Study of Hepatic Vascular Dynamics Based on Symmetrical Pulsating Perfusion

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Background: The traditionally used perfusion method is constant flow. This study proposes a novel method called Symmetric Pulsating Flow (SPF) and verified that this method is applicable.

Material/Methods: The fluid dynamic behavior of perfusate in the vessel, the shear stress, and the vascular deformation were simulated based on the bi-directional fluid-structure interaction. The differences of the fluid dynamic behaviors and the mechanical characteristics of vascular wall were studied and compared between the 2 methods during the process of hepatic perfusion. The simulations and comparisons were carried out on 3 different vascular models.

Results: Utilizing the constant flow perfusion, a double vortex clearly appeared at the rear end of the foreign matter and reflux retention can be caused by the double vortex. The reflux retention caused lower shear stress against the vascular wall and thus brought new accumulation of foreign matter. The SPF perfusion, however, prevented the double vortex, and avoided such reflux retention during the vascular perfusion. In addition, the SPF can clean the vascular wall better with a slower speed, which causes less injury to the vessel, and the pulsating effect can reduce the accumulation of new foreign matter.

Conclusions: The SPF perfusion can clean the vascular wall more thoroughly with less injury.

MeSH Keywords: Hydrodynamics • Liver Transplantation • Pulsatile Flow

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Background

The liver is an important organ of digestion, metabolism, and urea synthesis, and liver failure can have a disastrous effect on human health. At present, liver transplantation is an important means to treat liver failure and other end-stage liver diseases. However, the extreme shortage of donor livers and high-quality liver donors makes it necessary to use marginal livers, such as fatty livers [1]. Therefore, improving the quality of donor livers has become a key issue in liver transplantation [2,3]. Liver perfusion is key to preoperative cleaning and preservation, and method of preserving donor livers before surgery include simple cryopreservation and mechanical perfusion preservation [4]. Compared with the traditional cryopreservation method, the mechanical perfusion preservation method can reduce damage during storage and improve the viability of transplanted organs [5]. Appropriate liver perfusion not only removes foreign matter more thoroughly and reduces the occurrence of ischemic failure in liver tissue, but also avoids damage to its blood vessels and organ tissues caused by abnormal external changes, and this protection is conducive to better postoperative recovery.

Scholars have recently been studying the cleaning and preservation of pre-transplant donors to guide the preservation of kidneys, lungs, hearts, and other organs and to reduce injury during the operation [6–9]. The traditional mechanical perfusion method is carried out at low temperature, while in recent years, the normothermic liver perfusion has been proposed and studied [10,11]. Vogel et al. [12] pointed out that mechanical perfusion at body temperature can maintain the normal metabolism of cells, reduce damage in the preservation process, and assess the viability of the transplanted livers. In 2016, Ravikumar et al. [13] and Bral et al. [14] have performed liver transplantation under normothermic mechanical perfusion separately and successfully. The results show that the method is safe and feasible, which provides a great possibility to expand the liver pool. Because the distribution of blood vessels in the liver is more complicated than in other internal organs, Liu Jun et al. [15] analyzed the dynamic characteristics of the primary vessel in perfusion process, and the result can be used in clinical operations. Han et al. [16] compared the differences between conventional perfusion methods and retrograde perfusion methods, indicating the safety and effectiveness of retrograde perfusion techniques in clinical applications, while reducing organ damage during perfusion. Some scholars have studied the effects of changes in vascular dynamics on various vascular diseases, thus providing theoretical guidance for disease treatment. George et al. [17] studied the hemodynamics of the liver using magnetic resonance imaging (MRI) and computational fluid dynamics (CFD) and obtained new parameters of MRI to distinguish between healthy groups and patients, which is helpful in monitoring disease. Hsu et al. [18] proposed an iterative method for assessing the vascular tissue pre-stress for the formation of aneurysms in the cerebrovascular anatomy, suggesting that tissue pre-stress can be used to monitor vascular dynamics and plays a role in the formation of cerebral aneurysms. Kun Yang et al. [19] proposed a novel model for the measurement of blood perfusion on the local tissue, which was more accurate than others.

