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Flow visualization of heart valves prostheses in a steady flow model

Visualização do escoamento em próteses de válvulas cardíacas em sistema de fluxo contínuo

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Abstract
Although prosthetic heart valves have been used successfully for many years, an ideal prostheses has not been developed yet. Since the major part of heart valve prostheses related complications are due to flow disturbances, valve hydrodynamic characterization is an useful aid in designing new prostheses. In the present report, flow visualization in steady state flow model has been employed to study flow disturbances occurring downstream two types of bioprosthesis (porcine and bovine pericardium) tested in the mitral position. Flow visualization is an important tool for prosthetic valves evaluation using simple and low cost facilities.
Keywords: Flow Visualization, Dye Injection, Cardiac Bioprosthesis, Heart Valves Testing, Steady Flow

Resumo
Apesar das válvulas cardíacas artificiais serem utilizadas com sucesso por muito anos, a prótese ideal ainda não foi desenvolvida. Uma vez que a maior parte das complicações relacionadas às próteses de válvulas cardíacas são devidas aos distúrbios do escoamento, a sua caracterização hidrodinâmica é um auxílio útil no projeto de novas próteses. Neste trabalho, a visualização do escoamento em regime permanente foi utilizado para estudar distúrbios no escoamento que ocorreram a jusante de tipos de biopróteses (porcina e de pericárdio bovino) testadas na posição mitral. Visualização do escoamento é uma ferramenta importante para avaliação de próteses de válvulas utilizando equipamentos simples e de baixo custo.
Palavras-chave: *Visualização de escoamento; injeção de corante líquido; biopróteses cardíacas; teste de válvulas cardíacas; escoamento não-pulsátil.*

Introduction

Implantation of artificial heart valves is a routine procedure in most large surgical centers. However, there are some late valve-related complications such as hemolysis, thrombus formation, calcification, bioincompatibility, valves stenosis and/or insufficiency and material fatigue. Several authors (Leverett *et al.* ,1972; Sutera and Mehjardi ,1975; Wurzinger *et al.*, 1986; Blackshear and Blackshear, 1987) agree that hemolysis and thrombus formation are in close relationship to hemodynamic disturbance. Therefore a complete fluid dynamic characterization and evaluation of different artificial heart valve design is pertinent.

The fluid dynamic characterization of prosthetic heart valves has been described in the literature by using different testing methodologies (pulsatile or non-pulsatile flow models), test circuits, and data acquisition procedures (quantitative or qualitative flow visualization). Quantitative flow measurements using laser Doppler anemometer as described in Yoganathan *et al.* (1979) and Chew *et al.* (1993), ultrasonic pulsed Doppler as in Nygaard *et al.* (1994) and Farthing & Peronneau (1979) and hot-film anemometer as in Hansenkam *et al.* (1988-a) and Hansenkam *et al.* (1988-b) are common instruments employed for obtaining the velocity fields in predefined flow sections downstream artificial valves. Laser Doppler as well as hot-film anemometry are restricted to local small volume measurements. Flow visualization must be viewed as an important supplement. Flow visualization techniques are capable of providing a general view of the flow passing through prosthetic valves (Knock *et al.*,1988 and Yang, 1982). This is difficult to be achieved by quantitative techniques. It must be stressed that for a complete fluid dynamic characterization of the flow through a prosthetic heart valve both qualitative and quantitative flow visualizations are important.

The purpose of this paper is to describe the installation of a steady flow model assembled to allow quantitative and qualitative flow measurements as well as to discuss the choice of materials and techniques in order to perform flow visualization. Some preliminary results of flow visualization through two commercially available bioprosthesis installed in the mitral position are also presented. Steady flow setup is a convenient model for mitral position because it can be assumed that the mitral valve is fully open for a substantial fraction of the total cardiac cycle. In fact, the steady flow occurs when the mitral valve is fully open. Another important reason for testing prosthetic valves in the mitral position is the high surgical frequency of heart valve replacement (Haggag, 1990).

A comparative study with other types of prosthetic heart valves is very difficult simply because there is not any standardized test protocol, such as operational pressure, simulated peripheral resistance, upstream and downstream test section geometry, test fluid and valve orientation (Hansenkam, 1988-a).

Materials and Methodological Procedures

For complex flow fields, single-point measurements, such as those obtained from hot-wire or laser Doppler anemometers, do not allow for a good qualitative information of the flow structure, and hence a detailed flow visualization would be useful. In fact, flow visualization is an essential tool to understand the complex phenomena associated with most fluid flows and has been successfully applied in biology and medicine, Freymuth (1993). Such technique requires a flow generator, a flow visualization device and a recording system. Flow generator and visualization equipment often form an integrated set while the recording system is in a separate unit, such as a professional photographic or video camera.

