Review Article

The application of computational fluid dynamics in hepatic portal vein haemodynamics research: a narrative review

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Background and Objective: The diagnosis and treatment of many liver diseases are related to the assessment of the hepatic portal vein (PV). Noninvasive methods (medical imaging) and invasive methods (hepatic vein catheterization) are commonly used to analyse the haemodynamic information of the PV. In recent years, computational fluid dynamics (CFD) has emerged as a transformative tool in haemodynamics research, revolutionizing the understanding of blood flow behaviour, especially in various artery systems. The purpose of this review is the following: (I) introduce clinicians to CFD as a novel tool and describe its role in PV assessment; and (II) for clinicians and researchers who already use CFD, outline the progress in the application of CFD to the PV.

Methods: The English-language literature published from 1987 (when the first study supporting the study's aim appeared) to 2024 was selected for inclusion in a narrative review.

Key Content and Findings: This narrative review commences with an overview of principles of CFD and methods in PV studies, which involve model establishment, grid partitioning, boundary condition formulation, and error analysis. The focus then shifts to CFD's impact on the examination of the PV under different conditions such as portal hypertension in liver cirrhosis, PV thrombosis, post-transjugular intrahepatic portosystemic shunt (TIPS) procedure, and evaluation of the PV after liver transplantation. Finally, challenges and future directions about the CFD application in PV are outlined.

Conclusions: CFD has potential application value in PV haemodynamics, but of the few studies available, most involve only small samples. Therefore, more research is needed to clarify the feasibility and reliability of this new tool.

Keywords: Computational fluid dynamics (CFD); portal vein (PV); numerical simulation; wall shear stress (WSS)

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Introduction

The portal vein (PV) is one of the major blood vessels supplying the liver, accounting for 75–80% of the liver blood supply (1). The PV transports rich nutrients to the liver, providing energy for liver metabolism and serving as a material foundation for hepatic nutrient metabolism and detoxification. Chronic liver diseases and procedures such as liver resection and transplantation commonly lead to haemodynamic alterations in the PV. For instance, chronic liver disease can increase intrahepatic venous resistance, leading to sinusoidal intrahepatic portal hypertension in severe cases (2,3). After partial hepatectomy or liver transplantation (LT), the blood flow that had previously supplied the entire liver now supplies a reduced volume of liver tissue, resulting in a high-flow state within the liver and subsequent haemodynamic changes in the PV, which may cause liver failure due to ischemia-reperfusion injury (4,5). In clinic, the changes in PV haemodynamics are monitored to inform the diagnosis and treatment of liver diseases.

The principal methods for studying PV haemodynamics include ultrasound (US), computed tomography (CT), magnetic resonance imaging (MRI), and hepatic vein catheterization, the latter of which is used for pressure measurement. Among these, US allows for the observation of PV blood flow direction and the measurement of parameters such as PV diameter, flow velocity, and flow rate (6). It offers the advantages of noninvasiveness, convenience, nonradiation, repeatability, and bedside availability. However, one issue with US is inter- and intraobserver variability. Due to the influence of the imaging principle, sound beam direction, operator experience and equipment conditions, the repeatability and accuracy of flow velocity and rate measurement are controversial to some degree, but can be improved by cooperative training programs (7). CT/MR perfusion imaging techniques can assess hepatic arterial perfusion, PV perfusion, and mean transit time with the contrast agent based on the time-signal intensity curve, providing certain advantages in the evaluation of liver microcirculation and intrahepatic haemodynamics, which have certain value in the measurement of related diseases. Wm *et al.* analysed 41 patients who underwent perfusion CT prior to LT/liver resections and found that perfusion CT can be used to differentiate between liver fibrosis (F3) and liver cirrhosis (F5/F6) via the arterial liver perfusion, portal venous perfusion, and hepatic perfusion indices (8). However, CT exposes patients to radiation while MRI is relatively costly, and other issues such as low time resolution and contrast agent penetrating from blood vessels to tissue spaces can affect the accuracy of measurement. As it pertains to PV pressure measurement, since the PV is located between the digestive system and the liver's capillary bed, direct measurement of portal pressure is not feasible in most cases. Clinically, hepatic vein catheterization is often performed to invasively measure the hepatic venous pressure gradient (the difference between wedge hepatic vein pressure and free hepatic vein pressure) to determine the PV pressure gradient. Thalheimer *et al.* re-evaluated the studies comparing direct PV pressure with hepatic venous pressure gradient, and the results showed that the correlation and consistency were good (9). This method is primarily used in the risk assessment of oesophagogastric variceal bleeding, which is currently considered to be the gold standard diagnosis of sinus portal hypertension. In evaluating the haemodynamics of PV, the parameters provided by traditional imaging methods are limited, and hepatic vein catheterization entails a high degree of risk; therefore, they cannot meet the need for in-depth study. Thus, there is a clear need to develop novel noninvasive diagnostic methods that can provide more effective parameters.

With the increasing exchange of knowledge between different disciplines in recent years, computational fluid dynamics (CFD) has emerged as a novel tool for evaluating haemodynamics. CFD can simulate the complex flow that conventional experiments cannot and obtain a greater number of parameters in a noninvasive manner, which may help clarify the mechanism of disease and solve clinical challenges.

This narrative review aims to introduce CFD as a novel tool and describe its capabilities to clinicians involved in PV evaluation and to outline the progress in its application to the PV for researchers already familiar with CFD. Therefore, in this narrative review, we first introduce CFD, which has certain application value in haemodynamic research, by explaining the principle and method so that clinicians can better understand this technique. Moreover, we characterize the status of CFD in PV and we identify various challenges and prospects. This article is presented in accordance with the Narrative Review reporting checklist (available at https://qims.amegroups.com/article/view/10.21037/qims-24-1593/rc).

Table 1 Summary of the search strategy

Items	Specification
Date of search	July 12, 2023, to May 1, 2024
Databases and other sources searched	PubMed; Lin P. Numerical Modeling of Water Waves, 2008.
Search terms used	The details of search terms in PubMed are presented in Table 2
Timeframe	1987 to 2024
Inclusion and exclusion criteria	Inclusion criteria: review or research articles in English
	Exclusion criteria: full text not available, not related to CFD or PV, or other references expressing the same point
Selection process	The selection process was conducted independently by X.W., and consensus was achieved with the involvement of L.M. and H.X. when necessary

CFD, computational fluid dynamics; PV, portal vein.

Methods

The English-language literature published from 1987 (when the first literature supporting the study's aim appeared) to 2024 was selected for inclusion in a narrative review (*Tables 1*,*2*).

Narrative review

CFD

Overview

CFD is an emerging discipline based on the intersection of various disciplines, including fluid mechanics, computer science, computational geometry, and numerical analysis. CFD primarily utilizes numerical methods implemented via computers to solve mathematical equations that describe fluid flow. It quantitatively describes physical quantities within the flow field in both time and space, thereby revealing the physical characteristics of the fluid. In recent years, with the advances in (bio)medical imaging and (parallel) computational resources, as well as increased confidence regarding the capabilities of numerical simulation methods, researchers have been using CFD numerical simulations as a precise tool for studying biological processes. The application of CFD in scientific research has rapidly expanded, and interdisciplinary collaborations between academia and industry have propelled the development and progress in the field. The numerical simulations derived from engineering have evolved into powerful tools for biomedical scientists conducting scientific research. CFD is being increasingly applied in the study of vascular systems and plays a critical role in investigating the effect of haemodynamics on disease occurrence, development, treatment, and prognosis, especially in artery systems such as the coronary, cerebral, and hepatic arteries (10-12). Unlike traditional haemodynamic evaluations, CFD allows for the study of complex blood flow problems through flow simulations from the macroscale to the microscale (13). Based on CFD numerical simulation methods, model parameters can be modified using mathematical techniques to achieve specific objectives. Furthermore, with the advancement of experimental fluid mechanics techniques, the modelling results of CFD can be validated through techniques such as particle image velocimetry, thereby further enhancing the reliability of CFD. Important haemodynamic parameters that are not easily obtained through conventional physical experiments, such as pressure distribution, wall shear stress (WSS), blood flow impact force, oscillatory shear force, and wall particle residence time, can all be quantitatively and noninvasively assessed through CFD numerical simulations, and some of these have been proven to be related to pathology (14). This can provide more comprehensive and accurate haemodynamic information for the diagnosis and treatment of clinical diseases and may allow for the prediction of disease progression.