In research and clinical settings, the most commonly used method is still the constant flow perfusion method [20–22]. Its main feature is strong stability, and the flushing force on the vascular wall is determined by the inlet velocity [15–18]. To completely remove the foreign matter in the blood vessels, it is necessary to improve the inlet velocity, which is likely to result in increased vascular force and deformation, and thus cause damage to the liver. Compared with constant flow, the swirling flow method [23–25] used in some studies showed better effect in removing foreign matter in the vessel. However, the swirling flow requires complex equipment and special...
operation, which makes it difficult to apply in practice. Some studies have been done on perfusion devices [26], but further studies are needed before it can be used in hepatic perfusion.

To solve the above problems, a new perfusion method called Symmetric Pulsating Flow (SPF) is proposed in this paper. In this study, the simulation was performed using three-dimensional elastic vessel models of the liver and the bi-directional flow-solid coupling method. We analyzed the dynamic characteristics, including velocity, wall shear force (WS), and vascular deformation. The results of the dynamic characteristics of the SPF were compared with the constant flow, which can be used to analyze the effect of the SPF on liver perfusion and to determine its applicability in practice.

**Material and Methods**

**Vascular models**

The models used in this study were built based on computed tomography (CT) images of liver provided by a hospital of Tianjin, China. As shown in Figure 1, 3 models were built: the straight vessel with foreign matter, the straight vessel with stenosis and foreign matter, and the curved vessel with stenosis and foreign matter. Each model has 5 types, and the thickness of the vascular wall is separated into 1.2 times, 1.1 times, 1 time, 0.9 times, and 0.8 times of the following normal value.

The parameters of the vessels are as follows [27]. The Young’s modulus is 5X10^9 Pa, the vessel density is 0.941×10^3 kg/m^3, and the Poisson’s ratio is 0.45. The inner diameter of the vascular model is 4 mm, the outer diameter is 6 mm, and the wall thickness is 1 mm. The lengths of the vascular models shown in Figure 1 are 20 mm, 40 mm, and 50 mm, respectively. Medical studies have shown that the occurrence of spasms in the blood vessels can cause them to be in an abnormal contraction state, assuming a narrowing of about 50%, and thus the stenosis in Figure 1 appeared. The hemispheric foreign matter on the vascular internal wall is an accumulation of the necrotic muscle cells and endothelial cells, cellulose deposition, and degenerated collagen fibers, and its radius is r=2 mm.

**Fluid control equations**

Studies [28] have shown that as long as the arterial diameter is greater than 0.5 mm, the error caused by the use of Newtonian fluid instead of non-Newtonian fluid is no more than 2%. Since the vascular diameter is 4 mm in the paper, the Newtonian fluid is used in the calculation to simplify the model. The motion equation of incompressible viscous fluid is shown as follows:

\[
\frac{dv}{dt} = f - \frac{1}{\rho} \nabla p + v \nabla^2 v
\]

(1)

Previous studies had revealed that the perfusate is present in turbulent form using the constant flow method [15]. The general unsteady continuous equation and the Navier-Stokes equation are also applicable to the transient motion of turbulence [29]. In order to investigate the effects of intravascular pulsations, the time averaging method and the Reynolds-averaged method were adopted, and the sum of the average values and the pulse values were used instead of the flow variable values, which are shown as follow:

\[
\underline{u} = \overline{u} + u'
\]

(2)

where, the \(u, v, w, \) and \(p\) represent the flow variables, the \(\overline{u}, \overline{v}, \overline{w}, \) and \(\overline{p}\) represent the average values and the \(u', v', w'\) and \(p'\) represent the pulse values.

Subtle changes in density do not have a significant effect on flow, thus ignoring the effects of density ripple. The average flow control equation of compressible turbulent flow is as follows:

\[\frac{\partial p}{\partial t} + \text{div}(\rho \underline{u})=0\]

(3)

The momentum equations and equations of motion are shown below:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \overline{u})}{\partial x} + \frac{\partial (\rho \overline{v})}{\partial y} + \frac{\partial (\rho \overline{w})}{\partial z} = \frac{\partial (\rho u')}{\partial x} + \frac{\partial (\rho v')}{\partial y} + \frac{\partial (\rho w')}{\partial z} + S_u
\]

(4)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \overline{u})}{\partial x} + \frac{\partial (\rho \overline{v})}{\partial y} + \frac{\partial (\rho \overline{w})}{\partial z} = \frac{\partial (\rho u')}{\partial x} + \frac{\partial (\rho v')}{\partial y} + \frac{\partial (\rho w')}{\partial z} + S_v
\]

