Fetoplacental Network Hemodynamics Investigations Using Vascular Casting Model

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The placenta handles the exchange of oxygen and nutrients from the mother to the fetus. Normal placentation and placental development are critical for a successful pregnancy. In this study, the placenta is obtained from normal pregnancy and of normal vaginal delivery. The polymeric cast of the fetal vasculature of the full-term placenta is used to perform a numerical simulation of the blood perfusion in the placenta. Vascular corrosion casting is an established method of anatomical preparation that has proven to be an an excellent tool for detailed three-dimensional (3D) morphological examination of normal and pathological microcirculation. Performed numerical simulation indicated that the velocity profiles in the placental vessels are close to parabolic profiles.

Keywords: placenta, corrosion cast, numerical simulation, fetoplacental vasculature

The placenta is an essential organ for normal development of the fetus, and accordingly, inadequate blood perfusion may lead to abnormal fetal development. The placenta handles the exchange of oxygen and nutrients from the mother to the fetus. Normal placentation and placental development are critical for a successful pregnancy. Placental dysfunction is an important cause of pregnancy complications, such as intrauterine growth restriction (IUGR) [1, 2]. Intrauterine growth restriction (IUGR) occurs when the fetus fails to achieve its full growth potential. IUGR is the most important cause of perinatal mortality and morbidity [3, 4].

Clinical diagnosis of fetal condition is performed with Doppler Ultrasonography which may provide more in vivo data on disturbances in the fetoplacental circulation, but the Doppler measurements do not provide information about the status of blood perfusion within the placenta.

A computer model of the fetoplacental circulation has also proven to be a useful tool in the evaluation of the effects of structural changes [5]. Computational simulations of blood flow are very effective in predicting the performance of circulatory systems in normal as well as in pathophysiological states [6-8].

Vascular corrosion casting has proven to be a the an excellent tool for detailed three-dimensional (3D) morphological examination of normal and pathological microcirculation [9, 10]. Also, the geometry provided by these vascular casts can be further used to calculate hemodynamics parameter (like pressure drop, wall shear stress-WSS, residence time) in the arterial vascular bed using computational techniques.

The aim of this study was to characterize the morphological vascular features and to assess the associated changes blood hydrodynamics in the placental vascularization in different placenta models. The paper are structured in the following manner:

-the first part of this study focuses on the microvascular investigation of the placenta casts for different placenta types and cast models;

-in the second part of this study we performed a quantitative analysis of the blood flow dynamics and its repartition in placenta using computational fluid dynamics (CFD) methods.

From a biological point of view, casting represent the filling process of the anatomical and/or pathological spaces with different fluidized material to reproduces a three-dimensional replica of the investigated space [11, 12]. Corrosion refers to the removal of the tissue surrounding the cast hollow space.

Casting materials can use for [11]: (1) preparation of specimens for research; (2) preparation of specimens for anatomical teaching; (3) preparation of specimens for preservation.

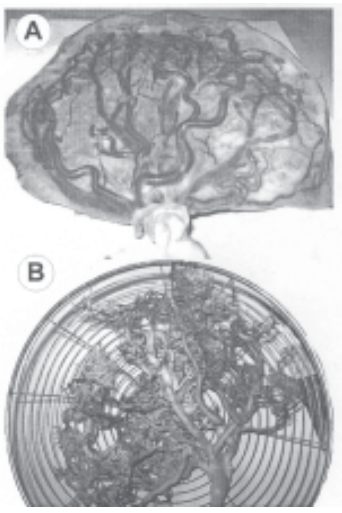

Fig. 1. Placenta with marginal umbilical cord insertion. Injection with Ago II plastic compound (product based on nitrocellulose E950) was injected in umbilical arteries and vein. Placental cast shows a complex anatomical spatial relationships between vasculature and a fine structures of the terminale villi

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Casts for research facilitated visualization of the 3D organization of structures and their position in normal and pathological conditions. At microscopic levels casting enhanced investigation of fine structures such as capillaries in the arterial tree.

The vascular corrosion casting has been applied to the study of the vascular pattern of normal organs and tissues, pathological processes, and developing structures [13, 14]. Vascular casts from organs and tissues are obtained by producing casts from vessel lumens with a low-viscosity resin, followed by corrosion with an alkaline solution of the tissue surrounding the polymerized resin [15].

The materials for vascular casting developed by manufacturers should meet the following criteria [16]: they have to be toxic; should not cause morphological alterations in the tissues and blood vessels; must have low viscosity; should polymerize within 3 to 15 min; must not undergo shrinkage during polymerization; must allow micro-dissection; should be resistant to the corrosion process; must maintain the structural configuration while drying; and must allow a quantitative analysis (figs. 1 and 2).

