Three Dimensional Fluid Structure Interaction Modeling of Hemodynamics with Continuous Postures

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Abstract— *A sudden postural change may produce symptoms or even syncope mainly due to orthostatic hypotension. To date, most hemodynamic studies in postural change focus on the response of static and definite postures. To quantify cardiovascular hemodynamics characteristics during continuous posture, we developed a three-dimensional fluid-structure interaction mathematical model of hemodynamics with continuous posture. In this model, the rotating inertial forces were introduced. By the finite element method, the distribution of blood flow pressure (DBFP) in the inner carotid artery in ±90° postures was numerically simulated with rotation and gravity concerned or not. The simulations are as follows: (1) whether gravity was considered or not, the DBFP varied from two-dimensional axisymmetrical distribution without rotation to three-dimensional asymmetrical one with rotation considered, and extreme pressures occurred in the same positions in the two cases. (2) The effect intensity of rotation is larger than the effect intensity of gravity. So, unlike gravity, rotation affected the DBFP. This indicates that hemodynamic characteristics in certain position during dynamic change of posture obviously differ from that in static and definite posture. This study may provide a novel way to characterize hemodynamics during continuous posture, and consequently help to evaluate the syncope patients, astronauts or pilots and athletes with unexplained syncope more accurately.*

Keywords— Blood flow pressure, Continuous posture, Gravity, Hemodynamics, Mathematical Model, Rotation, Syncope.

I. INTRODUCTION

A sudden postural change is associated with acute blood pressure fluctuation and may produce symptoms including dizziness, black-out or even syncope mainly due to orthostatic hypotension. In spaceflight, syncope attack is one of the most serious problems as it will disable astronauts and pilots to cope with emergency situations during the space mission [1].In sports, exercise-related syncope attracts great attention and anxiety, and syncope, especially unexplained syncope, prevents athletes from competing because its occasional attack on athletes is life-threatening [2-4].

Tilt table test is an effective tool and has been widely used to identify patients [5, 6], athletes [4] or astronauts and pilots [7] who may experience syncope during postural change. A key to avoiding or treating the dysfunction produced by postural change lies in the discovery of mechanisms, and so it is crucial to obtain the comprehensive information of hemodynamic response, as one of the primary biomechanical responses [8, 9].

The mechanisms responsible for hemodynamic and reflexive responses to postural change (from supine to the upright or vice versa) have been studied extensively by different tests and modeling methods [6, 10, 11]. However, there are still many questions unanswered. Many tests [6, 12, 13] measure the steady-state, non-invasive hemodynamic parameters for one chosen posture, then compare the static measurements in different postures to explain some phenomena induced by postural change, thus analyzing virtually static indicators. Additionally, some tests [14] monitor the transient hemodynamic response in a definite body position during postural transition, but the physical effect of postural transition on hemodynamics at a definite posture has not been investigated. And few measure the dynamic parameters during postural change. Moreover, owing to the limitation of non-invasive measurement, a comprehensive description could not be conducted, e.g. spatial profile of hemodynamics. Most published models [1, 11, 15] designed to simulate the hemodynamic response to body tilting, are based on the lumped parameter model and focused on elucidating the control mechanisms, and can neither reflect the spatial distribution of hemodynamics nor the vector nature of gravity during postural change. Overall, hemodynamic studies in this area mainly focus on the response of definite and static posture, and the spatial distribution of cardiovascular hemodynamics and its reaction to the dynamic process of body-position change are not well established.

To describe more accurately the spatial and temporal features of hemodynamics during continuous postural changes, we developed a three-dimensional (3D) fluid-structure interaction (FSI) mathematical model by applying the rotating inertial forces to the fluid and solid equations separately to quantify the hemodynamic characteristics in time and space while the posture changes continuously.

This model to describe postural change is unique in its incorporation of gravity as a vector and rotating inertial force simultaneously in the blood flow and vessel wall. Also, this study gives descriptions of the spatial features of 3D distribution of blood flow pressure (DBFP) in a vessel with rotation for the first time.

