 0.15$ was caused by the positive bias of W velocity described earlier, and therefore it was possible that the lateral orifice jet vortices comprised a four-cell streamwise vortex structure in the aortic sinus as shown in Figure 4.36(a). Downstream, as a result of the aortic sinus contraction, the four vortices likely moved inwards, closer to the aortic centerline which resulted in the four-cell vortex structure observed by Hanle et al. (1988).

However, an alternate explanation of the 3D flow structure is possible. The two lobed regions of elevated W/U_0 , shown in the dashed box region in Figure 4.35, may be evidence of a smaller set of counter-rotating streamwise vortices that occurred in the central jet. This is the first time that evidence of two counter-rotating vortices in the central jet has been seen. This explanation yields an eight-cell streamwise vortex structure in the aortic sinus, as shown in Figure 4.36(b). Due to the downstream aortic sinus contraction region, the out-of-plane velocity decreased downstream. This is shown as $W/U_0 \approx 0$ for $X/d > 0.50$ in the central jet. This caused the central jet vortices to weaken, and allowed merging of the central jet vortices with the larger lateral orifice jet vortices, to form a four-cell vortex structure. Downstream, as a result of the aortic sinus contraction, the four vortices likely moved inwards, closer to the aortic centerline to result in a four-cell structure shown in Figure 4.36(c). It should therefore be noted that the two alternative explanations of either a four-cell or eight-cell streamwise vortex structure in the aortic sinus resulted in the same four-cell vortex structure downstream observed by Hanle et al. (1988)

The streamlines shown in Figure 4.35 indicate the position of the upper and lower sinus vortices described in Section 4.3.3. Both the upper and lower sinus vortices were contained in regions of positive W/U_0 . Although velocity resolution was decreased in the upper and lower sinuses (as discussed in Section 4.3.2), the data indicated that the sinus vortices may have been convected azimuthally by the large streamwise vortices.

The 3D structure of the flow therefore contained the simultaneous occurrence of net positive W flow through the measurement plane, and large scale streamwise vortices. The net positive W flow can be thought of as a DC component of the flow, onto which AC component motion of the streamwise vortices are superimposed. From this description, the three dimensionality of the mean flow was apparent. Although the flow has been described previously as chaotic, it was seen that the mean out-of-plane flow field exhibited organization even at high Reynolds numbers.

4.3.7 Reynolds Stress and Total Shear Stress

In this section, results for the normalized in-plane Reynolds stress components, $\langle u'u' \rangle / U_0^2$, $\langle v'v' \rangle / U_0^2$ and $\langle u'v' \rangle / U_0^2$ are presented. Results for Reynolds stresses containing out-of-plane turbulence velocity w' are not given due to measurement uncertainty discussed in Appendix A.

Figure 4.37 Contours of Reynolds stress component $\langle u'u' \rangle / U_0^2$ shows higher values in the lateral orifice jet shear layers and the central jet. Peak values are found at the lower lateral orifice jet impingement location, $X/d > 0.21$.

Figure 4.38 Contours of Reynolds stress component $\langle v'v' \rangle / U_0^2$ show higher values in the lateral orifice jet shear layers and the central jet. Peak values are found downstream of the lower recirculation bubble around $X/d > 0.28$. Compare to Figure 4.37

Figure 4.39 Contours of Reynolds stress component $\langle u'v' \rangle/U_0^2$ shows higher values in the lateral orifice jet shear layers and the leaflet wake regions.

Figure 4.37 and Figure 4.38 show that relatively low Reynolds stresses were observed in the lateral orifice jet cores (roughly $0.20 < |Y/d| < 0.40$). This is contrasted to the higher magnitudes in the central jet (roughly $-0.20 < Y/d < 0.20$). In the central jet, regions of elevated stress are shown on either side of the X axis, separated by a region of lower stress for $-0.07 < Y/d < 0.07$, that extended for $0.05 < X/d < 0.52$. These off-axis peaks in the central jet have been observed in free jets, and were the result of the Reynolds normal stresses working against the mean shear (Hussein et al. 1994).

Similarly, in regions of high mean shear, increased Reynolds shear stresses were expected (Mathieu 2000). The lateral orifice jet shear layers exhibited the largest mean shear, $\partial(U/U_0)/\partial y$, in the flow, and elevated $\langle u'u' \rangle / U_0^2$ and $\langle v'v' \rangle / U_0^2$ values near the lateral orifice jet shear layers at roughly $|Y/d| > 0.4$ were observed. Energy transfer between the mean flow and turbulence occurred, and in this case with a benefit to the turbulence, which is commonly seen in free shear flows (Tennekes and Lumley 1972). In the context of turbulence kinetic energy, this mechanism is termed turbulence production.

It was mentioned in Section 4.3.2 that the mean flows in the upper and lower sinus regions were different, and a difference is also seen in the Reynolds stress distribution. Interestingly, in the upper sinus region, a reduction in both Reynolds normal stresses and Reynolds shear stresses was observed in the vicinity of the larger recirculation bubble. The plot of Reynolds shear stress in Figure 4.39 shows a contrasting case in the upper lateral orifice jet shear layer. For example, at $X/d = 0.38$ for $0.40 < Y/d < 0.45$, Reynolds shear stress is high at $\langle u'v' \rangle / U_0^2 \approx 0.10$, and then decreases to $\langle u'v' \rangle / U_0^2 \approx 0.05$ as the sinus wall is neared at $Y/d = 0.60$. This is contrasted with the lower sinus where a shorter recirculation bubble was present. In Figure 4.37, Figure 4.38 and Figure 4.39, in the lower lateral orifice jet shear layer, Reynolds stresses were elevated all the way to the sinus wall at $Y/d = -0.60$, which was downstream of the lower lateral orifice jet reattachment location at roughly $X/d = 0.28$ and $Y/d = -0.60$.

In Figure 4.40, Reynolds shear stress profiles are plotted at different axial locations. As noted previously in Section 3.9, to convert normalized $\langle u'v' \rangle / U_0^2$ to units of stress, $U_{0blood} = 1.00$ m/s and $\rho_{blood} = 1050$ kg/m³ were used. In previous studies, Reynolds shear stress has been used to identify regions potentially damaging to red blood cells and platelets. Because of the idealized axisymmetric aorta and steady flow rate used in the current study, it was difficult to directly correlate the results to possible blood cell and platelet damage in vivo, and the reader should keep this in mind when viewing these results. Figure 4.40 does, however, correspond quite well to values achieved in more complicated pulsatile flow studies (Yoganathan et al. 1986, Fontaine et al. 1996, Liu et al. 2000).

