UNSTEADY FLOW INVESTIGATION BEHIND THE END-TO-SIDE ANASTOMOSIS

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Abstract: Intimal hyperplasia and other unwelcome pathological changes are an often aftermath of the flow changes after cardiac surgery in the vascular system of a human patient. Studies on the mechanism underlying intimal hyperplasia of grafts have shown a consistent correlation between its pathogenesis and hemodynamic factors and graft/artery compliance mismatch. In order to ensure long-term patency of such a reconstruction, it is necessary to meet a number of conditions, including optimum hemodynamic characteristics of the reconstruction. The goal of this work was to describe the velocity field behind the distal end-to-side bypass junction in dependence on the connection angle in unsteady conditions both experimentally and numerically. This work is the continuation of works using steady conditions [1-3] .

Introduction

The long-term project is solved in author's workplace and its objective is to optimize the shape of anastomosis (end-to-side), which is used for the bypass anastomosis, and thus to minimize the negative impact of the flow dynamics on the vascular walls and blood, thanks to which the bypass failure risk can be successfully reduced. We present part of first results of this project which deals with unsteady periodic flow in this paper.

Because the PIV experimental measurement is of special importance in this project one of the aim in this work was to create the experimental equipment for measurement of the flow field in symmetry plane by PIV method and to create the measurement methodology by PIV method for unsteady periodic conditions. The next aim was to implement pressure transducer in the test circuit for static pressure measurement and to widen the measurement methodology in order to enable synchronization of the pressure measurement with PIV measurement.

If the optimal bypass junction shape was searched in an experiment many models would have to be constructed and each model would have to be checked in a great number of measurements. In order to choose the optimum models and to reduce the number of experiments a numerical solution is planned. Therefore numerical computations in the models similar to the experimental models were carried out in order to verify the selected type, the location and sufficient accuracy of appropriate boundary conditions which ensure a good agreement when comparing resultant flow characteristics obtained from numerical solution and experiment. The next aim was to create the periodic unsteady flow computation methodology. The velocity profiles obtained from PIV measurement were suggested as inlet boundary conditions. The aim was to create the technique for importing data from PIV to FLUENT with the help of user defined function in FLUENT and MATLAB.

Materials and Methods

Experimental equipment: The experimental equipment (fig. 1) that allows obtaining velocity flow field by PIV (Particle Image Velocimetry) method in models of bypass junction in required instants of unsteady flow period and which allows synchronizing the flow field with data obtained from pressure transducers was designed and produced.

The test circuit consists of several parts. The liquid which was pumped from the tank is conducted from the

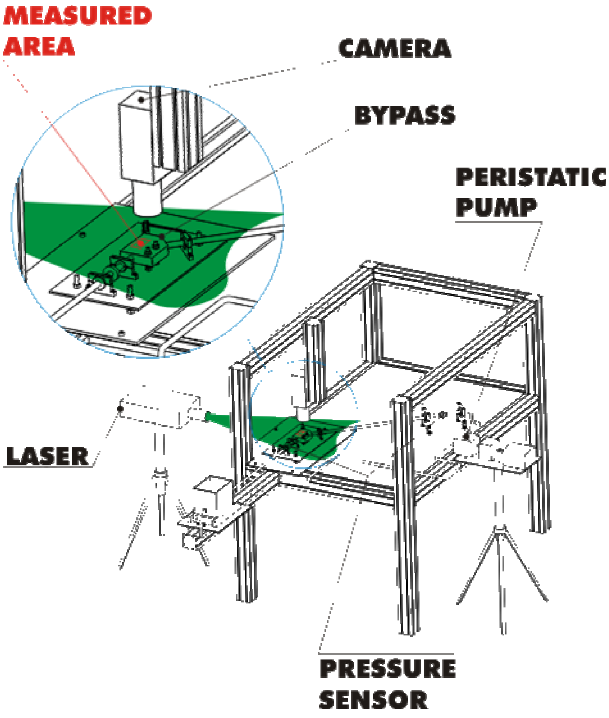

Figure 1: Scheme of experimental equipment.

