Ultrasound Obstet. Gynecol. 2 (1992) 300–305

Doppler assessment of the normal early fetal circulation

T. W. A. Huisman, P. A. Stewart and J. W. Wladimiroff

Department of Obstetrics and Gynecology, Academic Hospital Rotterdam-Dijkzigt, Rotterdam, The Netherlands

Key words: TRANSVAGINAL DOPPLER ULTRASOUND, EARLY FETAL BLOOD FLOW

ABSTRACT

Combined transvaginal and transabdominal Doppler ultrasound allows recording of fetal intra- and extracardiac flow velocity waveforms in late first- and early second-trimester pregnancies. At 10–12 weeks, end-diastolic flow velocities were always absent in the fetal descending aorta and umbilical artery, but were present in over half of the intracerebral artery waveforms. The pulsatility index in the three vessels decreased significantly with advancing gestational age, suggesting a reduction in fetal and umbilical placental vascular resistance. Peak velocities during atrial contraction (A-wave) were nearly twice as high as those during early diastolic filling (E-wave), reflecting low ventricular compliance. Continuous forward flow in the umbilical vein was associated with a pulsatile systolic and diastolic forward flow in the ductus venosus. Retrograde flow was only present in the inferior vena cava.

INTRODUCTION

Since the introduction of Doppler ultrasound, a host of reports has appeared on human fetal and placental blood flow under normal and abnormal circumstances. Most studies have put emphasis on flow velocity waveform characteristics, recognizing the limitations of diagnostic ultrasound in performing volume flow determinations. Flow velocity waveform studies have demonstrated the presence of a low fetal placental vascular resistance in normal late second- and third-trimester pregnancies[1,2], as well as reproducible changes in vascular resistance at the fetal trunk and cerebral levels in intrauterine growth retardation[3–5].

With the advent of transvaginal Doppler ultrasound, it became feasible to examine the maternal uterine and fetal circulation as early as the first trimester of pregnancy. Particularly during the late first- and early second-trimester, marked developmental changes occur both at fetal and placental levels, which should have an impact on fetal cardiovascular performance. The fetal heart rate changes from 170–180 beats/min to 140–150 beats/min with the appearance of beat-to-beat variation most likely resulting from parasympathetic nerve development[6]. At the same time, there is a remarkable differentiation in fetal movement patterns[7]. Furthermore, around 14 weeks a continuous intervillous flow pattern has been observed[8]. This is associated with an abrupt increase of the mean uterine blood flow velocity, which possibly corresponds to the complete dislocation of the trophoblast plugs, allowing uninhibited blood supply to the intervillous space[8].

This paper will present an overview on human fetal cardiovascular research in early pregnancy using non-invasive Doppler techniques.

RECORDING TECHNIQUE

The transvaginal technique results in a closer approach to the fetus and, therefore, allows higher carrier frequencies and thus higher image resolution. Doppler waveform recording may be attempted following visualization of fetal cardiac or extracardiac vessel structures. Color-coded Doppler is helpful in locating arterial vessels, but less so in establishing intracardiac and venous blood flow in early pregnancy. When applying Doppler techniques, energy levels should be taken into account. Energy output levels from the transvaginal Doppler transducer are clearly situated in the lower regions for acoustic output of Japanese and American diagnostic ultrasound equipment[9]. This is determined by the fact that the fetus is closer to the transducer with the transvaginal approach than with the abdominal approach and lower energy levels are required to detect it.

Table 1 The success rate of transvaginal and transabdominal Doppler ultrasound in obtaining fetal flow velocity waveforms relative to gestational age

	Gestational age (weeks)						
	10	*11*	*12*	*13*	*14*	*15*	*16*
Transvaginal scan (%)	100	100	100	60	20	0	0
Transabdominal scan (%)	0	0	0	40	80	100	100

Correspondence: Professor J. W. Wladimiroff, Academic Hospital Rotterdam-Dijkzigt, Erasmus University Rotterdam, Dr. Molewaterplein 40, 3015 GD Rotterdam, The Netherlands

