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Assessing Fetal Cardiac Function by Measuring Myocardial Radial Velocity Using the Phased-Tracking Method

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Key Words
Phased-tracking method · Fetal cardiac function · Myocardial velocity · Myocardial radial velocity ·Twin-to-twin transfusion syndrome · Intrauterine growth restriction

Abstract
Objective: This study aimed to assess the cardiac function of healthy and pathological fetuses by measuring radial velocity using phased tracking (PT). Based on phase differences, PT allows the displacement of a specified point to be detected with improved spatial and temporal resolution. ***Methods:*** PT was used to assess cardiac radial velocity in the basal free wall of the left and right ventricles in 134 healthy fetuses, 10 second-trimester intrauterine growth-restricted (IUGR) fetuses, and 10 recipient twins with twin-to-twin transfusion syndrome (TTTS). Maximum velocities were measured in systole and early diastole. ***Results:*** Maximum radial velocity was successfully measured in 126 healthy fetuses (94%) at gestational ages of 16–40 weeks. Systolic and early diastolic maximum velocities increased with gestational age in both ventricles. As compared with controls, IUGR fetuses had significantly lower early diastolic maximum velocities in the right ventricle, and recipient twins with TTTS had significantly lower systolic and early diastolic maximum velocities in both ventricles. ***Conclusions:*** PT demonstrated right ventricular diastolic dysfunction in second-trimester IUGR fetuses as well as systolic and diastolic dysfunctions in both ventricles in recipient twins with TTTS. PT could be useful for evaluating fetal cardiac radial function.

Introduction

In adults, cardiac function can be accurately – though invasively – evaluated by measuring parameters such as ventricular contractility (dP/dt), cardiac output, and pulmonary capillary wedge pressure through cardiac catheterization [1]. Furthermore, invasive evaluation techniques have been replaced by ultrasonography using M-mode and Doppler methods. Tissue Doppler and speckle-tracking techniques of measuring myocardial velocity have recently come into use, and it has been reported that myocardial velocity correlates well with systolic and diastolic performances that are assessed by cardiac catheterization [2, 3].

Cardiac dysfunction occurs in fetuses with intrauterine growth restriction (IUGR) and twin-to-twin transfusion syndrome (TTTS), affecting life expectancy and neu-

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rological prognosis. Accurate methods of assessing fetal cardiac function are required in cases of IUGR and TTTS. Since invasive examination methods cannot be performed in fetuses, noninvasive methods have been used to evaluate cardiac function [4–6], such as fractional shortening and myocardial performance index (MPI, or Tei index) assessment using ultrasound M-mode and Doppler methods. In addition, tissue Doppler and speckle-tracking techniques have also started to be used to measure myocardial longitudinal velocity for cardiac function evaluations in fetuses [7, 8]. However, the changes to myocardial radial velocity with gestational age are unknown, as are the differences in myocardial radial velocity between normal fetuses, fetuses with IUGR, and recipient fetuses with TTTS. The movement of the myocardium in the radial direction efficiently changes the ventricular volume; therefore, the radial velocity of the fetal myocardium is an important indicator of cardiac function. However, because the radial velocity is smaller than the longitudinal velocity, high spatial and temporal resolutions are required to measure the radial velocity.

Phased tracking (PT) has been reported to achieve greater precision than when performing measurements with conventional ultrasonographic techniques [9, 10]. Further, it has been reported to allow highly precise assessments of doxorubicin-induced myocardial dysfunction in adults [11]. Increases in the myocardial thickening rate have also been reported in healthy fetuses, indicating that such increases occur with gestational age [12]. The first objective of this study was to measure the myocardial maximum velocity using PT and thereby evaluate gestational age-related changes in systolic and diastolic performances in healthy fetuses. The second objective was to clarify the differences in cardiac function (classified as systolic and diastolic performances) between healthy fetuses, pathological fetuses with IUGR, and recipient fetuses with TTTS by measuring myocardial maximum velocity using PT.