Application principles of CFD in haemodynamics research

Fluid identification

Newtonian fluid refers to a fluid with constant viscosity, which can include pure liquids, low-molecular-weight compound solutions, and low-speed flowing gases, while

Table 2 The search terms used in PubMed

Section	Search terms
Introduction	("hepatic" or "liver") AND "medical imaging" AND ("PV" or "portal") AND ("haemodynamics" or "hemodynamics" or "hemodynamic" or "haemodynamic")
	("hepatic" or "liver") AND "medical imaging" AND ("cirrhosis" or "hypertension")
	("hepatic" or "liver") AND ("US" or "ultrasound" or "ultrasonography" or "doppler" or "sonography") AND ("PV" or "portal") AND ("haemodynamics" or "hemodynamics" or "hemodynamic" or "haemodynamic")
	("hepatic" or "liver") AND ("CT" or "computed tomography") AND ("PV" or "portal") AND ("haemodynamics" or "hemodynamics" or "hemodynamic" or "haemodynamic")
	("hepatic" or "liver") AND ("MRI" or "MR" or "magnetic resonance imaging") AND ("PV" or "portal") AND ("haemodynamics" or "hemodynamics" or "hemodynamic" or "haemodynamic")
Computational fluid dynamics	("CFD" or "computational fluid dynamics") AND "Newtonian" AND ("blood" or "arterial" or "artery" or "vein" or "venous")
	("CFD" or "computational fluid dynamics") AND "simulation" AND ("blood" or "arterial" or "artery" or "vein" or "venous")
	("CFD" or "computational fluid dynamics") AND ("medical imaging" or "imaging") AND ("blood" or "arterial" or "artery" or "vein" or "venous")
Application of CFD in PV research	("CFD" or "computational fluid dynamics") AND ("PV" or "portal")
	("WSS" or "wall shear stress") AND ("PV" or "portal")
	("CFD" or "computational fluid dynamics") AND ("LT" or "liver transplantation")
	("CFD" or "computational fluid dynamics") AND ("TIPS" or "transjugular intrahepatic portosystemic shunt")

PV, portal vein; US, ultrasound; CT, computed tomography; MRI, magnetic resonance imaging; CFD, computational fluid dynamics; WSS, wall shear stress; LT, liver transplantation; TIPS, transjugular intrahepatic portosystemic shunt.

the viscosity of non-Newtonian fluid can change. Human blood is a rather unique fluid, consisting of plasma and various blood cells, and in many studies, it has been treated as a Newtonian fluid (15,16). However, it has been claimed that blood has non-Newtonian characteristics, such as yield stress, viscoelasticity, thixotropy, and shear thinning, and thus should be treated as a non-Newtonian fluid (17,18). Some researchers have compared the differences between Newtonian and non-Newtonian fluid models using two fluid identification methods in arterial models under most physiological conditions, with the results indicating no significant differences in haemodynamic parameters. However, in some cases, such as within arterial aneurysms or at sites narrowed by atherosclerosis, the non-Newtonian characteristics of blood can be amplified (19,20). There are now numerous non-Newtonian blood models available, such as the Quemada (21), Cross (22), Casson (23), power-law (24), and Carreau-Yasuda (25,26) models. Among these, the power-law model fails to adequately describe the viscosity of large amounts of non-Newtonian fluid at very low and very high shear rates, which is a notable drawback of the model. The Quemada model is primarily used to simulate microcirculation in small arteries and capillaries. The Carreau-Yasuda model has been widely employed in the simulation of blood flow in narrowed arteries and has been shown capable of generally representing shear-thinning behaviour, with consistent predictive results under specific shear rates as compared to other models, including the Cross and Casson. Ho *et al.* (27) constructed PV models of different states based on CT images and analysed them using both Newtonian and non-Newtonian fluid models. The results indicated that there was no significant difference in the calculation results between the two fluid models under physiological conditions, except for a significant decrease in the PV rate.

In addition, clinical studies have shown that the solid matter (blood cells) in blood has a certain impact on the evaluation of local vascular lesions (28). Therefore, some scholars regard blood as a liquid (serum)-solid (blood cells) two-phase fluid (20,29). The current CFD research on PV mostly focuses on the overall characteristics of local flow field, ignoring the interaction between blood

cells and plasma, and thus adopts a single-phase flow model (16,30,31).

Mathematical equations

Flow refers to the motion of fluids, which is a complicated process, and thus the mathematical equations that describe fluid flow are also highly complex. Eqs. [1,2] are continuity and momentum equations, respectively, that are both suitable for the Newtonian and non-Newtonian fluid models:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad [1]$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \rho}{\partial x_i} + g_i + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} \quad [2]$$

where ρ is the fluid density, u_i is the fluid velocity in i-th direction, p is the pressure, g_i is the gravitational acceleration in i-th direction, and τ_{ij} is the second-order viscous stress tensor (32).

In solving the equation, besides the basic flow model, we also need to know the blood flow state in human vessels. For real fluids, viscosity and fluid inertia play a role in the motion properties, which can be characterized by the Reynolds number. When the Reynolds numbers is higher than 2,320, the turbulence occurs in the laminar flow, and turbulence models, such as the k-ε model and k-ω model, are needed (33). The blood flow velocity is relatively low with small Reynolds numbers in the PV, which is suitable for a laminar flow model and for which a turbulence model is unnecessary.

Wall motion and fluid-structure interaction (FSI)

The elasticity modulus and motion of blood vessels wall also exert an impact on the haemodynamic parameters and CFD simulation results. Compared to a rigid wall, a FSI should be considered in the elastic wall model, which markedly increases the workload and complexity, especially as the applied technology is not yet mature. Large elastic arteries such as the aorta, iliac arteries, and carotid arteries undergo expansion and contraction throughout the cardiac cycle, which poses a problem for the rigid wall model. Lopes *et al.* (34) compared the differences between rigid and elastic wall models in carotid artery flow and found that the rigid wall model overestimated the flow velocity and WSS compared to the elastic wall model. Given this situation, coupling FSI can be adopted, which is a method that allows for the simultaneous simulation of blood flow and arterial wall deformation (35). Although the coupled FSI technique can better capture physiological flows, it requires assumptions regarding the characteristics of the blood vessel and has higher computational demands as compared to traditional CFD methods. Some studies have demonstrated that assuming uniform wall thickness and geometric simplification can greatly alter vascular strain, both of which can have adverse effects on FSI simulations (10,36,37). Moreover, the resistance-compliance-resistance (RCR) model (also known as the three-element Windkessel model) is another applicable method and uses an electric circuit analogue to simulate arterial system elastic cavity (38). Liu *et al.* used CFD to calculate a new haemodynamic parameter (partial pressure ratio) and confirmed its reliability by comparing its results with those of invasive detection, using the RCR model to simulate the elasticity of arterial system wall (39). As for the PV, which shows a relatively low velocity and little change in flow rate, it is generally not necessary to consider the influence of wall motion and FSI.

Methods of CFD in haemodynamics research

A complete CFD research process typically includes the following four steps:

(I) Constructing a reverse three-dimensional flow geometry model based on geometric parameters or other imaging information;
(II) Selecting a strategy for volumetric meshing and generating the corresponding mesh model;
(III) Setting boundary conditions, determining solution control parameters, and discretizing equations based on the physiological characteristics of the fluid under investigation and assumptions about its motion;
(IV) Evaluating the rationality and accuracy of the numerical computation method through visual analysis of the flow field and consideration of the actual physical model's flow state.