Figure 4.40 Profiles of Reynolds shear stress. Physiological aortic velocity and blood density were used to display the values in dyne/cm^2 .

Liu et al. (2000) performed a pulsatile flow study and measured Reynolds shear stress in a Carbomedics BiMHV. Liu found peak values in the lateral orifice jet shear layers of around 750 dyne/cm^2 at $X/d \approx 0.4$. Yoganathan et al. (1986) and Fontaine et al. (1996) showed peak values of 1500 dyne/cm^2 at $X/d \approx 0.3$, and 700 dyne/cm^2 at $X/d \approx 0.4$ respectively for a St. Jude Medical BiMHV. Figure 4.40 shows peak values of about 950 dyne/cm^2 at $X/d = 0.36$. Therefore the current data was in the same range as previous studies.

The shape of the Reynolds shear stress profiles also agreed with previous data (Yoganathan et al. 1986, Fontaine et al. 1996, Liu et al. 2000). In the lateral orifice jet shear layers, which at $X/d = 0.36$ are near $Y/d = \pm 0.50$, peak values of Reynolds shear

stress of about 950 dyne/cm^2 are seen. As flow progressed downstream, the peaks moved outwards and followed the direction of the lateral orifice jet shear layers. Also, additional peaks in Reynolds shear stress have been seen in the leaflet wakes in previous studies (Yoganathan et al. 1986). In Figure 4.40 these corresponded to the peaks around $Y/d = \pm 0.10$. The leaflet wakes contributed to the production of turbulence in the region, and acted to increase Reynolds stress values, which has also been observed in confined bluff body wake flow (Taylor and Whitelaw 1984).

4.3.8 Summary

The SPIV results from the Full Aortic Sinus Dataset clearly showed the formation of the lateral orifice jets and the central jet. The axial velocity, U , of the lateral orifice jets was highest, and roughly four times greater than the transverse, V , and out-of-plane, W , velocities. Elevated vorticity was seen in the lateral orifice jet shear layers and central jet shear layers due to a dominant gradient $\partial U / \partial y$. The gradient was highest in the lateral orifice jet shear layers indicating that these were sites of intense mixing.

Upstream flow separation at the valve ring caused recirculation bubbles to form, and the presence of reverse flow in both upper and lower sinus regions was confirmed with velocity vector plots from the Near Wall Sinus Dataset. Vortex detection was also performed on this data, and showed the existence of a large scale vortex in the upper and lower sinus regions. Vortex detection performed on instantaneous velocity fields identified vortices in the central jet, but not in the lateral orifice jets which was consistent with previous observations by Yoganathan et al (1986), that the central jet was more disturbed than the lateral orifice jets. Vortex detection also showed that the largest instantaneous vortices occurred in the upper and lower sinus regions.

An asymmetry in the recirculation pattern of the upper and lower sinus regions was observed. Although large scale vortices occurred in both regions, the recirculation bubble in the lower sinus was shorter than in the upper sinus. The source of the asymmetry, although not specifically determined, was discussed. Influences from upstream conditions were likely as measurements of axial inlet turbulence showed that

higher inlet turbulence was present near the lower inlet piping side than the upper side. Tests were performed with the valve in different orientations, and this did not have an effect on the asymmetry. An influence from a small geometric imperfection in the model BiMHV geometry was therefore unlikely, but could not be definitively ruled out. It was concluded that because of this, and previous observations of asymmetries in steady BiMHV flow by Hanle et al. (1988) and Chandran et al. (1985), that recirculation bubble symmetry in an axisymmetric aortic sinus was difficult to achieve.

Axial velocity profiles showed the downstream spread the jets. The decay of axial velocity of all three jets were seen to be similar to that of free rectangular jets, where an initial zero-decay region is followed by a decay rate of $U_{max}^2 \propto X$ (referred to as the linear-decay region). The central jet was tested for self similarity and revealed that the jet became self similar at around the same axial location as the start of linear decay.

Jet expansion past the valve ring caused a net positive flow of W velocity through the measurement plane. Because of this net positive out-of-plane flow, the axial flow rate was not expected to be constant, and a small change in axial flow was observed. However, the change was found to be within measurement uncertainty estimates, and therefore was not statistically significant.

There was reasonable symmetry of W contours, and two alternate explanations of streamwise vortex (i.e. Ω_x) structure were proposed. It was possible that either a four-cell, or an eight-cell streamwise vortex structure was present. Both alternative explanations yielded the same four-cell streamwise vortex structure observed by Hanle et al. (1988) downstream of the current measurement plane at $X/d \approx 1.0$. Organization of 3D structures in the mean field was thus apparent.

Elevated Reynolds normal stresses were seen in the lateral orifice jet shear layers and in the central jet. The core regions of the lateral orifice jets showed lower Reynolds stress values. Reynolds shear stress profiles showed that the highest values occurred in the lateral orifice jet shear layers which has been noted in previous studies by Yoganathan et

al. (1986), Fontaine et al. (1996) and Liu et al. (2000). Smaller peaks in Reynolds shear stress were seen in the leaflet wakes and the central orifice jet shear layers. The production of turbulence in these regions was likely due to energy transfer from the mean shear which was highest in the lateral orifice jet shear layers and central jet shear layers.

The flow was seen to be complex and turbulent, with the combined interaction of three confined jets, leaflet wakes, and sinus recirculation. There was, however, a high degree of organization found in both the in-plane and 3D flow structures.

Chapter 5

Conclusions and Recommendations

In this chapter, the results of the study are summarized, and recommendations for future work are suggested.

5.1 Summary and Conclusions

The objectives for this thesis were:

1. Design and build a recirculating flow loop to provide steady flow to the experimental test section.
2. Obtain a three velocity component dataset using SPIV to measure steady flow downstream of a BiMHV at a peak systolic Reynolds number. The dataset will be used to investigate three dimensional flow structures, and for CFD code validation purposes.
3. Obtain a large independent measurement sample size for the above dataset to adequately resolve second order turbulence statistics (i.e. Reynolds stresses).

The objectives of the study were met. To perform the measurements, a flow loop was built to deliver steady flow to the test section. Initially, flow visualization images were obtained, followed by SPIV data acquisition. SPIV images were processed using standard procedures, and dewarped using a local weighted mean algorithm that had not been used previously for SPIV dewarping. The local weighted mean method was required to dewarp non-linear image distortions caused by imaging through the curved sinus contraction region, and gave much improved results over commonly used 2nd order

polynomial dewarping. SPIV velocity data for the entire aortic sinus was obtained with the Full Aortic Sinus Dataset with $N = 1105$ samples. In addition, the Near-Wall Sinus Dataset with $N = 718$ samples was obtained with a higher time separation to investigate the low-speed recirculating flow in the upper and lower sinuses with better accuracy.

