CEOG Clinical and Experimental Obstetrics & Gynecology

The application of high definition flow imaging in fetal hemodynamics

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Summary

Objective: This work aims to investigate the application of high definition flow imaging (HD-flow) in fetal hemodynamics, and establish reference range of hemodynamic parameters in fetal with different gestational ages. *Materials and Methods:* A thousand of normal pregnant women were divided into five groups: 18-22, 23-27, 28-32, 33-37, and 38-40 gestational weeks. Color Doppler flow imaging (CDFI) and HD-flow were adopted to display the heart structure and measure the blood flow velocity. The pulmonary vein display results were scored. The results of HD-flow and CDFI were compared. *Results:* The catheter peak velocity of fetal mitral, tricuspid, aortic, pulmonary artery, aortic arch, ductal arch, the inferior vena cava, pulmonary vein, and venous catheter increased continuously with the increase of gestational age, showing a linear correlation. HD-flow was superior to CDFI on the display of pulmonary vein in 18-22, 23-27, and 28-32 weeks ($p < 0.05$), but was not in 33-37 and 38-40 weeks. HD-flow was an accurate positioning method for the pulmonary veins. *Conclusion:* HD-flow can make accurate evaluation of fetal hemodynamics and the demonstration of low blood flow, such as pulmonary venous, is better than CDFI. Pulmonary veins can be accurately positioned with HD-flow. HD-flow can demonstrate the main blood vessels of the whole fetal circulation and can display the spatial relationship of the blood vessels. It is of important clinical significance in hemodynamic study.

Key words: HD technology; Hemodynamics; Pulmonary vein; Positioning.

Introduction

Structures of heart and great vessels and hemodynamic characteristics in fetus are different from those in newborn. Due to special anatomical structures of placenta, umbilical artery, umbilical vein, venous catheter, foramen ovale, and arterial catheter, the systemic circulation and pulmonary circulation communicate with each other, with regulation of placental blood flow. This leads to intricate and complicated changes in fetal hemodynamics. In addition, due to atelectasis and small body and heart, the blood vessels are small, with low blood flow rate. Therefore, previous ultrasound technologies have defects for evaluation of fetal hemodynamics.

In the past 30 years, with the development of ultrasound, the ability of prenatal diagnosis of fetal congenital heart disease has been improved. Compared with adult echocardiography, fetal echocardiography is more meticulous and comprehensive, in which not only is the observation in detail needed to understand the variability of cardiac anatomy caused by different diseases, but also to assess fetal hemodynamics which are very important due to the blood circulation relationship between fetus and placenta. Recently, many scholars adapt various technologies of echocardiography to evaluate fetal hemodynamics, and to measure all sorts of blood flow parameters via spectral Doppler technology, which is able to describe the trend of normal and abnormal fetal hemodynamics in different gestational age more accurately. Fetal intrauterine growth retardation [1], fetal hypoxia [2], fetal arrhythmia [3], and abnormal changes in fetal hemodynamics of congenital heart disease are assessed in order to suggest clinicians to choose a reasonable mode of production for pregnant women, to strengthen labor monitoring, and guide prenatal intervention and treatment, which can reduced perinatal fetus fetal mortality in the perinatal period greatly. Because of the poor display effect of previous technology for low blood flow, new technology is needed to show low blood flow. The high definition flow imaging technology (herein referred to as HD-flow for short) is a new technology which has appeared recently, which was applied to mammary gland, liver, etc.

Materials and Methods

Patients

A thousand cases of pregnant women were selected from October 2010 to October 2011 who came to the present hospital for fetal echocardiography, aging 24~33 years (average age: 28.1 ± 3.3), and gestational aging 23~32 weeks (average age: 25.3 ± 3.0). This study was conducted in accordance with the declaration of Helsinki. This study was conducted with approval from the Ethics Committee of Anzhen Hospital of Capital Medical University. Written informed consent was obtained from all participants. According to different gestational age, they were divided into five groups: 18~22 weeks, 23~27 weeks, 28~32 weeks, 33~37 weeks, and 38~40 weeks.

