Hemodynamics Variations of Umbilical Vein and Ductus Venosus due to different Material Properties

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Abstract: Disease is a cause for abortion of a fetus even in the early stages of pregnancy, a contributing factor to the increase in rate of such abortions over the last decade. The inefficiency of flow of blood from the placenta to the human fetus in clinical studies, especially the ductus venosus (DV) needs further investigation. The DV acts as a rope between the umbilical vein and the inferior vena cava (IVC) in the right atrium. Therefore, DV is an important part of the fetus's health. Any type of DV flow abnormity can lead to fetal abnormities. In this study, we have focused on the hemodynamics in human fetal UV/DV regarding four different mechanical properties of UV, consisting of elastic, viscoelastic, and rigid. The investigated hemodynamic parameters include velocity, shear stress, and maximum pressures of the Isthmus and UV parts. The results show that the maximum pressure did not change sufficiently across UV or Isthmus. But the maximum shear stress happened in hyper hyper-elastic model. The velocity of the Isthmus is also maximum for hyper-elastic models. This study has focused on the main hemodynamics parameters of blood flow in UV/DV, and the obtained results were in good agreement with clinical/experimental literature. We found out that the hyperplastic model of UV/DV vein is more conformed to the experimental data.

Keywords: Umbilical vein; Blood flow, Hemodynamics, Venous

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1. INTRODUCTION

The umbilical vein is the main part developed during the time of fetal development. It delivers blood to the fetus. The ductus venosus acts as a rope between the UV and the inferior vena cava (IVC) in the right atrium (Rezaee & Hassani, 2016). Thirty percent of the blood flow from the UV to the IVC is sent by the ductus venosus (Rezaee & Hassani, 2016). The UV is a hollow pipe that transports blood between the fetus and the placenta. There are normally two umbilical arteries and one umbilical vein for each fetus. The umbilical vein is 2 to 3 cm long and is connected to the central circulation by the portal vein.

The rate of abortion of the fetus has increased significantly during the last decade, therefore, an investigation is required to establish the possible causes of abnormalities of blood flow in UV/DV. To understand more about the health or abnormalities of the fetus, we should increase our knowledge about the hemodynamics of the UV and DV. There still exists some ethical and technical issues pertaining to velocity and pressure variations of the UV and DV.

We believe the study of blood flow hemodynamics parameters of UV/DV could help to find the possibility of some congenital heart diseases (Toyama, et al., 2004; Kiserud, Kessler, Ebbing, & Rasmussen, 2006). A Mostbeck et al, (Mostbeck, et al., 1989), evaluated the UV flow with duplex ultrasound. Bellotti et al (Bellotti, Pennati, De Gasperi, Battaglia, & Ferrazzi, 2000) studied the hemodynamic changes in UV and DV flow induced by uterine contractions. Leinan et al (Leinan, et al., 2013) obtained the velocity profiles in human DV using fluid structure interactions (FSI). On the other hand, Wada et al (Wada, et al., 2015) studied the alterations in time intervals of DV velocity waveforms in growth-restricted fetuses. Regarding the performed studies on DV, we can refer to Pennati et al, (Pennati, Migliavacca, Dubini, Pietrabissa, & de Leval, 1997) who studied the hemodynamic changes across the human DV using both mathematical and clinical methods.

Jatavan et al (Jatavan, et al., 2016) studied the hemodynamics of isolated absent DV. The mathematical models used information from ultrasound techniques to study blood flow in the UV and DV.

On the other hand, computational fluid dynamics is a useful method to solve the governing equations of blood flow in the cardiovascular system. It is used to simulate the hemodynamic changes in the whole cardiovascular system and investigate the abnormalities. It has also been used to study the patterns of blood flow in UV and DV.

In previous research, the hemodynamics of UV/DV was studied based on a viscoelastic model and obtained the velocity, pressure, and shear stress variations1. The present study investigated the main hemodynamics parameters of blood flow in UV/DV using a model of UV/DV to understand the physiology of the fetal blood circuit. The obtained results were in good agreement with clinical/experimental literature. It is established that the hyper elastic model of UV/DV vein is more conformed to the experimental data.