Flow visualization was performed and investigated features of the flow at $Re = 2200$, 3800 and 7600, prior to obtaining SPIV data. The formation of the lateral orifice jets and central jet were seen. At $Re = 2200$, a Coanda-type effect was observed in the central orifice jet flow, and caused asymmetric flow separation from the lower leaflet. This had a large influence on the wake structure on both leaflets at $Re = 2200$, and the asymmetrical condition was seen to be affected by bulk flow transients, the condition of inlet flow, and perhaps by small geometrical imperfections in the valve model.

Flow visualization identified multiple large scale vortices in the upper and lower sinus regions at $Re = 2200$ and $Re = 3800$. However, at $Re = 7600$, only single large scale sinus vortices were seen in the sinus regions. This was due to higher streamwise momentum of the lateral orifice jets and therefore lessened interaction with near-wall fluid at $Re = 7600$. Vortex shedding from the leaflets was seen, and expanded vortices were found downstream in the central jet. The flow visualization also showed that flow in the upper and lower sinus region was different. At $Re = 7600$, a large scale vortex in the upper sinus was clearly seen, but a large scale vortex in the lower sinus was consistently less distinct.

The SPIV datasets were performed at $Re = 7600$, and results corresponded to the flow visualization at the same Reynolds number. The data was ensemble-averaged and broken into mean and fluctuating components by Reynolds decomposition. The Full Aortic Sinus Dataset showed the formation of the lateral orifice jets and the central jet. The axial velocity, U , of the jets was dominant over the transverse, V , and out-of-plane, W , velocities. The lateral orifice jet shear layers and central jet shear layers were seen to have a high gradient $\partial U / \partial y$ as observed in the axial velocity profiles and plots of mean vorticity.

Upstream flow separation at the valve ring caused recirculation bubbles to form, and caused reverse flow in both upper and lower sinus regions. Vortex detection was performed on the Near Wall Sinus Dataset and showed the existence of a large scale vortex both the upper and lower sinus regions. Vortex detection was also performed on instantaneous velocity fields, and showed that the largest instantaneous vortices occurred in the upper and lower sinus regions. The detection identified vortices in the central jet, but not in the lateral orifice jets, showing that the central jet was more disturbed than the lateral orifice jets.

The existence of reverse flow and large scale vortices in the upper and lower sinuses indicated that flow was similar in these two locations. However, an asymmetry in the recirculating flow was observed, and the recirculation bubble in the lower sinus was shorter than in the upper sinus. Possible causes of the asymmetry were discussed. SPIV tests were performed with the valve in different orientations, and there was no apparent effect on the asymmetry. Therefore, influence from small geometric imperfections in the BiMHV model on recirculation bubble flow was unlikely, but could not be definitively ruled out. It was hypothesized that this asymmetry may have also been partly due to inlet conditions. Mean inlet axial profiles were approximately symmetric, but turbulence profiles showed that higher axial turbulence was present on the lower inlet piping side than the upper side. The higher turbulence on the lower side may have lead to the differing flow in the upper and lower sinuses. Also, it was noted that previous studies have shown that notably larger asymmetries occur in steady BiMHV flow than in pulsatile flow (Hanle et al. 1988), and because of these factors, it was concluded that recirculation bubble symmetry, in steady flow at $Re = 7600$, was difficult to achieve.

Comparing the transverse location and magnitude of peak jet velocities in the lateral orifice jets showed that the lateral orifice jets were highly symmetric about the X axis. The decay of axial velocity of all three jets was similar to that of free rectangular jets. A zero-decay region was followed by a region with a decay rate of $U_{max}^2 \propto X$ (referred to as the linear-decay region). The central jet was well centered, and was self-similar around

the same downstream location as the start of linear decay. This showed that even with complex flow interactions from the lateral orifice jets and leaflet wakes, the central jet could be analyzed using classical jet theory. Self-similarity of the central jet may be used as a criterion for CFD code validation, and it is possible that other primary flow structures such as the lateral orifice jets, recirculation regions, and leaflet wakes could be analyzed using similar techniques.

Jet expansion past the valve ring caused a net positive flow of W velocity through the measurement plane. Because of this net positive out-of-plane flow, the axial flow rate was not expected to be constant, and a small change in axial flow was observed. However, the change was found to be within measurement uncertainty estimates, and therefore was not statistically significant.

Two alternative explanations of streamwise vortex (i.e. Ω_x) structure were proposed. It was possible that either a four-cell, or an eight-cell streamwise vortex structure was present. Both alternative explanations yielded the same four-cell streamwise vortex structure observed by previous researchers downstream of the current measurement plane. A high degree of 3D structure organization was seen in the mean field. The presence of these streamwise vortices was shown due the ability to visualize 3D flow structures from SPIV data.

The highest Reynolds normal stresses were seen in the lateral orifice jet shear layers and in the central jet. The core regions of the lateral orifice jets showed lower Reynolds normal stress values. Reynolds shear stress profiles showed that the highest values occurred in the lateral orifice jet shear layers, which has been noted in previous studies (Yoganathan et al. 1986, Fontaine et al. 1996, Liu et al. 2000). Smaller peaks in Reynolds shear stress were seen in the leaflet wakes and the central orifice jet shear layers. The production of turbulence in the lateral orifice jet shear layers, central jet shear layers, and leaflet wakes, was likely due to energy transfer from the mean shear which was highest in these areas.

The above discussion illustrates the highly complex nature of BiMHV flow, as it combined the unsteady flow of three confined jets, leaflet wakes, and sinus recirculation regions. Steady flow at $Re = 7600$ was seen to be highly turbulent, however, there was a high degree of organization found in both the in-plane and 3D flow structures. The propensity of BiMHVs to thrombosis was described in Chapter 1, and analysis of BiMHV flow aids in the understanding of related flow phenomena. With continued analysis of this flow, it is hoped that valve designs can be improved and clinical complication rates will be reduced in the future.