Revised manuscript accepted for publication June 18, 2013

Table 1. — *The peak velocity (cm/s) of fetal mitral valve, tricuspid valve, aortic artery, pulmonary artery, aortic arch, and ductal arch at different gestational weeks.*

Gestational week	Cases	Aortic artery	Pulmonary artery	Aortic arch	Ductal arch	Mitral valve E	Mitral valve A	tricuspid valve E	tricuspid valve A
18-22	138	69.40±14.09	63.51±16.01	78.97 ±14.53	81.88±18.07	29.14±6.66	33.79±9.39	33.41±7.53	44.11±9.67
23-27	524	71.43±14.55	65.98±14.69	81.42±16.42	83.03±19.22	31.91±8.28	38.91±8.28	34.52±9.24	48.24±11.37
28-32	251	73.96±14.62	69.37±13.13	84.37±17.57	87.07±25.60	33.94±7.01	40.94±7.01	34.58±8.46	50.53±10.35
33-37	90	78.03±11.12	73.61±34.83	88.74±13.97	92.71±19.31	34.75±7.61	43.75±7.61	35.66±9.07	51.62±9.55
38-40	12	82.99±14.07	80.28±9.28	91.10±27.44	98.20±22.39	35.59±7.07	47.59±7.07	38.61±9.21	52.67±10.29

Table 2. — *The peak velocity (cm/s) of fetal inferior vena cava, venous catheter, and pulmonary vein at different gestational weeks.*

Gestational	Cases	Venous catheter			Inferior vena cava			Pulmonary vein		
week		S peak	D peak	A peak	S peak	D peak	A peak	S peak	D peak	A peak
18-22	138	43.92±13.44	39.48±12.20	22.08±9.40	24.43±9.63	16.38±7.03	-0.37±10.30	20.96±7.95	17.06±6.15	7.87±6.53
23-27	524	47.51±13.17	40.77±13.09	23.10±10.68	26.75±10.11	17.17±7.43	-0.17±10.37	23.10±7.14	18.67±6.24	8.63±6.39
28-32	251	53.92±14.22	45.94±13.17	25.09±10.75	31.31±9.28	18.86±7.59	0.63±10.92	25.08±15.47	20.09±6.38	9.96±8.69
33-37	90	56.99±13.36	48.38±11.45	28.53±14.18	32.96±8.79	20.31±9.21	1.16±12.50	26.42±7.33	21.64±5.66	11.21±10.82
38-40	12	61.72±13.15	55.64±11.47	33.45±13.11	36.15±9.80	23.00±7.30	1.24±14.45	27.25±6.53	22.30±7.04	13.20±8.32

Table 3. — *The rating of HD and CDFI for pulmonary vein at different gestational weeks.*

Pulmonary	18-22w		23-27w		28-32w		33-37w		38-40w	
vein rate	HD	CDFI	HD	CDFI	HD	CDFI	HD	CDFI	HD	CDFI
1	5	10	19	53	9	26	20	26	1	3
2	11	36	91	106	46	54	16	19	7	6
3	82	67	281	258	128	117	39	33	3	2
4	40	25	133	107	68	54	15	12	1	1

Pregnant women position

Pregnant women were in supine position. If fetal malposition occurred, left or right position could be used, and when necessary pregnant women were advised to adopt appropriate activities to change the baby's position.

Measurement of biological indicators

The conventional obstetric conditions were used to conduct the measurement of biparietal diameter, head circumference, abdominal circumference and femur length in order to clarify the overall fetal development. Abdominal cross-cutting was performed to clarify the visceral location.

Segmentation of the fetal heart

According to the segments, fetal heart condition was assessed. According to the guideline of American Society of Echocardiography (ASE) and the International Society of Ultrasound in Obstetrics & Gynecology (ISUOG), scanning sections included four-chamber, five-chamber, left ventricular outflow tract and right outflow tracts, dual-chamber short axis, main artery minor axis, aortic arch, catheter bow, three vessels and trachea, inferior vena cava long axis, etc. If there were abnormal findings, multi-slice, multi-angle continuous scanning were performed.

Data acquisition

Color Doppler imaging and high-resolution flow imaging were simultaneously used in each section above. The measurement included: fetal mitral, tricuspid, aortic, pulmonary artery, aortic arch, ductal arch, the inferior vena cava, venous catheter, and pulmonary vein.