Geometry

The construction of three-dimensional geometric models of blood vessels can be primarily classified into two methods. One method involves using modelling software to construct an ideal blood vessel model based on existing clinical experimental data. This approach offers the advantage of the easy adjustment and modification of various parameters of the ideal model, rendering it convenient for studying specific variations in flow characteristics, such as thrombus formation or stent placement (40). Initially, numerical simulations of blood flow in the PV were achieved through simplification of three-dimensional models. In this preliminary research, Petkova *et al.* (41) simplified the PV

into a symmetrical three-dimensional simple model and examined PV blood flow in the presence of thrombosis. However, this assumption is clearly unrealistic, as the diameters of the PV branches on the left and right sides differ significantly. Another other method uses imaging software to extract real images obtained from noninvasive vascular imaging techniques, such as X-ray angiography, MRI, CT, optical coherence tomography, and US. The advantages of X-ray angiography are the superior contrast-to-noise ratio, and high spatiotemporal resolution; however, this method involves limitations in the vessel wall measurement, a high risk from invasive catheterization, radiation exposure, and a risk of allergy to contrast agents. CT can noninvasively provide high-resolution images of blood vessels via radiation exposure. Meanwhile, MRI is able to discern between the intravascular region and the wall and can be considered the most effective technique for three-dimensional reconstruction if the expenditure in time and cost can be ignored (11). As for US, intravascular US, in combination with other imaging techniques, can be used for three-dimensional reconstruction, but only in patients already requiring cardiac catheterization and in animal models (42). Three-dimensional extravascular US can be used as an alternative to MRI and CT for superficial vessels (43). Meanwhile, optical coherence tomography is an intravascular imaging technology that is similar to intravascular US and is used in the same fields but can further provide more detailed information (44).

Overall, because PV is a deep blood vessel, it is better examined via CT or MRI. This process involves obtaining the imaging data of the target blood vessel and completion of pretreatment. Subsequently, the region of interest is identified and selected from the images and is then followed by tissue segmentation, slice reconstruction, and interpolation to generate spatial voxel parameters. Finally, the reconstructed three-dimensional model is displayed using computer software programs (*Figure 1*). Various commercial or open-source software programs, such as Amira, Geomagic, Mimics, Polydata, ScanIP, Avizo, and Parasolid, can be used for three-dimensional model construction and rendering via surface or volume triangulation methods. Unlike direct parameter-based modelling, this image-based approach provides a more realistic representation of the three-dimensional geometric parameters of human blood vessels (45,46). Botar *et al.* (47-49) reconstructed a three-dimensional model of the PV based on MRI images and used CFD software to calculate the flow parameters of blood in the model. The results showed a high degree of agreement with US measurements. Subsequently, the same group of researchers investigated the differences in haemodynamic parameters such as blood flow velocity, static pressure distribution, and wall shear force distribution inside the PV under rigid and elastic conditions. This study provided a reference for subsequent CFD applications in the PV.

Strategy for grid or mesh

In CFD computations, the grid or mesh serves as the geometric representation of the CFD model and acts as the medium for simulation calculations. The task of discretizing the grid is to generate appropriate grids based on the complex flow regions to correctly capture various meaningful flow phenomena. The quality of grid partitioning directly affects the convergence of numerical calculations and the accuracy of computational results. Volume grids typically employ structured, unstructured, and hybrid grid generation, and the cell is the basic element, consisting of tetrahedral, hexahedral, or polyhedral elements in the three-dimensional volume grid. Structured grids have the same number of neighbouring elements around each internal node, while unstructured grids allow for varying numbers of neighbouring elements. Considering the flow of vessels at different lengths and scales, vascular CFD models often employ unstructured tetrahedral element grid formats for partitioning. Tetrahedral elements are easy to refine but require larger computational resources and introduce artificial noise. On the other hand, polyhedral or hexahedral formats allow for the use of thinner grids, reducing the demand for computational resources and overcoming the inherent limitations of a single grid style (50,51). In the grid selection of PV model, given the difference and resolution in the wall boundary layer, the use of a mixed grid may be a good choice; for example, a hexahedral cell grid can be used near the blood vessel wall to better fit the wall and capture more subtle blood flow changes, while a tetrahedral cell grid can be used inside the blood vessel (*Figure 2*).

Boundary condition

The proper selection of boundary conditions is crucial in CFD numerical simulations of haemodynamics and represents the physiological flow in blood vessels. The setting of inlet and outlet boundary conditions primarily relies on the physiological pulsatile flow velocity and pressure in the blood vessels (52). The setting of inlet conditions with velocity can be measured using spectral doppler US or phase-contrast MRI (PC-MRI) *in vivo* imaging techniques. Spectral doppler US provides information on blood flow characteristics through different

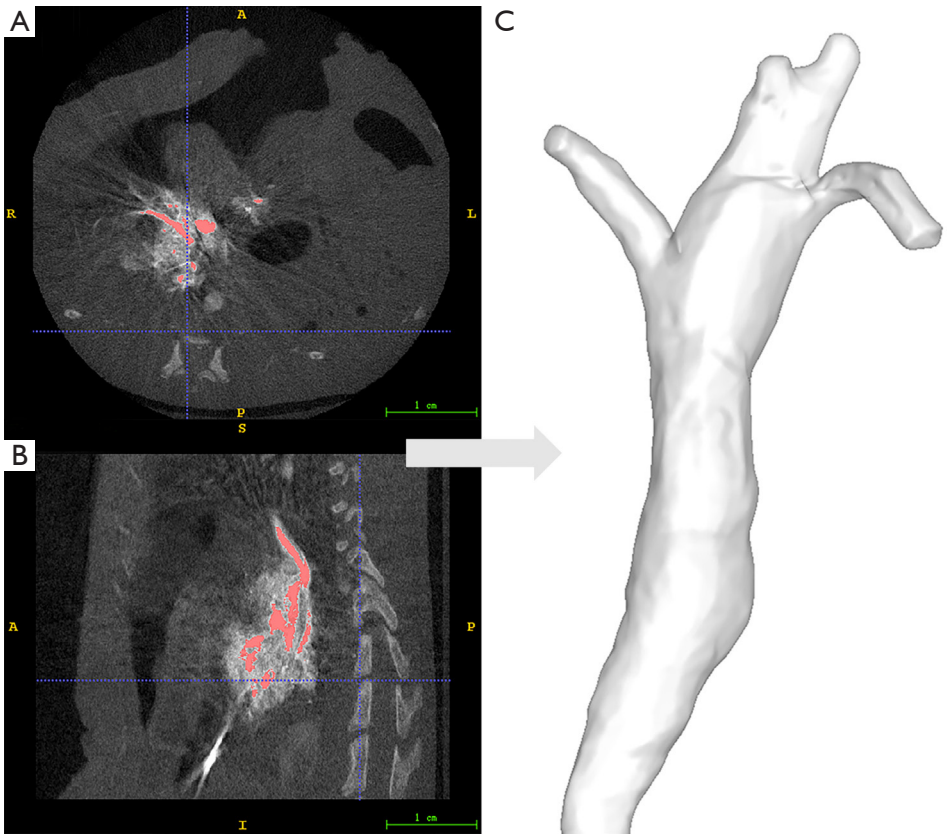

Figure 1 The PV images of Sprague-Dawley rats after 70% partial hepatectomy extracted using enhanced CT (A,B) and reconstructed into a three-dimensional model (C). PV, portal vein; CT, computed tomography.

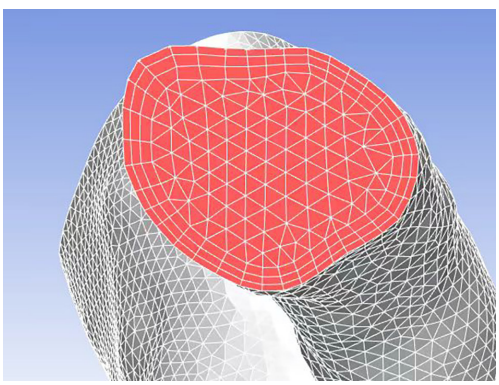

Figure 2 An example of the grid partitioning in tetrahedral and hexahedral elements.

waveforms, which can be useful for the setting of boundary conditions. However, spectral doppler US is subject to considerable subjective factors, such as sampling position, sampling volume, and angle correction, which can lead to inaccurate measurements of blood flow waveforms and velocities. PC-MRI can provide two-dimensional and three-dimensional flow profiles, offering more inflow information, but it has lower temporal resolution and longer acquisition times. Comparisons between the numerical simulations of spectral US and PC-MRI show overall good agreement, despite subtle differences (e.g., US tends to overestimate total flow). Pressure parameters are less commonly used in inlet condition settings because precise and local pressure measurements ideally require invasive measurements through catheters, which are challenging to obtain, particularly in small vessels. The outlet boundary conditions with velocity can also be specified based on measurements from US and PC-MRI. However, acquiring waveform data for all outlet boundaries in complex vascular models is challenging and time-intensive, requiring the consideration of characteristics related to the microcirculation network (53). Therefore, many studies use generalized boundary conditions described in the literature, Murray's law, or pressure and lumped parameter models rather than using specific individual boundary conditions (54,55). As for