5.2 Recommendations

5.2.1 Large Experimental Datasets

Measurement uncertainty is discussed in Appendix A, and was based on estimated experimental setup errors and statistical accuracy estimates. For the Full Aortic Sinus Dataset, errors in mean velocity was estimated at $\pm 4\%$ for U and V , and $\pm 8\%$ for W . Reynolds stresses had a higher uncertainty at $\pm 24\%$. Because statistical accuracy is dependent on the measurement sample size, N , it is necessary to have large sample sizes. For the Full Aortic Sinus Dataset, $N = 1105$, which was much higher than previous PIV studies in BiMHV flow (see Chapter 1). The estimated accuracy in Reynolds stresses was adequate to identify regions of high and low Reynolds stresses as shown in Chapter 4, although larger datasets will be needed if accuracy is to be improved. Using the current experimental setup, and uncertainty analysis outlined in Appendix A, a dataset of approximately $N = 4000$ samples would be required to reduce error in second order turbulence statistics to around $\pm 10\%$. It is likely that pulsatile flow studies would need even larger sample sizes to adequately filter cycle-to-cycle variations.

5.2.2 CFD Validation Datasets

The ability to model complex flows with efficient parallel CFD codes heightens the need for rigorous code validation with experimental datasets (Shahbazi 2007). The complexities of BiMHV flow are immense, as it was three dimensional, turbulent and unsteady. Three dimensional flows necessitate three velocity component datasets, and therefore it is recommended that CFD code validation is performed with the use of three velocity component spatial data provided by SPIV. Also, code currently used to model pulsatile BiMHV flow is inaccurate near peak systole (Dasi et al. 2007). If the entire cardiac cycle is to be modelled, code validation in steady flow with fixed boundary conditions should be performed prior to attempts at pulsatile simulations.

5.2.3 Steady and Pulsatile Experiments

Because the flow was highly three dimensional, new insight was gained from visualizing 3D flow structures with the use of SPIV measurements. By studying steady flow, the mean flow and turbulence was obtained without contamination from cycle-to-cycle variations as in pulsatile flow. 3D structures hidden in the pulsatile flow field may be more readily resolved in steady flow, and therefore additional steady flow studies should be undertaken. These studies should be done at peak systole, as Hanle et al. (1988, 1989) noted that pulsatile and steady flow studies most closely corresponded at peak systole. In addition, contrasting findings in steady and pulsatile flow may help identify phenomena resultant from pulsatile acceleration and deceleration.

Pulsatile studies using SPIV are also needed. Visualization of flow development is greatly enhanced in pulsatile flow using SPIV data (Kaminsky et al. 2008). In the past, however, primarily phase locked 2C-PIV measurements have been made. Inherent cycle-to-cycle variations in phase locked data, and the difficulty in filtering with a single cut-off frequency, has been noted by Ge et al. (2008). Because the flow structures are both space- and time-dependent, techniques such as discrete wavelet transform (DWT), or proper orthogonal decomposition (POD) may be beneficial, but have not yet been employed in this flow. High temporal resolution SPIV measurements have been made, however. Kaminsky et al. (2007a, 2008) obtained high temporal resolution (3 kHz acquisition rate) SPIV measurements in pulsatile flow on both the centerline perpendicular plane, and aortic cross section. Due to hardware restrictions, only small sample sizes were obtained. With hardware improvements it is likely that the full cardiac cycle could be measured with SPIV over many cycles. This would enable full spatio-temporal analysis on a plane in the flow, which may give greater insight into turbulence and vorticity dynamics.

5.2.4 Other Measurement Planes

The current study measured flow near the centerline plane, perpendicular to the leaflet pivoting axes. As described in Section 4.3.6, significant values of W velocity were recorded due to an expected net out-of-plane flow through the measurement plane due to jet expansion past the valve ring, and the presence of large scale streamwise vortices. However, because the measurement plane was close to the geometric symmetry plane, magnitudes of out-of-plane motion were likely decreased for the mean velocity field. Measuring more off-centerline planes would therefore be highly beneficial. In addition, SPIV measurements on planes parallel to the leaflets would provide further insight into the 3D jet structure. SPIV measurements of aortic cross-sectional planes would also be very useful, and an initial study of this has been performed by Kaminsky et al. (2008). For cross-sectional planes, however, axial velocity is the out-of-plane velocity, yet the out-of-plane velocity has errors of about twice that of the in-plane components (see Appendix A). Furthermore, axial velocity in this flow was seen to be around four times higher than the in-plane components, though SPIV image correlation is improved when out-of-plane motion is less than 1/4 the laser sheet thickness (Adrian 1991). This requires a thicker laser sheet to maintain the same dynamic range, yet thicker light sheets have been shown to degrade the quality of SPIV imaging (van Doorne and Westerweel 2007). Therefore, SPIV measurements on cross-sectional planes, although needed, have increased demands on experimental setup parameters.

5.2.5 High Spatial Resolution

Spatial resolution in the current study was $\Delta X = 0.59$ mm and $\Delta Y = 0.53$ mm which was restricted by camera resolution and field-of-view requirements. Ge et al. (2008) suggested that a spatial resolution of 0.27 mm was required to resolve most of the fine features of BiMHV flow, though shear stress was used as a metric to determine this, and not velocity spectra. Liu et al. (2000), using velocity spectra, estimated the Taylor microlength scale to be less than 500 μm and the Kolmogorov scale of turbulent eddies to be less than 50 μm . To resolve these eddies, probe size, i.e. PIV interrogation area size, must be around the same size. Higher spatial resolution will also be able to better resolve

the high velocity gradients seen in the lateral orifice jet shear layers, and may give insight into lateral orifice jet shear layer, and recirculation bubble interactions.

5.2.6 Controlled Inlet Conditions

Inlet conditions were well quantified by obtaining the Inlet Conditions Dataset. An asymmetry in inlet axial turbulence was measured. The likelihood of BiMHV flow sensitivity to inlet conditions was discussed in Section 4.3.4 with respect to recirculation bubble symmetry at $Re = 7600$, and Section 4.1.1 with respect to a central jet Coanda effect at $Re = 2200$. The use of steady flow, and an axisymmetric aortic sinus made these effects more obvious, and increases the need for controlled inlet conditions with such geometry. It is therefore recommended that inlet conditions be well quantified in future studies.

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Appendix A SPIV Measurement Uncertainty

It is important to recognize the difference between measurement *accuracy* and measurement *precision*, as the two are often confused in the literature. Accuracy refers to how close a measurement is to its true value, and precision refers to how well the measurement has been determined (Bevington 2003). Often estimates of precision are quoted as "measurement accuracy" which is incorrect. In an inhomogeneous turbulent flow, such as that in the current study, true measurement values are not known, but with appropriate precautions, measurement error can be minimized and the measurements can approach the true value.