(5)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \overline{u})}{\partial x} + \frac{\partial (\rho \overline{v})}{\partial y} + \frac{\partial (\rho \overline{w})}{\partial z} = \frac{\partial (\rho u')}{\partial x} + \frac{\partial (\rho v')}{\partial y} + \frac{\partial (\rho w')}{\partial z} + S_w
\]

(6)

where \(\rho\) represents the fluid density, \(p\) represents the vascular pressure, \(v, w, \) and \(u\) are the components of the velocity vector \(\underline{u}\) in the x, y and z directions, respectively, \(v\) represents the kinematic viscosity, \(m\) represents the dynamic viscosity of the fluid. \(S_u, S_v\) and \(S_w\) are the generalized source terms of the momentum conservation equations, where \(S_u=\mathbf{F}_x+\mathbf{S}_x, S_v=\mathbf{F}_y+\mathbf{S}_y\) and \(S_w=\mathbf{F}_z+\mathbf{S}_z\). For the incompressible fluid with a constant viscosity, we can get \(s_x=s_y=s_z=0\). \(\mathbf{F}_x, \mathbf{F}_y\) and \(\mathbf{F}_z\) are the volume force on the element. Here, \(\mathbf{F}_x=\mathbf{F}_y=0, \mathbf{F}_z=-p\mathbf{g}.\)
Solid control equations and flow-solid coupling equations

When the energy transfer between solid and fluid is ignored, the force balance equation of blood vessels can be given by Newton’s second law [30]:

$$\rho \cdot \ddot{d} = \nabla \cdot \sigma + f_s$$

(7)

where $\sigma$ represents the Cauchy’s stress tensor, $\rho$ represents the vascular density, $\ddot{d}$ represents the local acceleration vector in solid domain, and $f_s$ represents the volume force vector.

The bi-directional flow-solid coupling calculation also follows the energy conservation principle, so that the stress ($\tau$) and displacement ($d$) are equal or conserved at the interface of the flow-solid coupling. The equations are shown as follows:

$$\begin{align*}
\tau \cdot n_s &= \tau_s \cdot n_s \\
\ddot{d} &= \ddot{d}_s
\end{align*}$$

(8)

where $n$ represents the normal vector for the boundary, $\ddot{d}$ represents the displacement, and subscripts $s$ and $f$ represent solid and fluid, respectively.

Perfusion velocity analysis of the SPF

First, the calculation method of constant flow perfusion velocity is as follows [31]: incompressible viscous fluid will cause frictional resistance and differential pressure when it flows around objects. The total resistance $F_w$ is the sum of frictional resistance and differential pressure, assuming that it is equal to the contact friction ($F_c$) between the foreign matter and the vascular wall:

$$F_w = (C_f \cdot A_f + C_p \cdot A_p) \frac{\rho \cdot v^2}{2} = C_p \frac{\rho \cdot v^2}{2}$$

(9)

where, $C_f$ and $C_p$ are the coefficients of frictional resistance and differential pressure, $A_f$ is the effective area of shear stress, and $A_p$ and $A_s$ represent the projection area of the foreign matter in the direction of the fluid flow. $C_p$ is the flow coefficient and is determined mainly by the Reynolds number. The value of $C_p$ is derived according to the Reynolds number of the hepatic arterial blood, and the relation between resistance coefficient and Reynolds number, which is $C_p=0.4$.

The physical parameters of the perfusion are calculated as follows: the projection area $A$ is calculated from the 3-D simulations and $A=2.147 \, mm^2$, the quality of the foreign matter is $m=0.017 \, g$, and the frictional coefficient of the vascular wall is $\mu=0.75$ [15]. Using all the parameters above, the $F_w$ is calculated: $F_w=\frac{\mu \cdot m \cdot g \cdot v}{\rho}=0.000017 \, kg \cdot m/s^2 \cdot 0.75 = 0.000125 \, N$. Therefore, the pressure needed to flush the matter away is $P=58.22 \, Pa$ (the standard atmospheric pressure is assumed to be 0Pa). Substituting all the parameters to equation (9), the velocity can be calculated and $v=0.538 \, m/s$. In the paper, the perfusate is Sodium Chloride injection of 130/0.4 Hydrocarbon ethyl starch. The Molar Substitution Degree of it is 0.38-0.45, Molar Mass 150 000 g/mol, density $\rho=1029 \, kg/m^3$, and the dynamic viscosity $\eta = 5.763 \, MPa \cdot s$ [32]. Due to the small value of the perfusate viscosity and the small perfusion velocity, the perfusate is taken as an ideal fluid. Therefore, the heat loss caused by viscosity and the heat conduction between the perfusate and the vascular wall are neglected.