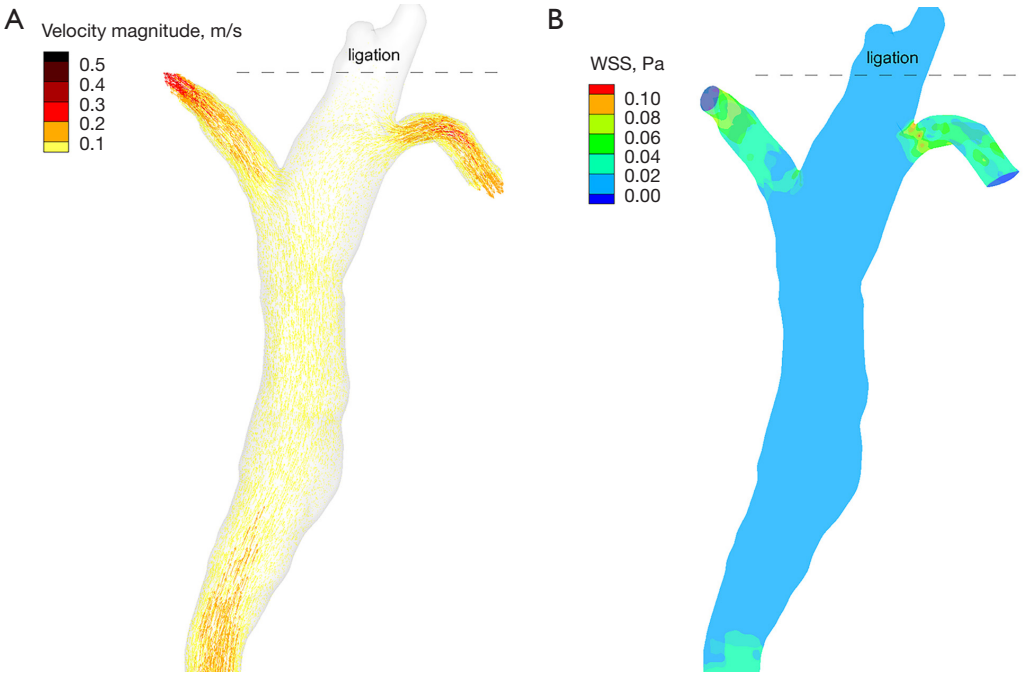

Figure 3 Velocity vector fields formed after the numerical simulation (A) and additional haemodynamic indices such as postprocess WSS (B). WSS, wall shear stress.

the PV, because the number of CFD studies on the PV is relatively small, the setting of inlet boundary conditions has primarily been based on US while that of outlet boundary conditions has relied on previous studies. The setting of boundary conditions directly impacts the accuracy of numerical simulation results, and thus efforts to improve it may be worthwhile.

Error analysis

The primary result of numerical simulation is the characterization of velocity vector fields, while other haemodynamic data can be obtained through postprocessing (*Figure 3*). It must be stressed, however, that there are four common errors in CFD. First, due to different influencing factors in geometry, governing equations, and boundary conditions, modelling error can be produced. A model only applies to specific cases and may be particularly limited for vessels with turbulent flow. In contrast, the PV is a vessel with laminar flow, so it is necessary to ascertain the error generated from geometry and boundary conditions. Regarding geometry, the selection of ideal models can introduce errors between this simple model and the real human blood vessels. The other method is to extract the image information from a real human body for modelling via imaging techniques. At present, CT and MRI are widely used, which can provide high-precision image information, but errors due to the influence of resolution are inevitable. The second error is discretization error, and using a grid with different sizes in one case can improve reliability. For example, the hexahedral cell grid can be used near the PV wall to ensure that it can better capture the blood flow-related parameters in the boundary layer, with the tetrahedral cell grid being used inside the PV. Other errors related to the arterial system, including, round-off error and iterative error, should not be ignored and can be minimized through use of the double precision and quite strict iterative convergence criteria (56). Because the blood flow in the PV is laminar and has a relatively low velocity, simple precision is sufficient for this type of study, and further improvement to accuracy provides no additional medical benefit.

Application of CFD in PV research

Current status of PV haemodynamics assessment

Currently, CFD technology is widely used in the research of various vascular problems, with a focus on diseases involving arterial vessels such as the cerebral arteries, carotid arteries, coronary arteries, abdominal arteries, and hepatic arteries. Through CFD numerical simulations,

Figure 4 An example of the RCR model as outlet boundary condition. RCR, resistance-compliance-resistance.

a deeper understanding of haemodynamic changes in diseases such as atherosclerosis, arterial stenosis, and arterial aneurysms can be achieved. This has important implications for assessing the condition, selecting treatment methods, and evaluating prognosis; for instance, CFD has been used in the noninvasive evaluation of intracranial artery stenosis (57), prognostic evaluation after vertebral artery stenting (58), the clarification of the relationship between coronary vulnerable plaque and WSS (59), the determination of the correlation between the abdominal aortic aneurysm parameters from CFD and rupture (60), and the creation of a liver cancer arterial perfusion model (61). The application of CFD technology in the PV has been relatively limited, perhaps due to the following two reasons: (I) the accuracy of CFD simulations heavily relies on the precise reconstruction of vascular anatomy models and the measurements of inflow velocities. However, obtaining the anatomical structure of hepatic veins and the PV is challenging. The complex structure of the hepatic vasculature and the PV requires comprehensive consideration of feedback from the capillary network outside the PV and vascular compliance. Under the currently available imaging technology such as CT, the distal small branches of PV are indistinguishable from the surrounding soft tissue. The RCR model may be effective in overcoming this problem as it does not to reflect the elastic influence of blood vessel wall but rather indirectly reflects the resistance of distal vascular network by regarding the branches below the secondary branch as resistors (*Figure 4*). (II) The other reason is that there are few CFD studies on the PV, and the boundary conditions that can be used as a reference are limited, which has a considerable influence on the results.

Application of CFD in the study of PV diseases

Portal hypertension in liver cirrhosis

Portal hypertension is a common complication of liver cirrhosis and can lead to gastroesophageal varices, ascites, splenomegaly, abdominal wall varices, and hepatic encephalopathy (62). Severe portal hypertension is the primary cause of death in patients with liver cirrhosis. According to Ohm's law ($\Delta P = Q \times R$, where ΔP is the portal pressure difference, Q is the blood flow rate, and R is the blood flow resistance), vascular changes play an important role in the occurrence and development of portal hypertension. The pathological process from chronic liver disease to liver cirrhosis is accompanied by structural changes in the liver microvascular system, including hepatic sinusoidal reconstruction, intrahepatic shunting formation, and endothelial dysfunction, leading to increased intrahepatic resistance (2). This is the initiating factor for elevated portal pressure in patients with liver cirrhosis. Furthermore, in chronic liver disease, splanchnic vasodilatation (hyperdynamic circulation) further increases portal pressure, which is a result of the elevated production of vasodilator substances and a reduced response to vasoconstrictor substances (63,64). In advanced liver cirrhosis, high-intensity portal hypertension (characterized by high dynamic splanchnic and systemic circulation) can lead to the formation of portosystemic collateral circulation and other complications. Patients with liver cirrhosis may experience a decrease in average PV blood flow velocity and even partial or total blood flow reversal and thrombus formation.

The hepatic venous pressure gradient is the gold standard evaluation of sinus portal hypertension in patients with liver cirrhosis, but it is an invasive procedure with certain operational risks. Several noninvasive imaging technique-based parameters are used to measure portal pressure, including vessel size and velocity of PV; however, these cannot fully meet the needs of clinical and scientific research, and thus novel CFD parameters are being tested. Combining three-dimensional reconstruction of CT images with CFD, Wang *et al.* proposed a flow resistance parameter that indirectly reflects portal pressure (65). The results showed higher sensitivity of this parameter as compared to that of commonly used vessel size measurements. Qiu *et al.* (66) treated the liver as a porous medium and reconstructed a specific computational model based on CT images, incorporating US technology to determine boundary conditions. Under this model, the portal pressure calculated was highly consistent with clinical measurement data, demonstrating the potential of using noninvasive CFD for the measurement portal pressure. However, the applicability and stability of this method, along with the individualized porous media parameters, need to be determined in further research that involves a larger sample of patients with portal hypertension.