Determining overall measurement accuracy and precision of a complex system such as SPIV is difficult to accomplish. Comparison of a result to its true value is not possible unless a well defined flow is studied. However, minimizing errors can be accomplished through various control parameters and has been the objective of a great deal of research (Adrian 1991, Prasad and Adrian 1993, Westerweel 1997a, and others). There are numerous sources of error in an SPIV experiment and the primary sources related to our experimental setup are listed below.

Experimental Setup Error Sources

- 1) signal-to-noise ratio
- 2) very large or very small particle displacements
- 3) correlation peak locking
- 4) image dewarping
- 5) laser sheet misalignment
- 6) lens plane angle
- 7) cross-correlation algorithm
- 8) interrogation area overlap

Flow Related Error Sources

- 9) high velocity gradients
- 10) turbulence intensity
- 11) turbulence scales

There are specific control parameters discussed in Raffel et al. (1998) to minimize errors, and are listed below.

Error Control Parameters

- 1) laser sheet thickness
- 2) particle density, displacement & particle image size
- 3) image dewarping & refractive index matching
- 4) correlation peak precision
- 5) spatial resolution
- 6) temporal resolution

The errors are discussed in relation to the control parameters in Section A.1, while error estimates are given in Section A.2.

A.1 Error Control Parameters

A.1.1 Laser Sheet Thickness

One important control parameter is laser sheet thickness. Using a laser sheet that is too thin can result in increased out-of-plane loss of particle image pairs, and a general rule of thumb is to have out-of-plane motion less than 1/4 the laser sheet thickness (Adrian 1991). Also, choosing a laser sheet that is too thick compromises spatial resolution, increases image noise, and decreases the signal-to-noise ratio (van Doorne and Westerweel 2007). Keeping this in mind, laser sheet thickness was chosen based on the

number of vectors rejected by the cross-correlation algorithm, which has been verified to give accurate results as discussed in Section A.2.3. The thickest laser sheet tested (2.5 mm), had more visible image noise, and twice the rejected vector count of that of the thinnest laser sheet tested of 1 mm. For this reason a 1 mm thick laser sheet was used. The average rejected vector count in the SPIV experiments was 3%. The rejected vectors were replaced by the average of their validated neighbouring vectors as discussed in Suk (1999).

A.1.2 Particle Density, Displacement & Size

Another factor affecting signal-to-noise ratio is the particle density. It has been shown that 10 - 20 particles per interrogation area is optimal (Adrian 1991). A particle density of 8 - 12 particles per interrogation area was typical in this study.

Particle displacement must be optimized to resolve the flow field. The relation of particle displacement to the system dynamic range and laser pulse time separation, Δt , was discussed in Section 3.8. As discussed, maximum particle displacement should be less than 1/4 of the interrogation area side length (Adrian 1991), and this was enforced in the present study.

Measurement error can also result when displacements are very small. When total displacement is less than 1 pixel, the recorded value can be off by as much as 100%. Sub-pixel displacements were observed in some of the low velocity regions of the sinus for the Full Aortic Sinus Dataset. As discussed in Section 3.8, the measurement accuracy in these areas suffered due to the large overall dynamic range required for the study. This error can also result from the peak locking effect, which is dependant on particle image size. When particles images are too small, at 1 pixel in diameter, then the correlation peak estimator tends to lock to integer displacement values (Raffel et al. 1998). In general, most particles were observed to be around 2 to 3 pixels in diameter, though some 1 pixel particles were observed.

To increase the dynamic resolution in the low velocity regions, the Near Wall Sinus Dataset was obtained using a larger Δt . The previous sub-pixel displacements were effectively increased to 1 pixel or more, which reduced peak locking effects and decreased measurement error in the area.

A.1.3 Image Dewarping & Refractive Index Matching

Errors due to image dewarping affect the placement of velocity vectors and have been quantified in Section 3.2. Because of the local weighted mean dewarping algorithm, and the index matching done between the NaI fluid and acrylic test section, the maximum dewarping error was small at 0.8 pixel and generally around 0.1 pixel.

A.1.4 Correlation Peak Precision

The cross-correlation algorithm used correlation peak estimation with precision of 0.1 pixel as described in Suk (1999) which indicated a measurement precision of 0.625% of the full dynamic range of 16 pixels.

A.1.5 Spatial Resolution

Velocity gradient and turbulence scale resolution is directly related to system spatial resolution. Large velocity gradients and high turbulent intensity in an interrogation area broaden the correlation peak (Meunier and Leweke 2003). The spatial filtering of the flow field that is inherent in PIV tends to underestimate turbulent energy (van Doorne and Westerweel 2007). By having high spatial resolution, velocity gradients are decreased across the interrogation area, and smaller turbulent scales can be captured. Having an interrogation area size comparable to the smallest turbulent scales is ideal, but not always practical. Hardware constraints, such as camera pixel resolution and the required field of view, determine the resultant spatial resolution of a system. Liu et al. (2000) estimated the Kolmogorov length scale downstream of a Carbomedics BiMHV to be between 25 and 43 μm at peak systole. However, Ge et al. (2008) has shown that a vector spacing (with 50% IA overlap) of 0.27 mm was sufficient to resolve most of the

fine features of BiMHV flow, though shear stress was used as a metric to determine this result and not velocity spectra. In the current study, 32 x 32 pixel interrogation areas were used on the second cross-correlation pass. The image magnification was 27 pixels/mm in the X direction and 30 pixels/mm in the Y direction, and therefore 370 $\mu\text{m}/\text{pixel}$ in X and 330 $\mu\text{m}/\text{pixel}$ in Y . The vector spacing (with 50% IA overlap) was $\Delta X = 0.59 \text{ mm}$ and $\Delta Y = 0.53 \text{ mm}$. It is difficult to estimate the amount of filtering that occurred due to the spatial resolution used. This would result in decreased Reynolds stresses although it was shown in Section 4.3.7 that Reynolds stress values were found to be in the range of previous studies.

A.1.6 Temporal Resolution

Adequate temporal resolution is needed to obtain statistically independent samples and calculate turbulence statistics. High sampling rates are only required if cycle-resolved results are desired in pulsatile flow studies, or if the time evolution of the flow is needed. To obtain valid turbulence statistics, the flow must be sampled at a lower frequency than the largest turbulence time scale, the integral time scale. Liu et al. (2000) estimated this to be around 1 ms for BiMHV flow at peak systole, and therefore the sampling rate used of 3 Hz ensured statistically independent data.