In the constant flow method, the ability of taking the foreign matter away is determined by the inlet velocity. As a result, to flush the vascular wall completely, the inlet velocity needs to be increased. However, the larger inlet velocity will increase the radial movement of the vascular wall, thereby increasing vascular deformation and damaging the tissue around the blood vessels.

The most important difference between the SPF method and the constant flow method is that the SPF will generate acceleration. The hydrodynamic theory shows that the magnitude and direction of the acceleration have a great effect on the frictional pressure drop. Thus, combining the constant flow with the pulsating flow, the perfusion method of the SPF is proposed. The perfusion cycle is set to $T=4s$ and the inlet velocity of the SPF in the current is calculated as follows:

$$v = \begin{cases} 
0.538 \, m/s \sin(2\pi t) + 0.538 \, m/s, & t \in [0s, 2s] \\
0.538 \, m/s, & t \in [2s, 4s]
\end{cases}$$

(10)

It can be seen from equation (10) that the SPF consist of the constant part and the pulsating part, and the amplitude during the perfusion may exceed the velocity of the constant flow (0.538 m/s). Under such conditions, the inlet velocity of the SPF can be reduced as long as the foreign matter can be flushed away. In this paper, the inlet velocity is set to 0.2 m/s and the inlet velocity of the SPF is as follows:

$$v = \begin{cases} 
0.2 \, m/s \sin(2\pi t) + 0.2 \, m/s, & t \in [0s, 2s] \\
0.2 \, m/s, & t \in [2s, 4s]
\end{cases}$$

(11)

All the simulations of straight and curved vessels will use the inlet velocity calculated by equation (11). The velocity curve of the SPF within one cycle is shown in Figure 2.

Vascular perfusion simulation

In this paper, ANSYS is used for grid partitioning and numerical simulation is carried out in ANSYS-CFX software. All of the vascular models are discretized using ANSYS-CFX software. Hexahedrons can ensure the adaptability of the mesh to the deformation of the vascular wall. The tetrahedron can optimize the irregular area. The mixing factor is set to 0.75, and the maximum residual value is set to $10^{-4}$. 

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The number of grid nodes in the 3 models is 43,804, 117,010, and 82,950, respectively.

The bi-directional flow-solid coupling method of elastic vascular wall was used to calculate and analyze the dynamic characteristics of the 3 vascular models. Since the flow-solid coupling bi-directional analysis is transient, in order to ensure that the time steps of the 2 analyses are the same, the time step is set to 1 s. The bounding conditions are as follows: First, the inlet velocity of the constant flow is set to 0.538 m/s and the inlet velocity of the SPF is calculated using equation (11). Second, in the calculation of the flow field, the inlet pressure (i.e., the reference pressure field) is set to 0 Pa in order to obtain the actual pressure of the vascular wall. Third, according to the reference pressure field, the relative pressure at the outlet is also set to 0 Pa. Finally, the perfusate is considered as an ideal viscous fluid, and the vascular wall is considered as an ideal smooth surface. There is no relative movement at the interface between the fluid and the vascular wall.

**Statistical analysis**

Data were analyzed with ANSYS-workbench (Version 15.0) for calculating the wall shear stress and vascular deformations during the process of hepatic perfusion in the 3 different vascular models. Each vascular model was simulated 5 times by using the constant flow method and the SPF method, respectively. We assessed the statistical significance of differences in the max values of vascular deformations and the wall shear force on the same perfusion method to discover the law of the change, comparing data of the same perfusion method and the different perfusion methods. The simulation results are expressed by figures in this paper.

**Results**

In this section, the simulation results of different models and different types of the same model are analyzed, including pressure, velocity, deformation, and wall shear stress. The feasibility of the SPF is verified by the bi-directional flow-solid coupling method and compared with the results of the constant flow.