The portal system is primarily formed by the confluence

of the superior mesenteric vein (SMV) and splenic vein (SV), which then divides into the left and right branches of the PV, in turn entering the left lobe and right lobe of the liver, respectively. Patients with late-stage liver cirrhosis often exhibit atrophy of the right liver lobe and hypertrophy of the left liver lobe, which may be related to the redistribution of blood flow, yet this is difficult to confirm through *in vivo* experiments. Li *et al.* (67) used CFD to establish ideal and patient-specific models for healthy controls and patients with liver cirrhosis. They calculated the changes in the diameters of the PV, SMV, and SV, along with the inflow velocities of the SV and SMV, resulting in substantial alterations in the mass fraction of spleen-derived blood flow to the left and right liver lobes. The results indicated that the distribution of blood in the SV and SMV differed in patients with portal hypertension, markedly affecting the atrophy of the right liver lobe and hypertrophy of the left liver lobe; this supports the hypothesis that liver volume is related to the blood distribution from the SV, which carries hepatic nutritional factors from the spleen and pancreas. George *et al.* (68) simulated portal hypertension using MRI and CFD technology, proposing several haemodynamic parameters that can reflect the distribution of hepatic blood flow, such as the flow ratio of the SV to PV. In this regard, they found significant differences between patients with liver cirrhosis and healthy individuals. Additionally, the study revealed that in patients with liver cirrhosis, the proportion of blood supply to the liver from the SMV was less than that in healthy individuals, possibly due to different pressures and nutrient contents in the SV and SMV.

In recent years, WSS in blood vessels has received widespread attention in haemodynamics research due to its substantial impact on the functionality of endothelial cells and the development of vascular diseases (69). According to reports, WSS is generally higher in the arterial system than in the venous system, and different locations within arteries exhibit variations in WSS (70-72). Recent findings indicate that the sites susceptible to atherosclerotic plaque development in arteries often coincide with regions of low WSS (73-75).

Therefore, to examine WSS in the PV during portal hypertension in patients with liver cirrhosis, some researchers created patient-specific CFD models based on enhanced CT images, treating blood as a Newtonian fluid and vessels as rigid walls, to simulate the changes and distribution of WSS in the PV during portal hypertension (76). The results demonstrated a significant reduction in PV WSS during portal hypertension. Different PV-SV angles and SMV-SV angles had varying effects on WSS magnitude and distribution, with low WSS regions often observed in smaller PV-SV angles and larger SMV-SV angles. Low WSS was commonly found in healthy individuals in the region where the SV meets the SMV, where the PV is divided into left and right branches, and in the outer wall area of the SV. It was also found that under oscillatory and low WSS conditions, endothelial cells exhibit a proinflammatory phenotype, increased procoagulant and adhesive properties, and reduced nitric oxide production (73,77). Endothelial dysfunction plays an important role in initiating the increase in intrahepatic vascular resistance during the development of portal hypertension. Additionally, hepatic sinusoidal endothelial cells exhibit a low-activity phenotype, characterized by reduced nitric oxide production (78). The appearance of low-WSS regions during portal hypertension may be related to endothelial cell dysfunction. However, it is still unclear how abnormal WSS in the PV affects endothelial dysfunction and whether dysfunctional endothelial cells play a significant role in other PV diseases such as thrombosis.

PV thrombosis

PV thrombosis is mainly caused by endothelial damage in the PV, coagulation disorders, increased blood viscosity, and blood stasis, while PV thrombosis caused by other reasons, such as acute pancreatitis and biliary infection, is relatively rare (79). In cases of portal hypertension caused by liver cirrhosis, endothelial cell dysfunction and slow portal blood flow are present. Additionally, decreased liver synthetic function leads to hypoalbuminaemia, causing plasma fluid to extravasate, blood to become hypercoagulable, and thus PV thrombosis more likely to occur. When hypersplenism occurs in patients with portal hypertension, splenectomy is an effective treatment, but postoperative PV thrombosis is one of its major complications, with an incidence rate of 18.3–30.1% (80,81). Slow blood flow in the blind end of the SV after splenectomy can easily lead to SV thrombosis; meanwhile, surgery can cause local vascular endothelial damage, activate the coagulation system, and promote thrombus formation (82). The formation of PV thrombosis leads to reduced blood supply to the liver, further exacerbating the deficiency of nutrients supplied to the liver and worsening its metabolic function and aggravating portal hypertension.

The formation of PV thrombosis can trigger a series of haemodynamic changes. The application of CFD technology to the study of haemodynamics-

related thrombus formation can help us gain a deeper understanding of its pathogenesis and progression. Some researchers have simulated blood flow in the PV in liver diseases under two conditions: without thrombus formation and with thrombus formation. They found important differences between the two models. Even under unchanged blood flow conditions, PV thrombosis can affect parameters such as blood flow velocity, blood viscosity coefficient, and WSS (83). Aktar *et al.* (40) established an ideal model with varying degrees of luminal narrowing caused by extrahepatic PV thrombosis (0%, 40%, and 85%). The study used CFD to calculate the haemodynamic parameters of different thrombus models, with an inlet velocity of 20 cm/s and an outlet pressure of 2,731.1 Pascal as boundary conditions. The results demonstrated that different degrees of PV thrombosis led to changes in haemodynamic parameters (such as flow velocity, pressure, resistance, and WSS) and even affected the flow distribution in the PV branches. Additionally, thrombosis in the main PV could decrease the flow in intrahepatic branches, potentially triggering new thrombus formation and causing morphological abnormalities in the liver. Xiong *et al.* (84) developed an ideal model of the PV combined with thrombosis and compared the risk of thrombus formation induced by different anatomical characteristics of the main branch veins in the PV using CFD. They found that the anatomical structure of the left gastric vein, the inferior mesenteric vein, and the angle of PV-SV had a strong correlation with thrombus formation.

Evaluation of transjugular intrahepatic portosystemic shunt (TIPS) placement

TIPS is an effective measure for treating complications of portal hypertension, including oesophageal variceal bleeding, refractory ascites in cirrhosis, hepatic hydrothorax, hepatorenal and hepatopulmonary syndrome, Budd-Chiari syndrome, and venous occlusive diseases (85). The TIPS procedure is a percutaneous image-guided surgery that creates a channel between the inside of the PV and the systemic venous system. The purpose is to decompress the PV, with the most common approach being the placement of a stent between the right hepatic vein and the PV. In more than 90% of cases, the TIPS procedure successfully reduces the portal pressure gradient. However, in the reduction of portal hypertension, it is also necessary to ensure liver perfusion and avoid the occurrence of hepatic encephalopathy (86). Furthermore, the specific selection of the shunt location, the diameter of the stent, and the evaluation afforded by different approaches in the post-TIPS period remain key research directions. Due to the limitations of traditional haemodynamic measurements, research on TIPS haemodynamics based on CFD numerical simulation techniques can facilitate the achievement of precision and personalized treatment in TIPS surgery. Using CT images, Yin *et al.* constructed three-dimensional geometric models of patients before and after the TIPS procedure and then simulated the changes in haemodynamics caused by different stent placements in TIPS surgery using CFD (87). The results showed that although there were subtle differences in the effects of left and right TIPS on post-TIPS portal pressure and shunt flow, compared to left TIPS, right TIPS resulted in a higher flow from the SMV into the stent, increasing the risk of hepatic encephalopathy. Additionally, the entry point of the stent should be as close as possible to the PV bifurcation to achieve a larger and more stable blood flow.

Evaluation of PV after LT

LT is an effective treatment for end-stage liver disease and is widely performed worldwide. Although advancements in surgical techniques and the use of new immunosuppressive therapies have improved the prognosis of liver transplant recipients, postoperative vascular complications remain a serious threat. Portal vein stenosis (PVS) is one of the common complications after LT. In its early stages, PVS may be overlooked due to a lack of specific clinical manifestations, but it can progress to thrombosis, leading to graft failure or even patient death. Timely intervention for high-risk PVS, including balloon dilation or stent placement, markedly reduces the occurrence of adverse outcomes. Therefore, the early diagnosis and intervention of PVS after LT are particularly critical (88,89).

