Acta Medica et Biologica
Vol.54, No.3, 77-83, 2006

Experimental Model for Shear Stress Measurement in Vascular Circulation by Micro Particle Image Velocimetry

Yoshinobu SATO[1], Nobuyuki FUJISAWA[2] and Katsuyoshi HATAKEYAMA[1]

[1]Division of Digestive and General Surgery, Graduate School of Medical and Dental Sciences, Niigata University, [2]Department of Mechanical and Production Engineering, Niigata University, Niigata, Japan

Received October 19, 2005; accepted May 15, 2006

Summary. **The present study investigated the basic architectonics of a micro particle image velocimetry (PIV) system and measured shear stress in a model of hepatic microcirculation for the purpose of understanding mechanical stress in small-for-size graft liver transplantation. The flow velocity was measured using a micro PIV system in a straight confluence, with bifurcation channels of the hepatic sinusoid model made of a clear acrylics that was 300 μm in width and 100 μm in height. In the micro PIV system, two strobes as a light source illuminated an object from underneath, and its visual flow images were recorded into a computer using a high-resolution CCD camera. The flow visualization was performed by adding distilled water to proper nylon tracer particles of 1 μm in diameter (specific gravity:1.02). The experimental velocity profile measured by this micro PIV system was in good accordance with both the results obtained using the three-dimensional Navier-Strokes equations on a square tube and Hagen-Poiseulle equations on a circular tube, which confirmed the suitability of this measurement system. The flow velocity after both confluence and branching in the model of hepatic circulation very rapidly became similar to that of the straight flow. The wall shear stress was calculated using an equation of $\tau = \mu \cdot du/dy$, based on the measured mean velocity distribution. The measurement data of shear stress in the straight flow was accurate with an error of 6%. This micro PIV system had sufficient reliability for measuring the shear stress in hepatic microcirculation and serve as a new instrument for understanding pathological conditions in hepatic microcirculation in small-for-size liver transplantation.**

Key words — flow visualization, micro PIV, microcirculation, shear stress, liver transplantation, velocity measurement.

INTRODUCTION

Microcirculation, which occurs in arterioles, capillaries, and venules with diameters of 5 to 50 μm, is the mechanism by which oxygen and other substances are delivered to the tissues and organs of the body. Because microcirculation is very important in the process of maintaining healthy tissues and organs, it is essential to measure velocity fields and to investigate the characteristics of microcirculation including abnormal microcirculation in a diseased system. Particle imaging velocimetry (PIV) has been the quantitative measurement method of instantaneous velocity fields in experimental fluid mechanics[1,2,3].

Size mismatch is a major obstacle in adult living-related donor liver transplantation (LRDLT) [4, 5]. It is well known that small donor grafts for recipients induce postoperative hyperbilirubinemia and liver injury, resulting in liver-regeneration failure. The mechanism for this failure remains unclear, though the existence of preoperative portal hypertension in recipients may promote postoperative liver injury.

We previously proposed that the acute elevation of portal pressure reflecting wall shear stress of sinusoidal

Correspondence: Yoshinobu Sato, M.D., PhD., Division of Digestive and General Surgery, Graduate School of Medical and Dental Sciences, Niigata University, 1-757 Asahimachi-dori, Niigata 951-8510, Japan.

Abbreviations – LRDLT, living-related donor liver transplantation; PIV, particle imaging velocimetry.

endothelial cells became a trigger for liver regeneration after partial hepatectomy, and that excessive portal hypertension induced liver failure [6,7]. Moreover, the reduction of excessive shear stress in portal hypertension prevented liver injury and hyperbilirubinemia after massive hepatectomy or adult LRDLT [8,9,10]. However, sinusoidal shear stress remained to be quantitatively measured.

The present study thus investigated the basic architectonics of a micro PIV system and measured microcirculation velocity in order to understand the mechanical stress in small-for-size graft liver transplantation.