**Simulation result of the straight vessel with foreign matter**

The inlet velocity is in accordance with the inlet boundary conditions and the perfusate flows from left to right. The pressure...
and velocity distributions around the foreign matter using the SPF method are shown in Figure 3. It can be seen from Figure 3A that the pressure difference between the front and rear ends is greater than 200 Pa, which is much higher than the required pressure difference (58.22 Pa). Besides, the pressure of the rear end of the foreign matter is negative, and this phenomenon means that the SPF method can flush away the foreign matter thoroughly. Figure 3B shows the velocity distribution around the foreign matter. In the constant flow method, the back end of the foreign matter tends to have a retention zone, whereas in Figure 3B, there is no such phenomenon and the perfusate flows smoothly in the vessel.

The simulation results of the SPF method are compared with the constant flow method and the difference of dynamic characteristics is shown in Figure 4. The velocity distribution is shown in Figure 4A, 4B. The maximum velocity of the SPF and the constant flow are 0.79 m/s and 0.95 m/s, separately, and both can flush the foreign matter away. The deformation distributions are shown in Figure 4C, 4D. The peak value of the deformation is 0.562 mm using the SPF, and 0.857 mm using the constant flow. The deformation of the constant flow is greater than that of the SPF, and a greater deformation is more likely to cause damage to the vessel. Figure 4E, 4F are the WS stress distributions. The peak value of the WS stress using the constant flow method is 25.4 Pa, which is higher than with the SPF method (20.7 Pa). It can be concluded from the results that the flow impact, vascular deformation and WS stress of SPF method are all less than the constant flow, so the SPF has less effect on blood vessels and perivascular tissue.

As seen in Figure 4C, 4D, the maximum deformation area of the SPF method is smaller than with the constant flow method, which indicates that the SPF can reduce the radial motion of the blood vessels and cause less damage to the tissue around the blood vessels.

Through the analysis of simulation results on different types of the straight vessel with foreign matter, the vascular deformations decrease with increasing the thickness of the vascular wall, and the max values of vascular deformations show an approximately linear change. In addition, the wall shear force reduces with increasing the thickness of the vascular wall too, and the changes of the wall shear force display a weak non-linear relationship.

**Simulation result of the straight vessel with stenosis and foreign matter**

Intravascular local stenosis has a certain effect on the velocity, pressure, and wall shear of the fluid in the vessel, so the change in hemodynamic parameters plays an important role in the diagnosis and treatment of the disease [33]. The effects of localized stenosis on the flushing of foreign matter were

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**Figure 4.** The hydrodynamic characteristics the SPF method and the constant flow method (A) velocity distribution of the SPF method (B) velocity distribution of the constant flow method (C) vascular deformation of the SPF method (D) vascular deformation of the constant flow method (E) WS stress distribution of the SPF method (F) WS stress distribution of the constant flow method.
studied using 2 perfusion methods. The velocity field distribution is shown in Figure 5. Figure 5A, 5B are the simulation results of the constant flow. It can be seen from Figure 5A that there is a significant double vortex phenomenon in the back of the stenosis, which indicates that the Reynolds number changes when the perfusate flows through the stenosis, and the flow is in the turbulent state, and this phenomenon is called the Cat’s Eye effect. Figure 5B shows that there is an obvious reflux retention zone behind the foreign matter, which can lead to a lower WS stress and form new foreign matter. When comparing Figure 5C with 5A and Figure 5D with 5B, it is clear that there is no double vortex and reflux retention zone using the SPF.

Simulation results of the curved vessel with stenosis and foreign matter

The deformation of the vessel is shown in Figure 6. The largest deformation occurs in the front of the stenosis and the foreign matter, whether using the SPF method or the constant flow method. This is because the stenosis and the foreign matter will cause higher resistance and the perfusate cannot flow through this area smoothly. However, the peak value of the deformation using the constant flow is 26.8 µm, which is much higher than the 16.1 µm achieved using the SPF. Although both methods can flush the foreign matter away, higher deformation may cause damage to the vessel. In addition, the simulation results on different types of the curved vessel with stenosis and foreign matter have similar changes with the model of the straight vessel.
Discussion

There are some similarities among the simulation results of straight vessels. First, the maximum velocity appears at the top of the foreign matter, and the velocity becomes smaller in the area near the vascular wall. Second, the largest deformation occurs in front of the foreign matter, and the deformation is smaller at both ends of the vessel. Third, the peak value of the WS stress appears at the top of the foreign matter. Comparing the SPF and the constant flow, the SPF causes smaller deformation to protect the tissue from damage. In addition, the SPF can clean the vascular wall more thoroughly and prevent the new accumulation of foreign matter. Therefore, the SPF method can provide a better perfusion quality.