2. MATERIALS AND METHODS

Presented here is an FSI model to simulate the DV with rigid and non-rigid wall boundaries using Doppler imaging data. The four different material properties for UV, consisting of a rigid model, elastic and viscoelastic ones were investigated. The process of specimen preparation circumferential testing method has been explained in our previous study. Regarding the uniaxial testing method, it used specimen 12 and performed the stress relaxation testing. The uniaxial tensile-test machine, consisting of a fixed and movable jaw, is shown in Fig. 1. We used 3D-Solid-Quadratic shell elements for our meshing system. We used a shell layer which its thickness was 0.5 mm. The blood flow was as follows:

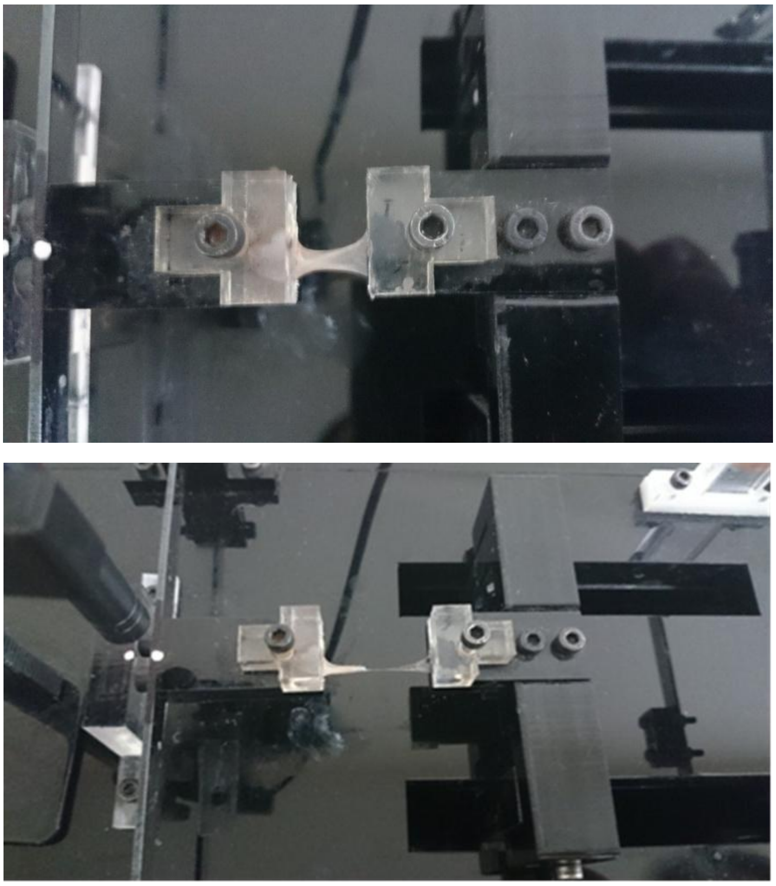

Figure 1. UV specimen under uniaxial test (above) and UV during axial testing just before tearing(down)

Newtonian, Incompressible, laminar and homogeneous.
The blood viscosity, dynamics, was μ = 0.004kg/m per sec, and blood was also considered with flexible walls. The density of blood vessels and blood were assumed to be 1200 and 1060 kg/m3. Moreover, the ratio of Poisson was assumed to be 0.49991. The coefficients of Ogden material were calculated by a nonlinear optimization method, where their consistency was checked by relevant data. Then, umbilical vein model, was made in accordance with the samples' anatomical data.

The software used for model meshing and other simulations including a finite element model was the commercial software ADINA. The obtained result for UV's young module was 2.67 MPa1. The result for circumferential testing was reported as 2.1 MPa (Karimi, Navidbakhsh, Rezaee, & Hassani, 2015). The hyper elastic assumption of UV was according to the Ogden model 1. We have used the FSI study to measure the hemodynamic parameters of UV/DV.