Received 14–5–92
Accepted 28–5–92

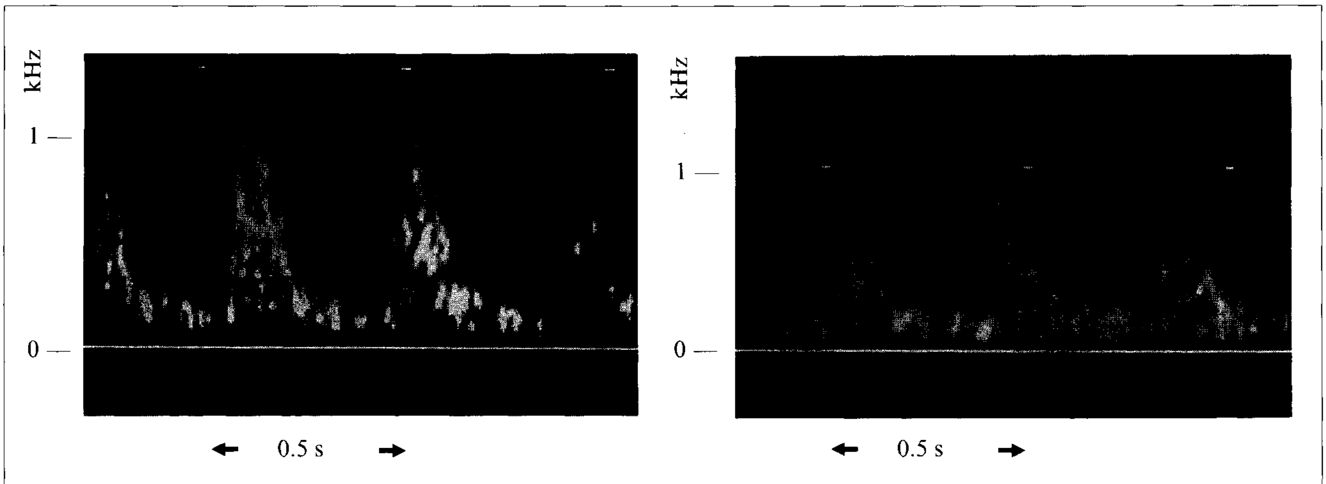

Figure 1 Intracerebral artery flow velocity waveforms at 11 weeks (left panel) and 16 weeks of gestation (right panel)

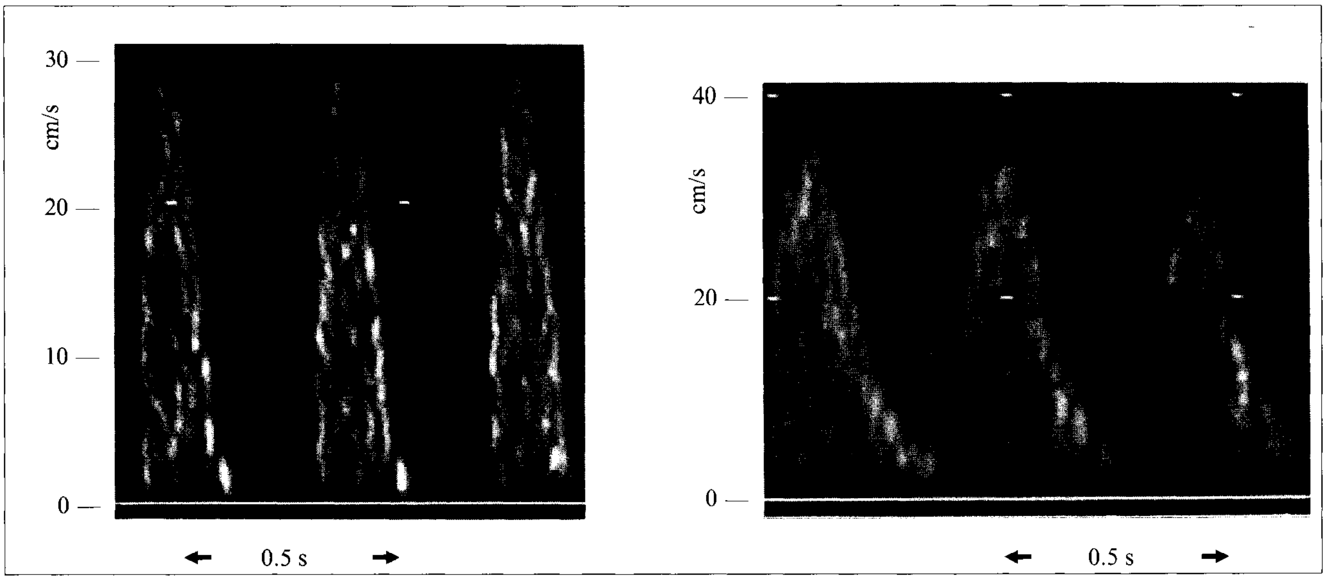

Figure 2 Flow velocity waveforms from the descending aorta at 11 weeks (left panel) and 15 weeks of gestation (right panel)

Whereas under 13–14 weeks of gestation the superiority of the transvaginal approach is unchallenged, the growing fetus renders this technique increasingly difficult beyond that stage of pregnancy (Table 1). Beyond 14 weeks, fetal flow velocity waveforms are nearly always obtained by means of transabdominal Doppler ultrasound.