The diagnosis of PVS primarily relies on imaging techniques, with invasive digital subtraction angiography being the gold standard, while conventional methods such as US, CT, and MRI have limited diagnostic capabilities (90). Ogiso *et al.* (30) attempted to use CFD to analyse the haemodynamics of the PV in the management of PVS after LT. They created a three-dimensional CT model, set boundary conditions using US, and finally simulated PV blood flow using fluid analysis software (Software Cradle, Japan). In their research, new abnormal parameters were found by CFD in the early stage when CT and US could not diagnose PVS, and PVS did appear in the patient 6 months after LT. However, in the future, it is necessary to expand the sample size and compare CFD with traditional evaluation tools in detail to further validate the specific advantages of CFD, such as earlier diagnosis or

more timely surgical intervention.

In addition to PVS, intractable ascites after transplantation is also a critical complication that affects the prognosis of LT recipients, and it is more commonly seen in patients who undergo left lobe LT than in those who undergo right lobe LT. Currently, there is no explanation for this difference. Qu *et al.* (91) used CFD based on CT images and finite element theory to establish a PV model of the transplanted liver under different flow rates in 56 patients with LT and compared it with the volume of ascites. The results showed that the portal pressure-velocity curve in patients with a left lobe transplant was significantly higher than that in patients with a right lobe transplant, along with greater intraluminal swirling flow in the left lobe. This study provides some explanation for this phenomenon and offers a new perspective for clinical practice.

Challenges and future directions

In the current medical field, CFD is mainly applied in manufacturing and basic medical research. Manufacturers use CFD to further improve the quality of their existing medical products and prepare for the development of new products. Meanwhile, medical researchers employ CFD purpose to obtain a greater variety of parameters. However, in the future, we can foresee the emergence of a third user group, clinicians, whose demand for CFD may differ from that of the first two groups. This will have a certain impact on the future development direction of CFD technology.

First, in the model extraction, if the distal small branches of PV can be reconstructed, the accuracy of the model can be directly improved. Although the accuracy can be improved by the development of imaging technology, the time and other costs required may also increase and should be considered in conjunction with the clinical effect.

The second challenge is the flow measurement for the determination of boundary conditions. As for PV, there should be more research on the setting of boundary condition. Moreover, with the participation of clinicians, a greater number and complexity of cases will appear in CFD research, which will bring attention to other influencing factors in the determination of boundary conditions, and perhaps additional boundary condition models similar to RCR will be developed.

The third challenge is the direction of research. At present, there are some limitations in the predictive research of CFD for specific liver diseases, including the time-consuming nature, small sample size, and occasional ethical issues. Perhaps, these challenges will be overcome to some extent in the future, and this types of research will be further developed.

The fourth challenge is the promotion of technology. Clinicians' use of CFD is completely interdisciplinary, so it is necessary to train them in the future. They need to become familiar with the principle, method, and application scope of this technology.

Conclusions

CFD is a novel, noninvasive tool and has been applied in various fields. Studies on PV haemodynamics have suggested its potential application value, which mainly involves evaluation of portal hypertension in liver cirrhosis, portal system thrombosis, conditions post-TIPS procedure, and the portal system after LT. However, the number of related studies is small, with only sample sizes being used. Therefore, to benefit doctors, patients, and other CFD users in the future, more studies, including multicentre, clinical trials, are urgently needed to verify the feasibility and reliability of CFD.

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Footnote

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References

1. Lautt WW. Hepatic Circulation: Physiology and Pathophysiology. San Rafael (CA): Morgan & Claypool Life Sciences; 2009.
2. Hess PR, Bunch SE. Management of portal hypertension and its consequences. Vet Clin North Am Small Anim Pract 1995;25:461-83.
3. Favier RP. Idiopathic hepatitis and cirrhosis in dogs. Vet Clin North Am Small Anim Pract 2009;39:481-8.
4. van den Broek MA, Olde Damink SW, Dejong CH, Lang H, Malagó M, Jalan R, Saner FH. Liver failure after partial hepatic resection: definition, pathophysiology, risk factors and treatment. Liver Int 2008;28:767-80.
5. Gonzalez HD, Liu ZW, Cashman S, Fusai GK. Small for size syndrome following living donor and split liver transplantation. World J Gastrointest Surg 2010;2:389-94.
6. Kok T, van der Jagt EJ, Haagsma EB, Bijleveld CM, Jansen PL, Boeve WJ. The value of Doppler ultrasound in cirrhosis and portal hypertension. Scand J Gastroenterol Suppl 1999;230:82-8.
7. Nelson RC, Lovett KE, Chezmar JL, Moyers JH, Torres WE, Murphy FB, Bernardino ME. Comparison of pulsed Doppler sonography and angiography in patients with portal hypertension. AJR Am J Roentgenol 1987;149:77-81.
8. Thaiss WM, Sannwald L, Kloth C, Ekert K, Hepp T, Bösmüller H, Klag T, Nikolaou K, Horger M, Kaufmann S. Quantification of Hemodynamic Changes in Chronic Liver Disease: Correlation of Perfusion-CT Data with Histopathologic Staging of Fibrosis. Acad Radiol 2019;26:1174-80.
9. Thalheimer U, Leandro G, Samonakis DN, Triantos CK, Patch D, Burroughs AK. Assessment of the agreement between wedge hepatic vein pressure and portal vein pressure in cirrhotic patients. Dig Liver Dis 2005;37:601-8.
10. Murayama Y, Fujimura S, Suzuki T, Takao H. Computational fluid dynamics as a risk assessment tool for aneurysm rupture. Neurosurg Focus 2019;47:E12.
11. Zhang JM, Zhong L, Su B, Wan M, Yap JS, Tham JP, Chua LP, Ghista DN, Tan RS. Perspective on CFD studies of coronary artery disease lesions and hemodynamics: a review. Int J Numer Method Biomed Eng 2014;30:659-80.
12. Aramburu J, Antón R, Rodríguez-Fraile M, Sangro B, Bilbao JI. Computational Fluid Dynamics Modeling of Liver Radioembolization: A Review. Cardiovasc Intervent Radiol 2022;45:12-20.
13. Ho H, Means S, Safaei S, Hunter PJ. In silico modeling for the hepatic circulation and transport: From the liver organ to lobules. WIREs Mech Dis 2023;15:e1586.
14. Hathcock JJ. Flow effects on coagulation and thrombosis. Arterioscler Thromb Vasc Biol 2006;26:1729-37.
15. Foutrakis GN, Yonas H, Sclabassi RJ. Saccular aneurysm formation in curved and bifurcating arteries. AJNR Am J Neuroradiol 1999;20:1309-17.
16. Wang K, Wang S, Xiong M, Wang C, Wang H. Non-invasive Assessment of Hepatic Venous Pressure Gradient (HVPG) Based on MR Flow Imaging and Computational Fluid Dynamics. In: de Bruijne, M., et al. Medical Image Computing and Computer Assisted Intervention – MICCAI 2021. MICCAI 2021. Lecture Notes in Computer Science, vol 12907. Springer, Cham.
17. Liu H, Lan L, Abrigo J, Ip HL, Soo Y, Zheng D, Wong KS, Wang D, Shi L, Leung TW, Leng X. Comparison of Newtonian and Non-newtonian Fluid Models in Blood Flow Simulation in Patients With Intracranial Arterial Stenosis. Front Physiol 2021;12:718540.
18. Mirza A, Ramaswamy S. Importance of Non-Newtonian Computational Fluid Modeling on Severely Calcified Aortic Valve Geometries-Insights From Quasi-Steady State Simulations. J Biomech Eng 2022;144:114501.
19. Lou Z, Yang WJ. A computer simulation of the non-Newtonian blood flow at the aortic bifurcation. J Biomech 1993;26:37-49.
20. Morales HG, Larrabide I, Geers AJ, Aguilar ML, Frangi AF. Newtonian and non-Newtonian blood flow in coiled cerebral aneurysms. J Biomech 2013;46:2158-64.
21. Das B, Enden G, Popel AS. Stratified multiphase model for blood flow in a venular bifurcation. Ann Biomed Eng 1997;25:135-53.
22. Kim Y H VPJ, Lee JS. Multiphase Non-Newtonian Effects on Pulsatile Hemodynamics in a Coronary Artery. Int J Numer Methods Fluids 2008;58:803-25.
23. Fan Y, Jiang W, Zou Y, Li J, Chen J, Deng X. Numerical simulation of pulsatile non-Newtonian flow in the carotid artery bifurcation. Acta Mechanica Sinica 2009;25:249-55.
24. Johnston BM, Johnston PR, Corney S, Kilpatrick D. Non-Newtonian blood flow in human right coronary arteries: transient simulations. J Biomech 2006;39:1116-28.
25. Chen J, Lu XY, Wang W. Non-Newtonian effects of blood