II. METHODS

2.1 Mathematical model

2.1.1 Modeling foundation

The distributed-parameter model is one of two main kinds of hemodynamic models. On the basis of it, we established the first mathematical model of hemodynamics with posture in 2009 [16]. In this model, gravity, as a term of body force, was introduced to represent the postural change. This model could thus reflect the real effect of gravity. However, the model is merely adapted to fluid-only situation, and it did not embody the interaction between fluid and solid. Therefore, the effect of vessel wall on the blood flow couldn't be presented by the above model. For this reason, another postural model of hemodynamics was developed, in which fluid-solid interaction (FSI) was considered [17]. By applying the body force terms of gravity to the fluid equation and the vessel wall equation respectively, this FSI postural model expresses the coupling action of vessel wall and blood flow, and provides a better physiological understanding than the previous model. However, these models mainly focus on the steady-state hemodynamic characteristics at a definite posture.

2.1.2 Term representing continuous postural change

From analysis results, we suppose that centrifugal force and Coriolis force are the key factors to represent the continuous change of posture. Then, applying the centrifugal force and Coriolis force to the fluid and solid equations, respectively, of the FSI postural model presented [17], we have a FSI hemodynamic mathematical model with continuous posture. With the model, the dynamic information during the continuous posture can be obtained.

2.1.3 Mathematical model with continuous posture

Assuming the vessel rotates at a constant angular velocity around the fixed axis, and blood flow references the rotating vessel as a frame of reference, namely a non-inertial planar rotating frame of reference. Chen et al. [18] has demonstrated that the acceleration of the fluid particle in a rotating frame of reference is not equal to that in an inertial reference system because Newton's second law is merely valid in an inertial frame of reference. Thus, the equation of motion needs to be modified. Meanwhile, for solid, the equation of equilibrium also requires revision in this non-inertial frame of reference [19].

The basic assumptions in this paper were as follows. The blood was assumed to be incompressible, viscous and Newtonian fluid. The flow was laminar. The vessel wall was assumed to be isotropic, homogeneous, incompressible and elastic material. The coupling interface between blood and vessel wall was set to a non-slip condition, i.e., the wall moved with the blood flow. Considering all these factors, we had the FSI math model of hemodynamics with continuous posture, which was founded on the FSI postural model presented previously.

For fluid part, the equation of continuity [20] is

$$\nabla \bullet (\mathrm{A}\vec{\upsilon}) = 0 \tag{1}$$

and the equation of motion is

$$\frac{D(\rho\vec{\upsilon}_r)}{Dt} = \rho\vec{F}_b + \nabla \bullet \overset{=}{P} - \rho\vec{\omega}\times(\vec{\omega}\times\vec{r}) - 2\rho\vec{\omega}\times\vec{\upsilon}_r \tag{2}$$

where $\frac{D(\rho\vec{\upsilon}_r)}{Dt}$ is the inertial force, $\nabla\bullet\vec{\vec{P}}=\mu\nabla^2\vec{\upsilon}-\nabla p$ is the surface force, $\rho\vec{F}_b$ is the body force including gravity, which was identified as the key term to reflect the postural change, and $-\rho\vec{\omega}\times(\vec{\omega}\times\vec{r})$ stands for the centrifugal force, and $-2\rho\vec{\omega}\times\vec{\upsilon}_r$ is the Coriolis force due to the movement of the reference system. The last two terms were caused by the rotation of the vessel. ρ denotes the blood density, $\vec{F}_b$, the body force per unit mass of blood, $\vec{\vec{P}}$, the second order stress tensor of the blood pressure, $\vec{\upsilon}$, the blood velocity, and A is the cross-section area of the vessel, $\vec{\upsilon}_r$ is the relative velocity vector of blood, $\vec{\omega}$ is the angular velocity vector, $\vec{r}$ is the rotating radius vector and μ is the viscosity of the blood.

Inertial forces due to rotation were considered to represent the continuous postural change. The boundary conditions for the fluid model were the pressure conditions $p|_{inlet}=p_{in}(t)$ and $p|_{outlet}=p_{out}(t)$, the velocity conditions $\partial\vec{\upsilon}_r/\partial n\,|_{inlet,outlet}=0$, and the coupling conditions at the interface $\vec{\upsilon_r}|_{\Gamma}=\partial\vec{X}/\partial t$.