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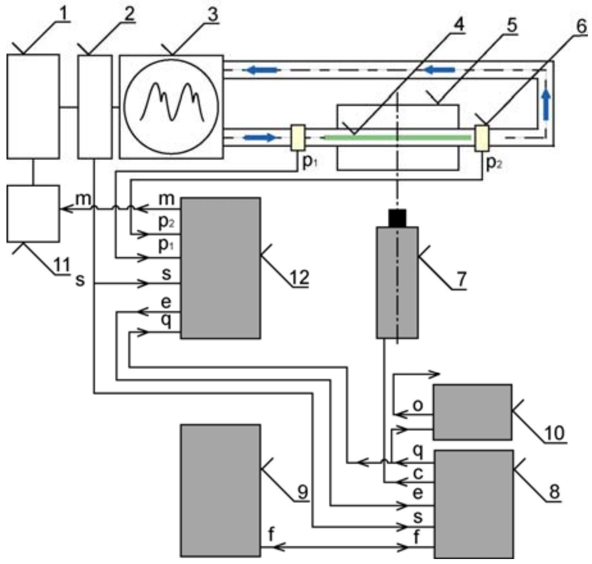

Figure 2: Scheme: 1-drive, 2-synchronization signal generator, 3- generator of periodical unsteady flow, 4-laser sheet, 5-measured space, 6-pressure transducer, 7-camera, 8-FlowMap, 9-PC for PIV system control, 10-laser supply, 11-control of motor, 12-PC S-synchronization signal, p1- pressure transducer signal, p2- pressure transducer signal, e-enable signal, c-camera control and data cable, q–laser control, m-motor control, f- PIV system control.

peristaltic pump into the model. One meter long pipe is placed before the model and the pressure transducer is placed in the pipe's beginning. The second pipe is placed downstream the model. The liquid is conducted from the model through the outflow pipe (length one meter and diameter ten millimeters) into the tank. It is conducted from the tank into the peristaltic pump.

The peristaltic pump which is used as a source of periodical unsteady flow is driven by stepping motor with 4 Nm moment. Mechanical connection with the pump is implemented with the help of elastic coupling which reduces vibration. The control electronics allows setting precise position with precision 1.8 degree. It is possible to increase stepping accuracy (pump rotation) by microstepping with the help of control electronics. The control electronics is connected to the PC which enables to control the motor movement. The device with optical sensor which generates synchronization pulses (0/5V) was placed in the shaft between pump and motor.

The PIV system from Dantec Dynamics, which comprises these components: a pair of cameras Dantec HiSense, 1 024k x 1 280k pixel CCD, frequency 4.5 Hz for double frame mode and 9Hz for single frame mode; a pair of pulsed lasers Nd:YAG New Wave Geminy 15 Hz-120 mJ, with optics; PIV processor Dantec FlowMap 1500, 2 x 1Gb buffer, PC DELL Precision 2 x P4 Xeon 2 800 MHz, was used. The FlowManager (commercial software from Dantec Dynamics) for obtaining and basic data processing was used.

Unsteady flow measurement by PIV method: The measurement of unsteady flow field by PIV method is limited by parameters of the system used and by camera and laser frequency in the first instance. The cameras in our system have frequency 4.5 Hz in double-frame regime and laser frequency is 15Hz. The flow in the cardiovascular system has average maximum values of frequency parameter which is defined as $\beta = 0.5d\sqrt{2\pi f/\upsilon}$, where d is diameter, f is frequency and ν is kinematics viscosity $\beta = 17$ for physiological state and $\beta = 35$ for increased heart frequency. These values of β correspond with maximum frequency f = 0.5 Hz and f = 1.9 Hz for model of characteristic dimension d = 20 mm and for working fluid viscosity near to water viscosity and they correspond with maximum frequency f = 1 Hz and f = 3.5 Hz for working fluid viscosity near to blood viscosity.

Concerning these values of periodic flow frequency it is not possible to obtain the progress of flow field during one period by PIV method with sufficient resolution. For that reason periodic character of flow is used and measurement methodology is created which enables to obtain the flow field in concrete instant of period for selected number of periods. These values enable to calculate mean values of flow field for individual instants of period and allow assembling the progress of mean flow field during whole period. The synchronization signal is used for obtaining images in the required instant and is connected to the control unit of PIV system. The control of PIV system is set so that the system saves double-image after coming of rectangular pulse. The double-image allows calculating the instantaneous flow field. Instantaneous flow fields are saved in structured variable of program MATLAB for next processing.