A.2 Error Quantification

Estimates can be given to specific bias errors of the PIV system and error for a single sample can be estimated. In addition, if homogeneous flow is assumed in certain regions, statistical accuracy can be defined. This is discussed below.

A.2.1 Laser Sheet Misalignment

Laser sheet misalignment occurs when the laser sheet is not precisely positioned on the calibration grid image plane (Willert 1997). When data is input into the SPIV reconstruction equations (Section 3.5), slightly different regions of flow are combined which results in an error in velocity. This bias can be accounted for with a 'disparity'

vector plot by cross correlating images from either camera. This was not performed for this study, but with careful alignment of the laser sheet, this error can be minimized. Instead, this error was estimated by assuming a 0.5° rotation of the laser sheet as discussed in the following.

For rotation of the laser sheet about the Y direction, the error in the two component velocity is directly related to the velocity gradient in the flow as (van Doorne and Westerweel 2007)

$$e_{u,v,pos} = \left(\frac{\partial(U/U_o)}{\partial y} \right) \frac{e_{pos}}{U/U_o} \quad \text{Equation A.1}$$

The variable $e_{u,v,pos}$ is the relative error in the two component velocity vector, and e_{pos} is the local position error due to laser sheet misalignment. The gradient $\partial U/U_o / \partial y$ was used in Equation A.1 as it was observed to be the largest of any of the spatial velocity gradients. Equation A.1 is similar to that given in van Doorne and Westerweel (2007) but uses the three component SPIV mean velocity vector instead of the two component velocity vector. For the purposes of calculating laser sheet misalignment errors we ignore the effect of out-of-plane motion. The SPIV velocity vector is then a good approximation to the two component vector for a symmetrical camera configuration. In order to estimate the error, gradients and velocities from the mean velocity field are used. This is not the most rigorous approach since gradients in the mean field are smoothed, but we can be conservative by taking the maximum mean field gradient of 0.93 mm^{-1} located in the upper lateral orifice jet shear layer. Note that units of mm^{-1} are used because velocity was normalized by the inlet velocity U_o throughout the study. Also, the corresponding minimum velocity in the upper lateral orifice jet shear layer of around, $U/U_o = 0.5$, is used to be conservative in the calculation. The edges of the cropped PIV images were approximately $X = 6.7 \text{ mm}$ from the center of the uncropped images. Assuming that a $\zeta = 0.5^\circ$ rotation of the light sheet occurred

about the center of the uncropped images (i.e. the center of the camera field of view), and $\alpha = 30^\circ$, a maximum value of $e_{pos} = X \tan(\zeta) \tan(\alpha) = 0.03$ mm at the edges of the images is obtained. Using these values, a maximum error of $e_{u,v,pos} = 6\%$ in the two component velocity due to laser sheet misalignment is given. Because the lens angle in the XY plane, β , is very small, slight laser sheet rotation about the X direction does not affect the measurements.

A.2.2 Lens Plane Angle

The lens plane angle, α , is a parameter that must be considered since it affects both in-plane and out-of-plane displacements. The theoretical optimum is $\alpha = 45^\circ$, but it has been shown that for real (i.e. non-synthetic) images a choice of $20^\circ < \alpha < 30^\circ$ is best (Lawson and Wu 1997). A value of $\alpha = 30^\circ$ was chosen in this study.

In addition, errors in out-of-plane motion can also result from imprecise measurement of α (Fei and Merzkirch 2004). Precision Dantec Dynamics Scheimpflug camera mounts were used to minimize this error; however, if an angle error is assumed, the relative error in w is (Fei and Merzkirch 2004)

$$e_{w,\alpha} = \frac{e_\alpha}{\sin(\alpha) \cos(\alpha)} \quad \text{Equation A.2}$$

For $\alpha = 30^\circ$ and $e_\alpha = 0.0087$ radians (i.e. 0.5°), a value of $e_{w,\alpha} = 2\%$ was obtained.

A.2.3 Cross-correlation Algorithm

The accuracy of the adaptive cross-correlation (ACC) algorithm and vector validation scheme developed by Usera (1999) was evaluated based on analysis from Tang (2002). Tang used synthetic (i.e. computer generated) 2C-PIV images created by Okamoto (2000) from the Visualization Society of Japan (VSJ) and available at <http://www.vsj.or.jp/piv/>. These so-called 'standard images' provide a means to evaluate PIV algorithms by

comparing results to those of CFD simulations. Tang tested eight different scenarios in which particle density, displacement, diameter and laser sheet thickness were varied. This therefore gives a performance metric on how well the cross-correlation algorithm and validation scheme perform under different situations. Relative error in the ACC algorithm, e_{ACC} , was defined as (Tang 2002)

$$e_{ACC} = \frac{\sqrt{(u - u_{true})^2 + (v - v_{true})^2}}{\sqrt{u_{true}^2 + v_{true}^2}} \quad \text{Equation A.3}$$

where u and v are velocities given by the ACC, and u_{true} and v_{true} are velocities given by Okamoto's LES simulations. The results are shown below (taken from Tang 2002).

Scenario (VSJ designation)	average absolute e_{ACC} (pixels)	average relative e_{ACC} (%)
PIV01 - standard	0.35	5.3
PIV02 - large displacement	2.75	12.8
PIV03 - small displacement	0.23	10.8
PIV04 - high particle density	0.29	4.4
PIV05 - low particle density	0.51	7.7
PIV06 - small particle diameter	0.32	4.9
PIV07 - large particle diameter	0.32	4.9
PIV08 - thin light sheet	0.40	6.1
average of scenarios	0.65	7.1

Table A.1 Results of ACC error analysis from Tang (2002).

It can be seen that overall the performance of the ACC is good with an average relative error of 7.1%. It should be noted that the largest errors occur in the large and small displacement scenarios (PIV02 and PIV03). For this reason, system dynamic range was carefully evaluated and optimized as discussed in the preceding paragraphs and Section 3.8.

A.2.4 Interrogation Area Overlap

During the course of data analysis it was discovered that regular velocity fluctuations occurred in the data as seen in Figure 4.30 where maximum axial jet velocity is plotted versus downstream distance. The source of the systematic error was determined from examining the distance in the X direction between the peaks and valleys in Figure 4.30. It was found that the spacing was on average 34.7 pixels which closely matched the second cross-correlation interrogation area size of 32×32 pixels.

