Investigation of Chorionic Artery Bifurcation Using Micro Vascular Casting Model

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Vascular corrosion casting was used for detailed three-dimensional (3D) morphological examination of the normal placental microcirculation. This paper is focused on blood flow dynamics in the branching microvessels of the human placenta. The 3D computational analysis of fetal blood flow in the placenta was performed on simple branching networks of the chorionic and Intra placental arteries. Numerical simulation results can evaluate the correlation between the placental vessels tree distribution and the fetal blood flow in the chorionic plate.

Keywords: placenta artery bifurcation, placenta vasculature, corrosion cast, numerical simulation

Normal fetal development is largely dependent on adequate placental blood perfusion. The human placenta vasculature has been investigated post delivery using different techniques such as injection of dye, polymer casts, angiography and microscopy [1-3].

The examination of the placental vasculature, from the umbilical cord insertion to the smallest segment of the villus tree, is important into assessing placental pathologies associated with intrauterine growth retardation and pre-eclampsia [4-7].

It is known from studies of the bifurcation that secondary motion, flow separation and shear layers are generated which give rise to the unsteady and periodical flow features [8, 9].

Therefore, in repeatedly branching channel flow separation and secondary motions in the branches might induce in addition to preferential flow partitioning due to skewed flow profiles [10].

Vascular corrosion casting has an excellent tool for detailed three-dimensional (3D) morphological examination of normal and pathological microcirculation [11-13]. The geometry provided by these vascular casts can be used to calculate hemodynamics parameter (pressure drop and velocity field and distribution) in the placental arterial vascular bed using computational techniques [14, 15].

Vascular casts facilitated visualization of the 3D organization of the structures of the placental tree both in normal and pathological conditions and enhanced investigation of fine structures such as capillaries and villi in the arterial tree. The vascular corrosion casting has been applied to the study of the vascular pattern both of normal and pathological organs [16-18]. Vascular casts from the placenta are obtained by producing casts from vessel lumens with a low-viscosity resin, followed by corrosion of the tissue surrounding the polymerized resin [19].

The materials for vascular casting should meet the following criteria [20]: should not cause morphological alterations in the blood vessels; they have to be toxic; should polymerize within 3 to 15 min; must have low viscosity; must not undergo shrinkage during polymerization and must allow a quantitative analysis.

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

-the first part of this study focuses on the microvascular investigation of the placenta casts (ramification, arteries diameter, artery bifurcation angle);

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

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, and the birth weight was of 2560 g. After the delivery of the baby and the placenta (fig.1a), the intra placental (IP) vascular tree was cleared of blood cloth (fig. 1b). The commercial dental polymer mixture was injected into to artery to achieve a vascular model demonstrating the intra placental branching pattern (fig.1c).

The polymeric cast of the full-term fetal placenta provides information of the geometry of the chorionic and into placental vessels (figs.1, 2a and 3a). The fetoplacental vasculature is a complex branching network of arteries and veins (figs.1 and 2). The polymeric casts can provide a very fine details regarding the structure of the placental capillaries and villi (figs. 2a and 3a).

Classification of branching networks in bioengineering and physiology was done by using the definitions of dichotomous and monopodial patterns [21-23]. 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 relatively constant diameter while small diameter daughter tubes branch off to the sides

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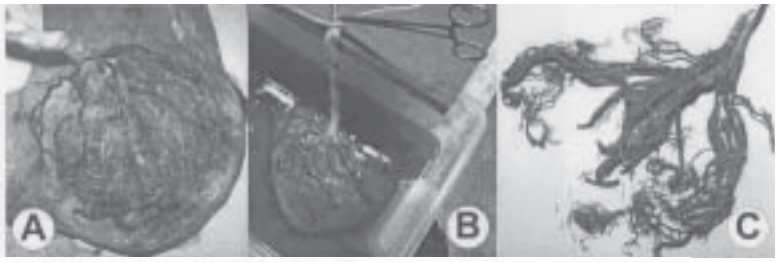

Fig. 1. Placenta with the colored dental polymer mixture in the arterial and venous system. A) Placenta with a marginal cord insertion and dominant dichotomous bifurcations. B) Placenta preparation for casting process after delivery. C) The placental cast shows a complex anatomical spatial relationship between vasculature and fine structures of the terminal villi