Settings of PIV system: Two external signals are used for control of PIV system: the synchronization signal (it is generated from source of periodic unsteady flow) and the enable signal (it is used in order to synchronize the PIV system with other measure systems). The PIV system is set up during the measurement so that the double-images were recorded only when both signals have the value *on*. In order to enable to connect the flow field with other measured variables the PIV system was set up so that it generated the signal for control of laser q (Q-switch) in output connector AUX 3 with longer duration.

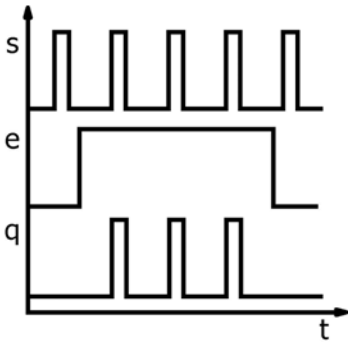

Figure 3: Scheme of synchronization.

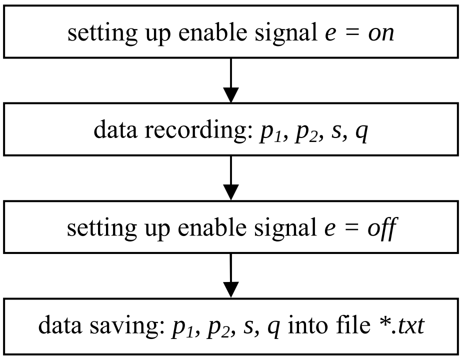

Figure 4: Diagram of program in LabVIEW for measurement control and data saving.

One hundred double-images were measured for every measured instant of period. The instant flow fields were evaluated from these double-images (in Flow Manager software from Dantec Dynamics) by following analysis sequence:

- substract mean image map
- mask image
- adaptive correlation
- mask vectors
- peak validation
- moving-average validation.

The statistics was evaluated from the instant flow fields. The set of statistics was exported from Flow Manager to MATLAB with the help of command "Link to MATLAB" and saved for next post processing.

Pressure measurement: The pressure transducers XTM-190M-0.7BAR D made by Kulite company are used for pressure measurements upstream and downstream the bypass model. The signal from pressure transducers (p_1 and p_2) together with synchronization signal (s) and signal for laser control (q) are connected to measuring card PCI-6024E made by National Instruments company.

Synchronization: In order to enable measuring simultaneously flow fields by PIV and pressure behavior by pressure transducer the LabVIEW program was used. The program which sets up control signal for PIV system and records and saves data from the measuring card (p_1, p, s and q_2) was built in the LabVIEW. Before running this program the PIV system is ready to measure and is waiting for the enable signal (e). This program works in following steps (fig. 4): setting up the enable signal e = *on* (in this moment the PIV system begins to measure always when the synchronization signal is switched *on*), recording data (p_1, p, s and q_2) from measuring card, setting up the enable signal e = *off*, saving the data (p_1, p, s and q_2) in columns in files of ASCII format into file (**.txt).*

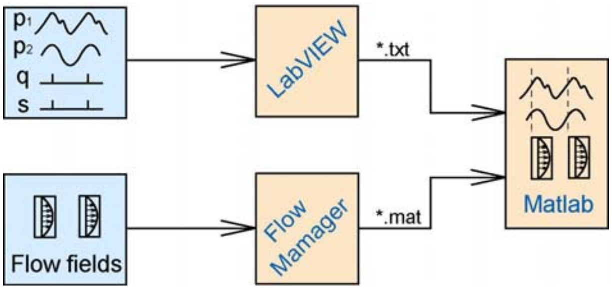

Figure 5: Scheme of synchronization

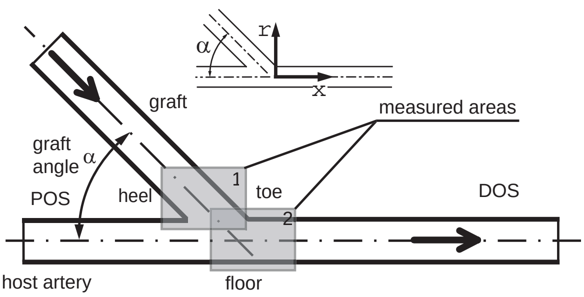

Figure 6: Scheme of bypass.