For solid part, the equation of equilibrium [19] is

$$\sum_{j=1}^{3}\frac{\partial\sigma_{ij}}{\partial x_j}+\rho_w g_i+\rho_w\omega^2 x_i=\rho_w\frac{\partial^2 v_i}{\partial t^2}\qquad(i=1,2,3)\qquad(3)$$

and the equation of geometry is

$$\varepsilon_{ij}=\frac{1}{2}\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}\right)\qquad(i,\ j=1,2,3)\qquad(4)$$

where $\vec{\vec{\sigma}}$ is the second order stress tensor, $\vec{\vec{\varepsilon}}$ is the second order strain tensor, $\vec{v}$ stands for the solid replacement vector, $\vec{x}$ is the coordinate vector, ρ_w is the density of vessel wall, and g_i is the acceleration component of gravity. $\rho_w\omega^2 x_i$ was considered the key term of continuous postural change for vessel wall. The boundary conditions for the solid model were a natural equilibrium condition $\sigma_{ij}\bullet n_j|_{out\_wall}=\vec{F}_i=0$ at the outer surface, (i.e., a free surface), and a natural traction equilibrium condition $\sigma_{ij}^{f}\bullet n_j|_{interface}=\sigma_{ij}^{w}\bullet n_j|_{interface}$ at the interface (i.e., the internal surface of the vessel wall).

2.2 FE model

The inner carotid artery, which is one of the large systemic arteries, is taken as a computational case.. The assumptions of a large artery made in this paper were thus suitable [21-24]. The geometric dimensions [25] of the vessel are length of the vessel L=145mm, inlet and outlet diameters of the vessel D1=10.74mm and D2=7.72mm, and wall thickness h=0.35mm. For the vessel wall [21], the density ρ_w =1150kg/m^3, Poisson ratio υ_w =0.495, and elastic modulus E_w =4e+6Pa. The properties of the blood [21, 26] are density ρ_f =1050kg/m^3, viscosity μ_f =0.0035Pa·s, and the material parameters are equal to the normal values for human blood at 37 ℃.

The boundary conditions were rotational angular velocity of 120°s^{-1}, and constant inlet and outlet pressures with a pressure difference of 199.98 Pa (1.5 mmHg). The vessel rotated around a fixed axis at its big end. The initial conditions were set following Heusden et al. [11]. The steady-state hemodynamic parameters for supine posture were used as the starting point. Gravity pushed the blood flow forward (i.e., the direction of gravity is the same as blood flow) for the upright posture (+90° posture), while gravity pulled the blood flow backward, (i.e., the direction of gravity is opposite to that of the blood flow) for the upside-down position (-90° posture).

ADINA, a commercial finite element software package (ADINA R&D, Inc, Watertown, MA, USA), was used for simulation. Researchers [27, 28] have used the package to study various biological systems. As the body force and rotating effect were considered in this study, three dimensional fluid elements and solid elements were meshed for the blood and vessel wall, respectively. The numerical computational model (i.e., finite element model) was shown in Fig. 1.

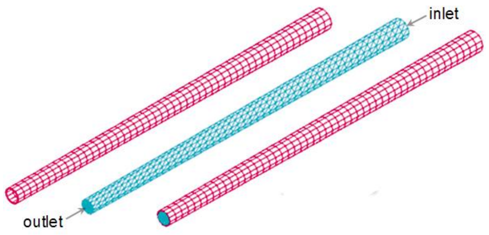
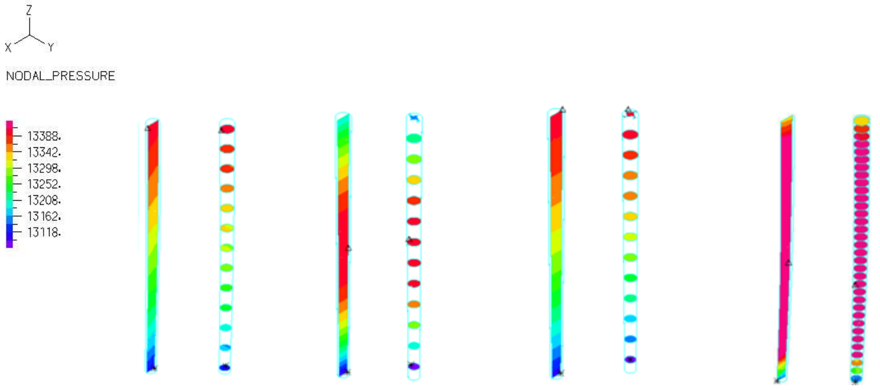