EXTRACARDIAC ARTERIAL FLOW VELOCITY WAVEFORMS

Waveforms have so far been studied in the umbilical artery[10–18], fetal descending aorta[14,16–18] and intracerebral arteries[16,18]. Intracerebral waveforms were obtained from the internal carotid or middle cerebral artery[16,18]. A distinction between these two vessels is often not possible. Before 10 weeks of gestation, all waveforms depict absent end-diastolic flow velocities, suggesting a higher vascular resistance at fetal and umbilical placental levels than in late pregnancy[12]. Wladimiroff and colleagues established the appearance of end-diastolic flow velocities occurs in over 50% of intracerebral artery flow velocity waveforms between 10 and 12 weeks of gestation (Figure 1), whereas in the umbilical artery and descending aorta end-diastolic velocities are still absent[18]. These data suggest a relatively low cerebral vascular resistance and perhaps preferential cerebral blood flow under otherwise physiological circumstances. However, after 12 weeks, end-diastolic velocities also gradually appear in the umbilical artery and descending aorta, indicating a reduction in fetal placental vascular resistance[18] (Figure 2). Similar observations were made by Loquet and co-workers[10] and Rizzo and colleagues[16]. A reduction in vascular resistance was also reported for the uterine artery in this early stage of pregnancy[12,19,20]. Of interest at this point is the secondary trophoblast invasion of the spiral arteries in early second-trimester pregnancy, resulting in low resistance uteroplacental vessels[21]. This ensures optimal placental perfusion, which is necessary to accommodate the increased blood flow to the developing fetus. During the early second trimester of pregnancy, end-diastolic flow velocities are consistently present in all three aforementioned fetal arterial vessels, and a drop in the pulsatility index has been established (Figures 3–5).

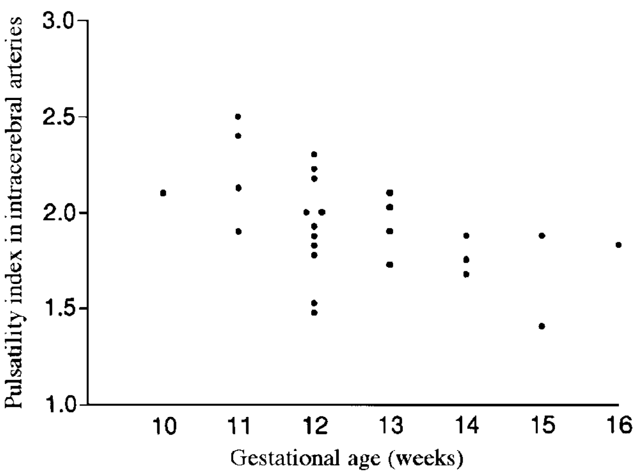

Figure 3 Pulsatility index in the fetal intracerebral arteries relative to gestational age

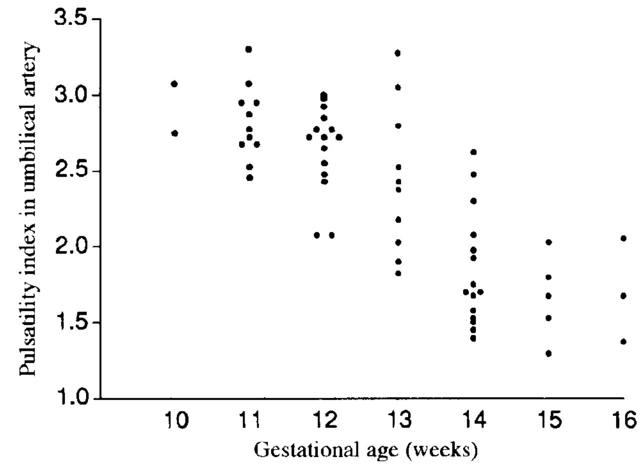

Figure 5 Pulsatility index in the fetal umbilical artery relative to gestational age

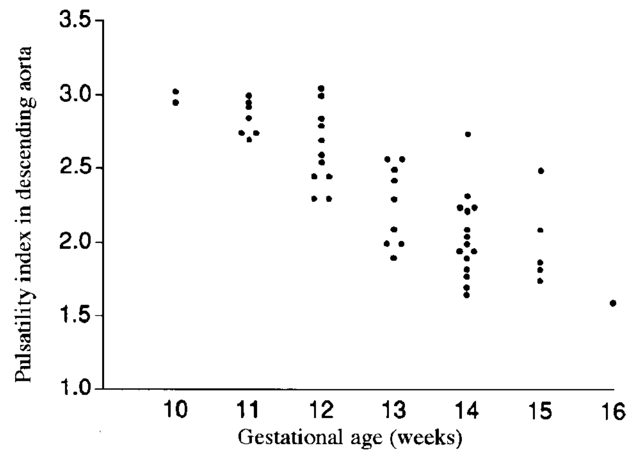

Figure 4 Pulsatility index in the fetal descending aorta relative to gestational age