When all of the blood flows above were measured, the angle between the acoustic beam and the blood flow were controlled within 30 degrees. All measurements are performed three times and the averages were taken. All data were analyzed by SPSS17.0 software. Measurement data were expressed as mean ± standard deviation. *T*-test was used in the comparison between groups. There was a statistically significant difference when $p < 0.05$. All images and data were then stored for further analysis.

Results

General information

The peak velocity (mean ± standard deviation) of fetal mitral, tricuspid, aortic, pulmonary artery, aortic arch, ductal arch, the inferior vena cava, venous catheter, and pulmonary vein increased with the increase of gestational age, which was positively associated with gestational age and are shown in Tables 1 and 2.

The systolic and diastolic of fetal aortic, pulmonary artery and aortic arch, as well as the systolic and diastolic of catheter arch, and the peak E and peak A of mitral valve and tricuspid valve in different gestational age varied according to the gestational age. Linear correlation analysis was adopted, showing a linear correlation.

HD and CDFI rating

The display of HD technology for pulmonary vein was significantly better than CDFI. According to the display number of pulmonary vein, the display of pulmonary vein

Table 4. — *The comparison of pulmonary vein rate at different gestational weeks (X^2 test).*

Gestational weeks	X^2	p
18-22	19.938	0.000
23-27	20.996	0.000
28-32	10.998	0.012
33-37	1.847	0.599
38=40	1.277	0.735

was rated, which was divided into grades 1, 2, 3, and 4. The rate of HD and CDFI for pulmonary vein according different gestational age was shown in Table 3.

Pulmonary vein rate

The integral situations of pulmonary vein in each group (different gestational age) were tested by the chi-square method (Table 4). Results showed that HD technology was superior to CDFI on the display of pulmonary vein in 18-22 weeks, 23-27 weeks and 28-32 weeks, of which the difference was statistically significant ($p < 0.01$). When pregnant for 33-37 weeks and 38-40 weeks, HD was not superior to CDFI, and there was no statistical significance ($p > 0.05$).

Discussion

Generally, it is relatively comprehensive to observe fetal hearts when pregnant more than 18 weeks [4], so the earliest elections of research objects in our study were 18 weeks pregnant.

During the measurement of fetal hemodynamics, because standard views are not uniform, measurement methods are not the same, measurement sites are different as well as fetal position, the measurement reproducibility is poor, strictly according to the guideline of American Society of Echocardiography (ASE) and the International Society of Ultrasound in Obstetrics & Gynecology (ISUOG), scanning sections included four-chamber, five-chamber,

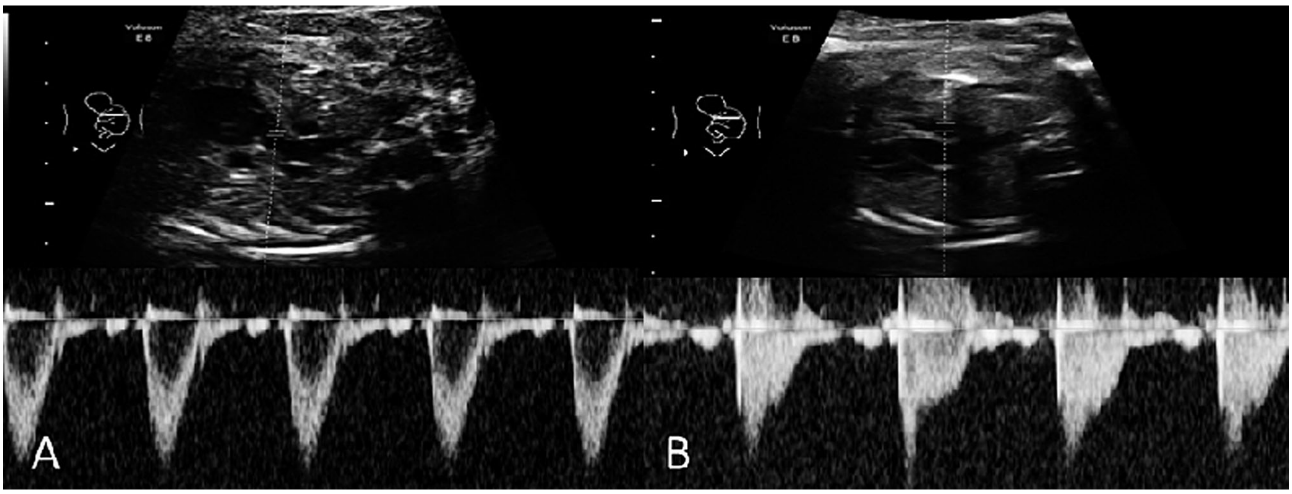

Figure 1. — Spectrum of aortic and pulmonary arteries.