MATERIALS AND METHODS

Micro PIV system

Our micro PIV system is demonstrated in Fig. 1 for an analysis of hepatic microcirculation. In this system, two strobes as a light source illuminated an object from underneath, and its visual flow images were then recorded into a computer using a high-speed CCD camera. This camera was able to take two pictures as one pair at a very short time interval (4ms) by using a double shutter function. Those visual flow images were captured into a computer as digital information by the frame grabber. A pulse generator controlled the delicate timing between lighting by strobes and camera signals.

Hepatic microcirculation model

Fig. 2 shows the hepatic microcirculation model made of a clear acrylic that was 300 μm in width and 100 μm in height. A combination of a straight, confluence, and branch flow channels was considered a basic model of hepatic microcirculation.

The flow visualization was performed by adding distilled water to proper nylon tracer particles of 1 μm in diameter (specific gravity:1.02). Fig. 3 shows these particles in the original picture.

In this method, the interrogation between the sequential two images was carried out using a direct cross-correlation algorithm with a gray level difference method, where the sub-pixel interpolation technique was induced to improve the accuracy of velocity measurement.

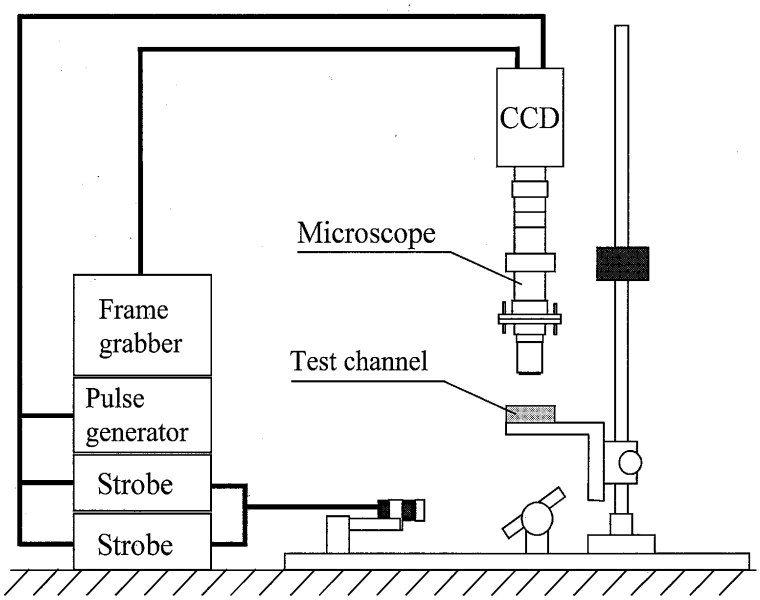

Fig. 1. Schema of micro PIV system. In this system, two strobes as a light source illuminated an object from underneath, and its visual flow images were recorded into a computer using a high-resolution CCD camera. This camera could take two pictures as one pair at a very short time interval (4ms) by using a double shutter. Those visual flow images were captured into a computer as digital information by the frame grabber. A pulse generator controlled the delicate timing between lighting by the strobes and camera signals.