According to the simulation result of the curved vessel, the deformation of the SPF method is 37% smaller than that of the constant flow method, which is helps reduce the damage caused by the vascular deformation.

The biggest advantage of the SPF method is that it will not cause the double vortex behind the stenosis and the reflux retention behind the foreign matter. The pulsation of the SPF will cause irregular velocity disturbances, which can destroy the double vortex and the reflux retention area, and then reduce the new accumulation of foreign matter.

Conclusions

In this paper, to solve the problems existing in the current constant flow and swirling flow methods, a new perfusion method called the SPF is proposed, which combines the advantages of constant flow and pulsating flow. Under the same boundary conditions, the vascular deformation of SPF is smaller than that of the traditional constant flow method. The novel SPF method reduces the radial movement of blood vessels, resulting in less flow impact and less damage to the tissues surrounding the vessels. In addition, the SPF can avoid the double vortex and the reflux retention phenomenon, and reduce the new accumulation of foreign matter. Finally, the SPF can flush the vascular wall more thoroughly and smoothly, and improve the perfusion quality remarkably.

References:

1. Vogel T, Brockmann JG, Quagliola A et al: The 24-hour normothermic machine perfusion of discarded human liver grafts. Liver Transpl, 2017; 23(2): 207–20
2. Guan Z, Lv Y: Research progress of improving the quality of the marginal donor liver in liver transplantation. Medical Recapitulate, 2015; 21(4): 671–74
3. Selzner M, Goldaracena N, Echeverri J et al: Normothermic ex vivo liver perfusion using steen solution as perfusate for human liver transplantation: first north American results. Liver Transpl, 2016, 22(11): 1501–8
4. Zhao Y, Chen W. [Research progress of low radiation dose computed tomography perfusion of the liver] Sheng Wu Yi Xue Gong Cheng Xue Za Zhi, 2016; 33(2): 400–4 [in Chinese]
5. Op Den Dries S, Karimnan M, Sutton ME et al: Ex vivo normothermic machine perfusion and viability testing of discarded human donor livers. Am J Transplant, 2013; 13(5): 1327–35
6. Cury RC, Kiih TM, Feheney K et al: A randomized, multicenter, multivendor study of myocardial perfusion imaging with regadenoson CT perfusion vs. single photon emission CT. J Cardiovasc Comput Tomogr, 2015; 9(2): 103–12
7. Gorantla RS, Ahmed S, Voruganti D, Menzies DH: Hypodynamic left ventri- cle on radionuclide myocardial perfusion imaging (RNMI). A marker of diastolic dysfunction in patients presenting with dyspnea on exertion. Int J Cardiol Heart Vasc, 2015; 9(5): 43–47
8. Suszynski TM, Rizzari MD, Scott WE et al: Persufflation (or gaseous oxygen perfusion) as a method of organ preservation. Cryobiology, 2014; 64(3): 125–43
9. Palma RK, Campillo N, Uriarte JI et al: Pressure- and flow-controlled media perfusion differently modify vascular mechanics in lung decellularization. J Mech Behav Biomed Mater, 2013; 10: 37–51
10. Liu, Q, Nassar A, Farlas, K et al: Sanguineous normothermic machine perfusion improves hemodynamics and biliary epithelial regeneration in do- nation after cardiac death porcine livers. Liver Transpl, 2014; 20(6): 987–99
11. Ravikumar R, Levenenik H, Friend PI: Normothermic liver preservation: A new paradigm. Transplant Int, 2015; 28(6): 690–9
12. Vogel T, Brockmann, JG, Coussios C et al: The role of normothermic extra- corporeal perfusion in minimizing ischemia reperfusion injury. Transplant Rev, 2012; 26(2): 156–62