3. RESULTS

The velocity contour for elastic 1 case and similar contour of elastic 2 case is shown also in Fig.2 (a) and Fig.2 (b) Receptively.

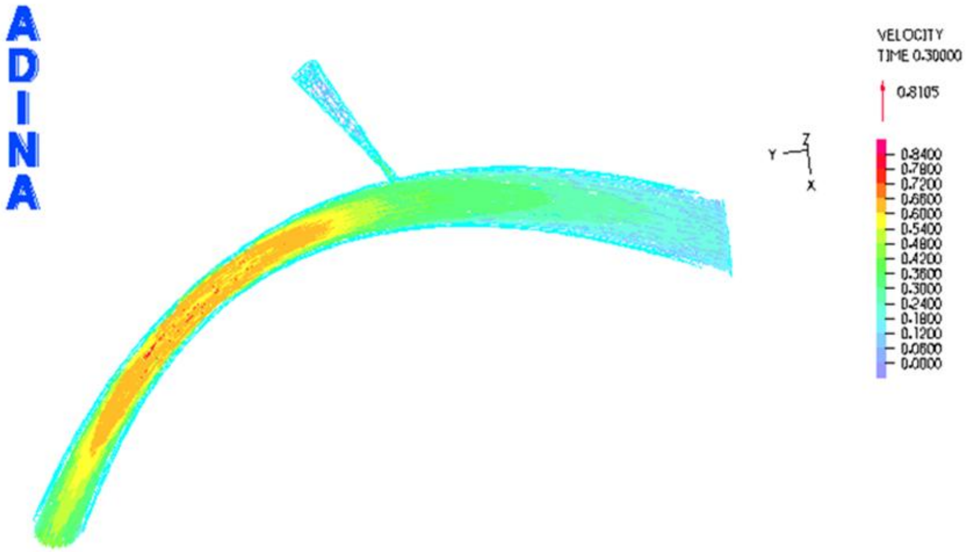

Figure 2 (a)

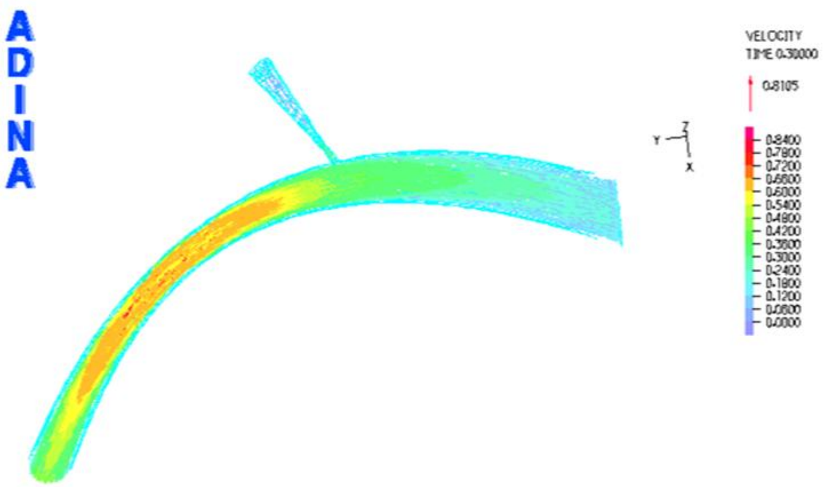

Figure 2 (b).

Figure 2. The velocity contour of UV/DV for elastic 1 and elastic 2 cases.

The pressure contour for elastic 2 case is presented in Fig.3. On the other hand, the pressure contour of hyper elastic case is shown again in Fig.4.