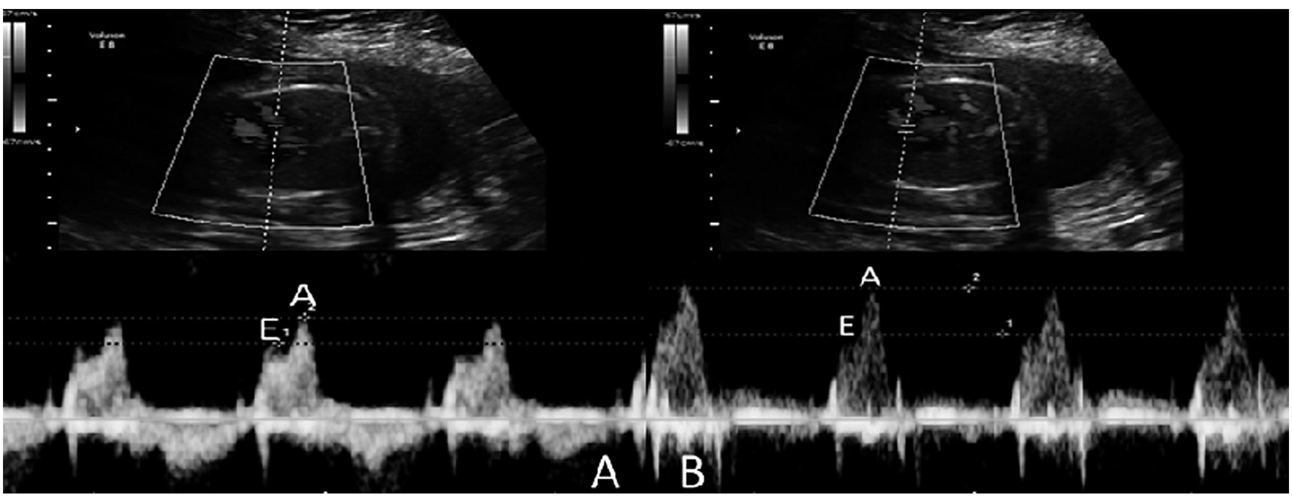

Figure 2. — Spectrum of mitral and tricuspid valves.

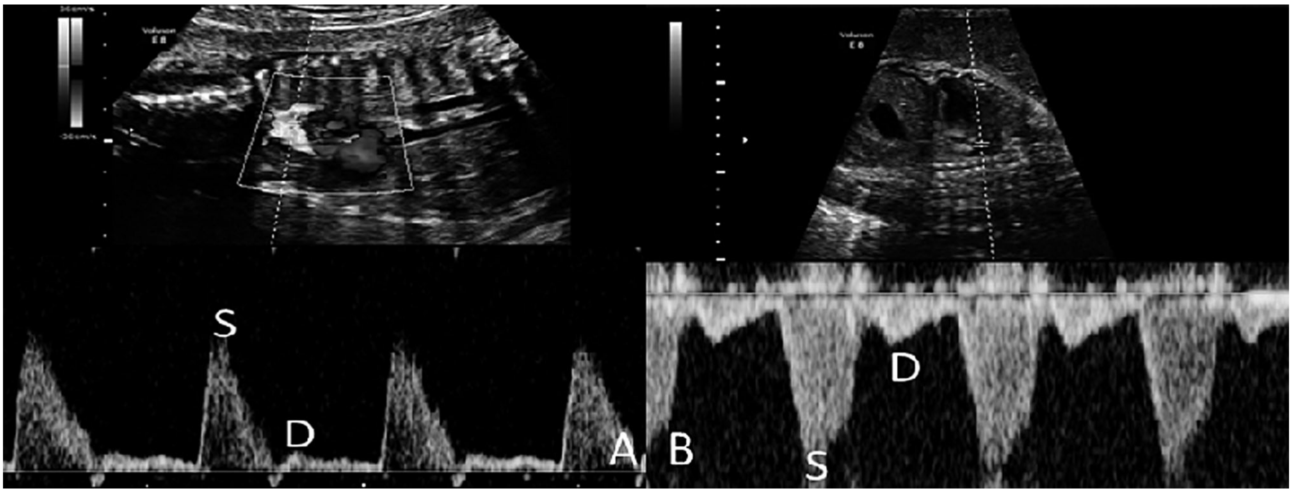

Figure 3. — Spectrum of aortic arch and artery ductal arch.

