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Application of computational fluid dynamics (CFD) and fluid-structure interaction (FSI) in biofluids simulation to solve actual surgery tasks

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Abstract

Computational fluid dynamics (CFD) is a dynamically developing tool in mechanical engineering and interdisciplinary research. Medicine is one of the areas, where the application of current computational methods is extremely necessary. This study presents the results of using computational fluid dynamics methods to solve actual problems of surgery (modeling of blood flow in the patient-specific aorta of a child with congenital heart disease during bypass surgery; modeling of the flow of bile in the biliary system to predict cholecystectomy outcome; modeling of the chime flow in the colon). Simulation of blood flow in the aorta during shunting. Cardiovascular diseases are most common in the population and cause the prevailing part of premature mortality and disability in both adults and children. Blalock-Taussig shunting is mainly used to eliminate pathological changes in children. However, this procedure is carried out empirically: surgeons use their own experience.

FSI enabled to numerically evaluate the shunt parameters and its location for proper lung development in children with congenital heart disease after shunt installation. Biomechanical analysis of the bile flow in healthy state, pathology, and after cholecystectomy. Cholecystectomy (removal of the surgical gallbladder) is usually taken to treat patients suffering from gallbladder disease and gallbladder pain. However, it should be noted that the results of the operation are not always successful. The biomechanical patient-specific model was created to assess the cholecystectomy outcome. Study of the chyme flow features in the colon. The large intestine is a long hollow muscle tube of complex shape, which digests and absorbs nutrients and water from food (which is commonly called chyme in medicine). The goal is to create a patient-specific model of the chyme and feces flow in the colon in the healthy state and pathology. Clinical applications of this model can be expressed in the description and understanding of the causes of the disorders as well as drug efficiency assessment to reduce the number of patients.

KEYWORDS: CFD; FSI; shunt; cholecystectomy; chyme

Introduction

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This study presents the results of using computational fluid dynamics methods to solve actual problems of surgery (modeling of blood flow in the patient-specific aorta of a child with congenital heart disease during bypass surgery; modeling of the flow of bile in the biliary system to predict cholecystectomy outcome; modeling of the chyme flow in the colon).

Simulation of blood flow in the aorta during shunting

About 25-30% of all congenital heart anomalies are related to aorta coarctation [1]. It is necessary to use systemic-pulmonary anastomoses for radical correction [2,3]. The first Blalock-Taussig operation was performed in 1945 [4]. In 1975 de Leval modified this technique by using a polytetrafluoroethylene shunt known as the modified Blalock Taussig shunt (MBTS) [5]. This method has become a standard intermediate palliative operation for the cyanotic heart diseases to provide a dosed pulmonary blood flow.

It is noteworthy that literature data indicate MBTS as a relatively high-risk procedure with a total mortality of 7.2% [6,7]. It competes with the risk of mortality in the range of many neonatal open-heart procedures with artificial circulation [8]. Potential disadvantages of these shunts include excessive volumetric load, acute thrombosis and low diastolic blood pressure, which leads to coronary insufficiency [9,10,11].

Biomechanical analysis of the bile flow in healthy state, pathology and after cholecystectomy

Gallstones affect 10 to 15% of the adult population in the World at average. Cholecystectomy is the most commonly performed abdominal operation for the treatment of patients suffering from gallbladder disease in Western countries [12,13]. Nevertheless, the operation outcome is not always positive. To predict outcomes of cholecystectomy, the computational simulations are good tool for providing more realistic choledynamic factors (bile flow velocities, pressures, WSS). A thorough review of current publications in this field reveals that bile flow has been mostly investigated in separate ducts of the biliary system. Some attempts to make patient-specific models of cystic ducts [14] and biliary tree [15] have been made. So far, however, there has been no attempt to create a patient-specific model of bile flow. The aim of work is to study bile flow to predict outcomes of surgical operations using patient-specific approach and created the entire biliary system model.

Study of the chyme flow features in the colon

The diseases of the intestine, as a rule, include inflammatory forms of the disease (most often it is Crohn’s disease or ulcerative colitis), benign or malignant neoplasms,

and functional disorders [16]. According to statistics, about 5 million people in the world suffer from various kinds of inflammatory bowel diseases, in Europe – about 0.3% of the population. In 2018, colon and rectal cancer was diagnosed in 1.8 million people.

Treatment of bowel disease may be conservative or operative. In the case of surgery, the percentage of complications reaches up to 60%. When functional disorders of the intestine are applied, as a rule, conservative methods of treatment [17].