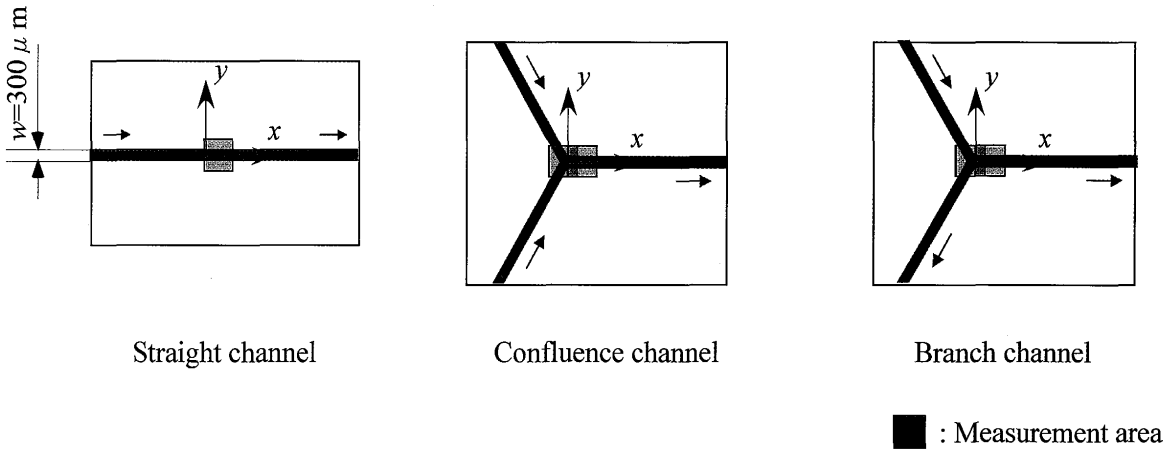

Fig. 2. Schema of hepatic sinusoidal microcirculation models made of clear acrylics. This model was 300 μm in width and 100 μm in height. A combination of a straight, confluence, and branch flow channels is thought to be a basic model of hepatic microcirculation.

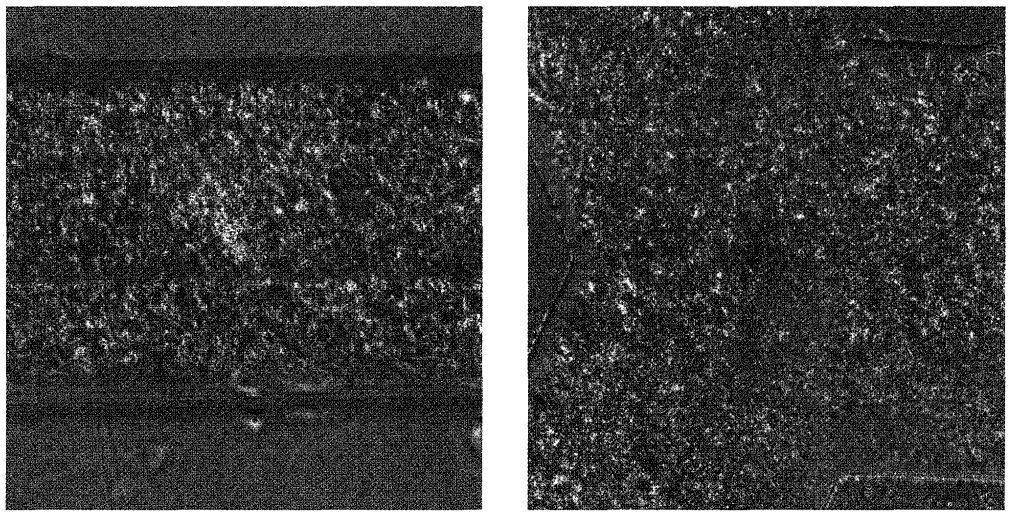

Fig. 3. Original pictures of both straight and Y channels for confluence and branching. The flow visualization was performed by adding distilled water to proper nylon tracer particles of 1 μm in diameter (specific gravity:1.02).

RESULTS

The flow velocity field in a straight tube is shown in Fig. 4. The result was obtained by time-averaging 150 velocity fields measured by the present particle image velocimetry with the direct cross-correlation algorithm. This result was obtained based on the assumption that Reyolds Number Re (= Ud/ν) equaled to 0.2 for flow in the flow tube of 300 μm in width. The flow in a straight tube was along the surface, and the velocity near the surface was decreased by the viscous effect of the flowing fluid. Therefore, the flow velocity normal to the surface was slight and became maximum at the center of the straight tube.

The axial mean velocity profiles of the straight flow tube are shown in Fig. 5 with the results obtained using both the three-dimensional Navier-Strokes equations on the square tube and Hagen-Poiseuille equations on the circular tube for proofs of the appropriateness of

this measurement system. Both results were in good accordance with the experimental velocity profile, which indicated the suitability of this measurement system.

The results of the flow velocity field in the confluence area are shown in Fig. 6. The flow velocity of the center area seemed to increase. However, the velocity distribution immediately after the confluence resembled that of the straight flow velocity because the flow field after confluence maintained its symmetry for the geometric condition.

