Doppler Flow Velocity Waveforms of Human Fetal Ductus Arteriosus and Branch Pulmonary Artery

Doppler waveforms of the human fetal ductus arteriosus and the branch pulmonary artery are distinct in their shape and might reflect fetal cardiovascular hemodynamics and vessel wall characteristics. The waveform of ductus arteriosus had two peaks, a higher one in systole and a lower one in diastole. Both peaks had slow acceleration and deceleration and looked like two narrow base isosceles triangles. This unique waveform might be due to vessel wall characteristics and an instantaneous pressure gradient between the main pulmonary artery and descending aorta. The waveform of the branch pulmonary artery showed very steep acceleration with the onset of ejection followed by steep decline, then low velocity flow during diastole. The characteristic shape of the branch pulmonary artery might be related to high vascular resistance, decreased capacitance and the earlier reflection wave of pulmonary vessels.
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Key Words : *Fetus; Doppler; Ductus arteriosus; Branch pulmonary artery*

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INTRODUCTION

Most of the knowledge on fetal circulation is derived mainly from the studies carried out on animal models particulary in lambs (1, 2). Since the introduction of fetal echocardiography, the human fetal heart became accessible. Various fetal cardiac anomalies were identified and some hemodynamic studies were carried out (3, 4). As physiologic information of the human fetal heart can be obtained only by fetal echocardiography, it seems imperative to make most of the Doppler analysis to speculate on the hemodynamic meaning of the fetal cardiovascular system.

Ductus arteriosus is a large vessel that connects the pulmonary trunk with the descending aorta during fetal life. Thus, it acts as a large conduit diverting a considerable amount of the right ventricular output away from the lungs. Because of it's important position in the fetal circulation, ductus arteriosus has been studied by several groups. Huhta et al. (5) demonstrated the technical feasibility of Doppler study from ductus arteriosus in normal and abnormal human fetuses. Van der Mooren et al. (6) reported normal values of Doppler parameters obtained from human fetal ductus and also reported that these parameters were influenced by the fetal behavioral state and breathing movement (7, 8). Although shapes of Doppler waveforms was described, the description has not been complete. The meaning of the typical shape has not been discussed in detail. Compared to ductus arteriosus, the branch pulmonary artery received little attention. Choi et al. (9) described the characteristic shape of waveforms, and De Vore and Horenstein (10) reported that simultaneously obtained Doppler waveforms from the branch pulmonary artery and vein were useful for the diagnosis of fetal arrhythmia.

The purposes of this study were : 1) to describe shapes of Doppler waveforms from the ductus arteriosus and the branch pulmonary artery and to speculate their hemodynamic meaning, and 2) to measure the various parameters of Doppler waveforms from the ductus arteriosus and the branch pulmonary artery, and to see whether these parameters changed with gestation age.

MATERIALS AND METHODS

Pregnant women referred to the echocardiographic laboratory of Seoul National University Children's Hospital for fetal echocardiography were prospectively assessed. The inclusion criteria for this study were : 1) pregnant women without major illnesses such as diabetes mellitus, hypertension, eclampsia, etc. which might affect fetal well-being, 2) no major fetal diseases or anomalies, and 3) singleton fetus.

One hundred and thirty one pregnant women satisfied the above criteria. Gestational age was estimated from the last menstrual period. Fetal biparietal diameter and femur length were also considered. Ultrasound examinations were performed in a supine or semisitting position using Advanced Technology Laboratories Ultramark 8. At first, a two dimensional echocardiography was used for assessment of fetal cardiac anatomy and function. For the pulsed Doppler study, a 5.0 MHz mechanical transducer was used. The Doppler study was performed when the fetus was not moving or breathing. Fetal tachycardia or bradycardia were excluded. The sample volume size was 1.5 mm. A wall filter of 100 Hz was used in most studies. Angle correction was not used. Examination was abandoned when presumed insonation angle was more than 10 degrees. Doppler waveforms of the ductus arteriosus were acquired in semihorizontal images of a fetal upper thorax in which the aortic arch and the ductal arch were running parallel and joined together at the descending aorta. In this view, two arches and their junction looked like a narrow "V" or inverted "V". The Doppler sample volume was placed at the narrowest area along the ductus arteriosus initially, then moved back and forth until the maximum velocity was recorded as a ductal waveform. Doppler interrogation of the branch pulmonary artery was performed in a short axis view at great artery level. The sample volume was placed at distal right pulmonary artery near the hilum, where there were no other arteries nearby.