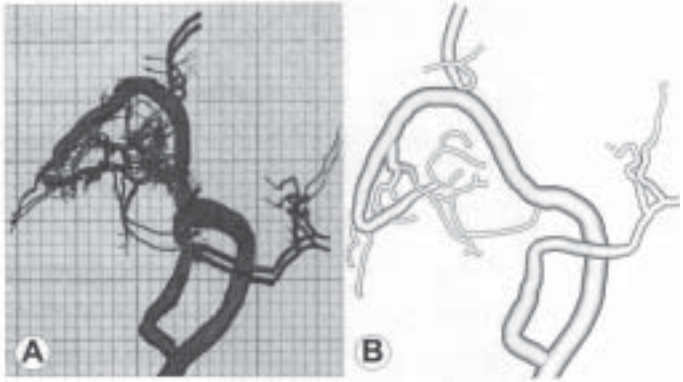

Fig. 2. Details regarding the investigated first arterial branches. A) Polymer casts show the complex geometry of the arterial tree including capillaries and villi. B) Three-dimensional (3D) reconstruction of the casts for numerical investigation

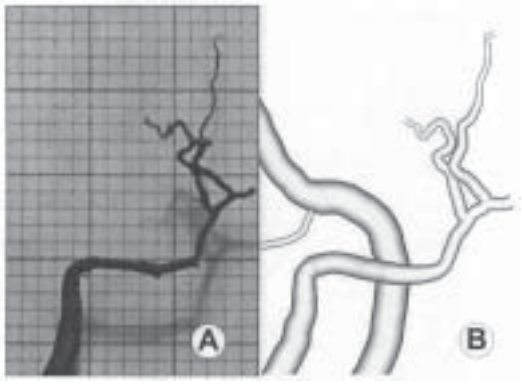

Fig. 3. Details regarding the marginal part of the investigated artery branches. A) Casts of the terminal capillary (D=0.4 mm) and terminal villi (D=0.1 mm). B) Reconstruction of the computational domain. As can see the 3D reconstruction of the artery are in good agreement with the real artery geometry

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 [24].

Computational fluid dynamics analysis of the placental blood flow

The fluid dynamic simulations in the patient-specific placenta model were performed under the assumptions of Newtonian fluid for the blood [25]. The scope of the present study was to assess the velocity distributions and profiles in the placental arterial bifurcations (fig. 4).

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 [26]. The imposed inlet boundary conditions intended to reflect the physiological values obtained by Doppler ultrasonography (fig. 5 and table 1). Velocity in the umbilical artery before placental insertion was assumed to be 0.25 m/s similar to the physiological values [4].

The velocity profiles in the artery are generally of a parabolic shape with peak velocities of about 0.25 m/s (fig. 5). For investigated case, the flow is periodic and mono-directional (i.e. no negative flow).

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.

As usually adopted by most previous investigations, the distension of the blood vessel wall is neglected [14, 15]. The outlet boundary condition the pressure was defined to be 0 Pa (fig. 6). The fluid is incompressible having a dynamic viscosity (μ) of 0.00408 Pa.s and a density (ρ) of 1050 kg/m^3.

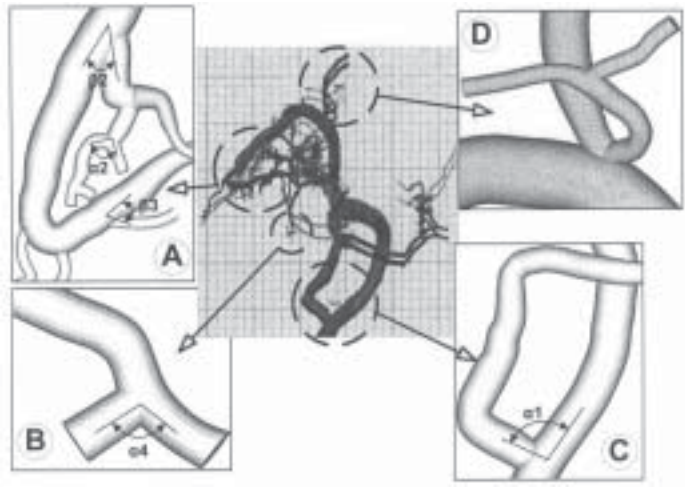

Fig. 4. Three-dimensional reconstruction of the placental artery cast model. Visualization of the bifurcation angle along the main artery branches (A, B and C). Computational domain discretization (D)