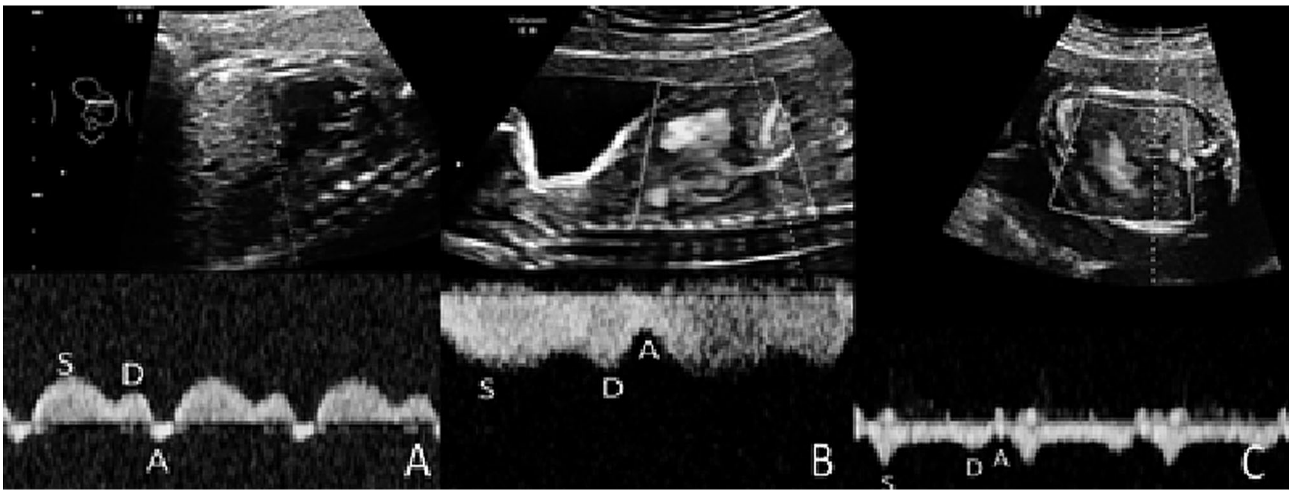

Figure 4. — Spectrum of the inferior vena cava and pulmonary vein.

left ventricular outflow tract and right ventricular outflow tract, dual-chamber short axis, main artery minor axis, aortic arch, catheter bow, three vessels and trachea, inferior vena cava long axis, etc.

With the changes of gestational age, the fetal structures to hemodynamics varied [5]. Seeking variation is greatly helpful for the diagnosis of heart abnormal in the early stage. Hence, it was necessary to establish the normal range of different gestational age of fetal cardiac hemodynamics. The results in the present research showed that the peak velocity of fetal mitral, tricuspid, aortic, pulmonary artery, aortic arch, ductal arch, the inferior vena cava, venous catheter, and pulmonary vein increased with the increase of gestational age, which was positively associated with gestational age [6]. In the 38^{th}-40^{th} weeks of gestation, the peak blood flow velocity in left and right semilunar valve and atrioventricular valve were slightly decreased, but the reason has not been reported. The authors' previous studies on anatomical structure found that the foramen ovale and arterial duct become smaller in the 38^{th}-40^{th} weeks of gestation, which may be the cause of hemodynamic change. The diminishing of foramen ovale can cause decreased preload on left ventricle, and the reduced arterial duct diameter will lead to increased afterload on right ventricle. Therefore blood flow velocity is decreased. However this needs to be further confirmed with larger sample studies.