Among 131 attempted studies, 61 studies of the ductus arteriosus and 65 studies of the branch pulmonary artery were obtained satisfactorily and recorded on a videotape. The built-in software program was used for the Doppler measurement. Five Doppler waveforms with clear envelopes were measured and averaged.

The measured parameters of Doppler waveforms from the ductus arteriosus were systolic and diastolic peak velocities, acceleration time (time to reach systolic peak velocity), and the proportion of systolic time-velocity integral to total time-velocity integral (Fig. 1). The measured parameters of Doppler waveforms from the branch pulmonary artery were systolic peak velocity, end-diastolic velocity, and acceleration time (Fig. 1). Heart rate was calculated from cycle length. The values were expressed as mean ± standard deviation. The correlations between all the measured values and gestational age were determined using a SAS statistical package. A P-value lest than 0.05 was considered significant. If the correlation was significant, the slope and intercept of the regression curve were calculated.

RESULTS

The number of examinations in each gestational week is shown in Fig. 2. The mean gestational age at examination for the ductus arteriosus was 26±10.2 (range ; 16-38) weeks and for the branch pulmonary artery was 25±8.5 (range ; 18-35) weeks.

The typical Doppler waveform of ductus arteriosus is shown in Fig. 3. Ductal waveform had 2 peaks, a higher one in systole and a lower one in diastole. With the onset of systole, flow velocity rose slowly until the peak velocity was reached. After this peak, flow velocity decreased slowly. In many cases (46/61), the diastolic peak began to rise before the systolic wave returned to the baseline (Fig. 3, upper panel). In other cases (15/61), diastolic flow began after the systolic peak returned to baseline (Fig. 3, lower panel). Acceleration and deceleration of the diastolic peak were also slow. Therefore the

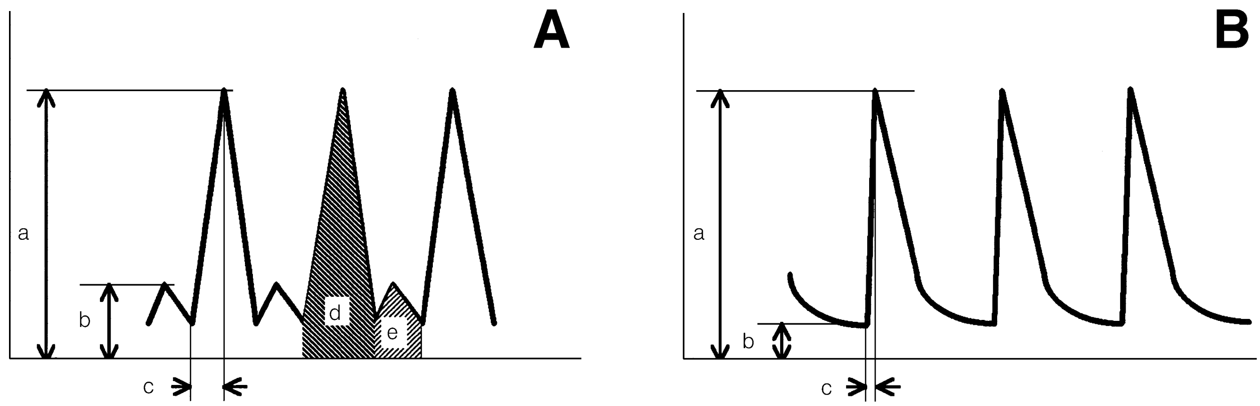
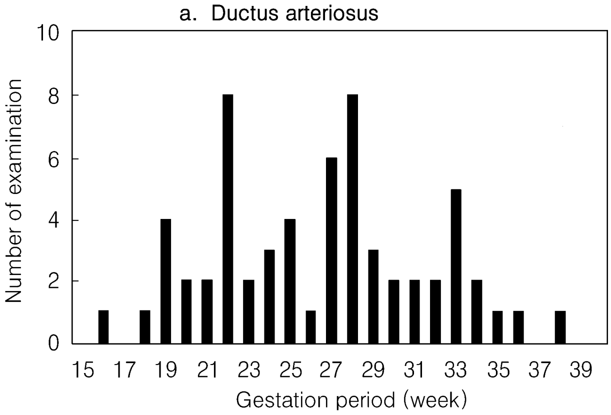


Fig. 1. Measured parameters of Doppler waveforms from the ductus arteriosus (A) and the branch pulmonary artery (B).
A : Ductus arteriosus. a; systolic peak velocity, b; diastolic peak velocity, c; acceleration time, d; systolic time-velocity integral, e; diastolic time-velocity integral.
B : Branch pulmonary artery. a; systolic peak velocity, b; end-diastolic velocity, c; acceleration time.