Flow Generator

Low turbulence level and flat velocity profile are the desirable flow characteristics in the test section of a properly designed flow generator. Several types of equipment have been presented in the literature for testing heart valves prostheses in steady flow regime Hasenkam *et al.* (1988-b). The flow generator proposed in the present work is similar to a small horizontal water tunnel with an open test section and operated either in closed or open circuit.

The steady flow setup (Figure 1) may be divided in three main parts, namely flow straightener, test section and outlet diffuser. The upstream assembled flow straightener has been designed to generate a 24 mm diameter low-turbulence jet entering the test section. For this, proper flow conditions in the outlet portion of the flow straightener has been obtained by forcing the flow through a flow laminator, composed of several distinct subsections. The first one is the inlet diffuser (DF), in which the action of fine mesh wire screens eliminates perturbations caused by hydrodynamic boundary layer separation on the divergent section. The flow then passes through honeycombs inside the stagnation chamber (SC) to reduce the vorticity level. Finally, before entering the

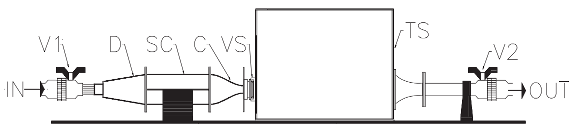


Figure 1. Flow Generator [V1 / V2 = Inlet/outlet valves; SC=Stagnation Chamber; VS= Valve Prostheses Support; DF= Inlet Diffuser; CT= Contraction; TS= Test Section]

test section, the flow faces a contraction subsection (CT), which is a very important component to obtain a flat velocity profile in the test section (TS). An accurate contraction design and construction is mandatory to reduce boundary layer thickness and obtain most favorable condition to homogeneous velocity profile.

Flow Visualization

Flow visualization is the art and science of obtaining a clear image of a physical flow field as well as the ability to capture the image on sketch, photograph, or other video storage device for display or further processing (Freymuth, 1993). For this purpose tracers, correct illumination and, appropriate image capture system are necessary.

In low speed homogeneous liquid flow, tracer methods for flow visualization are usually the best choice. Tracers, liquids, gases or solids particles, are transported by the flow with the same local velocity and direction of the flow field. In bioengineering applications the most common tracers are microscope hydrogen bubble, solids micro-particles and liquid inks obtained from food dyes (Mueller, 1983). In the present article, liquid ink tracers obtained out of a mixture of dye pigments, ethyl alcohol, for density effects correction, and anti-dispersing agents have been employed. The tracer is injected into the flow immediately before the flow laminator (Figure 1) by means of a long hypodermic needle, in order to guarantee a well-mixed flow before entering the test section.

Illumination

The first step to obtain a clear image is the correct scene illumination. A most perfect agreement between lighting and capture systems is essential to obtain scientifically relevant pictures. This has been proved to be a difficult trial-and-error task, hence in many experimental works with visualization of physical phenomena a great number of preliminary tests to obtain the best lighting conditions are rather common.

In the present work, two distinct types of illumination have been tried for the flow past a valve prostheses. The first one consisted of eight (250 W) G.E. Photo Flood lamps placed in line with the camera and shielded by white velvet-like paper to provide a uniformly bright background against which the die patterns were photographed. Photo Flood low-cost lamps supply white light with high color temperature, adequate to image capture on chemical photographic films. The second one, happened to be the best choice as it will be further discussed, employed a thin light-cutting plane sheet obtained using a slide projector and a specially prepared high-contrast opaque black, except for a transparent slit (Figure 2).

Image Capture

The images are captured in a SLR (single lens reflex) Nikon F4s camera on 24 ´ 36 mm negative film, up to 5.7 fps (frames per second), equipped with high luminosity Nikor macro 60 mm/f.1:2.8 AF-D objective. The photographs have been developed using Kodak Ektacolor Pro 160 (ISO 160) or Kodak Ektapress Plus Multispeed PJM (variable ISO 100-1000,