The results of the flow velocity field in the branching area are shown in Fig. 7. Contrary to the results of the confluence area, the velocity in the central area gradually seemed to decrease. The velocity immediately after branching did not become parallel to that at the wall surface in the center of channel, and showed the downward flow components because of the geometrical formation of unsymmetrical flow fields. However, such flow components disappeared immediately in the straight channel downstream, and the velocity distribution became similar to that of a straight flow.

Measurement of shear stress

The wall shear stress was calculated using a equation of $\tau = \mu \cdot du/dy$ with the measured mean velocity distribution near the wall. The shear stress coefficient $C_f (=2\ ^{\delta/\bar{n}}\ U^2)$ in the straight channel is shown in Table 1. The result is compared with that obtained using the three-dimensional Navier-Stokes equations in the straight channel and that obtained using the Hagen-Poisuelle equations on a circular tube. The shear stress data of the straight flow accurately corresponded to the numerical and theoretical values with an error of 6%. These data suggested that our micro PIV system was reliable for shear stress measurement of the vascular wall in hepatic circulation.

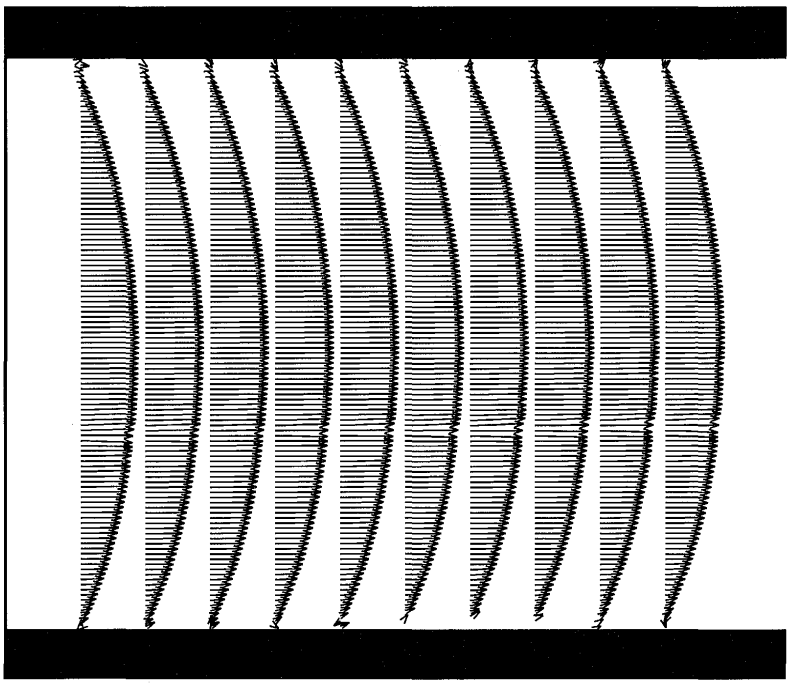

Fig. 4. The results of a flow velocity field in a straight tube. The flow in a straight tube was along the surface, and the velocity near the surface was decreased by the viscous effect of the flowing fluid. Therefore, the flow velocity normal to the surface was small and became maximum at the center of the straight tube.