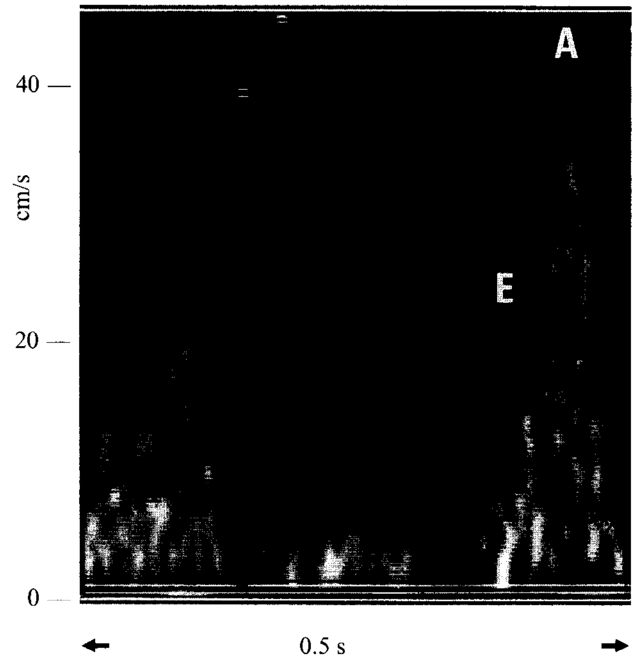

Figure 6 Waveform recording at the level of the fetal atrioventricular valves at 11 weeks, depicting the E-wave (early diastolic filling) and the A-wave (atrial contraction)

INTRACARDIAC FLOW VELOCITY WAVEFORMS

Transvaginal fetal echocardiography has been shown to be effective in the visualization of normal early fetal cardiac anatomy and, therefore, is suggested to have a significant potential for the diagnosis of gross fetal cardiac anomalies during the late first and early second trimester of pregnancy[22]. Doppler flow velocities have been collected at atrioventricular and outflow tract levels[16,23].

Transtricuspid and transmitral waveforms can be obtained from the two-dimensional image in the four-chamber view. The sample volume (0.1–0.3 cm) should be placed immediately distal to the tricuspid and mitral valves. The interrogation angle should always be kept at 20° or less. Up to 11–12 weeks of gestation, it is sometimes not possible to differentiate between the two atrioventricular valves. Figure 6 depicts an atrioventricular waveform recording at 11 weeks, consisting of the early diastolic or E-wave component and late diastolic or A-wave component. The waveform demonstrates that differentiation between passive diastolic filling and atrial contraction is already feasible at this very early stage of gestation. Of interest is the relatively low peak E-wave velocity when compared with peak A-wave velocity, resulting in an E/A ratio of approximately 0.5 as opposed to E/A ratios ranging between 0.8 and 0.9 in late pregnancy[23,24]. The clear A-wave dominance at the atrioventricular level reflects the relative stiffness of the cardiac ventricles in early gestation. At 11–12 weeks, mean peak E-wave and A-wave velocities of 20.5 ± 3.2 cm/s and 38.6 ± 4.7 cm/s, respectively, have been established[23]. Both at mitral and tricuspid valve levels, there is a marked rise in peak E-wave velocities and E/A ratios with advancing gestational age. This suggests a shift of blood flow from late towards early diastole, which may be due to increased ventricular

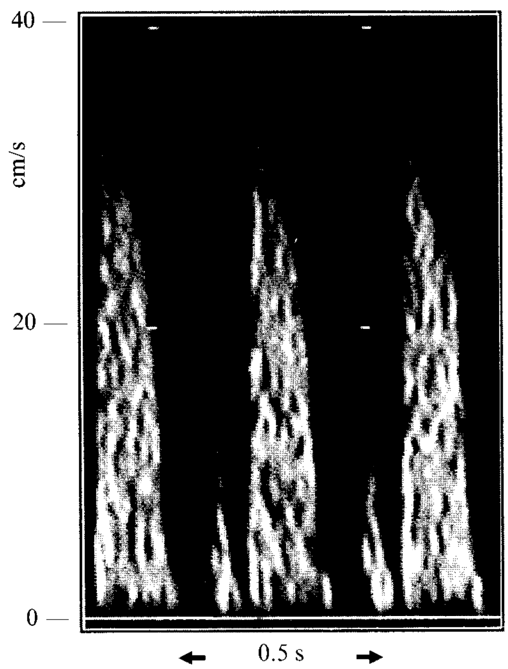

Figure 7 Fetal pulmonary artery flow velocity waveforms at 11 weeks of gestation

compliance and/or a raised ventricular relaxation rate[25]. Similar observations were made by Rizzo and colleagues comparing 11–13 weeks with 20 weeks of gestation[16]. After 12 weeks, transtricuspid mean, peak E-wave and peak A-wave velocities are higher than transmitral flow velocities[25]. Since volume flow is equal to mean velocity multiplied by vessel area, the higher transtricuspid mean velocities may reflect increased right ventricular stroke volume and output.