Data Connection: Connecting flow fields data with pressure behaviors data was carried out in MATLAB program where set of scripts was made. Assorting of mean flow field with correspondent instant of pressure period was carried out with the help of signal q (signal for laser control) which determinates the instant when measuring the flow field. The process used is possible to use for connecting instant flow field with pressure behavior. Other scripts were created for checking the measurement process. They test if the pressure behavior is periodic and they test their agreement with other measurements which make possible to detect eventual bubble presence which occur for example after model changing.

The bypass models were made from plexiglass with connection angles 20°, 30°, 45°, 60° and 90°. The host artery and graft diameter was 10 mm. The flow field was measured in symmetry plane of the model for unsteady conditions (mean inlet Re=1000). Ten measurements were carried out during the whole period. Water was used as a working fluid. Polyamide particles were used as seeding particles. The camera was placed perpendicular to the laser sheet. The pressure transducers were placed upstream and downstream the model.

The construction enables fixed holding of cameras, laser and models in optimal position for measurements, their rotation and shifting with regard to the model (fig. 1). The accuracy of PIV measurement is dependent on precise setup of the whole system, precise position of PIV component and choosing the appropriate sequence analysis [4,5]. The camera, which was placed perpendicular to the laser sheet, was fixed on the guideway which enables camera moving along the host artery axis.

Numerics: The numerical model geometry was derived from the geometry of the experiment. Unlike the experiment it was simplified because of smaller computational grid. 3D computation grid was generated using the pre-processor Gambit with hexahedron and tetrahedron elements. The grid used differs from the previous solutions [1]. Unlike the previous model this model does not have one meter long tube upstream the junction. The graft was modeled by one diameter long tube upstream the junction. Due to this fact the model was smaller and it was possible to make the computational grid with better discretization. For the numerical solution commercial CFD program Fluent was used. The calculation was unsteady. The solver was set up on double precision segregated-implicit formulation. The mathematical model was selected as laminar. Simulations were performed for the same cases as experiment. The boundary conditions were set up on the input to the graft – velocity inlet, on input to the host artery - wall, on the output – pressure outlet. The velocity profiles obtained from PIV measurement were used as inlet boundary conditions (fig. 7) in the graft. Because the profiles were measured only in symmetry plane the scripts in MATLAB were made which created three-dimensional rotational shapes of velocity profiles. The MATLAB scripts created the UDF program in C language for unsteady periodic inlet boundary conditions in ASCI format. This program was compiled in FLUENT. The velocity profiles were saved in three-dimensional matrix in this program. The first index is face index, second index is x, y, z coordinate and third index is period instant. The program fulfills the inlet conditions by velocity profile based on the current time step. It enabled to create the pulsatile flow.

Results and Discussion

The unsteady periodic flow in the model of bypass anastomosis is very complex. The velocity profiles behavior during the period in the host artery one diameter downstream the junction for graft angle $\alpha = 20$ and $\alpha = 45$ is seen in figure 13 and 14. The velocity profiles have the maximum value near the floor for longer part of the period. The velocity gradient which is connected with the wall shear stress is higher on the floor than on the opposite side. The second peak of velocity occurs near the side opposite the floor in some parts of the cycle. It is caused by secondary flow. The secondary flow is intensive in models with greater angle. Unlike the flow in steady conditions the greater vortex structures and reverse flow appeared especially in decelerate part of the cycle (figures 9-12). The velocity fluctuations were the other evaluated flow characteristics. The comparison of velocity fluctuation between two angles for two instant of period is seen in figures 15 – 18. The magnitude of fluctuations varies during the period. The area with higher magnitude is downstream the junction. This area is bigger for greater angle. The maximum fluctuation values that are seen near the wall are caused by worse signal.

Conclusions

The experimental equipment for measurement of the flow field in symmetry plane by PIV method was created and the measurement methodology by PIV method for unsteady periodic conditions was developed. The pressure transducer was implemented in test circuit and the measurement methodology was widened in order to enable synchronization of the pressure measurement with PIV measurement. The flow field was measured in symmetry plane of the model for unsteady conditions. The bypass models were made from plexiglass with connection angles 20°, 30°, 45°, 60° and 90°. The host artery and graft diameter was 10 mm. Ten measurements were carried out during the whole period. Water was used as a working fluid. Polyamide particles were used as seeding particles. The camera was placed perpendicular to the laser sheet. The pressure transducers were placed upstream and downstream the model.