The causes of intestinal diseases are hereditary factors or external – sedentary lifestyle, bad habits, unhealthy diet, stress. To understand the processes occurring in the intestine in normal and pathological conditions, as well as to assess the effectiveness of treatment, it is necessary to consider a number of factors: the movement of chyme, mixing, absorption of nutrients. Methods of mathematical modeling allow us to describe the transport of chyme in the intestine, taking into account peristalsis, to take into account changes in the properties of the intestinal wall due to various diseases.

Materials and methods

Simulation of blood flow in the aorta during shunting

Based on MRI, we constructed a patient-specific models of system “aorta-pulmonary artery-shunt” to analyze hemodynamics in 10 children with congenital heart pathology.

Blood was considered as a Newtonian fluid. The boundary conditions for children were obtained using ultra-sound measurement techniques. The aim was to get the main hemodynamical parameters (velocity, pressure, flow rate, Qs/Qp, OSI, WSS, TAWSS, e.t.c.) at different shunt configurations to evaluate the surgery effectiveness.

Biomechanical analysis of the bile flow in healthy state, pathology, and after cholecystectomy

Different models (for example, Windkessel model, peristaltic fluid motion, FSI algorithm) can describe fluid motion in the elastic and compliant ducts. Our approach is decomposition of the biliary system into three compartments (extra-hepatic biliary tree, gallbladder, major duodenal papilla). Bile flow in the extra-hepatic ducts is simulated using FSI algorithm. Bile flow in the gallbladder can be described as flow in the reservoir with compliant ducts using Windkessel model. Bile flow in the major

duodenal papilla is considered as peristaltic fluid motion, because the wall contraction is really important factor of fluid motion in that segment. The coupling of these compartments is performed by boundary conditions. The biliary system geometry was obtained using MRI patient-specific data. It was confirmed that normal bile can be modeled as Newtonian fluid and lithogenic bile can be modeled as non-Newtonian fluid (Carreau fluid). Bile ducts were modeled as hyperelastic material. Bile flow analysis was performed for several patients.

Study of the chyme flow features in the colon

MRIs of colon were used. Chyme was considered as a non-Newtonian power-law fluid. Navier-Stokes equations and the continuity equation were used for CFD computations.

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\left(\mathbf{v}\cdot\nabla\right)\mathbf{v}\right)=-\nabla\cdot\boldsymbol{\sigma}+f\ ,$$

$$\nabla\cdot\mathbf{v}=0,$$

where $\mathbf{v}$ is chyme velocity, $\boldsymbol{\rho}$ – density, $\boldsymbol{\sigma}$ – the stress tensor, f – mass forces.

Rendering and segmentation of MRI was performed by open source software ITK-Snap to create patient-specific 3D colon model. Open FOAM software was adopted to permorm CFD simulations.

Results and conclusions

Simulation of blood flow in the aorta during shunting

Velocity, pressure and WSS distributions were numerically obtained. It was shown that blood flow in the pulmonary arteries is asymmetric. Wall shear stress, which is a biomechanical assessment of thrombosis formation, has maximal values in the shunt region. Biomechanical modelling enables to predict an effectiveness of shunt functioning at its different modifications.

Biomechanical analysis of the bile flow in healthy state, pathology and after cholecystectomy

The effect of bile pathology on the velocity and pressure distributions in the patient-specific extrahepatic biliary tree was investigated using a one-way FSI approach. Several patients were analyzed. Comparisons were made for healthy and lithogenic bile in terms of fluid flow, WSS and pressure. Lower values of pressure in the extrahepatic biliary tree in the case of the healthy bile were related to the difference in the rheological properties (the lithogenic bile was more viscous than the healthy bile). It was shown that bile rheology and geometry changes played an important role in the changes of the velocities, pressures and stresses, which could lead to gallbladder disease progression. Moreover, cholecystectomy changes in the bile flow and stress distributions were found. Therefore, the proposed model could be applied to medical practice to evaluate the circumstances of surgical interventions.

Study of the chyme flow features in the colon

As a result of the implementation, a model of the flow of chyme and feces in the three-dimensional geometry of the intestine, obtained by processing MRI images of a particular patient, was obtained.

The resulting model will open up broad prospects in medicine and pharmacology:

- assessment of the effect of drugs on the transport of chyme and feces;
- analysis of the current state of the patient on the basis of a numerical assessment of the hydrodynamic parameters of the chyme in this segment of the digestive system, as well as a comparison with normal values for a particular patient;
- strength analysis of colorectal anastomoses to reduce a high mortality;
- evaluation of the effectiveness of the treatment of inflammatory bowel disease for a particular patient.

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