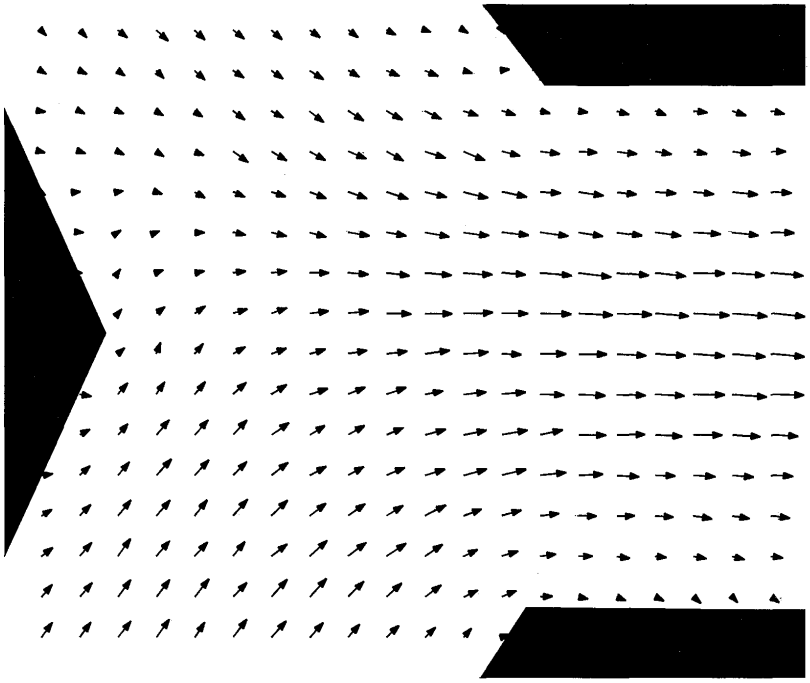

Fig. 5. The stream-wise velocity profile of a straight flow channel and the results obtained based on both three-dimensional Navier-Strokes equations on a square tube and Hagen-Poiseuille equations on a circular tube for the proofs of appropriateness of this measurement system. Both numerical results were in good accordance with the experimental velocity profile, which indicated that this measurement system was reliable.

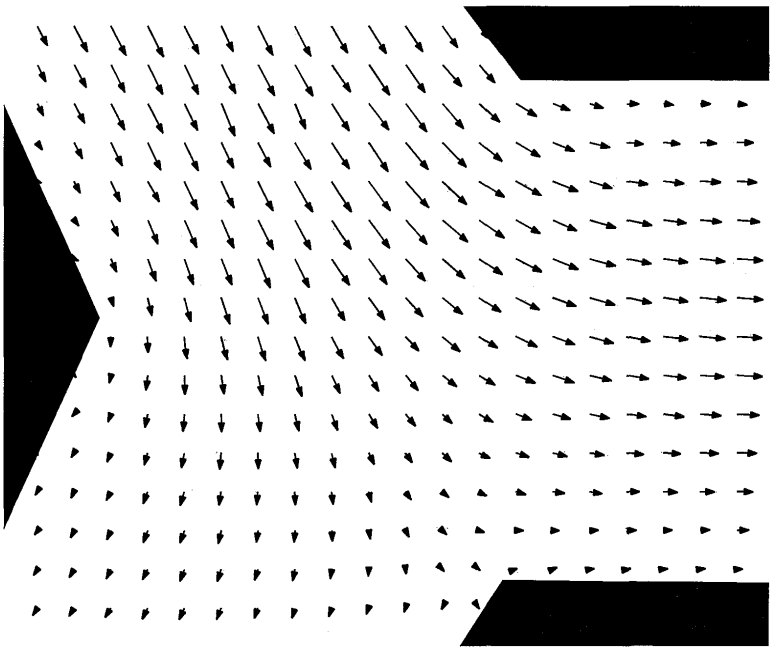

Fig. 6. The results of the flow velocity field in the confluence area. The flow velocity of the center area seemed to increase, but the velocity distribution immediately after the confluence resembled that of the straight flow velocity because the flow field after a confluence kept symmetry for the geometric conditions.