Corrosion is the dissolution of tissues surrounding the cast, and is performed by sodium hydroxide (NaOH) and potassium hydroxide (KOH) [13, 15, 17]. For the corrosion to be faster, the solution must remain at a constant temperature of 40^0C [13, 18].

Experimental part

The study used placenta obtained from the normal pregnancy of vaginal delivery (Age: 31 years old, parity 1, and gestation 38 weeks). The pregnancy is normotensive (mean systolic pressure, 110 mmHg; mean diastolic pressure, 66 mmHg). Birth weight 2560g. The basal tone in chorionic plate arteries are 2.1 ± 0.3 kPa. After the delivery of the baby and the placenta (fig. 2a), the Intra Placental (IP) vascular tree was cleared of blood cloth. The commercial polymer mixture was injected into to artery to achieve a vascular model demonstrating the Intra placental branching pattern (fig. 2b).

The polymeric cast of the full-term fetal placenta provided information on the geometry of the umbilical, chorionic and intra placental vessels. The feto-placental vasculature is a complex branching network of arteries and veins. The umbilical arteries and vein branch off at the insertion in the placenta into 6–8 generations that traverse over the whole chorionic plate (fig. 2b).

The branching pattern of the chorionic vessels was defined as disperse for a branching network that courses from a central cord insertion, and as magistral for branching vessel that courses from a marginal cord insertion to the opposite edge [19]. The chorionic vessels are relatively large and much smaller vessels branch off this network at almost right angles and penetrate into the placenta toward the maternal side to constitute the IP vessels.

Classification of branching networks in bioengineering and physiology was done by using the definitions of dichotomous and monopodial patterns [20-23]. The dichotomous pattern defines a symmetric network that repeatedly branches into two fairly similar daughter vessels. The monopodial pattern defines a main long mother tube with a fairly constant diameter while small diameter daughter tubes branch off to the sides.

Computational fluid dynamics analysis of the placental blood flow

Several recent works investigated the effect of blood rheology assumptions on the axial velocity profiles in bifurcation models founding a satisfactory agreement between the non-Newtonian viscosity and Newtonian viscosity flow based on a characteristic shear rate [24].

The laminar model was used in this study to solve the time dependent 3D Navier-Stokes equations for an incompressible viscous fluid. The blood flow is simulated using the commercial available CFD software Ansys Fluent 6.3 package [25]. The imposed boundary conditions intended to reflect the physiological values obtained by Doppler ultrasonography (fig. 3). Velocity in the umbilical artery before placental insertion was assumed to be 0.32 m/s similar to the physiological values [4].

The velocity profiles in the main artery are generally of a parabolic shape with peak velocities of about 0.25 m/s (figs. 3 and 4). In this case, the flow is periodic and mono-directional (i.e. no negative flow), and we used at inlet velocity.

We investigated three different meshes for the computational domain. The number of cells varied between 860.000 and 2.000.000. The mesh was refined in the near-wall region. The blood flow near to the wall was modeled using the standard wall function in the current simulations.

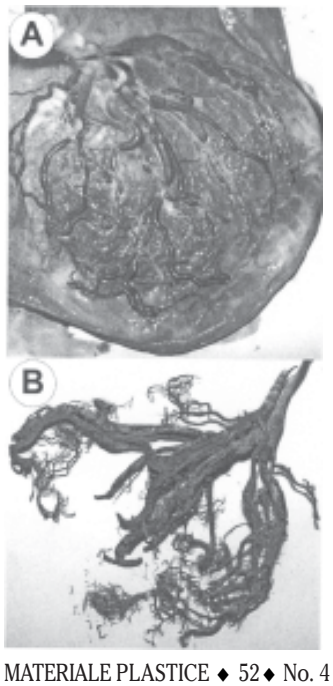

Fig. 2. Placenta with the colored dental polymer mixture in the arterial and venous system before the surrounding tissue has been dissolved by hydrochloric acid. The cast of the placenta with a marginal cord insertion and dominant dichotomous bifurcations. Resulted corrosion cast are fragile and break off easily