Doppler waveform of the aorta and the pulmonary artery was similar (Figure 1), and aortic blood flow was slightly higher than the pulmonary blood flow. With increasing gestational age, the peak systolic velocity of aorta and pulmonary artery gradually increased . Aortic peak systolic velocity was greater than the pulmonary artery flow velocity, because the pulmonary valve ring is slightly larger, or because after cerebral circulation, the aortic afterload was reduced [7].

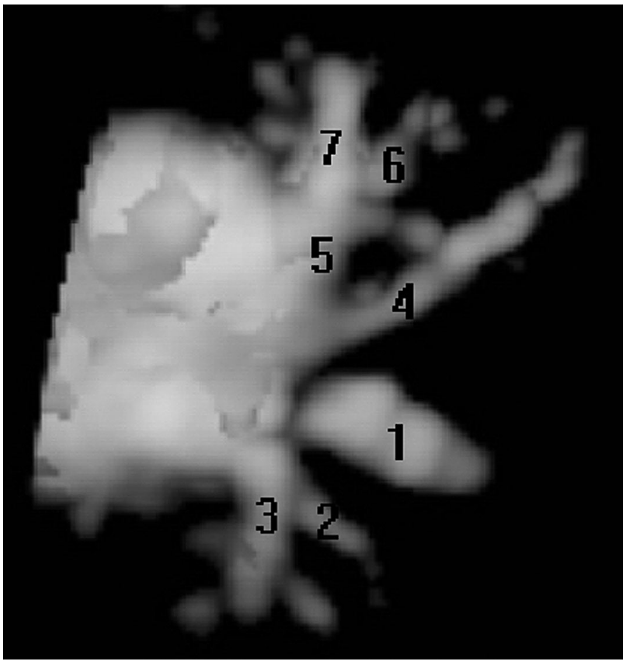

Figure 5. — Four pulmonary veins overall shown by STIC combined with HDF. 1) Thoracic aorta; 2) left inferior pulmonary vein; 3) left superior pulmonary vein; 4) right inferior pulmonary vein; 5) right superior pulmonary vein; 6) right middle lobe pulmonary vein; 7) right upper lobe pulmonary vein.

The flow spectrum of mitral and tricuspid are bimodal, peak E and peak A, corresponding to early and late diastolic of heart (atrial systole) (Figure 2). The different point is that blood flow of the aorta was visible in systole on mitral spectrum. Peak A is greater than the peak E, which might be related to the high level of myocardial stiffness [8]. The tricuspid peak E velocity was higher than mitral peak E velocity, which was similar to the results confirmed by previous research, the blood flow of tricuspid was greater than that of mitral, and cardiac output of right ventricular was greater than that of left ventricular. These confirmed fetal right heart system was dominant [9].

Aortic arch was similar to ductus arteriosus arch (Figure 3). They are both systolic high-speed flow spectrum and diastolic low-speed flow spectrum. The different point is that aortic arch diastolic peak was close to the front of which the flow spectrum was placed, while the ductus arteriosus arch diastolic peak was close to the back, showing crest-like pattern [10]. This might be related to the muscular structure of the arterial duct wall which has contractibleness. In addition, the systolic blood flow of artery catheter arch was higher than systolic aortic arch [11].

The spectrum on proximal end of inferior vena cava was a three-phase wave (Figure 4). Peak flow rate of the three peaks increased with gestational age, which showed linear correlation [12]. The ratio of reverse blood flow of peak A [13], which was the time integral of atrial systolic divided by the entire time integral of forward flow velocity, reflected the pressure gradient between the right atrium and right ventricle end-diastolic. The ratio of reverse blood flow in inferior vena cava depended on the ventricular compliance and right ventricular end-diastolic pressure [14]. It decreased with increasing gestational age, possibly due to the increased ventricular compliance and the decline in peripheral resistance. The spectrum of venous catheter was bimodal, which was peak S and peak D, while the trough corresponded to peak A. Different from inferior vena cava, venous catheters were forward flow throughout the cardiac cycle. Venous catheter diameter was fine and wall was thick, with sphincter in it, which could play a role as "valve" [15], making the blood flow into the right atrium more quickly and then into the left atrium through the foramen ovale. Three peak flow velocity of the venous catheter increased with gestational age, showing linear correlation. The flow velocity of the pulmonary vein reflected the cyclic changes in left atrial throughout the cardiac cycle, triphasic wave, and peak A showed in trough [16].