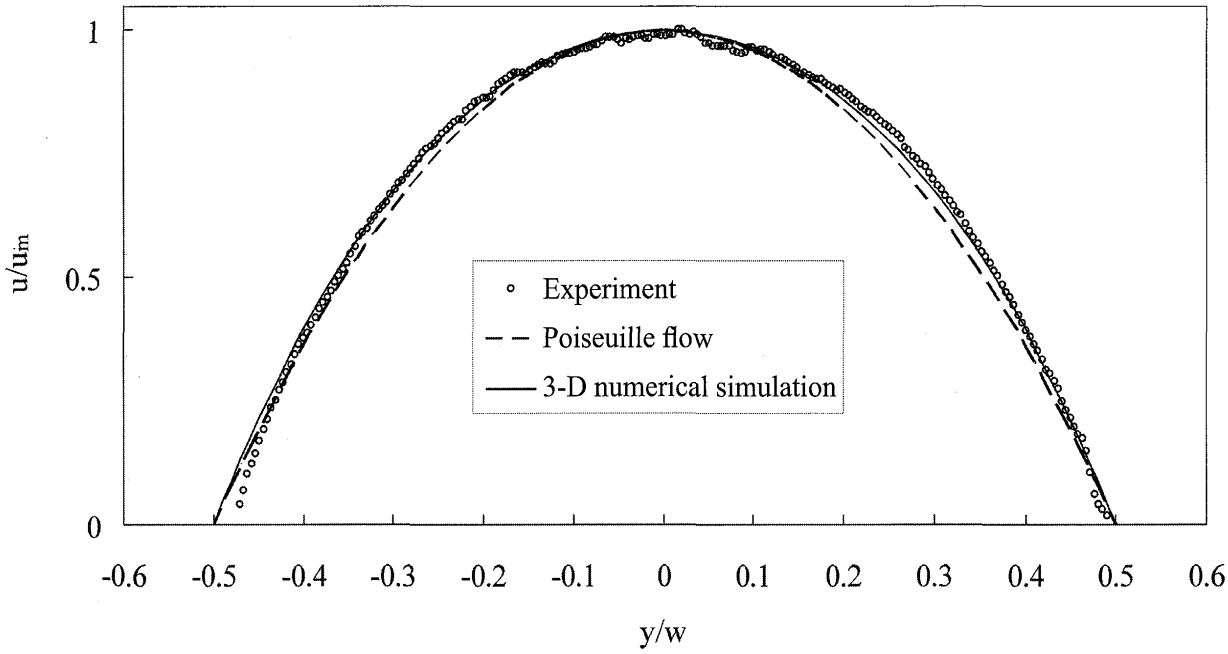

Fig. 7. The results of flow velocity field in the branching area. The velocity of central area gradually seemed to decrease. The velocity immediately after branching did not become parallel to that at the wall surface and showed downward flow components because of the geometrical formation of unsymmetrical flow fields. However, such flow components disappeared immediately in the straight channel downstream, and the velocity distribution became similar to that of a straight flow.

Table 1. Shear stress coefficient evaluated in the present measurement, and by using three-dimensional Navier-Strokes equations and Hagen-Poisuelle equation on a circular tube

	Experiment	Three-dimensional N-S equation	Hagen-Poiseuille equation
Shear stress coefficient C_f	44.5 (+6.0%)	42.0 (0%)	40.0 (-4.8%)

( ) Error relative to three-D numerical simulation.

DISCUSSION

We previously proposed that the shear stress of sinusoidal endothelial cells is very important for understanding liver regeneration and liver injury following both major hepatectomy and small-for-size graft liver transplantation. [6,7] Furthermore, we reported that the reduction of excessive portal hypertension after these surgeries by several surgical devices prevented liver injury in both experimental studies and clinical studies. However, the exact shear stress in hepatic microcirculation has not been clinically or experimentally measured. The portal pressure may be very useful for understanding the pathological conditions following LRDLT, but an exact measurement method of sinusoidal wall shear stress is required for understanding the exact conditions of hepatic microcirculation and for preventing liver injury after small-for-size LRDLT. A micro PIV system has been studied in the cardiovascular

field [11, 12] but not in the hepatic field. The present study has shown the architecture of a micro PIV system and the propriety of flow field measurement in the hepatic microcirculation model as a preliminary research in order to investigate the relationship between the wall shear stress of portal vein and the small-for-size graft liver transplantation. Furthermore, the measurement of the confluence and the branching flow fields as well as straight flow field was performed for the analyses of whole pictures of hepatic microcirculation. Measurement of shear stress in the hepatic sinusoid might be difficult because of complications from the presence of both confluence and branching venous flows. However, our micro PIV system might be able to measure the wall shear stress in hepatic microcirculation because the flow velocity after both confluence and branching in the model of hepatic circulation very rapidly became similar to that of the straight flow. Therefore, the shear stress after both confluence and branching could be obtained as the measurement of the straight flow field within a permissible error range.

