ANALYSIS OF FETO-PLACENTAL VASCULATURE AND BLOOD CIRCULATION

Zoya Gordon[1], David Elad[1], Yenon Hazan[2], Ariel J. Jaffa[3], Osnat Eytan[3]

[1]Department of Biomedical Engineering,
Faculty of Engineering, Tel Aviv University,
Tel Aviv 69978, Israel

[2]Department of Obstetrics and Gynecology,
Kaplan Medical Center,
Rehovot 76100, Israel

[3]Ultrasound Unit in Obstetrics and Gynecology,
Lis Maternity Hospital, Tel Aviv Sourasky Medical Center,
Tel Aviv 64239, Israel

INTRODUCTION

The feto-placental blood circulation within the placenta vasculature is responsible for producing a healthy baby by delivering the required oxygen and nutrients. It originates at the insertion of the two umbilical arteries and terminates at the umbilical vein. The umbilical arteries are usually fused together via Hyrtl's anastomosis just proximal to the umbilical cord insertion [1]. In the placenta the relatively large arteries and veins that branch off the umbilical vessels run in the chorion plane with the arteries always overlaying the veins. The branching pattern of the chorionic vessels was defined as *disperse* for the dichotomic network and *magistral* for the monopodial system (e.g., small branches from single stem similar to plants). Smaller arteries branch off from the chorion arteries towards the maternal side to constitute the stem villi that perfuse the cotyledons [2]. Placenta insufficiency due to high placental vascular resistance may result in a small for gestational age baby which is prone to higher risks of morbidity and mortality. Doppler ultrasonography is commonly utilized in prenatal care to measure flow velocity waveforms from fetal or maternal blood vessels for assessment of fetal condition [3]. This information, however, provides only an empirical estimation of peripheral resistance to umbilical blood circulation. The existing mathematical models for simulations of blood flow in the placental vasculature are mostly simplified networks of resistors and capacitors that represent the vessel's resistance and compliance, respectively [4]. In order to extend the scope of prenatal care, we investigated structure of placental vasculature from cast models and have started to develop physical models of placental fetal circulation.

METHODS

Cast models of the placental vasculature were produced by placental plastination with dental casting materials. The casting material was a mixture of 4 gr powder diluted with 20 ml liquid (Unifast Trad, GC Dental Co., Japan) and a colored ink. Human placentas were recruited within 5 min after delivery. The placenta was perfused with a solution of saline and 5,000 units/ml of heparin sulfate via the umbilical vessels in order to drain the blood from all the placenta. The casting material was injected via the three umbilical vessels (e.g., 2 arteries and 1 vein) by separate syringes, each filled with the casting material mixed with a different color. The placenta filled with the casting mixture was stored in the refrigerator for four days to allow for hardening of the casting material. Then, the whole organ was immersed in a solution of 60% KOH and distilled water to erode all the biological tissues that surround the hardened cast. The dimensions of diameters, lengths and branching angles of the chorionic and some intra-placental vessels were measured with a digital caliper.

The three-dimensional computational analysis of fetal blood flow within placental units was performed on simple dichotomous and monopodial branching networks of the chorionic arteries with intra-placental arteries that branch off at angles of 90^0 with the chorionic plane (Fig. 1). The geometry and mesh for the dichotomous network, which was constructed by GAMBIT, is demonstrated in Fig. 2. The analysis of blood flow pattern in this complex geometry was conducted by implementing the finite volume numerical software of FLUENT for no-slip conditions on the walls.

RESULTS AND DISCUSSION

Plastination of placental vasculature was performed from 10 placentas that were obtained immediately after delivery of healthy babies weighting 2.7 to 3.9 Kg on weeks 38-41 of gestation. The resulted casts provided a clear image of the whole vasculature including the umbilical vessels, chorionic vessels, stem, intermediate, mature and terminal villi (Figs. 3). Hyrtl's anastomoses were observed in almost all the placentas and resulted the mix up of the casting material of different colors that were injected in the two umbilical arteries. The range of diameters of the umbilical arteries and veins at the placenta insertion was 2.30-4.37 mm and 4.46-8.0 mm, respectively. Within the chorionic plate, the arteries always overlaid the veins. The chorionic vessels spread from the insertion with multiple bifurcations of reduced diameters (e.g., 6 to 8 generations) until reaching diameters less than 1 mm at the chorionic plate margin. The disperse pattern was

assigned to the dichotomic branching pattern in which the ratio of daughter-to-mother diameter was larger than 70%, and the averaged ratio between the daughter tubes diameter was higher than 50% (Fig. 3, left). The magistral pattern was assigned to a monopodial network in which the main (i.e., stem) vessel represented a very small reduction in diameter (e.g., less than 10% along the chorionic plate) with at least three branches from the stem vessel with a ratio of branch-to-stem diameter smaller than 40% (Fig. 3, right). The disperse pattern was observed when the umbilical cord insertion was in the chorionic plate center, while the magistral pattern appeared when the insertion was near the chorionic plate margin. However, in many placentas both patterns existed; the first 3-4 generations are extended in a dichotomous pattern from the cord insertion and continued in the monopodial branching pattern. The main intra-placental vessels branched off the chorionic vessels at angles of 60° to 90°, but with very small diameters; the ratio of daughter-to-mother diameters may be as low as an order of magnitude (Fig. 4).