The numerical model geometry was derived from the geometry of the experiment. For the numerical solution commercial CFD program Fluent was used. The solver was set up on double precision segregated-implicit formulation. The mathematical model was selected as the laminar. The boundary conditions were set up on the input to the graft – velocity inlet, on input to the host artery - wall, on the output – pressure outlet. The process of implementation of experimental data into numerical computations was developed. The velocity profiles measured by PIV were transformed with the help of MATLAB to UDF function. It enabled simulating inlet unsteady periodic boundary conditions in FLUENT in the graft inlet.

Acknowledgements

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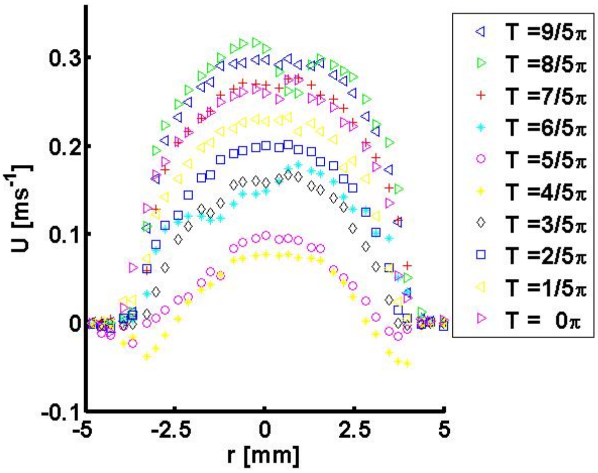

Figure 7: Velocity profiles behaviour during the whole period in the graft one diameter upstream the junction.

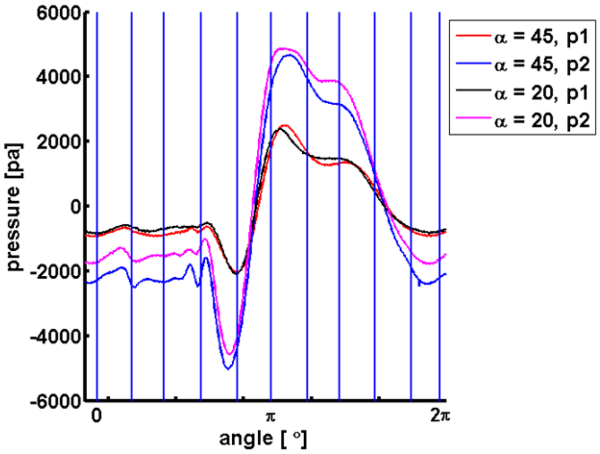

Figure 8: Pressure behaviour for two models with graft angle $\alpha = 20$ and $\alpha = 45$ upstream (p1) and downstream (p2).

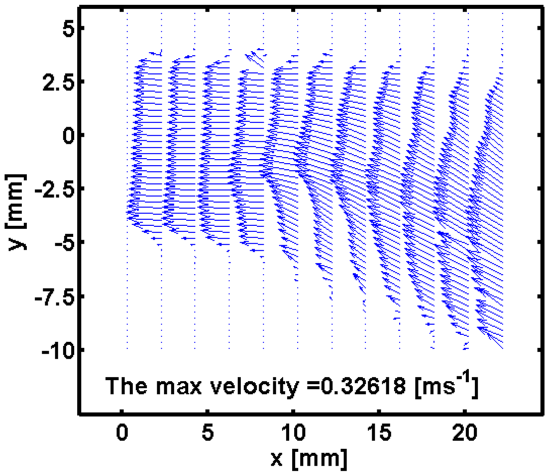

Figure 9: Velocity profile for graft angle $\alpha = 20$ and for period instant T = 9/5π.

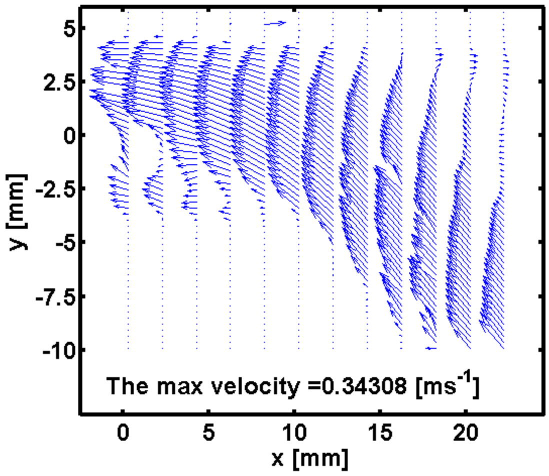

Figure 10: Velocity profile for graft angle $\alpha = 20$ and for period instant T = 9/5π.