13. Ravikumar R, Jassem W, Mergenthal H et al: Liver transplantation after ex vivo normothermic machine preservation: A phase 1 (first-in-Man) clinical trial. Am J Transplant, 2016; 16(6): 1779–87
14. Bral M, Gala-Lopez B, Bigam D et al: Preliminary single-center canadian experience of human normothermic ex vivo liver perfusion: Results of a clinical trial. Am J Transplant, 2016; 17(4): 1071–80
15. Liu J, Fan Y, Liu Y: Preliminary studies on the dynamic behaviors and mech- anisms of hepatic vessel perfusion with simple vessel models. Journal of Biomedical Engineering, 2016; 33(2): 260–67
16. Han XW, Zhang XD, Wang Y: Short- and long-term outcomes of kidney trans- plants with kidneys lavaged by retrograde perfusion technique. Chronic Dis Transl Med, 2015; 1(3): 163–68
17. George SM, Eckert LM, Martin DR, Giddens DP: Hemodynamics in normal and diseased livers: Application of image-based computational models. Cardiovasc Eng Technol, 2015; 6(1): 80–91
18. Hsu MC, Bazilevis Y: Blood vessel tissue prestress modeling for vascular fluid-structure interaction simulation. Finite Elements in Analysis and Design, 2011; 47(6): 593–99
19. Yang K, Liu W: A novel model of the pulse decay method for measurement of local tissue blood perfusion. Med Eng Phys, 2004; 26(3): 215–23
20. Kinutani H, Shinke T, Nakayama K et al: High perfusion pressure as a pre- dicator of reperfusion pulmonary injury after balloon pulmonary angioplasty for chronic thromboembolic pulmonary hypertension. Int J Cardiol, 2015; 116(1): 1–6
21. He Y, Terry CM, Nguyen C et al: Serial analysis of lumen geometry and hemodynamics in human arteriovenous fistula for hemodialysis using mag- netic resonance imaging and computational fluid dynamics. J Biomech, 2013; 46(1): 165–69
22. Roos MW, Wadbro E, Berggren M: Computational estimation of fluid mechan- ical benefits from a fluid deflector at the distal end of artificial vascular grafts. Comput Biol Med, 2013; 43(2): 164–68
23. Morbiducci U, Ponzini R, Grigioni M: Helical flow as fluid dynamic signa- ture for atherogenesis in aortocoronary bypass A numeric study. J Biomech, 2007; 40(3): 519–34
24. Caro CG, Cheshire NJ, Watkins N: Preliminary comparative study of small amplitude helical and conventional ePTFE arteriovenous shunts in pigs. J R Soc Interface, 2005; 2(3): 261–66
25. Zhan F, Fan YB, Deng XY: Swirling flow created in a glass tube suppressed platelet adhesion to the surface of the tube: its implication in the design of small-caliber arterial grafts. Thromb Res, 2010; 125(5): 413–18
26. Conklin BS, Surowiec SM, Lin PH, Chen CY: A simple physiologic pulsatile perfusion system for the study of intact vascular tissue. Med Eng Phys, 2000; 22(6): 441–49
27. Chen H, Liu Z, Han Y et al: Effects of stent parameters on vascular wall shear stress. Journal of Medical Biomechanics, 2016; 31(1): 8–12
28. Aenis M, Stancampiano AP, Wakhloo AK, Lieber BB: Modeling of flow in a straight stented and nonstented side wall aneurysm model. J Biomech Eng, 1997; 119(2): 206–12
29. Wang FJ: Principles and applications of CFD software. Beijing (China): Tsinghua University Press, 2004
30. Song XG, Cai L, Zhang H: ANSYS Fluid-structure coupling analysis and engineering examples. Beijing (China): China Water & Power Press, 2012
31. Liu DW: Clinical hemodynamics. Beijing (China): People's Medical Publishing House, 2013
32. Liu J, Fan Y, Liu YH, Wang SL: Study on dynamics of the perfusion process of liver blood vessels with defects under the condition of multiple coupling. Journal of Medical Biomechanics, 2016; 31(1): 19–27
33. Rukhlenko OS, Dudchenko OA, Zlobina KE et al: Mathematical modeling of intravascular blood coagulation under wall shear stress. PLoS One, 2015; 10(7): e0134028