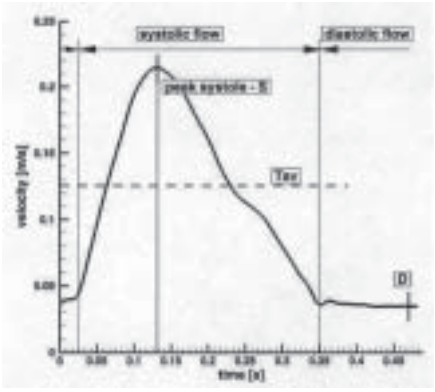

Fig. 5. Physiologically realistic velocity waveform based on flow waveforms acquired with an intravascular ultrasound Doppler probe at the umbilical artery insertion in the placenta [4]. S – peak systolic velocity, D – end diastolic velocity, Tav – time average velocity

Table 1
BLOOD FLOW CHARACTERISTICS

No	Velocity [m/s]	Flow rate [µl/min]	Re number [-]
1	0.034	1000	23.80
2	0.0619	1800	42.856
3	0.102	3000	71.42
4	0.187	5500	130.95
5	0.255	7500	178.57

Table 2
AVERAGE DIAMETERS OF THE INVESTIGATED ARTERIAL SEGMENTS

Artery segment	Artery Diameter [mm]
1-1	2.29
1-2	1.52
1-3	1.48
1-4	1.29
1-5	1.3
1-6	0.92
1-7	0.59
1-8	0.25
1-9	1.42
1-10	1.21
1-11	0.51
1-12	1.16
1-13	0.81
1-14	0.31

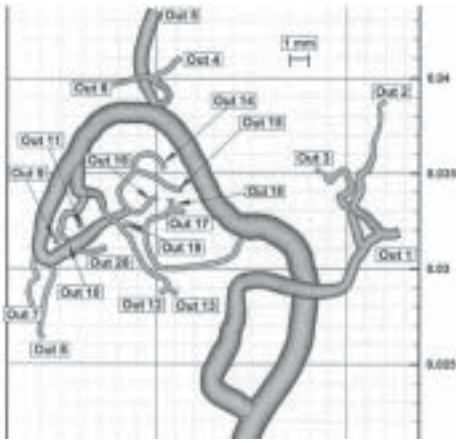

Fig. 6. Pressure boundary condition was used at the each outlet sections of the investigated placental arterial tree (20-th outlet sections corresponding to marginal part of the placenta (fig.1).

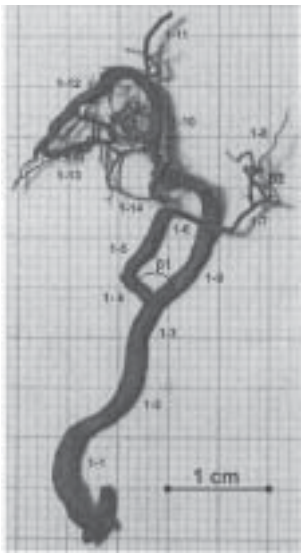

Fig. 7. Investigated artery segment notation and measurements

Results and discussions

In normal placentas, there were many complex and thin branches, originating from primary and secondary branches and representing the branches of the villi. The space between these capillary networks corresponded to intervillous space (figs.1 and 6).

The diameter of all the vessels was measured with a digital caliper with an accuracy of ± 10 µm. This data was used to compute the diameter ratio between the daughter (Dd) and the mother (Dm) vessels for further non-dimensional analysis of the anthropometry of the chorionic vessels.

In cases of marginal cord insertion (fig. 7), the first 1–3 generations bifurcate in a dichotomous pattern, whereas the rest of the bifurcations follow the monopodial pattern.

Measurements of the chorionic vessels showed that the first dichotomous bifurcation of the umbilical arteries was about 1 cm from the insertion (fig. 1) and the second one 2–4 cm from the insertion (fig. 1). The daughter-to-mother diameter ratio (Dd/Dm) for the first bifurcations ranged from 0.6 to 0.8 with an angle of 70–100° between the daughter arteries (fig. 7). The daughter-to-mother diameter ratio of the ramifications near to the placenta margin was 0.1–0.3 (fig. 7 and table 2).

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 placental bifurcation (fig. 7) extracted from the representative placental cast (fig. 1) eas analyzed using computational fluid dynamics techniques.

The diameters of the investigated arterial branches was 2.3 mm, and those of the last generations near the margins was 0.3 mm (fig. 7 and table 2) with is in good correlation with observation of Gordon [23]. The angle ramifications and main branches ranging from 60 to 90° (figs. 4 and 7). The reconstruction technique adopted in the present study was based on measurements of the 3-D cast model. The computational simulation was conducted for unsteady fetal blood flow in the first bifurcation of the branching network of the chorionic arteries (fig. 6).