Methods

PT Method

Using ultrasonic diagnostic equipment (Aloka Prosound F75; Aloka Co., Ltd., Tokyo, Japan), the direction of the ultrasonic beam passing through the measurement points was selected in the four-chamber view B-mode cross-sectional images so as to be almost perpendicular to the right (RV) and left ventricle (LV) during measurement. Just after selection, the direction of the ultrasonic beam was fixed and the beam-formed radio frequency (RF) signal was converted from analog to digital (A/D) at a sampling frequency of 20 MHz during several heartbeats. The ultrasound system used in the present study (Aloka F75) was modified by the manufacturer to allow the acquisition of RF signals. The acquired RF signals were processed offline to obtain the M-mode image, velocity, and other parameters. The principles of the PT method, including theoretical and in vivo evaluations of the myocardial layer-thickening rate, have been previously described in detail [9, 10].

In brief, RF pulses with an angular frequency of $\omega 0 = 2\pi f0$ ($f0 = 5$ MHz) are transmitted at time intervals of ΔT from an ultrasonic transducer on the maternal abdominal wall. The phase difference, $\Delta\theta(x; t)$, between the phase $\theta(x; t)$ of the quadrature-demodulated signal of the received signal, $y(x; t)$, and the phase $\theta(x; t + \Delta T)$ of the quadrature-demodulated signal $z(x; t + \Delta T)$ of the subsequently received signal, $y(x; t + \Delta T)$, is given by

$$\Delta\theta(x; t) = \theta(x; t + \Delta T) - \theta(x; t) = -(2\omega 0)/c0 \cdot \Delta x(t), \quad (1)$$

where $\Delta x(t) = x(t + \Delta T) - x(t)$ is the movement of the object during the short period ΔT around time t, and c0 is the acoustic velocity in the soft tissue. In the present study, the period ΔT was set at 238 μs. That is, the frame rate was 421 Hz, so that the measurable velocity was set at a fair limit of 0.32 m/s (at $f0 = 5$ MHz). By dividing the movement Δx by the period ΔT, the average velocity $v(t + \Delta T/2)$ of the object during the period ΔT is given by

$$v(t + \Delta T/2) = (\Delta x(t)) / \Delta T = c0\,(2\omega 0) \cdot \Delta\theta(x; t)/\Delta T. \quad (2)$$

The phase difference $\Delta\theta(x; t)$ is accurately determined by the constrained least squares approach, based on the complex cross-correlation between $z(x; t)$ and $z(x; t + \Delta T)$, under the condition that the signal waveforms only change in terms of phase values during the period ΔT. It is impossible to accurately determine the true lag value from the complex correlation function, which is derived from the standard normalized mean squared difference between the quadrature-modulated signals of the successively received signals [13]. However, the introduction of the constraint is effective for determining the lag between these complex signals. By multiplying the resultant velocity $v(t + \Delta T/2)$ by the period ΔT, the next depth $x(t + \Delta T)$ of the object is estimated by

$$\Delta x(t + \Delta T) = x(t) + v(t + \Delta T/2) \cdot \Delta T. \quad (3)$$

Using the resultant signal $x(t + \Delta T)$, the displacement of the object (the position of the region of interest) in the heart wall is successfully tracked, and the velocity signal $v|Ax(t)$ of the large motion due to the heartbeat is accurately measured.