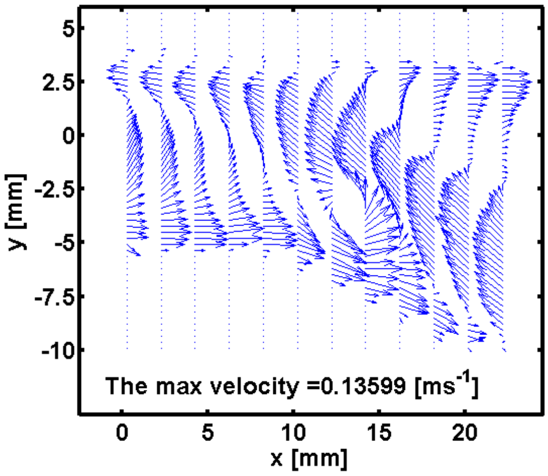

Figure 11: Velocity profile for graft angle $\alpha = 20$ and for period instant T = 4/5π.

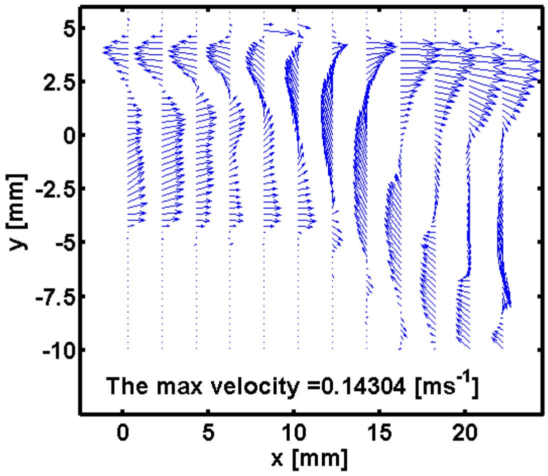

Figure 12: Velocity profile for graft angle $\alpha = 20$ and for period instant T = 4/5π.

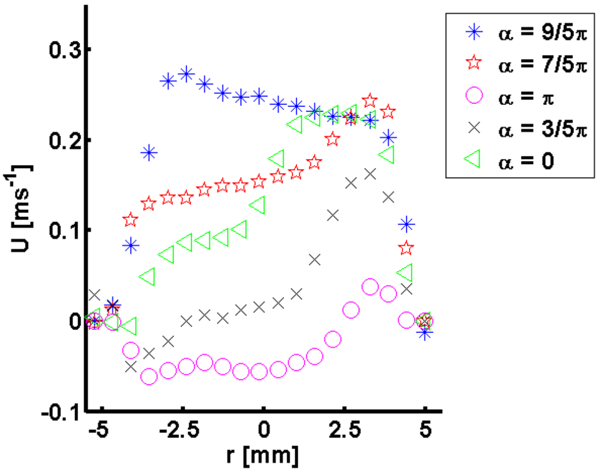

Figure 13: Velocity profiles behaviour during the period in the host artery one diameter downstream the junction for graft angle $\alpha = 20$.

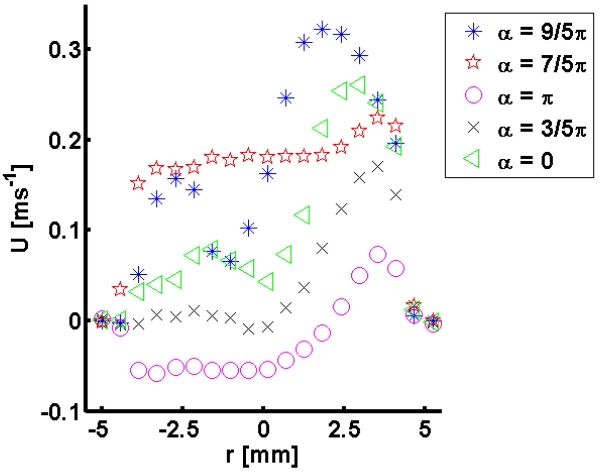

Figure14: Velocity profiles behaviour during the period in the host artery one diameter downstream the junction for graft angle $\alpha = 45$.