Because 50% interrogation area overlap was used, the interrogation area overlap for the first cross-correlation pass was 32 pixels and for the second cross-correlation pass was 16 pixels. This resulted in less accurate displacement estimates being added to data points located 16 pixels on either side of the interrogation area center point calculated on the first cross-correlation pass. The spacing of the less accurate data points was thus 32 pixels. This resulted in the approximately 32 pixel spacing of the peaks and valleys shown in Figure 4.30. The effect of interrogation area overlap has been discussed by Raffel et al. (1997).

To estimate the resulting error, linear regression analysis was performed on the peak velocity decay data of the lateral orifice jets shown in Figure 4.30. The standard error in the regression was $\Delta U/U_0 = 0.06$ which is 3% of $U/U_0 = 2.2$, the smallest velocity for the upper lateral orifice jet (shown in Figure 4.30). It is assumed that this same percentage error was present in V/U_0 data also, and therefore the error due to interrogation area overlap was approximated as 3% for both U/U_0 and V/U_0 .

A.2.5 Error Propagation

To give an estimate of performance of the SPIV system, error propagation through the SPIV recombination equations was applied. For images from camera 0, the two component velocities u_1 , v_1 resulted, and for camera 1, the two component velocities, u_2 ,

v_2 , resulted. If it is assumed that these have standard deviations $\sigma_{u1} = \sigma_{u2} = \sigma_{u1,2}$ and $\sigma_{v1} = \sigma_{v2} = \sigma_{v1,2}$, respectively, this gives for the SPIV vectors u , v and w (Prasad 2000)

$$\sigma_u = \frac{\sigma_{u1,2}}{\sqrt{2}} \quad \text{Equation A.4}$$

$$\sigma_v = \frac{\sigma_{v1,2}}{\sqrt{2}} \quad \text{Equation A.5}$$

$$\sigma_w = \frac{\sigma_{u1,2}}{\sqrt{2} \tan(\alpha)} \quad \text{Equation A.6}$$

We assume that the addition of the relative errors due to laser sheet misalignment, camera angle, and ACC is approximately equal to the standard deviation of the two component velocity vectors.

Although the experimental control parameters were optimized as discussed above, an additional $e_{other} = 5\%$ error was added to be conservative. Estimates of the standard deviations in the two component velocity vectors due to the experimental setup were thus

$$\sigma_{u1,2} = \sigma_{v1,2} = e_{u,v,pos} + e_{ACC} + e_{other} \quad \text{Equation A.7}$$

With $e_{u,v,pos} = 6\%$, $e_{ACC} = 7\%$, and $e_{other} = 5\%$, values of $\sigma_{u1,2} = \sigma_{v1,2} = 18\%$ are obtained

The error in w is extended to include $e_{w,\alpha}$,

$$\sigma_{w,\alpha} = \sigma_w + e_{w,\alpha} \quad \text{Equation A.8}$$

For $e_{w,\alpha} = 2\%$, using Equation A.4, Equation A.5, and Equation A.6 we then obtain the errors in the three component SPIV velocities due to experimental setup for a single sample.

$$\sigma_u = 13\%$$

$$\sigma_v = 13\%$$

$$\sigma_{w,\alpha} = 24\%$$

It should be noted that the estimated error in the out-of-plane velocity component was about twice that of the in-plane components which was consistent with that given by Willert (1997).

A.2.6 Statistical Accuracy

Statistical accuracy can be estimated if the flow turbulence is homogeneous (Tennekes and Lumley 1972). This is not the case in BiMHV flow because of the interactions between sinus recirculation fluid and lateral orifice jets and the interactions of the three jets and leaflet wakes. Sinus vortex movement and lateral orifice jet shear layer flapping were observed in flow visualization which indicated that the flow was inhomogeneous overall. There were regions, however, such as the lateral orifice jet cores, where the flow exhibited relatively steady turbulence. Although the flow may not have been truly homogeneous in the lateral orifice jet cores, it is useful to examine statistical accuracy to investigate the effect of sample size. Homogeneous turbulence analysis is usually inaccurate at turbulence intensities above 10% (Liu et al. 2000), and very high turbulence intensity in w was observed compared to u and v . This was because of the combined effect of low velocities and higher error in the out-of-plane component. This caused w -component turbulence and also turbulence intensity to be artificially exaggerated. For this reason, statistical error analysis of W , and all 2nd order quantities involving w' , i.e. $\langle u'w' \rangle$, $\langle v'w' \rangle$ and $\langle w'w' \rangle$, was not performed.

The standard errors in mean first and second order statistics are (Wernet et al. 2000, Ullum et al. 1998)

$$\sigma_{U,V} = \sqrt{\frac{TI_{u,v}^2 + \sigma_{u,v}^2}{N}} \quad \text{Equation A.9}$$

$$\sigma_{<u'u'>, <v'v'>} = \sqrt{\frac{2(TI_{u,v}^4 + \sigma_{u,v}^4)}{N}} \quad \text{Equation A.10}$$

where $TI_{u,v}$ is the local flow turbulence intensity in u and v respectively and N is the sample size. The average turbulence intensities in the central region of the lateral orifice jets were $TI_u = 20\%$, and $TI_v = 20\%$, which are greater than 10%; nonetheless, we give estimates of statistical accuracy as a reference. For the Full Aortic Sinus Dataset, $N = 1105$, and we obtain estimates of statistical accuracy for mean velocity U , V , and Reynolds normal stress components $<u'u'>$, $<v'v'>$ in the lateral orifice jet cores of

$$\sigma_U = 1\%$$

$$\sigma_V = 1\%$$

$$\sigma_{<u'u'>} = 18\%$$

$$\sigma_{<v'v'>} = 18\%$$

The in-plane Reynolds shear stress component $<u'v'>$ was estimated to have the same error as the Reynolds normal stress components, and therefore,

$$\sigma_{<u'v'>} = 18\%$$

As mentioned previously, statistical accuracy estimates apply to homogeneous flow. Although this was not strictly the case in the present flow, the above values give an estimate of error, and underscore the importance of obtaining large sample sizes, especially to accurately resolve 2nd order turbulence statistics.