In conclusion, the results of this study suggest that our micro PIV system has sufficient reliability for measuring shear stress in hepatic microcirculation and could serve as a new instrument for understanding the pathological conditions of hepatic microcirculation in small-for-size liver transplantation.

Acknowledgments. Gratitude is expressed to Mr. Y. Nakamura and Mr. F. Matsuura, Graduate School of Science and Technology of Niigata University, for their help in the present experiments.

REFERENCES

1) Santiago JG, Werely ST, Meihard CD, Beebe DJ, Adrian RJ: A micro particle image velocimetry system. *Exp Fluids* **25**: 316-319, 1998.
2) Funatani S, Fujisawa N: Simultaneous measurement of temperature and three velocity components in planar cross section by liquid-crystal thermometry combined with stereoscopic particle image velocimetry. *Meas Sci Technol* **13**: 1197-1205, 2002.
3) Kiuchi T, Kasahara M, Uryuhara K, Inomata Y, Uemoto S, Asonuma K, Egawa H, Fujita S, Hayashi M, Tanaka K: Impact of graft size mismatching on graft prognosis in liver transplantation from living donors. *Transplantation* **67**: 321-327, 1999.
4) Kita Y, Harihara Y, Hirata M, Kusaka K, Sano K, Ito M, Yoshino H, Kubota K, Nakao A, Kawarasaki H, Takayama T, Maekawa K, Makuuchi M: Factors influencing persistent hyperbilirubinemia following adult-to adult living-related liver transplantation. *Transplant Proc* **32**: 2193-2194, 2000.
5) Hirano K, Sato Y, Kobayashi T, Yamamoto S, Nakatsuka H, Oya H, Kato T, Watanabe T, Kameyama H, Hatakeyama K: Carbon monoxide hemoglobin and bilirubin metabolism in adult living-related liver transplantation. *Hepato-Gastroenterol* **50**: 1745-1748, 2003.
6) Sato Y, Koyama S, Tsukada K, Hatakeyama K: Acute portal hypertension reflecting shear stress as a trigger of liver regeneration following partial hepatectomy. *Surg Today* **27**: 518-526, 1997.
7) Sato Y, Tsukada K, Hatakeyama K: Review: Role of shear stress and immune responses in liver regeneration after a partial hepatectomy. *Surg Today* **29**: 1-9, 1999.
8) Sato Y, Yamamoto S, Oya H, Nakatsuka H, Tsukahara A, Kobayashi T, Watanabe T, Hatakeyama K: Splenectomy for reduction of excessive portal hypertension after adult living-related donor liver transplantation. *Hepato-Gastroenterol* ***49***: 1652-1655, 2002.
9) Sato Y, Kobayashi T, Nakatsuka H, Yamamoto S, Oya H, Watanabe T, Hatakeyama K: Splenic arterial ligation prevents liver injury after a major hepatectomy by a reduction of surplus portal hypertension in hepatocellular carcinoma patients with cirrhosis. *Hepato-Gastroenterology* **48**: 831-835, 2001.
10) Koyama S, Sato Y, Hatakeyama K: The subcutaneous splenic transposition prevent for liver injury induced by excessive portal pressure after massive hepatectomy. *Hepato-Gastroenterology* **50**: 37-42, 2003.
11) Amadeo A, Grigioni M, Oppido G, Daniele C, D`Avenio G, Pedrizzetti G, Giannico S, Filippelli S, Di Donato RM: The beneficial vortex and best spatial arrangement in total extracardiac cavopulmonary connection. *J Thorac Cardiovasc Surg* **124**: 471-478, 2002.
12) Meyer RS, Deutsch S, Bachmann CB, Tarbell JM: Laser doppler velocimetry and flow visualization studies in the reguration leakage flow region of three mechanical mitral valves. *Artif Organs* **25**: 292-299, 2001.