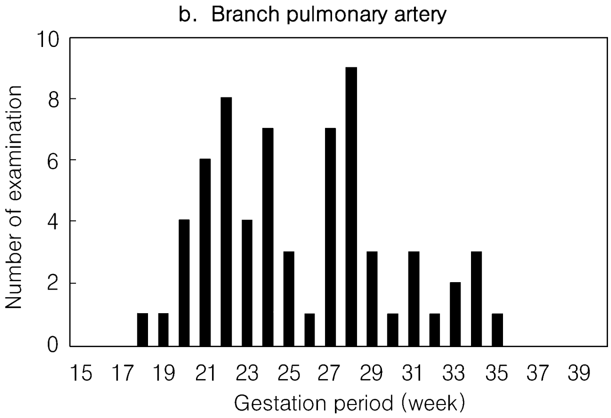


Fig. 2. The number of examinations in each gestational week. a; the number of examinations from the ductus arteriosus, b; the number of examinations from the branch pulmonary artery.

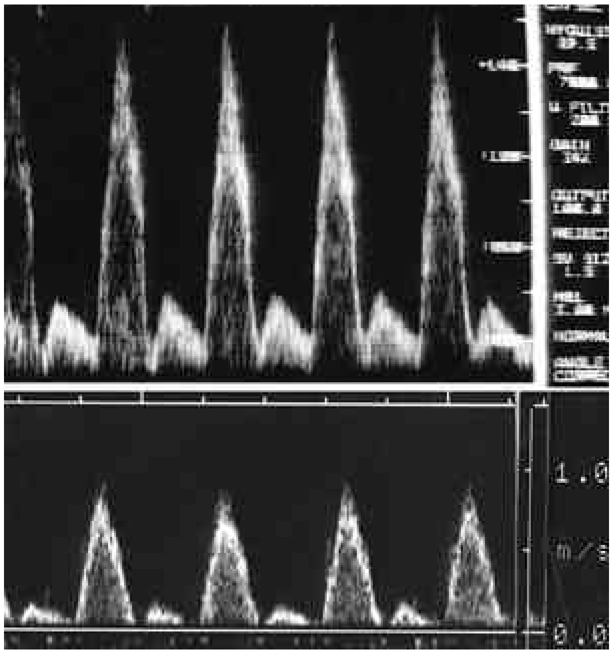


Fig. 3. Doppler waveforms of ductus arteriosus. Upper panel shows more common pattern of flow, in which the diastolic peak begins to rise before the previous systolic peak returns to baseline. Lower panel shows two separate peaks.

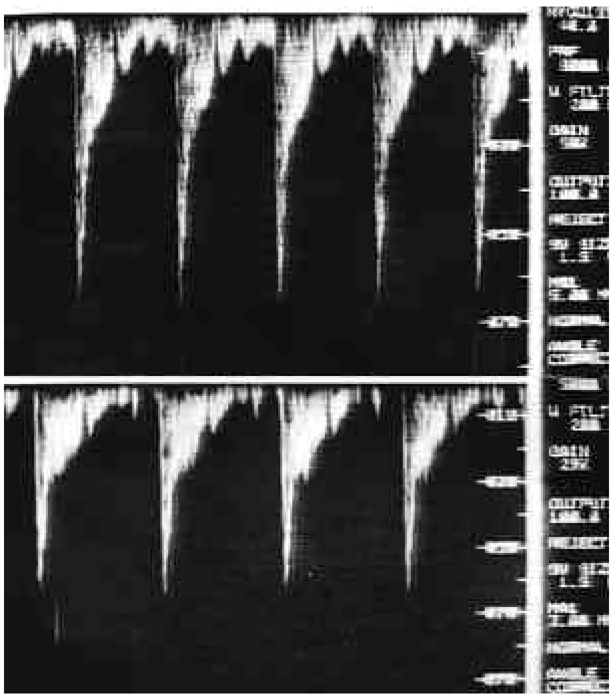


Fig. 4. Doppler waveforms of the branch pulmonary artery. Upper panel shows continous diastolic flow till the next systole. Lower panel shows diastolic flow returns to baseline before the next systole begins.