At outflow tract level, aortic and pulmonary artery flow velocities may also be recorded as early as 10–11 weeks of gestation (Figure 7). Velocity waveforms in the ascending aorta are obtained from the five-chamber view[26]; pulmonary artery velocity waveforms are recorded in the conventional echocardiographic short-axis view[26]. Doppler sample volumes (0.1–0.3 cm) should be placed in the great vessels immediately distal to the semilunar valves. Also here, the interrogation angle should always be kept at 20° or less. At 11–12 weeks, peak and time-averaged flow velocities are lower than those observed in late pregnancy[24], with mean values of 32.1 ± 5.4 cm/s and 11.2 ± 2.2 cm/s in the ascending aorta and 29.6 ± 5.1 cm/s and 10.8 ± 2.1 cm/s, respectively in the pulmonary artery[23]. Peak velocities at outflow tract level were also reported by Sharkey and colleagues[27], who measured a mean peak velocity of 30.2 ± 5.4 cm/s at 13 weeks, without differentiating between ascending aorta and pulmonary artery. In both vessels, a gestational age-related rise in peak velocities can be demonstrated during the early second trimester of pregnancy, with highest velocities in the ascending aorta[25]. The products of time–velocity integrals and heart rate recorded from all four cardiac valves demonstrate a rise with advancing gestational age, suggesting an increase in cardiac output[16]. A difference in left and right cardiac blood flow in favor of the right side was calculated during the first half of the second trimester of pregnancy[16]. It should be realized, however, that no data are available on fetal blood pressure and venous and arterial volume flows in the late first trimester. It is, therefore, unknown how umbilical–placental resistance precisely affects cardiac flow velocity waveforms at this stage of pregnancy. The higher peak-systolic velocities in the ascending aorta compared with the pulmonary artery may be a result of a difference in semilunar valve area between the two vessels, as has been suggested on the basis of similar findings in late pregnancy[28]. Alternatively, a relatively low fetal cerebral vascular resistance with a subsequent lower afterload to the left ventricle may be responsible for the aforementioned difference. The latter seems more likely, since a marked drop in pulsatility index has been established in both the fetal descending aorta and umbilical artery at 12–14 weeks of gestation[10,18], compared with constantly present low pulsatility index values at the cerebral level[18].

EXTRACARDIAC VENOUS VELOCITY WAVEFORMS

Flow velocity waveforms from the inferior vena cava can be obtained in a sagittal view which includes the fetal right atrium, right ventricle and ascending aorta. The sample volume is positioned over the inferior vena cava immediately proximal to the right atrium[29]. As in late pregnancy, the waveform is characterized by a systolic and early diastolic forward component and a late diastolic retrograde component (Figure 8)[30,31]. The percentage reverse flow at 11–12 weeks is as high as 25–30%, which is approximately a six-fold over that seen in late third-trimester pregnancies[30,31]. A low cardiac compliance or decreased ventricular relaxation rate may be responsible for these high retrograde flow velocities. An association of increased reverse flow with pulsations in the umbilical vein was reported by Rizzo and colleagues[32], suggesting a relationship between these waveform characteristics and cardiac filling patterns. Umbilical vein pulsations observed in first-trimester pregnancies may reflect a high placental resistance, also demonstrated by the high pulsatility index values at umbilical artery level at this stage of pregnancy[10,18].

The ductus venosus, which macroscopically resembles a continuation of the intra-abdominal part of the umbilical vein, joins the inferior vena cava close to the right atrium. The vessel cannot often be visualized in late first-trimester pregnancies[33]. However, by placing the sample volume immediately above the umbilical sinus, visualized on a transverse cross-sectional view, waveforms can be accepted as originating from this vessel on the basis of their similarity to ductus venosus waveforms observed in late pregnancy[34,35]. Waveforms from the ductus venosus are characterized by a systolic and early diastolic forward component without a late diastolic reverse component. Ductus venosus velocity waveforms may be recorded as early as 9–10 weeks of gestation (Figure 9). A clear systolic and early diastolic