flow on hemodynamics in distal vascular graft anastomoses. J Biomech 2006;39:1983-95.
26. Molla MM, Paul MC. LES of non-Newtonian physiological blood flow in a model of arterial stenosis. Med Eng Phys 2012;34:1079-87.
27. Ho H, Bartlett A, Hunter P. Non-newtonian Blood Flow Analysis for the Portal Vein Based on a CT Image. In: Yoshida H, Hawkes D, Vannier MW. (eds) Abdominal Imaging. Computational and Clinical Applications. ABD-MICCAI 2012. Lecture Notes in Computer Science, vol 7601. Springer, Berlin, Heidelberg; 2012.
28. Radaelli AG, Augsburger L, Cebral JR, Ohta M, Rüfenacht DA, Balossino R, Benndorf G, Hose DR, Marzo A, Metcalfe R, Mortier P, Mut F, Reymond P, Socci L, Verhegghe B, Frangi AF. Reproducibility of haemodynamical simulations in a subject-specific stented aneurysm model--a report on the Virtual Intracranial Stenting Challenge 2007. J Biomech 2008;41:2069-81.
29. Ku DN. Blood Flow in Arteries. Annual Review of Fluid Mechanics 1997;29:399-434.
30. Ogiso S, Nakamura M, Tanaka T, Komiya K, Kamei H, Onishi Y, Jobara K, Kurata N, Itatani K, Ogura Y. Computational Fluid Dynamics-Based Blood Flow Assessment Facilitates Optimal Management of Portal Vein Stenosis After Liver Transplantation. J Gastrointest Surg 2020;24:460-1.
31. Atkar MK, Islam MT. A Bypassing Technique for the Remedy of Portal Hypertension Through Extra Hepatic Portal Vein Obstruction by CFD Analysis. GANIT: Journal of Bangladesh Mathematical Society 2018;38:89-104.
32. Lin P. Basic Equations for Hydrodynamics. Numerical Modeling of Water Waves. London: CRC Press; 2008.
33. Lin P. Turbulent Flows and Turbulence Modeling. Numerical Modeling of Water Waves. London: CRC Press; 2008.
34. Lopes D, Puga H, Teixeira JC, Teixeira SF. Influence of Arterial Mechanical Properties on Carotid Blood Flow: Comparison of CFD and FSI Studies. International Journal of Mechanical Sciences 2019;16:209-18.
35. Lin P. Coupled Fluid-structure System. Numerical Modeling of Water Waves. London: CRC Press; 2008.
36. Khalafvand SS, Ng EY, Zhong L. CFD simulation of flow through heart: a perspective review. Comput Methods Biomech Biomed Engin 2011;14:113-32.
37. Lopes D, Puga H, Teixeira J, Lima R. Blood flow simulations in patient-specific geometries of the carotid artery: A systematic review. J Biomech 2020;111:110019.
38. Frank O. Die Grundform Des Arteriellen Pulses. Zeitung fu¨r Biologie. 1899;37:483-586.
39. Liu J, Yan Z, Pu Y, Shiu WS, Wu J, Chen R, Leng X, Qin H, Liu X, Jia B, Song L, Wang Y, Miao Z, Wang Y, Liu L, Cai XC. Functional assessment of cerebral artery stenosis: A pilot study based on computational fluid dynamics. J Cereb Blood Flow Metab 2017;37:2567-76.
40. Aktar MK, Islam MT. A Computational Analysis of Blood Flow Through Portal Vein Under Normal and Extrahepatic Obstructions. Journal of Bangladesh Academy of Sciences 2017;41:183-99.
41. Petkova S, Hossain MA, Naser J, Palombo E. CFD Modelling of Blood Flow in Portal Vein Hypertension with and Without Thrombosis. In: Third International Conference on CFD in the Minerals and Process Industries CSIRO, Melborne, Australia. 2003; 10-2.
42. Liu Y, Lai Y, Nagaraj A, Kane B, Hamilton A, Greene R, McPherson DD, Chandran KB. Pulsatile flow simulation in arterial vascular segments with intravascular ultrasound images. Med Eng Phys 2001;23:583-95.
43. Domanin M, Bissacco D, Le Van D, Vergara C. Computational fluid dynamic comparison between patch-based and primary closure techniques after carotid endarterectomy. J Vasc Surg 2018;67:887-97.
44. Migliori S, Chiastra C, Bologna M, Montin E, Dubini G, Aurigemma C, Fedele R, Burzotta F, Mainardi L, Migliavacca F. A framework for computational fluid dynamic analyses of patient-specific stented coronary arteries from optical coherence tomography images. Med Eng Phys 2017;47:105-16.
45. Park ST, Yoon K, Ko YB, Suh DC. Computational Fluid Dynamics of Intracranial and Extracranal Arteries using 3-Dimensional Angiography: Technical Considerations with Physician's Point of View. Neurointervention 2013;8:92-100.
46. Isoda H, Ohkura Y, Kosugi T, Hirano M, Alley MT, Bammer R, Pelc NJ, Namba H, Sakahara H. Comparison of hemodynamics of intracranial aneurysms between MR fluid dynamics using 3D cine phase-contrast MRI and MR-based computational fluid dynamics. Neuroradiology 2010;52:913-20.
47. Botar CC, Vasile T, Sfrangeu S, Clichici S, Agachi PS, Badea R, Mircea P, Cristea MV, Moldovan R. CFD Simulation of the Portal Vein Blood. In: Vlad S, Ciupa RV, Nicu AI, editor. International Conference on Advancements of Medicine and Health Care through Technology 2009;359-362.
48. Botar CC, Vasile T, Sfrangeu S, Clichici S, Agachi PS, Badea R, Mircea P, Cristea MV. Validation of CFD