The technology of examination for hemodynamics developed from the earliest CDFI to later PD, e-flow, and the emerging HD-flow technology [17].

Due to the small size of fetal heart and lung, spatial position among the pulmonary vein are adjacent to each other, which makes the image of fetal pulmonary system more complicated and the display effect more difficult to guarantee. The emergence of new image technology of hemodynamics, such as HD-flow, has made certain achievements in low blood flow (such as in ovarian and breast tumors) imaging [18, 19]. In consideration of the characteristics of the fetal pulmonary venous system, HD-flow was used in the imaging of fetal pulmonary venous system, expecting to find a more intuitive and accurate method to display the pulmonary vein.

Bidirectional power Doppler technique and two-way PDI coding were used in the HD-flow technology to display the blood flow direction and the density information, which were suitable for the imaging of microvessel [20] such as endometrial blood vessels, ovarian vessels, intrahepatic vessels, and fetal cardiovascular because of the high sensitivity to the imaging of microvessel and reduction of the color overflow. The traditional color Doppler flow imaging (CDFI) had angular dependence, which could not display the blood signal perpendicular to the sound. Common power Doppler (PD) could show the subtle blood flow but could not display directionality [21]. There were overflow artifacts of blood flow in CDFI and PD, which meant blood flow signal overflow out of the vessels. Therefore a part of the two-dimensional gray-scale image was blocked. By contrast, HD-flow combined the advantages of the two previous ones, which could display the directionality without the angular dependence and greatly reduce blood flow overflow artifacts. While displaying the bloodstream, it could clearly show the edge of the two-dimensional blood vessel or tissue [22].

According to the results of the present research, HD-flow was superior to CDFI on the imaging of pulmonary vein in pregnancies of 18-22 weeks, 23-27 weeks, and 28-32 weeks, with $p < 0.05$. In the second and early third trimesters, due to the moderate size, the fetus could move appropriately in utero and form an appropriate fetal position, while the fetal movement was not frequent as in the first trimester, which contributed to the ultrasound probe. Simultaneously, during this period, amniotic fluid is greater, placental maturity is moderate, and skeletal ossification of fetus is not obvious, which did not produce significant acoustic shadows. Under favourable imaging conditions, based on the sensitivity of low blood flow imaging, HD-flow was better than CDFI on the display of low speed pulmonary vein. Moreover, HD-flow was not superior to CDFI with the display of pulmonary vein at 33-37 weeks and 38-40 weeks, $p > 0.05$, of which differences were not statistically significant. In the third trimester, fetal position rendered ultrasonic inspection difficult due to the large size. Generally, amniotic fluid gradually decreases and the maternal abdominal wall is thick, which were unfavorable factors for the display of fetal pulmonary vein by ultrasonic technology. Of course, HD-flow technology was also greatly restricted. At present, the accepted screening time of fetal cardiac malformation is 18-24 weeks when HD-flow is superior to CDFI with the display of pulmonary vein during this period. So HD-flow technology is still useful in clinical application when pregnant woman has fetal echocardiography indications at 18-24 weeks' gestation.

Fetal pulmonary vein positioning method: compared with the adult pulmonary vein positioning method, fetal pulmonary vein positioning was much more difficult, in which the important anatomical structures were selected as mark to position the pulmonary vein by reference to the adult pulmonary vein positioning. Upper right pulmonary vein was close to side of atrial septum, lower right pulmonary vein was close to thoracic aorta side, left pulmonary vein was close to the left atrium side, and lower left pulmonary vein was close to thoracic aorta side. It was easier to be understood and be more accurate with this method to positioning pulmonary vein (Figure 5).

USES bidirectional PD coding is adopted in HD-flow technology, which can show blood flow direction without the angular dependence. It is extremely sensitive to low speed flow due to short pulse. Therefore the technology is suitable for the display of fetal pulmonary vein blood flow condition and is more accurate for pulmonary vein positioning.

Conclusion

HD-flow technology, which can accurately evaluate fetal hemodynamics and is superior to CDFI with the image of pulmonary vein, can be applied to accurate positioning for pulmonary vein as well and has important clinical significance in fetal cardiac hemodynamics study.

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