In conventional ultrasonographic techniques, deviations of a point of interest that are smaller than the wavelength cannot be detected because they are measured based on the amplitude of the reflected waves. For this reason, the precision of distance measurements in the transmitted beam direction is 0.5–1 mm at a frequency of 3–5 MHz, which is used in fetal measurements. However, the measurement principle of the PT method differs from that of conventional methods. In the PT approach, an ultrasonic pulse is transmitted from the ultrasound probe and reflected by the cardiac wall with slight movement. By the time it returns to the probe, a phase delay has occurred in the ultrasound pulse due to propagation length. By detecting the phase difference between two ultrasonic pulses that are continuously transmitted and received, it is possible to estimate displacements of a point of interest that are smaller than the wavelength with a velocity measurement precision of 0.1 mm/s and a distance measurement precision of 0.5 μm [10]. In this study, a high-speed A/D converter was used to acquire beam-formed RF signals, which were received by a 5-MHz convex-

type ultrasonic transducer connected to modified ultrasonic diagnostic equipment. The use of a converter with large-scale memory allowed us to collect data for several cardiac cycles.

The lateral four-chamber view is a fetal cardiac screening cross-section that is in wide clinical use. In this study, we rendered a lateral four-chamber view of the fetal heart in the B-mode of the ultrasound diagnostic equipment and transmitted a beam perpendicular to the basal portion of the ventricular free wall at the level of the tip of the atrioventricular valves (fig. 1). We tracked the radial velocity of the subendocardial myocardium in the LV and RV for 2 s and determined the average maximum systolic velocity and maximum early diastolic velocity for 3 or 4 heartbeats in which there was no fetal movement and the myocardial velocity was reproducible (fig. 2).

Subjects

The study design was approved by the institutional review board, and each woman provided informed consent before participating in the study.

The study subjects were healthy single fetuses who had an estimated body weight within ±1.5 standard deviations (SDs) of the standard values of ultrasonographic fetal biometry of the Japan Society of Ultrasonics in Medicine [14]. Fetuses with structural or chromosomal abnormalities were excluded. Using PT, maximum systolic and maximum early diastolic velocities were measured in 134 subjects at 16–40 weeks of pregnancy (mean ± SD, 26.4 ± 6.1 weeks). The parameters were measured in both the LV and RV, and the correlation with gestational age was examined. Furthermore, we used PT measurements to examine differences between the LV and RV in terms of maximum systolic velocities and maximum early diastolic velocities with adjustments for gestational age. Intraobserver agreement was evaluated using the intraclass correlation coefficient (ICC) in 10 subjects at 17–37 weeks of pregnancy. Interobserver agreement was evaluated for two observers using the ICC of 10 subjects at 22–33 weeks of pregnancy. The coefficient of variation was analyzed in systole and early diastole.

The subjects for the chronic reduced cardiac function model were second-trimester IUGR fetuses. The IUGR group consisted of 10 fetuses with gestational ages of 18–28 weeks and an estimated body weight of less than –1.5 SD of the Standard Values of Ultrasonographic Fetal Biometry of the Japan Society of Ultrasonics in Medicine [14]. Twenty fetuses with gestational ages of 18–28 weeks and an estimated body weight within ±1.5 SD of the Standard Values of Ultrasonographic Fetal Biometry of the Japan Society of Ultrasonics in Medicine [14] were randomly selected as the control group. Fetuses with structural or chromosomal abnormalities were excluded. The IUGR and control groups were compared in regard to gestational age, estimated body weight, the absence of end-diastolic velocity in the umbilical artery and the ductus venosus, and the presence of a cerebroplacental ratio of ≤1.0. In addition, the two groups were compared in terms of MPI, as assessed by the Doppler blood flow method, and fractional shortening, as assessed by the M-mode technique. MPI and fractional shortening are conventional indicators of fetal cardiac function. Maximum systolic velocity and maximum early diastolic velocity in the two groups were then measured by PT. The parameters were measured in both the LV and RV.