FIG.1 THREE-DIMENSIONAL FINITE ELEMENT MODEL OF A VESSEL

III. RESULTS

3.1 Effect of Rotation on the Distribution of Blood Flow Pressure

The contour charts of the blood flow pressure under different conditions in the inner carotid artery are shown in Fig. 2. The DBFP was not only affected by the posture and gravity, but also by the rotation. For $\vec{\omega} = 0$ (i.e., rotation is neglected), in upright (+90°) and upside-down (-90°) positions and no matter gravity was considered or not ($\vec{G} \neq 0$ or $\vec{G} = 0$), the DBFP was always two-dimensional (2D) axisymmetrical distribution. When $\vec{G} \neq 0$, at +90°, the maximum pressure (P_{max}) was approximately located in the middle of the vessel, and at -90°, it was at the inlet. When $\vec{G} = 0$, P_{max} was at the inlet of the vessel for both +90° and -90° postures. Under the various conditions described above, the minimum pressure (P_{min}) remained at the outlet of the vessel. However, for $\vec{\omega} \neq 0$ (i.e., rotation was considered), at ±90°, the DBFP was 3D and asymmetrical when neglecting gravity ($\vec{G} = 0$). P_{max} was at the inlet and P_{min} remained at the outlet of the vessel, which were the same positions as those for $\vec{\omega} = 0$.

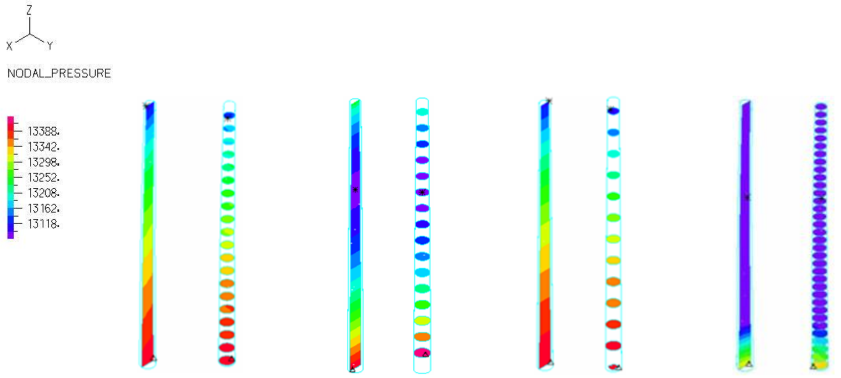


(i) (ii) (i) (ii) (i) (ii) (i) (ii)

a. $\vec{\omega}\neq 0$ $\vec{G}=0$ b. $\vec{\omega}=0$ $\vec{G}\neq 0$ c. $\vec{\omega}=0$ $\vec{G}=0$ d. $\vec{\omega}\neq 0$ $\vec{G}\neq 0$

(T=1.75s) (T=3.00s) (T=3.00s) (T=1.75s)

(1) upright position (+90°position)



(i) (ii) (i) (ii) (i) (ii) (i) (ii)

a. $\vec{\omega}\neq 0$ $\vec{G}=0$ b. $\vec{\omega}=0$ $\vec{G}\neq 0$ c. $\vec{\omega}=0$ $\vec{G}=0$ d. $\vec{\omega}\neq 0$ $\vec{G}\neq 0$

(T=3.25s) (T=3.00s) (T=3.00s) (T=3.25s)

(2) upside-down position (-90°position)

Fig.2 distribution of blood flow pressure of single vessel under different conditions (△ represents the position of the maximum pressure; * is the position of the minimum pressure; T is the time from the supine posture to the current position). (1) in upright position (+90°position); (2) in upside-down position (-90°position). (a) with rotation considered and with gravity neglected ($\vec{\omega}\neq 0$ and $\vec{G}=0$); (b) without rotation and with gravity considered ($\vec{\omega}=0$ and $\vec{G}\neq 0$); (c) without rotation and with gravity neglected ($\vec{\omega}=0$ and $\vec{G}=0$); (d) with rotation considered and with gravity considered ($\vec{\omega}\neq 0$ and $\vec{G}\neq 0$). (i) the longitudinal pressure distribution; (ii) the axial pressure distribution.

3.2 Effect intensity of rotation

To express easily the effect of vessel rotation on hemodynamics, a new physical variable called the effect intensity of rotation (EIR) was defined as

$$EIR = \frac{\left(P_{W\max} - P_{0\max}\right) - \left(P_{W\min} - P_{0\min}\right)}{L} \tag{5}$$

where $P_{W\max}$, $P_{W\min}$ are the maximum and minimum pressures of a longitudinal section of a single rotating vessel, respectively. $P_{0\max}$, $P_{0\min}$ are the same extreme pressures without rotation. L is the length of the vessel.