Doppler waveform looked like two narrow base isosceles triangles with slow acceleration and deceleration. The typical waveform of the branch pulmonary artery is shown in Fig. 4. Waveforms of the branch pulmonary artery had very steep acceleration with the onset of ejection, followed by a steep decline and then a low velocity flow until the end of diastole (Fig. 4, upper panel). In some cases (17/65), diastolic flow returned to baseline and no flow was detected until the next systole (Fig. 4, lower panel).

The relation between the Doppler parameters of ductus arteriosus and gestational age is shown in Fig. 5. Heart rate decreased with increasing gestation ($R=-0.32$, $P<0.05$, heart rate $=-0.43\times$ gestation period $+155$). The systolic peak velocity, diastolic peak velocity, and acceleration time increased with advancing gestation. The regression equations were ; systolic velocity $=3.34\times$ gestation period -4.59 ($R=0.70$, $P<0.05$), diastolic velocity $=0.57\times$ gestation period -0.31 ($R=0.44$, $P<0.05$) and acceleration time $=2.11\times$ gestation period $+19.2$ ($R=0.80$, $P<0.05$). The proportion of systolic area

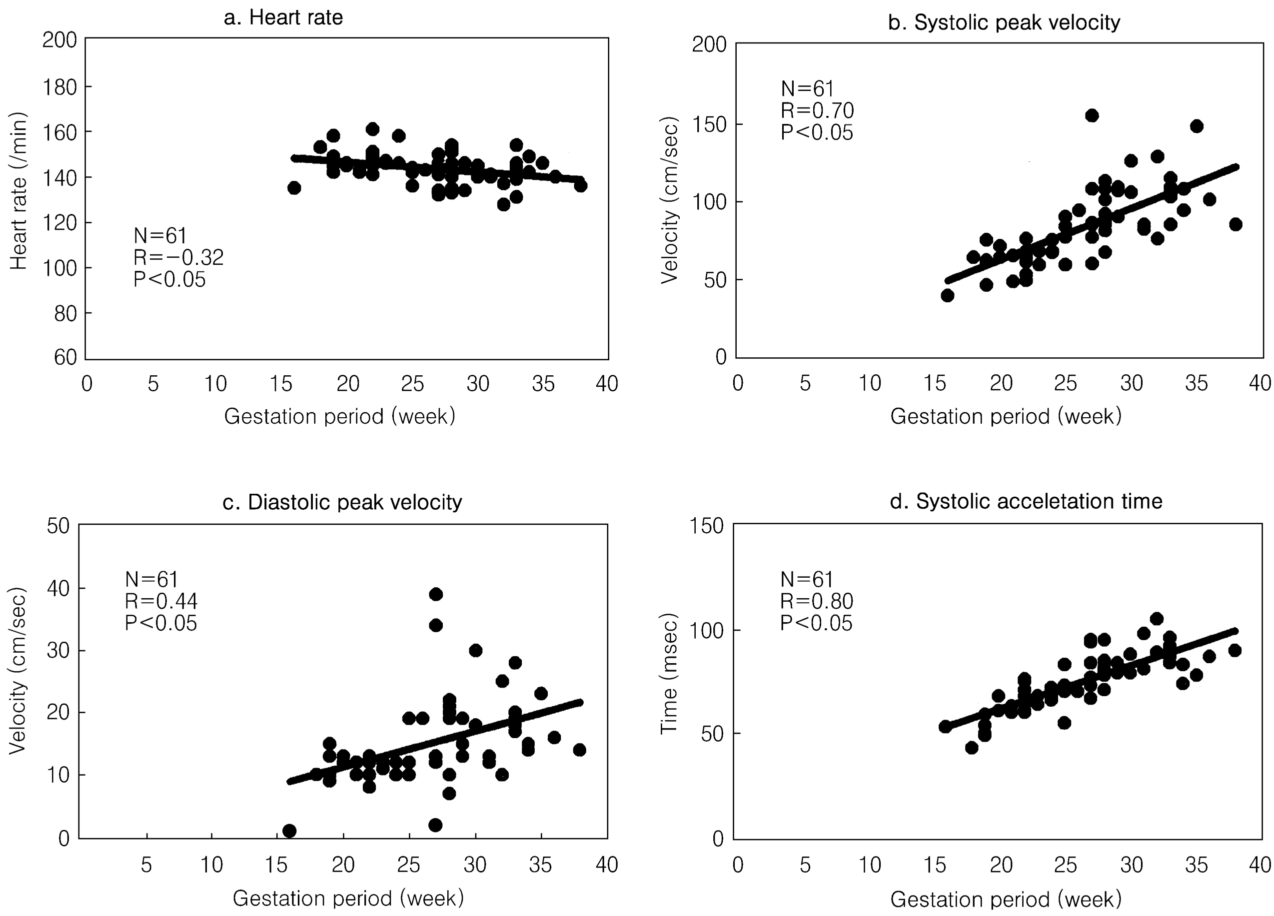


Fig. 5. The scattergrams between gestational age and Doppler parameters of ductus arteriosus. The relation between gestational week and heart rate (a), systolic peak velocity (b), diastolic peak velocity (c), and systolic acceleration time (d). Regression lines are superimposed.

to total area was 84±4.8% (range ; 71-97). The proportion of systolic area to total area tended to increase with gestational age, but it did not reach to a statistically significant level.