The subjects for the acute reduced cardiac function model were 10 TTTS recipients with gestational ages of 18–22 weeks who had not yet undergone fetoscopic laser photocoagulation of placental

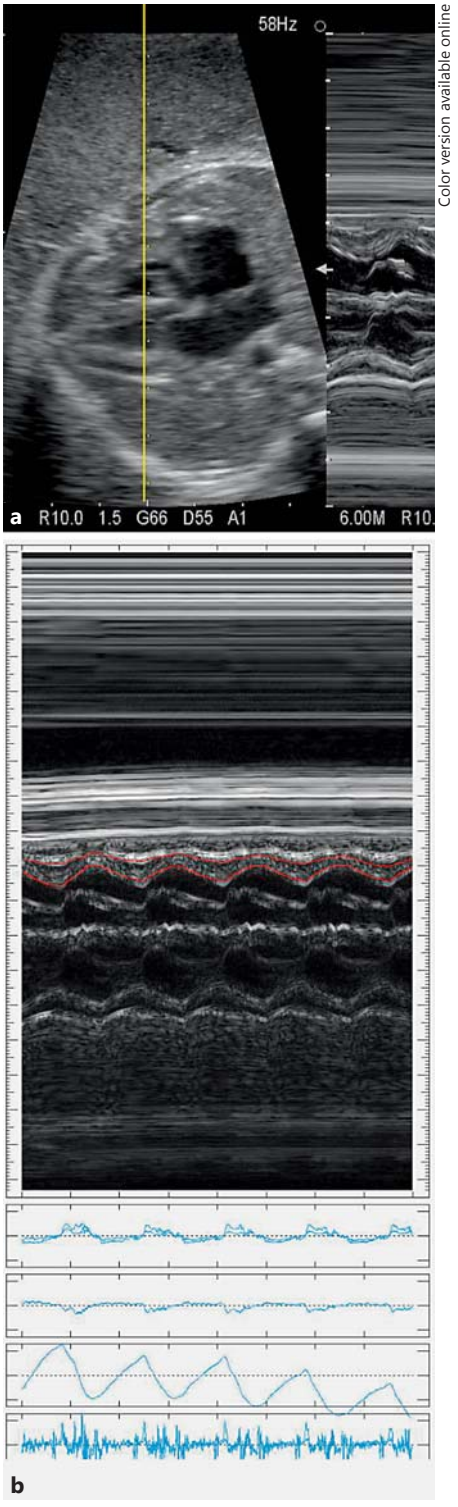

Fig. 1. Lateral four-chamber view of a fetal heart displayed in B-mode cross-sectional imaging. The beam is transmitted perpendicular to the basal portion of the ventricular free wall (**a**). Based on the acquired data, the starting point of the sites to be measured is set offline with an M-mode image as a guide, and the program tracks the velocity of the specified part using the PT method (**b**).

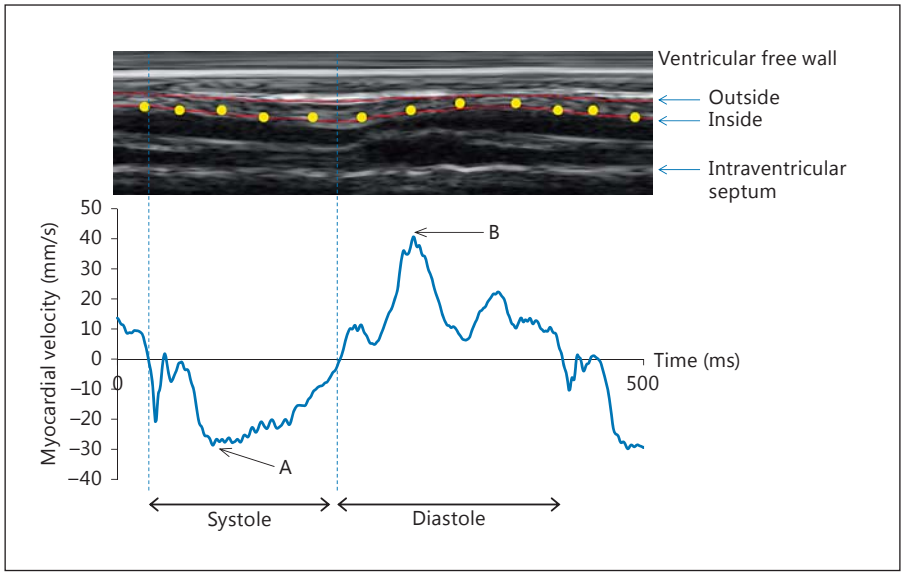

Fig. 2. Change over time in the myocardial velocity inside the ventricular free wall, as measured using PT. The measurement sites are indicated by dots. A = Maximum systolic velocity; B = maximum early diastolic velocity.