The computational simulation was conducted for steady fetal blood flow in the simple dichotomous branching network of the chorionic arteries (Fig. 2). Based on measurements from the cast models, the diameters of the main chorionic artery and the intra-placental arteries were chosen to be 2 mm and 0.4 mm, respectively. The inlet velocity to the main artery was assumed to be 0.32 m/s similar to existing clinical data. The resulted predictions in the chorionic plane of the main chorionic artery and proximal to the first bifurcation showed a parabolic distribution with a peak velocity of 0.31 m/s (Fig. 5, left). However, peak velocities in the intra-placental arteries were of an order of magnitude higher (e.g., 1.67 m/s in the first branch of the model, Fig. 5 right) as expected due to the significant reduction in vessel cross-section. The peak velocity distal to the first chrionic bifurcation was 0.24 m/s, similar to clinical data.

SUMMARY

The technique for plastination of the placental vasculature with dental casting material provided detailed information on the very delicate structures within the placenta cotyledons. The main observation was the relatively small diameter ratio between the main intra-placental arteries and their parent chorionic vessel, which is expected to impose a significant resistance to the cotyledons blood perfusion. Knowledge of the governing parameters of feto-maternal circulation both in normal and pathological placentas is essential for developing reliable diagnostic and monitoring techniques.

REFERENCES

1. Ullberg U, Sandstedt D, Lingman G. Hyrtl's anastomosis, the only connection between two umbilical arteries. A study in full term placentas from AGA infants with normal umbilical artery blood flow. *Acta Obstet Gynecol Scand*, 80: 1-6, 2001.
2. Benirschke K, Kaufmann P. *Pathology of the Placenta*, Springer-Verlag, New York, pp 342, 1995.
3. Kingdom JCP, Burrel SJ, Kaufmann P. Pathology and clinical implications of abnormal artery Doppler waveform. *Ultrasound Obstet Gynecol*, 9: 271-286, 1997.
4. Thompson RS, Trudinger BJ. Doppler waveform pulsatility index and resistance, pressure and flow in the umbilical placental circulation: An investigation using a mathematical model. *Ultrasound Med Biol,* 16: 449-458, 1990.

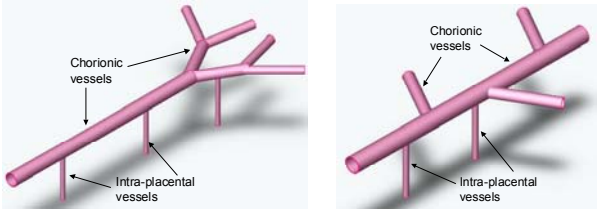

Figure 1. Dichotomous (left) and monopodial (right) branching networks.

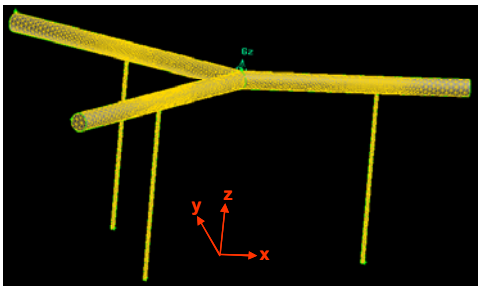

Figure 2. The model for a dichotomous unit of chorionic arteries.

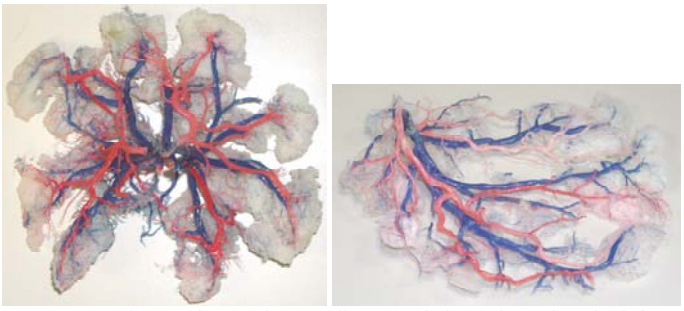

Figure 3. Placental vasculature: disperse (left) and magistral (right).

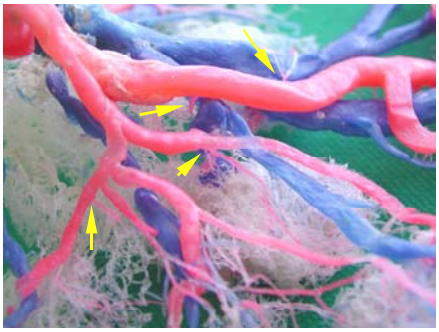

Figure 4. Intra-placental arteries that branch off the chorionic arteries.

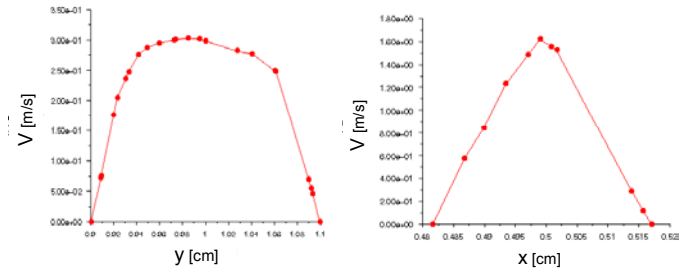

Figure 5. Velocity magnitude in the chorionic (left) and intra-placental (right) arteries.