The relation between the Doppler parameters of the branch pulmonary artery and the gestational age is shown in Fig. 6. Heart rate decreased with increasing gestation ($R=-0.37$, $P<0.05$, heart rate $=-0.53\times$ gestation period $+159$). The systolic peak velocity, end-diastolic velocity, and acceleration time increased with advancing gestation. The regresssion equations were ; systolic velocity $=1.66\times$ gestation period $+24$ ($R=0.50$, $P<0.05$), diastolic velocity $=0.25\times$ gestation period -2.37 ($R=0.25$, $P<0.05$), and acceleration time $=0.58\times$ gestation period $+20.1$ ($R=0.51$, $P<0.05$).

DISCUSSION

Fetal circulation is different from postnatal circulation in many aspects (2). The most important difference may be the fact that fetal ventricles act in parallel rather than in series. As a result, ductus arteriosus in the fetal circulation is an important pathway which carries a significant portion of the right ventricular output to the descending aorta. Pulmonary circulation is relatively minor and of no functional significance.

Although many workers used Doppler technique to study human fetal ductus arteriosus (11, 12, 13), technical details have not been discussed. Because fetal supracardiac vessels are small and close to each other, Doppler examination of fetal vessels requires a meticulous technique. In order to obtain specific Doppler signals from a fetal vessel, the pulsed Doppler system should be used and the size of sample volume should be small. In our experience, it was not difficult to obtain a good spectral display using the pulsed Doppler system with a sample size of 1.5mm in fetal echocardiography. The continuous Doppler system not only lacks a range resolution, but also has wide beam width. Two-dimensional