A.2.7 Overall Error Estimate

The error in the mean velocities due to interrogation area overlap was calculated at 3% which should be added to the values of σ_U and σ_V . To estimate the effect on 2nd order quantities, standard error propagation was used. This gave the error in 2nd order quantities due to interrogation area overlap as 6%. Therefore a total of 3% error was added onto σ_U and σ_V and 6% error was added onto $\sigma_{<u'u'>}$, $\sigma_{<v'v'>}$ and $\sigma_{<u'v'>}$ to give estimates of overall accuracy of the SPIV results. As discussed in A.2.6, statistical error analysis was not performed for the out-of-plane component W , and therefore the error was based on that of a single sample. The errors in w were approximately twice that of u and v for a single sample, and therefore the error in W was estimated to be twice that of U and V .

$$\sigma_{U_{overall}} = \pm 4\%$$

$$\sigma_{V_{overall}} = \pm 4\%$$

$$\sigma_{W_{overall}} = \pm 8\%$$

$$\sigma_{<u'u'>_{overall}} = \pm 24\%$$

$$\sigma_{<v'v'>_{overall}} = \pm 24\%$$

$$\sigma_{<u'v'>_{overall}} = \pm 24\%$$

Appendix B 2C-PIV Measurement Uncertainty

The estimates of error given in Appendix A for SPIV can be used to evaluate the error in the 2C-PIV Inlet Conditions Dataset. It should be noted that the error in 2C-PIV due to perspective distortion was eliminated because a telecentric lens was used. As noted in Section 4.2, the v velocity component was negligible in the Inlet Conditions Dataset, and therefore error in only axial velocity, u , is given. Using the same $e_u = e_v = 18\%$ found in Appendix A, the statistical accuracy was calculated based on an average value of $TI_u = 7\%$. For the Inlet Conditions Dataset $N = 1080$, and the error estimate in first and second order quantities was thus

$$\sigma_{U_{overall}} = \sigma_U = 0.6\%$$

$$\sigma_{<u'u'>_{overall}} = \sigma_{<u'u'>} = 14\%$$

The fluctuating component, $\sqrt{\langle u'u' \rangle} / U_0$, was found to be constant at all downstream locations and therefore the turbulence can be considered homogeneous.

Appendix C Convergence

Convergence of the Full Aortic Sinus Dataset was based on convergence of the mean axial velocity, U/U_0 . It was determined by calculating the difference between the ensemble averaged values using a specified sample size, and the ensemble averaged values using all available samples ($N = 1105$). In this way, the values from the ensemble with $N = 1105$ were taken as reference values, and other sample sizes were compared to them. The quantity used to describe the convergence was the root mean squared deviation given as,

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n_{vec}} [(U/U_0)_{N^*} - (U/U_0)_{ref}]_i^2}{n_{vec} - 1}} \quad \text{Equation C.1}$$

where $(U/U_0)_{N^*}$ is the value of U/U_0 of vector i of sample size N^* , and $(U/U_0)_{ref}$ is the value of U/U_0 of vector i of sample size $N = 1105$. Taking the average over all vectors, $n_{vec} = 1982$, in the flow field, enables the convergence to be expressed as a single data point for a particular N^* . A plot of $RMSD$ is shown below.

Figure 5.1 Convergence of U/U_0 data based on root mean squared deviation.

The root mean squared deviation, $RMSD$, fell below 0.01 at approximately $N^* = 850$ showing that a reasonably high degree of convergence of U/U_0 was obtained in the Full Aortic Sinus Dataset by using the total $N = 1105$.

Appendix D Local Weighted Mean Approximation Method

This appendix outlines the method of the local weighted mean transformation used to dewarp SPIV images. The method proved to be highly useful in dewarping images with non-linear optical distortions that could not be handled by 2nd order polynomial dewarping methods often used in literature. The method was implemented by the Matlab 6.5 *cp2tform.m* function.

The local weighted mean method is defined through a set of mapping functions, $f(x,y)$,

$$f(x, y) = \frac{\sum_{i=1}^{N_{CP}} R_i(x, y) p_i(x, y)}{\sum_{i=1}^{N_{CP}} R_i(x, y)} \quad \text{Equation D.1}$$

which maps irregularly spaced control points to corresponding uniformly spaced control points. For each control point pair there is a unique function $f(x,y)$. In Equation D.1, the variables x and y correspond to control point coordinates in the uniform grid image, index i cycles over all N_{CP} control points, and $p_i(x,y)$ is an interpolating polynomial of degree two (defined below). $R_i(x,y)$ acts as a weighting function, defined as

$$R_i(x, y) = \begin{cases} 1 - 3r_i^2 + 2r_i^3, & 0 \leq r_i \leq 1 \\ 0, & r_i > 1 \end{cases} \quad \text{Equation D.2}$$

with the ratio r_i given by

$$r_i = \frac{\sqrt{(x - x_i)^2 + (y - y_i)^2}}{r_b} \quad \text{Equation D.3}$$

With R_i defined as above, each $f(x,y)$ is continuous and smooth everywhere in the mapping domain (Goshtasby 2005). b is a user-adjustable parameter (see below), and r_b

is the distance between control point i and its $(b-1)$ st nearest neighbouring control point. Defining r_i as above causes each polynomial $p_i(x,y)$ to have only a local radius of influence, r_b .

There is an interpolating polynomial $p_i(x,y)$ for each of the N_{CP} control point pairs. The parametric definition of $p_i(x,y)$ which maps control points (q,k) of the distorted calibration grid image to uniformly spaced control points (x,y) is

$$\begin{aligned} q &= A_0 + A_1x + A_2y + A_3xy + A_4x^2 + A_5y^2 \\ k &= B_0 + B_1x + B_2y + B_3xy + B_4x^2 + B_5y^2 \end{aligned} \quad \text{Equation D.4}$$

A second degree polynomial is sufficient when control point density is rather uniform, as in the current case (Goshtasby 2005). To solve for the coefficients A_i and B_i , (q,k) coordinates are used from control point i and from the $(b-1)$ st nearest neighbouring control points. The selection of an appropriate value of b depends on both the density of control points and the geometric differences between the images (Goshtasby 2005). The value of b can be thought of as a smoothness parameter with low values of b being able to reproduce sharp geometric differences, and higher values of b yielding a smoother output image. For polynomials of degree 2, b can be as low as 7, making $(b-1)$ as low as 6. However, using the minimum value of b runs the risk of having ill-conditioned polynomials (Goshtasby 2005).

Because of the high density of control points in this study, $b = 9$ was chosen, meaning that in addition to the coordinates of control point i , $(b-1) = 8$ nearest neighbour control points were used to calculate the local polynomials. This gave accurate and smooth image dewarping. The resulting system of 18 equations obtained by applying Equation D.4 at $b = 9$ points was solved for the 12 unknown polynomial coefficients ($A_0 \dots A_5$, $B_0 \dots B_5$) by least squares.