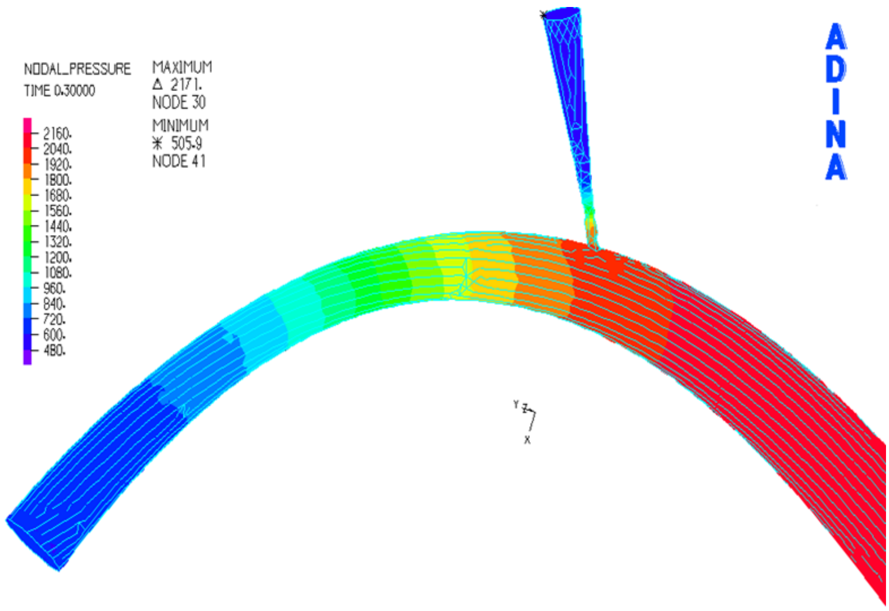

Figure 3 (a)

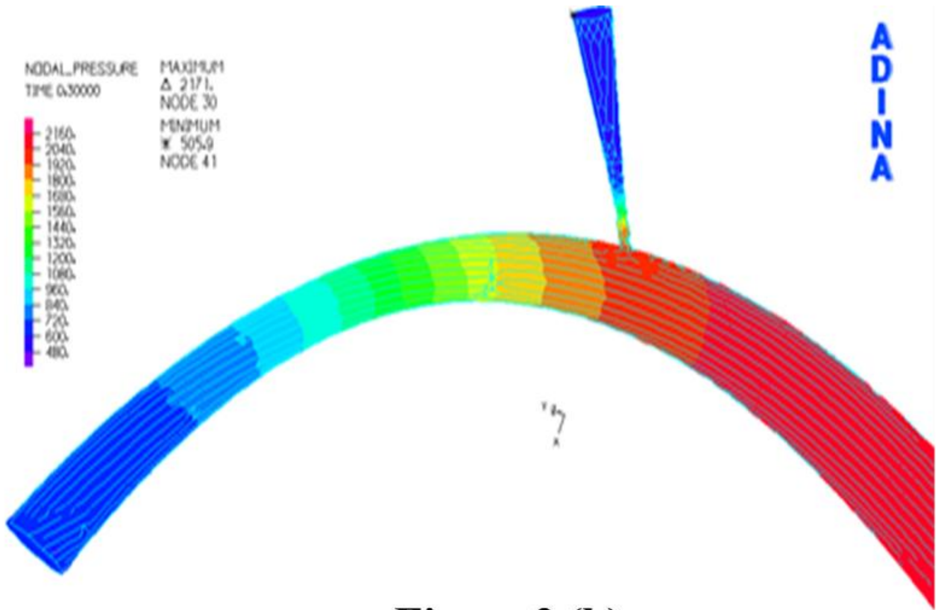

Figure 3 (b).

Figure 3. The pressure contour of UV/DV for elastic.1 case (a) and hyper elastic case (b)

The shear stress contours of elastic 1 and hyper elastic cases are presented in Fig. 4.