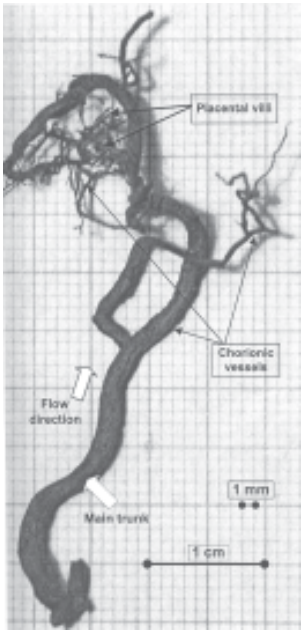

Fig. 3. Cast model of the first placental artery bifurcation

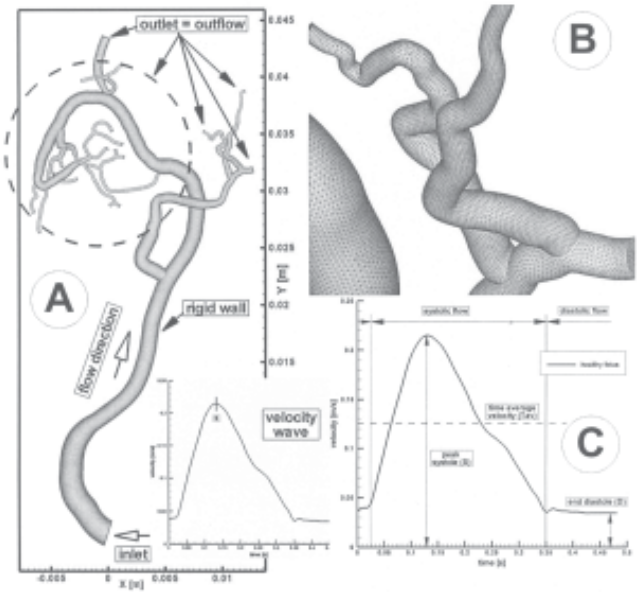

Fig. 4. Tree-dimensional reconstruction of the placental artery cast model and boundary conditions. Computational domain discretization. Reconstructed umbilical artery velocity waveform profile at the insertion in the placenta. S – peak systolic velocity, D – end diastolic velocity, Tav – time average velocity

Results and discussions

In the present investigation, pulsatile blood flow model in the umbilical artery was used to study the contribution of anatomical and physiological parameters to the variability of the fetal blood flow rate. The three-dimensional (3D) geometry of the first placental bifurcation representing a fundamental dichotomous branching unit (fig. 3 and 4) extracted from the representative placental cast (fig. 2b) are analyzed using computational fluid dynamics techniques.

The diameters of the first dichotomous arterial branches ranged from 1.8 to 5.6 mm, and those of the last dichotomous generations near the margins from 0.12 to 1 mm (fig. 2b) with is in good correlation with observation of Gordon [26]. The angle between ramifications and main branches ranging from 60 to 90° (figs. 3 and 4). The reconstruction technique adopted in the present study was based on measurements of the 3-D cast model. Moreover, proper boundary conditions were imposed on the computational model to avoid influences on the velocity profiles calculated at the region of interest. The computational simulation was conducted for unsteady fetal blood flow in the first bifurcation of the dichotomous branching network of the chorionic arteries (figs. 5 and 6).

The primary effort is to provide a comprehensive understanding of the characteristics of the flow fields through the placenta. In this work, the flow fields in the placental vascularization are numerically studied in detail for the patient-specific placenta. The dynamics of the flow are revealed by the streamline and velocity fields (figs. 5 and 6). The propagation of blood flow along the fetal arterial tree relates to complex interactions between anatomical, physiological, and rheological parameters [27].

From the point of view of the biomedical application, a vessel bifurcation is a place where many diseases start. We are not able to change the geometry of vessel bifurcation, but the understanding of blood flow in it helps us to cure better vessel diseases or to anticipate them.

At a bifurcation the flow in the upstream parent vessel divides into the two daughter vessels so as to bring high velocity blood at the center of the parent vessel in close proximity to the wall of the flow divider [28].

Fig. 5. Longitudinal velocity vector field in the first bifurcation region. At a bifurcation the flow in the upstream parent vessel divides into the two daughter vessels so as to bring high velocity blood at the centre of the parent vessel in close proximity to the wall of the flow divider

Fig. 6. The hemodynamic field in different cross sections of the first bifurcation network at the time T=0.12s (corresponding to the peak systole, see figure 4). Contour plot of the velocity vector field shows a close to parabolic profiles in all arteries

Conclusions

Alterations in pregnancy hemodynamic start early in pregnancy and are maintained to the third trimester. Computational simulations of blood flow have been shown to be very effective in predicting the performance of circulatory systems in normal as well as in patho-physiological states.

The computational results together with the echo-Doppler measurements allowed us to quantify the uterine blood flow rate in pregnant women and its repartition in placenta branches.

The clinical application of simulation-based medical planning techniques is a new approach to treatment planning. In the case of placenta disease, these methods could enable physicians to develop the patient-specific treatment plans to improve blood flow.

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