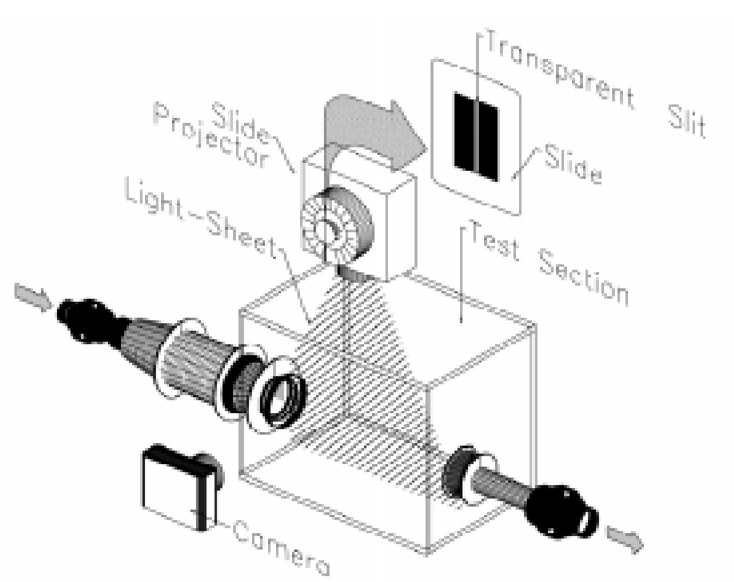


Figure 2. System for obtaining a thin light-sheet.

best results in ISO 640) color negative films, with high contrast colors and high image definition, ideal for scanner reproductions. Using the negative film, the resulting photographic images could be digitalized with a fairly low (600 dpi) optical resolution flat bed scanner. Some noise filtering and finishing were performed with the help of Corel Photo Paint 5.0 software.

Biological Prostheses

In this work the flow characteristics through two types of bioprosthesis has been studied: porcine and bovine pericardium low profile cardiac bioprostheses, showed in Figures 3a and 3b respectively. The porcine bioprosthesis is manufactured using leaflets of swine aortic valve and the bovine pericardium bioprosthesis is made from bovine pericardium, both previously tanned in glutaraldehyde.

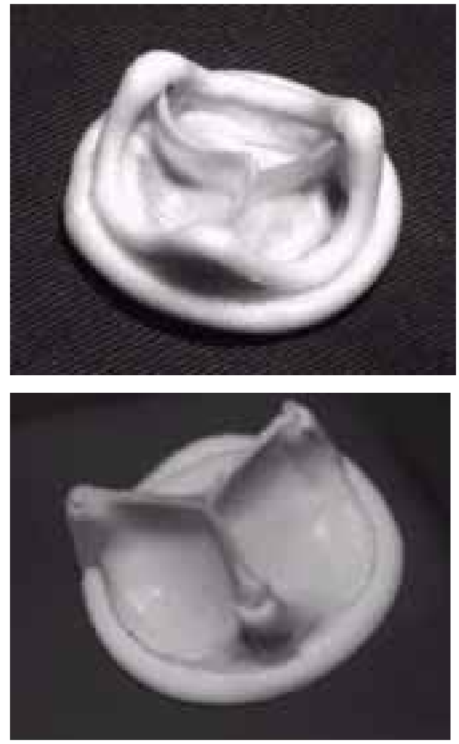
Both tested prostheses have an external diameter of 29 mm and internal diameter of 24 mm. The information about the internal diameter has been used to design the flow laminator (inlet diffuser, stagnation chamber and contraction, depicted in Figure 1). If it would be necessary to test another prostheses, it must have an internal diameter of 24 mm otherwise a new contraction section must be redesigned.

Strange as it may seems, blood is not an adequate working fluid mainly due to some strongly inconvenient factors, e.g. difficult fresh blood supply and conservation, serious precautions in blood dealing and a difficult blood anticoagulation protocol. An artificial blood-like fluid could be used, but it would need regular checks of its physical properties (density and viscosity). However, using the similarity principle it is indeed possible to test the bioprostheses with a fluid exhibiting well-known and fairly stable physical properties albeit quite different from blood.

In steady flow the elasticity of the vessel walls can be neglected, and similarity is obtained with the reproduction of free-flow based Reynolds number

$$Re = \frac{Q}{15 \pi D_V \nu_B}, \qquad (1)$$

where Q is the flow in liters per minute, D_V is the internal diameter of the valve and n_B is the kinetic viscosity of the blood, in m^2/s. At the physiological peak systolic flow range of $10 \leq Q \leq 40$ l/min, the natural average mitral internal diameter of 24 mm and a kinematic viscosity of blood of $\nu_B = 3{,}5.10^{-6}$ m^2/s, the typical Re number range for the peak flow phase amounts to be $2500 \leq Re \leq 10000$ as in Knoch *et al.* (1988).



(a)

(b)

Figure 3. Porcine bioprosthesis (**a**) and Bovine pericardium bioprosthesis (**b**).

In this study, water has been employed throughout as the test fluid ($\nu_W = 1{,}0.10^{-6}$ m^2/s) and bioprostheses with the same internal diameter as the natural valves have been assumed. Therefore, for the same Re numbers range, the test flow rate should have been within the range of $2.8 \leq Q \leq 11.3$ l/min, achieved by controlling V_1 and V_2 valves.