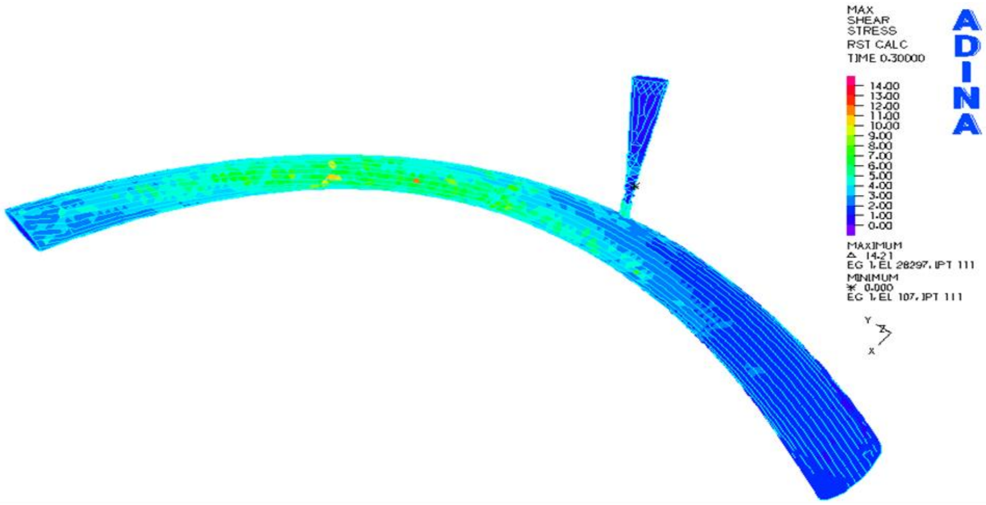

Figure 4 (a)

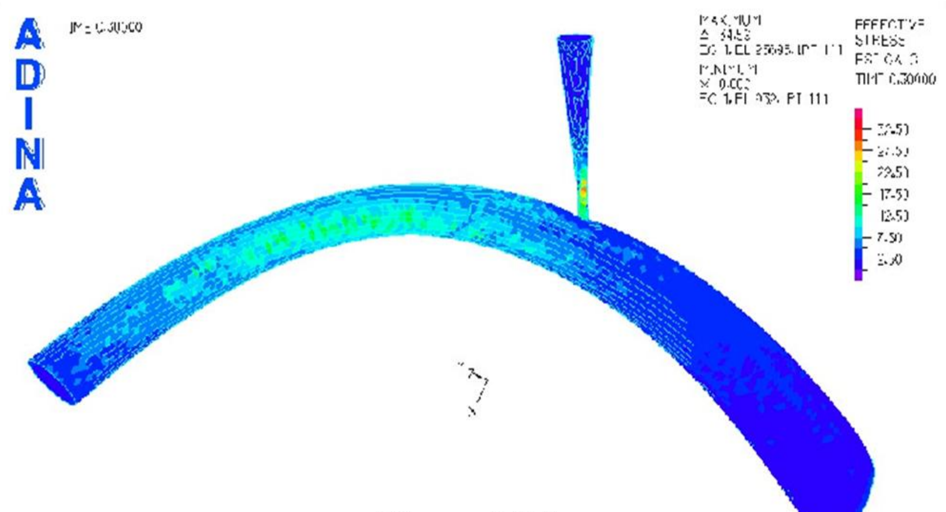

Figure 4 (b).

Figure 4. The shear stress contour of UV/DV for elastic.1 case (a) and hyper elastic case (b)

The blood flow streams with a low-profile velocity in the umbilical vein. Based on the fluid dynamic laws, these types of flows are treated as laminar across the UV and DV. Moreover, when the blood enters DV, its acceleration increases. The velocity profile of UV and DV is somehow skewed to one side. This is because of the geometry of the vessels, the curvatures of the vessels, and the tapering of the vessels. The required driving pressure in DV normally comes from the pressure gradient between the UV and central venous pressure. The exact value of the pressure gradient is still unknown, but could be close to the UV value. The velocity of blood flow at the inlet of DV is high and is a reflection of the pressure gradient, therefore, it may maybe possible to obtain the gradient by the Bernoulli equation.