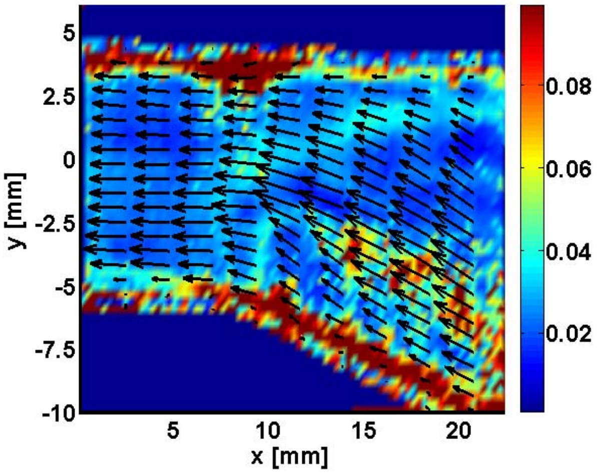

Figure 15: Velocity fluctuation distribution for graft angle $\alpha = 20$ and for period instant $T = 9/5\pi$.

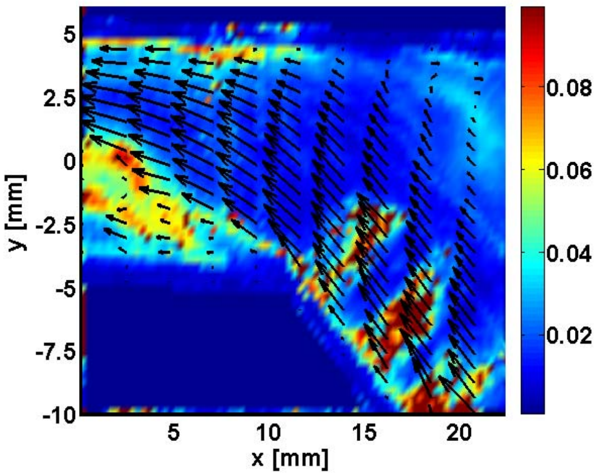

Figure 16: Velocity fluctuation distribution for graft angle $\alpha = 45$ and for period instant $T = 9/5\pi$.

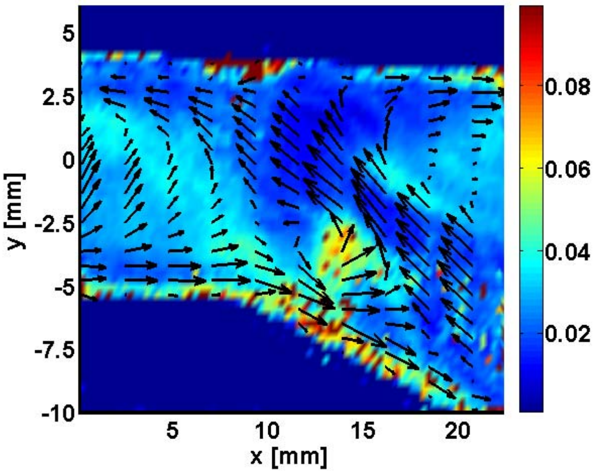

Figure 17: Velocity fluctuation distribution for graft angle $\alpha = 20$ and for period instant $T = 4/5\pi$.

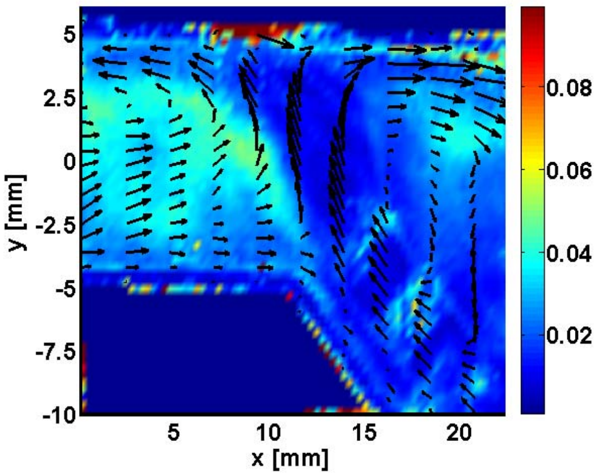

Figure 18: Velocity fluctuation distribution for graft angle $\alpha = 45$ and for period instant $T = 4/5\pi$.