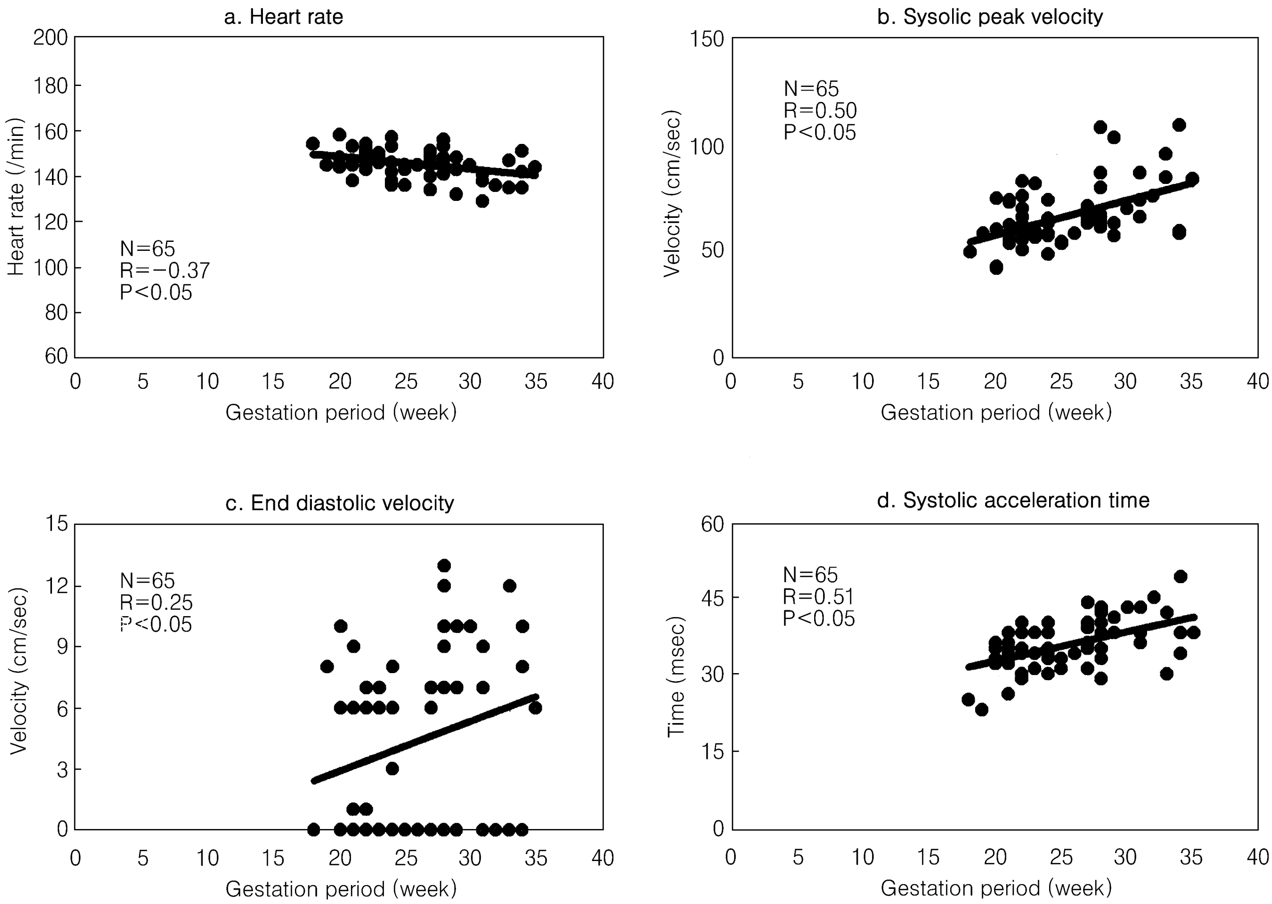


Fig. 6. The scattergrams between gestational age and Doppler parameters of branch pulmonary artery. The relation between gestational week and heart rate (a), systolic peak velocity (b), end-diastolic velocity (c) and acceleration time (d). Regression lines are superimposed.

images for guiding Doppler examination should be easy to get and to standardize. In addition, two-dimensional images should be oriented in such a way that minor fetal movements should not affect the examination and also that superimposition of signals from surrounding structures, seen or unseen, should be minimal. So far, most studies on ductus used the continuous Doppler system and adopted semisagittal views for Doppler interrogation. In semisagittal orientation, it is not difficult to differentiate the ductal arch from the aortic arch. However minor fetal movement may affect the examination. Furthermore continuous Doppler beam directed through ductus in this view may contain unwanted signals from the main pulmonary artery and descending aorta. The view used in our study was easy to get and permitted accurate placement of sample volume on the ductus. Moreover, in this view, superimposition of signals from surrounding structures was minimal. Therefore we think that the semihorizontal image is better for ductal interrogation. For Doppler interrogation of the branch pulmonary artery, the sample volume was placed at the distal right pulmonary artery, because interrogation of proximal portion often produced superimposed signals from aorta. In the distal position, the only signal that could be superimposed was the pulmonary venous signal,

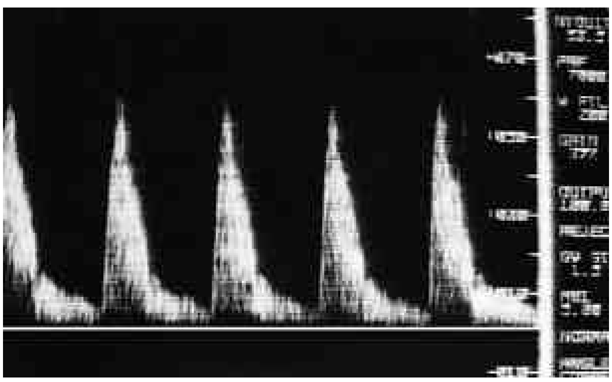


Fig. 7. Doppler waveforms of aortic arch. Unlike ductal waveforms, downslope of systolic flow is continuous with diastolic flow, which decays exponentially.

which was in the opposite direction and completely different from the arterial signals.