The primary effort is to provide a comprehensive understanding of the characteristics of the flow fields through the placenta arteries branches. In this work, the flow fields in the placental vascularization are numerically studied in detail for the patient-specific placenta. The dynamics of the blood flow are revealed by the velocity field distribution in the arteries bifurcation and the arteries end (fig. 8 and table 3). The propagation of blood flow along the fetal arterial tree relates to complex interactions between anatomical and physiological aspects of the placental vascularization [27].

One can see in figure 8 the dynamic behavior of the separation region in the daughter branches of the first bifurcation influences the distribution gravely in the next bifurcation.

Consequently, the main flow region and the shear layer between recirculation region and main flow is shifted to the rightward wall that seems to be coupled with a reduction of mass flux through the branch. The enlarged separation region in branch 2 (between outlet 19 and outlet 18, in fig. 8) at the outside wall forces the main flow to enter branch 3 (between outlet 17 and outlet 18 in fig. 8). However, the main flow in branch 2 arrive in the outlet section 19 as a compact jet and a lower speed flow will travel in direction of the outlet sections 17 and 18 behind the dividing edge in branch 2 (fig. 8).

From the point of view of the biomedical application, a vessel bifurcation is a place where many diseases start [6, 7, 23]. We are not able to change the geometry of vessel

Table 3
HEMODYNAMICS PARAMETERS AT THE PEAK SYSTOLE (TIME T=0.13 S,FIG. 5)

Section	Artery diameter D [mm]	Blood velocity V [m/s]	Flow rate Q [ml/min]
inlet	2.319	0.2014	54.155
out-01	0.549	0.8117	-12.199
out-02	0.247	0.1157	-0.395
out-03	0.247	0.2218	-0.760
out-04	0.307	0.2485	-1.275
out-05	0.809	0.6316	-20.061
out-06	0.307	0.2296	-1.192
out-07	0.307	0.3315	-1.714
out-08	0.307	0.2843	-1.452
out-09	0.307	0.3659	-1.897
out-10	0.307	0.2688	-1.365
out-11	0.307	0.6849	-3.610
out-12	0.307	0.0999	-0.507
out-13	0.307	0.103	-0.518
out-14	0.307	0.1145	-0.622
out-15	0.307	0.1236	-0.627
out-16	0.307	0.3683	-2.018
out-17	0.307	0.0371	-0.189
out-18	0.307	0.0462	-0.233
out-19	0.307	0.1428	-0.733
out-20	0.307	0.5297	-2.788

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, 29].

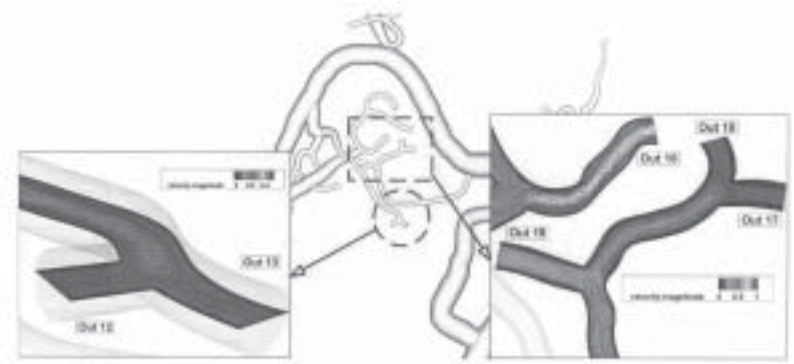

Fig. 8. Longitudinal velocity vector field in the different bifurcation region. At a bifurcation the flow in the upstream parent vessel divides into the two daughter vessels so as to bring high velocity blood at the centre of the parent vessel in close proximity to the wall of the flow divider.

Conclusions

In this paper, the fetal blood flow in complex branching patterns of the placenta arterial tree was studied using the three-dimensional computational analysis.

The chorionic vasculature anthropometry depends on the location of the umbilical cord insertion. Also, the chorionic arteries distribute fetal blood flow over the whole surface of the placenta chorion to ensure adequate perfusion of the placental volume [23].

Alterations in hemodynamic pregnancy start early in pregnancy and maintained to the third trimester [4, 24]. 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 pathophysiological states.

In conclusion, computational analysis of blood flow in the placenta branching tree can evaluate the correlation between the placental vessels distribution and blood flow in the chorionic plate.

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