Table 1. The velocity of blood in the Isthmus area

Material of the vessel	Isthmus velocity(m/s)	Isthmus Shear Stress (Pa)	Maximum Shear Stress (Pa)	Isthmus Pressure (Pa)	Outlet Pressure (Pa)
Elastic. 1 (E=2.1MPa)	0.2416	7.386	14.16	399.761	508
Elastic.2 (E=2.67MPa)	0.2422	7.489	14.21	403.241	508
Hyper elastic (Ogden)	0.3631	9.954	18.93	387.860	508
Rigid	0.16	4.784	13.7	401.781	508

Table 1 represents the velocity magnitude at the entrance of DV (Isthmus) in different cases. As can be seen, the maximum velocity of blood found in hyper hyperplastic model but the minimum velocity was seen in the rigid model. Table 1 also shows the maximum shear stress in UV/DV as well as the shear stress of the Isthmus area in different cases. The highest shear stresses were seen in hyper elastic model where the lowest was found in the rigid vein model. The pressure of isthmus was the highest (400 Pa) in the elastic 2 model, but it was the lowest in the hyperplastic model (385 Pa) according to Table 1.

4. DISCUSSION

The blood flow's hemodynamic variations, UV/DV, are important factors for the diagnosis of different fetal abnormalities. In this study, we performed a comprehensive study to obtain the hemodynamics of blood in UV/DV of the fetus, including velocity, pressure, and shear stresses. Our typical Doppler velocimetry recordings of isthmus area 1 reported the value of 0.34 m/s, which is closely near to our numerical investigations according to Table.1. Our results also presented that the blood flow increased through the ductus venosus, and umbilical veins from about 30 to 70 ml/min and 40 to 360 ml/min throughout the gestation. The reflection of blood velocity wave is seen in the DV, which can modify the velocity in the junctions of the DV as well as the body of the vessel. But there was no significant difference between the inlet and outlet velocity of DV. The elastance and impedance play an important role in the propagation of blood pressure wave and the pulsation of velocity returns to the nature of the vessel and its wall viscosity or the geometry, but it was seen that the pulsation of velocity is a wave in the inlet of DV compared to the outlet.

Another important factor is the length of the DV and UV regarding the impedance and viscous effects. In large arteries and veins, the viscous effects are significant due to the length, but DV and UV are not lengthy; therefore, the velocity waves could be transmitted much more easily. In fact, DV operates as a path connected to UV, and it follows the same fluid mechanics laws as the arteries.

On the other hand, Hellevik et al (Hellevik, Kiserud, Irgens, Stergiopulos, & Hanson, 1998) reported the average of 3 mm Hg for UV and entrance of DV, which is equal to the pressure of 400 Pa. Table 3 results for the isthmus pressures are in good agreement with the mentioned literature. Brown et al (Brown & Boussiotis, 2008) measured the shear stress of umbilical cord cells between 100 to 285 Dyn/cm^2 (10 to 285 Pa). The results of Table 2 are approximately in the range of experimental reported values.

Our results concerning the hemodynamics factors mentioned that the hyper elastic model was more comparable to the relevant clinical and experimental results, with acceptable values.

Our study has some limitations. Firstly, UA is considered a uniform circular cross-section. Secondly, the blood is a homogeneous liquid but Newtonian. The veins will collapse due to negative transmural pressure. Although, we see rarely for UV/DV in fetal life. We have not studied it here. On the other hand, the human fetus's venous circulation and the fetal sheep are similar, therefore, we suggest that similar material properties are considered for the UV and DV. Therefore, we think that the obtained results of hemodynamic parameters could be used for human UV and DV until further human data are available. Finally, the complete comparison of our results was not possible due to differences in methodologies or geometries of the existing models. In this study, we studied the hemodynamics of the blood flow in UV/DV using an elastic model, a hyperplastic and a rigid model. Therefore, we performed a finite element simulation to analyze the models, and the results were obtained for different vein material characteristics.

5. CONCLUSION

In our study, we investigated the main variation of hemodynamics for blood flow in UV/DV, and the obtained results were in good agreement with clinical/experimental literature. We found out that the hyper elastic model of UV/DV vein is more conformed to the experimental data. We believe that the presented models could be helpful for studying the hemodynamic parameters involved in fatal diseases.

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