Although our method differs from the methods used by others, our results showing the ductal Doppler parameters is generally in agreement with other studies (5, 6, 13). There was a linear increase of Doppler parameters with advancing gestation. Regression lines of peak systolic velocity of our study and others (6) are nearly identical and this may be due to the fact that the measurement of the systolic peak velocity is less affected by differences in method. However there are some differences in other parameters, which might be explained by differences in method.

Our result of ductal shape concurs with the previous description (5, 13) and showed a unique shape of two peaks with slow acceleration and deceleration. More importantly, the shape of the ductal diastolic peak was different from diastolic velocities of other fetal vessels such as the aortic arch and the descending aorta, which was continuous with the systolic peak and showed exponential decay toward the end diastole (Fig. 7). Flow velocity profiles of the ductus and the branch pulmonary artery show two patterns each. The type of flow pattern is not related to gestational period, but seems to be related to flow volume.

It seems very difficult to study the hemodynamics of the human fetal cardiovascular system because the pressure and the flow can not be measured (14). Moreover, the fetal ventriculo-vascular system is more complex, in that two circulations are connected by the ductus arteriosus. Nonetheless it could be possible to speculate on some aspects of hemodynamics on the basis of Doppler information and the general principles of hemodynamics. The pressure, flow velocity, and flow volume in a vessel are related to each other and influenced by contraction of ventricles, characteristics of vessel wall, reflection, and other factors (15). Therefore, the shape of the Doppler waveforms from a vessel is influenced by many factors such as ventricular contractility, distance from the semilunar valve, peripheral conductance, and vessel compliance (16).

Our previous study on the shape of Doppler waveforms showed that patterns of flow through the aortic and pulmonary valve were similar (systolic velocity only), and waveforms of the aortic arch, descending aorta and branch pulmonary artery were more or less similar and typical of elastic arteries (systolic peak followed by exponential decay), but the shape of ductal waveforms was completely different from other sites (9). This suggested that the ductus was not an integral part of either the aortic or the pulmonary arterial system, but seemed to be a conduit between two vascular systems. Based on this observation, it may be assumed that one of major factors affecting the ductal Doppler waveform is the instantaneous pressure gradient between the main pulmonary artery and the descending aorta. Although no pressure data on human fetal vessels are available, animal studies showed slightly higher pulmonary arterial pressure than aortic pressure (14). In the pulmonary artery, the systolic pressure rise was more rapid and dicrotic notch was more prominent (17). Pressure decay of the descending aorta in diastole may be more prominent because of low resistant placenta (6). Therefore it might be reasonable to speculate that, in the human fetus, instantaneous pressure gradients develop in the systole and the diastole and these pressure gradients generate two peaks of ductal waveform. Another factor which might affect ductal waveform is wall characteristics of the ductus. Unlike elastic arteries of the aorta and the main pulmonary artery, the ductus arteriosus has different wall characteristics (18). The different wall characteristics of the ductus might explain slow acceleration and deceleration. Therefore, our hypothesis is that ductal waveform is related not only to ductal wall characteristics but also to the instantaneous pressure gradients developed in systole and diastole. The Doppler waveform of the branch pulmonary artery was not unexpected and might be related to a high vascular resistance, decreased capacitance, and earlier reflection waves of the pulmonary arterial system. Similar Doppler waveform of branch pulmonary artery in cases with persistent fetal circulation syndrome support this hypothesis (19).

In fetal cardiac and pulmonary diseases, flow distribution among proximal vessels and/or flow pattern may be altered. It would be interesting to study Doppler waveforms of the ductus and the branch pulmonary artery in fetal cardiac anomalies. Flow patterns of the branch pulmonary artery might be useful in assessing lung development and lung diseases.

The limitation of this study is that there is no pressure or flow volume data in the human fetus. Flow volume could be measured by the echo-Doppler technique (20) but the accuracy of the diameter measurement of small vessels is not sufficient. Further studies using animal or computer simulation vascular models seem necessary for elucidation of cardiovascular physiology in the human fetus.

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