Simulation Results in Case of Portal Vein Blood Flow. Computer Aided Chemical Engineering 2010;28:205-10.
49. Botar CC, Agachi P S, Clichici S. Computational Fluid Dynamics Applied to Study the Hemodynamics in Sangvin Vessels. Case Study-the Portal System. Computer Aided Chemical Engineering. 2009;26:677-682.
50. Guo X, Su QW, Zhang LZ. The Measurement of Permeate Flux Based on a Noninvasive Method for Membrane Distillation: Experiment and Model Validation. Int J Heat Mass Transfer 2021;164:120482.
51. Nambu I, Misaki K, Uchiyama N, Mohri M, Suzuki T, Takao H, Murayama Y, Futami K, Kawamura T, Inoguchi Y, Matsuzawa T, Nakada M. High Pressure in Virtual Postcoiling Model is a Predictor of Internal Carotid Artery Aneurysm Recurrence After Coiling. Neurosurgery 2019;84:607-15.
52. Moon JY, Suh DC, Lee YS, Kim YW, Lee JS. Considerations of blood properties, outlet boundary conditions and energy loss approaches in computational fluid dynamics modeling. Neurointervention 2014;9:1-8.
53. He F, Hua L, Gao LJ. A seepage outlet boundary condition in hemodynamics modeling. Biomed Tech (Berl) 2017;62:521-7.
54. Zhou H, Meng L, Zhou W, Xin L, Xia X, Li S, Zheng H, Niu L. Computational and experimental assessment of influences of hemodynamic shear stress on carotid plaque. Biomed Eng Online 2017;16:92.
55. Mohd Adib MAH, Ii S, Watanabe Y, Wada S. Minimizing the blood velocity differences between phase-contrast magnetic resonance imaging and computational fluid dynamics simulation in cerebral arteries and aneurysms. Med Biol Eng Comput 2017;55:1605-19.
56. Rosetti GF, Vaz G, Fujarra ALC. URANS Calculations for Smooth Circular Cylinder Flow in a Wide Range of Reynolds Numbers: Solution Verification and Validation. J Fluids Eng 2012;134:121103.
57. Liu H, Lan L, Leng X, Ip HL, Leung TWH, Wang D, Wong KS. Impact of Side Branches on the Computation of Fractional Flow in Intracranial Arterial Stenosis Using the Computational Fluid Dynamics Method. J Stroke Cerebrovasc Dis 2018;27:44-52.
58. Qiao A, Dai X, Niu J, Jiao L. Hemodynamics in stented vertebral artery ostial stenosis based on computational fluid dynamics simulations. Comput Methods Biomech Biomed Engin 2016;19:1190-200.
59. Timmins LH, Molony DS, Eshtehardi P, McDaniel MC, Oshinski JN, Giddens DP, Samady H. Oscillatory wall shear stress is a dominant flow characteristic affecting lesion progression patterns and plaque vulnerability in patients with coronary artery disease. J R Soc Interface 2017;14:20160972.
60. Soudah E, Ng EY, Loong TH, Bordone M, Pua U, Narayanan S. CFD modelling of abdominal aortic aneurysm on hemodynamic loads using a realistic geometry with CT. Comput Math Methods Med 2013;2013:472564.
61. Aramburu J, Antón R, Rivas A, Ramos JC, Sangro B, Bilbao JI. Liver cancer arterial perfusion modelling and CFD boundary conditions methodology: a case study of the haemodynamics of a patient-specific hepatic artery in literature-based healthy and tumour-bearing liver scenarios. Int J Numer Method Biomed Eng 2016.
62. Buob S, Johnston AN, Webster CR. Portal hypertension: pathophysiology, diagnosis, and treatment. J Vet Intern Med 2011;25:169-86.
63. Iwakiri Y. Endothelial dysfunction in the regulation of cirrhosis and portal hypertension. Liver Int 2012;32:199-213.
64. Hennenberg M, Trebicka J, Sauerbruch T, Heller J. Mechanisms of extrahepatic vasodilation in portal hypertension. Gut 2008;57:1300-14.
65. Wang Y, Zhao L, Zheng Z, Zhang Y. Flow Resistance Analysis of Clinically Significant Portal Hypertension in Patients with Liver Cirrhosis. Can J Gastroenterol Hepatol 2022;2022:9396371.
66. Qiu Y, Tai Y, Lei J, Zeng Y, Wu H, Li K. Modelling the liver region as porous media to noninvasively measure portal vein pressure gradient (PPG) with numerical methods. J Biomech 2023;155:111660.
67. Li X, Wang XK, Chen B, Pu YS, Li ZF, Nie P, Su K. Computational hemodynamics of portal vein hypertension in hepatic cirrhosis patients. Biomed Mater Eng 2015;26 Suppl 1:S233-43.
68. George SM, Eckert LM, Martin DR, Giddens DP. Hemodynamics in Normal and Diseased Livers: Application of Image-Based Computational Models. Cardiovasc Eng Technol 2015;6:80-91.
69. Hsieh HJ, Liu CA, Huang B, Tseng AH, Wang DL. Shear-induced endothelial mechanotransduction: the interplay between reactive oxygen species (ROS) and nitric oxide (NO) and the pathophysiological implications. J Biomed Sci 2014;21:3.
70. Malek AM, Alper SL, Izumo S. Hemodynamic shear stress and its role in atherosclerosis. JAMA 1999;282:2035-42.
71. Soulis JV, Farmakis TM, Giannoglou GD, Louridas GE. Wall shear stress in normal left coronary artery tree. J Biomech 2006;39:742-9.

72. Shojima M, Oshima M, Takagi K, Torii R, Hayakawa M, Katada K, Morita A, Kirino T. Magnitude and role of wall shear stress on cerebral aneurysm: computational fluid dynamic study of 20 middle cerebral artery aneurysms. Stroke 2004;35:2500-5.
73. Peiffer V, Sherwin SJ, Weinberg PD. Does low and oscillatory wall shear stress correlate spatially with early atherosclerosis? A systematic review. Cardiovasc Res 2013;99:242-50.
74. Phinikaridou A, Hua N, Pham T, Hamilton JA. Regions of low endothelial shear stress colocalize with positive vascular remodeling and atherosclerotic plaque disruption: an in vivo magnetic resonance imaging study. Circ Cardiovasc Imaging 2013;6:302-10.
75. Wentzel JJ, Chatzizisis YS, Gijsen FJ, Giannoglou GD, Feldman CL, Stone PH. Endothelial shear stress in the evolution of coronary atherosclerotic plaque and vascular remodelling: current understanding and remaining questions. Cardiovasc Res 2012;96:234-43.
76. Wei W, Pu YS, Wang XK, Jiang A, Zhou R, Li Y, Zhang QJ, Wei YJ, Chen B, Li ZF. Wall shear stress in portal vein of cirrhotic patients with portal hypertension. World J Gastroenterol 2017;23:3279-86.
77. Zhou J, Li YS, Chien S. Shear stress-initiated signaling and its regulation of endothelial function. Arterioscler Thromb Vasc Biol 2014;34:2191-8.
78. Van Steenkiste C, Trachet B, Casteleyn C, van Loo D, Van Hoorebeke L, Segers P, Geerts A, Van Vlierberghe H, Colle I. Vascular corrosion casting: analyzing wall shear stress in the portal vein and vascular abnormalities in portal hypertensive and cirrhotic rodents. Lab Invest 2010;90:1558-72.
79. Intagliata NM, Caldwell SH, Tripodi A. Diagnosis, Development, and Treatment of Portal Vein Thrombosis in Patients With and Without Cirrhosis. Gastroenterology 2019;156:1582-1599.e1.
80. Zhe C, Jian-wei L, Jian C, Yu-dong F, Ping B, Shu-guang W, Shu-guo Z. Laparoscopic versus open splenectomy and esophagogastric devascularization for bleeding varices or severe hypersplenism: a comparative study. J Gastrointest Surg 2013;17:654-9.
81. Huang L, Yu Q, Wang J. Association Between Changes in Splanchnic Hemodynamics and Risk Factors of Portal Venous System Thrombosis After Splenectomy with Periesophagogastric Devascularization. Med Sci Monit 2018;24:4355-62.
82. Wu LF, Bai DS, Shi L, Jin SJ, Zhou BH, Jiang GQ. Predictors of portal vein thrombosis after laparoscopic splenectomy and azygoportal disconnection in hepatitis B cirrhosis: a prospective study. Surg Endosc 2022;36:4090-8.
83. Soares AA, Gonzaga S, Silva JS, Marinho D, Silva A, Rouboa A. Non-newtonian Blood Flow in Portal Vein with Thrombosis: A Study by Computational Fluid Dynamics. AIP Conf Proc 2011;1389:171-4.
84. Xiong Z, Yan Y, Wang X, Liu Z, Luo X, Zheng T. The effect of splenic vein diameter on the diagnosis of portal vein thrombosis. Med Phys 2023;50:6614-23.
85. Tripathi D, Stanley AJ, Hayes PC, Travis S, Armstrong MJ, Tsochatzis EA, Rowe IA, Roslund N, Ireland H, Lomax M, Leithead JA, Mehrzad H, Aspinall RJ, McDonagh J, Patch D. Transjugular intrahepatic portosystemic stent-shunt in the management of portal hypertension. Gut 2020;69:1173-92.
86. Patel RK, Chandel K, Tripathy TP, Mukund A. Complications of Transjugular Intrahepatic Portosystemic Shunt (tips) in the Era of the Stent Graft - What the Interventionists Need to Know. Eur J Radiol 2021;144:109986.
87. Yin K, Wang X, Zheng T. Computational hemodynamic analysis for optimal stent position in the transjugular intrahepatic portosystemic shunt procedure. J Biomech 2022;143:111303.
88. Sambommatsu Y, Shimata K, Ibuki S, Narita Y, Isono K, Honda M, Irie T, Kadohisa M, Kawabata S, Yamamoto H, Sugawara Y, Ikeda O, Inomata Y, Hibi T. Portal Vein Complications After Adult Living Donor Liver Transplantation: Time of Onset and Deformity Patterns Affect Long-Term Outcomes. Liver Transpl 2021;27:854-65.
89. Craig EV, Heller MT. Complications of liver transplant. Abdom Radiol (NY) 2021;46:43-67.
90. Delgado-Moraleda JJ, Ballester-Vallés C, Marti-Bonmati L. Role of imaging in the evaluation of vascular complications after liver transplantation. Insights Imaging 2019;10:78.
91. Qu W, Li X, Huang H, Xie C, Song H. Mechanisms of the ascites volume differences between patients receiving a left or right hemi-liver graft liver transplantation: From biofluidic analysis. Comput Methods Programs Biomed 2022;226:107196.

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