Results and Discussion

Firstly, it is very important to select the best illumination procedure. Figure 4 has been obtained using the first method previously described, i.e. by providing a uniformly bright background against which the die patterns jet were photographed. As it can be verified from Figure 4, this procedure has shown to be inadequate because many jet flow details have been missed. The second method described, light-sheet illumination has been tried, which produced a much better image quality of the flow. As a consequence, all subsequent tests have been performed using the light-sheet illumination technique.

In order to test for the quality of flow obtained in the test section, free flow (no valves) is allowed. As can be seen in Figure 5, the jet in the inlet test section just by the contraction outlet is cylindrical, increased momentum diffusion and turbulence onset appearing only past a distance $2D_V$ downstream, revealing that the flow is laminar in the entrance of test section. Turbulence level measurements performed with the help of hot-film anemometer in this region have shown less than 0.6 %, attesting for the quality of the apparatus.

In Figures 6 and 7, obtained for Reynolds number of about 7600, the flow structure past each prosthesis has revealed some significant discrepancies. For bovine pericardium prosthesis (Figure 6) the outlet flow remained quite laminar for a distance of at least D_V downstream, whereas for porcine bioprosthesis (Figure 7) it presented large disturbances and turbulence onset right at the valve outlet.

For Reynolds numbers of about 8250, Figures 8 and 9, both valves induced much higher perturbation levels. In the case of bovine valve, a regular flow structure could still be detected a short distance from the outlet, whereas for porcine one, the jet emerged strongly disturbed just immediately past the valve. The main conclusion is that porcine bioprostheses generate larger flow perturbations and consequently, earlier turbulence, than the bovine bioprostheses for the same Reynolds number.

Conclusion

An apparatus to test artificial heart valve bioprostheses in steady water flow has been described in this work, employing similarity analysis and capable of several types of flow measurements, such as direct flow visualization, or hot-wire and laser Doppler anemometry. Direct liquid dye injection as well as light-sheet illumination techniques for flow visualization have also been proposed, capable of revealing some qualitative details of the flow field structures downstream the valves. Preliminary results have highlighted higher perturbation levels in the flow induced by porcine valves in comparison to bovine pericardium valves. Although good enough for some

Figure 4. Jet through porcine valve: image obtained with diffuse incident backlight, Re=2874.

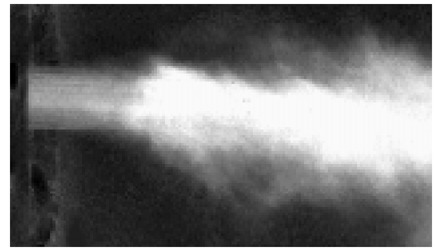


Figure 5. Free jet (no valves): image obtained with light-sheet illumination, Re=8000.

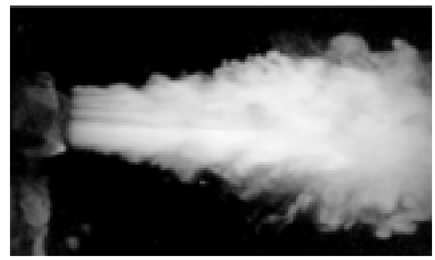


Figure 6. Jet through bovine pericardium: image obtained with light-sheet illumination, Re=7600.

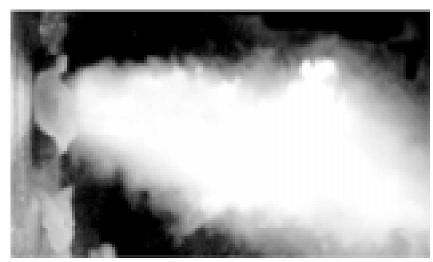


Figure 7. Jet through porcine valve: image obtained with light-sheet illumination, Re=7600.

Figure 8. Jet through bovine pericardium valve: image obtained with light-sheet illumination, Re=8250.

Figure 9. Jet through porcine valve: image obtained with light-sheet illumination, Re=8250.

simple applications, the present flow visualization technique provided inadequate qualitative and quantitative data, which can be obtained by direct injection of solids micro-particles. In this technique, the image is captured by light scattering produced by very small solid spherical particles. Higher illumination power will be needed to provide scattered light intense enough to be registered onto chemical photo-sensitive film. For this case, power lasers are the best choice since laser light sheets are capable of producing images with low noise level and good quality for scientific utilization. Also high-sensibility negative film of higher sensibility should be employed. Unfortunately, high-sensibility films produce images with higher noise levels as well, thus needing special photograph finishing care.

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