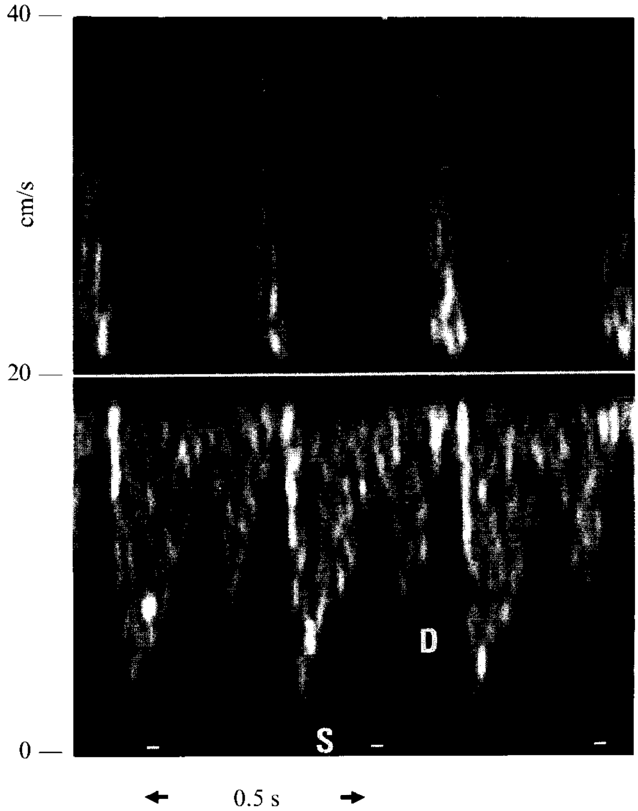

Figure 8 Flow velocity waveform recording from the fetal inferior vena cava at 12 weeks of gestation. S = systole; D = diastole. Note the marked late diastolic retrograde flow

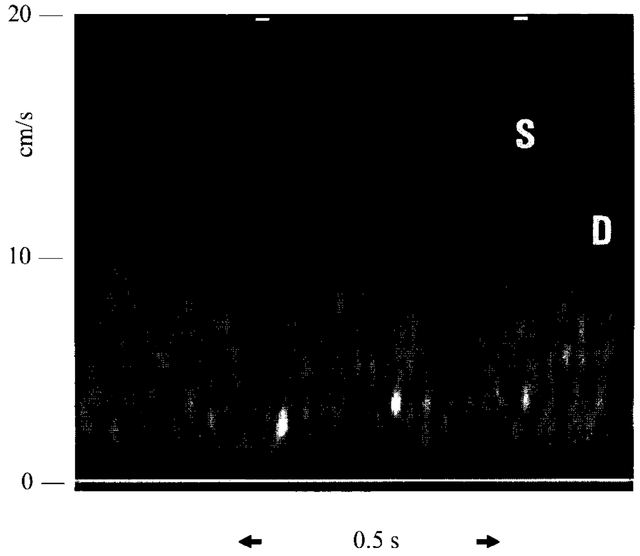

Figure 9 Fetal ductus venosus flow velocity waveforms at 9 weeks of gestation. S = systole; D = diastole

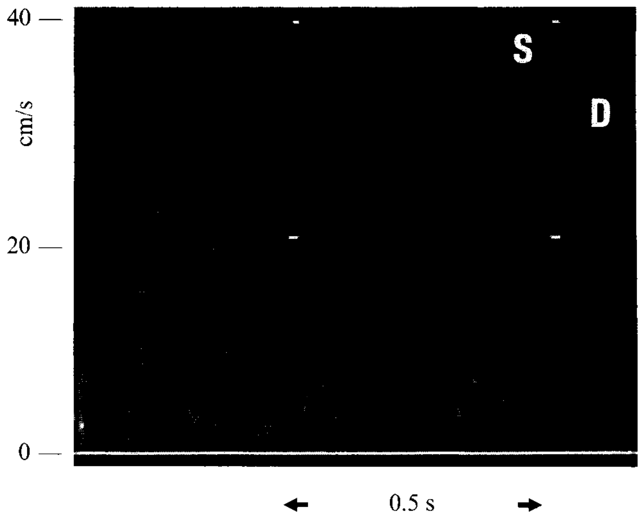

Figure 10 Fetal ductus venosus flow velocity waveforms at 12 weeks of gestation. S = systole; D = diastole

component will become visible from 11–12 weeks, with peak velocities reaching as high as 30 cm/s at 12 weeks (Figure 10)[33]. The time-averaged velocity in the ductus venosus is approximately three times higher than that in the inferior vena cava and umbilical vein[33]. Differences in flow velocities in these venous vessels may result in a tendency not to mix and, therefore, support the idea that preferential streaming of ductus venosus blood flow towards the foramen ovale could be present in the human fetus, as was demonstrated in the fetal lamb by Edelstone and Rudolph[36].