To determine the effects of rotation and gravity on the blood flow pressure respectively, the ratio of the EIG (effect intensity of gravity) to the EIR was computed. The results are shown in Table 1. In upright position, the ratio is 1:3.632, while in upside-down one, it is 1: 2.671.

TABLE1. RATIO OF THE EIG TO THE EIR

Postures	EIG （Pa/mm）	EIR （Pa/mm）	Ratio EIG：EIR
upside-down (-90°)	1.385	3.700	1:2.671
Upright (+90°)	2.285	8.300	1:3.632

IV. DISCUSSIONS

In this paper, by introducing the rotating inertial forces into the steady-state postural model that we presented previously, we developed a 3D FSI mathematical model to study the spatial hemodynamic characteristics with continuous postural change, which is one of the highlights of this study. This is the first study in which the spatial distribution of hemodynamics with rotation was analyzed in a vessel. Our model can reproduce comprehensive hemodynamic features of a vessel from the temporal and spatial aspects during postural change.

During the modeling process, it was assumed that the vessel rotated at a constant angular velocity around a fixed axis, which simplifies the complex question to some extent. The characteristic terms in hemodynamics resulting from the continuous postural change can be described analytically by mathematical formula. Therefore, the postural model of hemodynamics spanned from the inertial system to the non-inertial one. This study eliminated the limitation of the existed postural models that were unable to reflect the spatial distribution of hemodynamics during continuous postural change. This model may lay the theoretical foundation for further research on postural change, with the aim of obtaining more comprehensive hemodynamic features to elucidate the mechanisms of syncope produced by postural change. Overall, this study provides a novel approach to obtain the temporal and spatial information of hemodynamics during continuous postural change even though many aspects of this model still need to be improved to get close to physiological conditions.

Using the continuous postural model of hemodynamics, the effect of rotation on the DBFP in the inner carotid artery was simulated for ±90° postures. The simulations indicate a significant difference in the effects on the DBFP in a vessel between rotation and gravity. As shown in Fig.2, the DBFP took on a 3D asymmetrical distribution with rotation considered, and a 2D axisymmetrical one without rotation. This result didn't concern with gravity. The positions of extreme pressures varied depending on whether gravity was considered, but the style of the DBFP remained the same. Thus, rotation had an essential effect on the style of the DBFP but not on the positions of extreme pressures. Additionally, gravity affected the positions of extreme pressures, but not the style of the pressure distribution. The simulating results agreed with our previously obtained results [29].

Therefore, the hemodynamic features induced by continuous postural change differ from those for a single posture. Continuous posture corresponds to a dynamic or transient process, while a single posture is associated with a static or steady-state process in most cases. So, the hemodynamic parameters measured for a single posture would be different from those measured during continuous postural change. Capturing the comprehensive dynamic features of hemodynamics in postural change helps in evaluating the effect of hemodynamics and the cardiovascular regulative ability accurately. Consequently, our study may improve the diagnosis of syncope patients and the selection, training & assessment of athletes, astronauts and pilots with unexplained syncope. Yet most researchers investigating the hemodynamic responses of definite postures are in fact focusing on the steady-state or transient parameters of hemodynamics for single and static postures [1, 6, 14], and they ignore the dynamic information during a postural change. Hemodynamic transients, e.g. beat-to-beat blood pressure, heart rate, could be obtained in the modeling study [15, 30] as well as measured in the tilt table test [14, 31]. However, the spatial distribution of hemodynamic variables and the effect of the postural transition on hemodynamics were not investigated for dynamic postural changes in the previous studies. The mechanism involved may depend, to some extent, on the spatial distribution characteristics of hemodynamic transients.

As presented in this study, a modeling approach of obtaining the spatial distribution of hemodynamic parameters provided more information to elucidate the mechanism of syncope produced by continuous postural change. Meanwhile, the effect of rotation on the DBFP in a vessel indicates that the model developed in this paper is able to reflect the hemodynamic variation during continuous postural change. So this study may provide a novel approach to obtain immediate hemodynamic variation and cardiovascular regulating ability during continuous postures, which will subsequently be helpful in evaluating syncope patients, astronauts or pilots and athletes with unexplained syncope more accurately.

V. CONCLUSION

The 3D FSI mathematical model of hemodynamics with continuous postures was established in this study, and it described quantitatively the 3D transient information of hemodynamics during continuous postural change. With the model, by simulating the DBFP for ±90° positions during continuous change of postures, we suggests that hemodynamic characteristics for certain positions during dynamic change of postures obviously differ from those for static and definite postures.

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