CONCLUSIONS

Present transvaginal Doppler techniques give detailed information on fetal waveform characteristics and velocities as early as 8–9 weeks of gestation. Cardiac and extracardiac arterial and venous flow studies have demonstrated the presence of a high fetal placental vascular resistance in normal late first-trimester pregnancy, followed by a marked reduction in resistance in early second-trimester pregnancy. Complete dislocation of the trophoblastic plugs at this stage of pregnancy may be responsible for the observed hemodynamic changes.

Doppler studies in early pregnancy provide important information on fetal hemodynamics. Its clinical relevance at this early stage of gestation still needs to be determined.

ACKNOWLEDGEMENT

This work was supported by the Dutch Foundation for Medical Research MEDIGON (Grant: 900-568-215).

REFERENCES

1. Griffin, D. R., Bilardo, K., Masini, L., Diaz-Recasens, J., Pearce, J. M., Willson, K. and Campbell, S. (1984). Doppler blood flow waveforms in the descending thoracic aorta of the human fetus. *Br. J. Obstet. Gynaecol.*, **91**, 997–1006
2. Trudinger, B. J., Giles, W. B. and Cook, C. M. (1985). Flow velocity waveforms in the maternal uteroplacental and fetal umbilical placental circulation. *Am. J. Obstet. Gynecol.*, **152**, 155–63
3. Wladimiroff, J. W., Tonge, H. M. and Stewart, P. A. (1986). Doppler ultrasound assessment of cerebral blood flow in the human fetus. *Br. J. Obstet. Gynaecol.*, **93**, 471–5
4. Arduini, D., Rizzo, G. and Romanini, C. (1987). Fetal blood velocity waveforms as predictors of growth retardation. *Obstet. Gynecol.*, **70**, 7–11

5. Groenenberg, I. A. L., Wladimiroff, J. W. and Hop, W. C. J. (1989). Fetal cardiac and peripheral arterial flow velocity waveforms in intrauterine growth retardation. *Circulation*, **80**, 1711–17
6. Wladimiroff, J. W. and Seelen, J. C. (1972). Doppler tachometry in early pregnancy. Development of fetal vagal function. *Eur. J. Obstet. Gynaecol. Reprod. Biol.*, **2**, 55–63
7. de Vries, J. I. P., Visser, G. H. A. and Prechtl, H. F. R. (1982). The emergence of fetal behaviour. I. Qualitative aspects. *Early Hum. Dev.*, **7**, 301–22
8. Jauniaux, E., Jurkovic, D., Campbell, S. and Hustin, J. (1992). Doppler ultrasound features of the developing placental circulation: correlation with anatomic findings. *Am. J. Obstet. Gynecol.*, **166**, in press
9. Ide, M. (1989). Acoustic data of Japanese ultrasonic diagnostic equipment. *Ultrasound Med. Biol.*, **15**, 49–53
10. Loquet, Ph., Broughton Pipkin, F., Symonds, E. M. and Rubin, P. C. (1988). Blood velocity waveforms and placental vascular formation. *Lancet*, **2**, 1252–3
11. Griffiths, K., Gill, R., Torode, H., Dixon, K. and O'Conell, D. (1988). The umbilical artery in early pregnancy: when does diastolic flow appear? *J. Ultrasound Med.*, **7**, S100 (abstr.)
12. den Ouden, M., Cohen-Overbeek, T. E. and Wladimiroff, J. W. (1990). Uterine and fetal umbilical artery flow velocity waveforms in normal first trimester pregnancies. *Br. J. Obstet. Gynaecol.*, **97**, 716–19
13. Guzman, E. R., Schulman, H., Karmel, B. and Higgins, P. (1990). Umbilical artery Doppler velocimetry in pregnancies of less than 21 weeks' duration. *J. Ultrasound Med.*, **9**, 655–9
14. Kurjak, A., Jurkovic, D., Alfirevic, Z. and Zalud, I. (1990). Transvaginal color Doppler imaging. *J. Clin. Ultrasound*, **18**, 227–34
15. Arduini, D. and Rizzo, G. (1991). Umbilical artery velocity waveforms in early pregnancy: a transvaginal color Doppler study. *J. Clin. Ultrasound*, **19**, 335–9
16. Rizzo, G., Arduini, D. and Romanini, C. (1991). Fetal cardiac and extracardiac circulation in early gestation. *J. Matern. Fetal Invest.*, **1**, 73–8
17. Wladimiroff, J. W., Huisman, T. W. A. and Stewart, P. A. (1991). Fetal and umbilical flow velocity waveforms between 10 and 16 weeks of gestation; a preliminary study. *Obstet. Gynecol.*, **78**, 812–14
18. Wladimiroff, J. W., Huisman, T. W. A. and Stewart, P. A. (1992). Intracerebral, aortic and umbilical artery flow velocity waveforms in the late first trimester fetus. *Am. J. Obstet. Gynecol.*, **166**, 46–9
19. Thaler, I., Manor, D., Rottem, S., Timor-Tritsch, I. E., Brandes, J. M. and Itskovitz, J. (1990). Hemodynamic evaluation of the female pelvic vessels using a high-frequency transvaginal image-directed Doppler system. *J. Clin. Ultrasound*, **18**, 364–9
20. Jauniaux, E., Jurkovic, D. and Campbell, S. (1991). *In vivo* investigations of the anatomy and the physiology of early human placental circulations. *Ultrasound Obstet. Gynecol.*, **1**, 435–45
21. Pijnenburg, R., Dixon, G., Robertson, W. B. and Brosens, I. (1980). Trophoblastic invasion of human decidua from 8 to 18 weeks of pregnancy. *Placenta*, **1**, 3–19
22. Dolkart, L. A. and Reimers, F. T. (1991). Transvaginal fetal echocardiography in early pregnancy: normative data. *Am. J. Obstet. Gynecol.*, **165**, 688–91
23. Wladimiroff, J. W., Huisman, T. W. A. and Stewart, P. A. (1991). Cardiac Doppler flow velocities in the late first trimester fetus; a transvaginal Doppler study. *J. Am. Coll. Cardiol.*, **17**, 1357–9
24. Van der Mooren, K., Barendregt, L. G. and Wladimiroff, J. W. (1991). Fetal atrioventricular and outflow tract flow velocity waveforms during the normal second half of pregnancy. *Am. J. Obstet. Gynecol.*, **165**, 668–74
25. Wladimiroff, J. W., Stewart, P. A., Burghouwt, M. T. and Stijnen, Th. (1992). Normal fetal cardiac flow velocity waveforms between 11 and 16 weeks of gestation. *Am. J. Obstet. Gynecol.*, in press
26. Reed, K. L., Anderson, C. F. and Shenker, L. (1987). Fetal pulmonary artery and aorta: two-dimensional Doppler echocardiography. *Obstet. Gynecol.*, **69**, 175–8
27. Sharkey, A., Tulzer, G. and Huhta, J. (1991). Doppler blood velocities in the first trimester of pregnancy. *Am. J. Obstet. Gynecol.*, **164**, 331 (abstr. 312)
28. Allan, L. D., Chita, S. K., Al-Ghazali, W., Crowford, D. C. and Tynan, M. (1987). Doppler echocardiographic evaluation of the normal human fetal heart. *Br. Heart J.*, **57**, 528–33
29. Wladimiroff, J. W., Huisman, T. W. A., Stewart, P. A. and Stijnen, T. (1992). Normal fetal Doppler inferior vena cava, transtricuspid and umbilical artery flow velocity waveforms between 11 and 16 weeks' gestation. *Am. J. Obstet. Gynecol.*, **166**, 921–4
30. Reed, K. L., Appleton, C. P., Anderson, C. F., Shenker, L. and Sahn, D. J. (1990). Doppler studies of vena cava flows in human fetuses. Insight into normal and abnormal cardiac physiology. *Circulation*, **81**, 498–505
31. Huisman, T. W. A., Stewart, P. A. and Wladimiroff, J. W. (1991). Flow velocity waveforms in the fetal inferior vena cava during the second half of normal pregnancy. *Ultrasound Med. Biol.*, **17**, 679–82
32. Rizzo, G., La Marca, N., Caforio, L. and Arduini, D. (1991). Venous blood flow in early gestation. Presented at *5th International Fetal Cardiology Symposium*, Rome, Nov. 26th, Abstr., p. 56
33. Huisman, T. W. A., Stewart, P. A. and Wladimiroff, J. W. (1992). Flow velocity waveforms in the ductus venosus, umbilical vein and inferior vena cava in normal fetuses at 12–15 weeks' gestation. *Pediatr. Res.*, submitted
34. Kiserud, T., Eik-Nes, S. H., Blaas, H. G. K. and Hellevik, L. R. (1991). Ultrasonographic velocimetry of the fetal ductus venosus. *Lancet*, **338**, 1412–14
35. Huisman, T. W. A., Stewart, P. A. and Wladimiroff, J. W. (1992). Ductus venosus blood flow velocity waveforms in the human fetus; a Doppler study. *Ultrasound Med. Biol.*, **18**, 33–7
36. Edelstone, D. I. and Rudolph, A. M. (1979). Preferential streaming of ductus venosus blood to the brain and heart in fetal lambs. *Am. J. Physiol.*, **237**, H724–9