communicating vessels for TTTS. According to the Quintero stage classification [15], 5 subjects were stage I, 2 subjects were stage II, 2 subjects were stage IIIc, and 1 subject was stage IV. Twenty fetuses with gestational ages of 16–22 weeks and an estimated body weight within ±1.5 SD of the Standard Values of Ultrasonographic Fetal Biometry of the Japan Society of Ultrasonics in Medicine [14] were randomly selected as the control group. The TTTS recipient and control groups were compared in regard to gestational age, estimated body weight, absent or reverse end-diastolic velocity of the ductus venosus, tricuspid regurgitation, mitral regurgitation, monophasic tricuspid valve inflow, and monophasic mitral valve inflow. In addition, the two groups were compared in regard to MPI, as assessed by the Doppler blood flow method, and fractional shortening, as assessed by the M-mode technique. Maximum systolic velocity and maximum early diastolic velocity in the two groups were then measured by PT. The parameters were measured in both the LV and RV.

Statistical analysis

Data were analyzed using JMP 10.0.2 statistical software (SAS Institute, Inc., Cary, N.C., USA). Results are expressed as mean ± SD values or proportions. Fisher's exact test, one-way analysis of variance (ANOVA), and two-way ANOVA were used for statistical comparisons, and $p < 0.05$ was considered significant.

Results

First, the correlation between myocardial maximum velocity and gestational age was examined in the healthy fetuses. Measurement was possible in 126 (94%) of the 134 subjects. In the other subjects, measurement was not possible due to fetal presentation. The intra-observer agreement using the ICC of maximum systolic velocity was 0.926 [95% confidence interval (CI), 0.746–0.981] for the LV and 0.708 (95% CI, 0.214–0.917) for the RV. The ICC of maximum early diastolic velocity was 0.870 (95% CI, 0.584–0.966) in the LV and 0.966 (95% CI, 0.878–0.991) in the RV. The inter-observer agreement using the ICC of maximum systolic velocity was 0.924 (95% CI, 0.740–0.980) for the LV and 0.987 (95% CI, 0.951–0.957) for the RV. The ICC of maximum early diastolic velocity was 0.984 (95% CI, 0.941–0.996) for the LV and 0.985 (95% CI, 0.944–0.996) for the RV. The coefficients of variation of maximum myocardial velocities were 17.9% in systole and 12.4% in early diastole. Maximum systolic and maximum early diastolic velocity correlated positively with gestational age in both the LV and RV (LV maximum systolic velocity, $r = 0.84$, $p < 0.01$; LV maximum early diastolic velocity, $r = 0.69$, $p < 0.01$; RV maximum systolic velocity, $r = 0.52$, $p < 0.01$; RV maximum early diastolic velocity, $r = 0.56$, $p < 0.01$; fig. 3). When comparing the myocardial maximum velocities of the LV and RV adjusted for gestational age using two-way ANOVA, no significant difference in the maximum systolic velocity was observed between the two ventricles, but the maximum early diastolic velocity was higher in the RV than in the LV ($p < 0.01$).

Second, the myocardial maximum velocities were compared between the second-trimester IUGR and control groups. The gestational age at the time of examination was 23.4 ± 3.8 weeks in the IUGR group and 23.3 ± 3.0 weeks in the control group (table 1). The estimated body weight at the time of examination was 458 ± 296 g

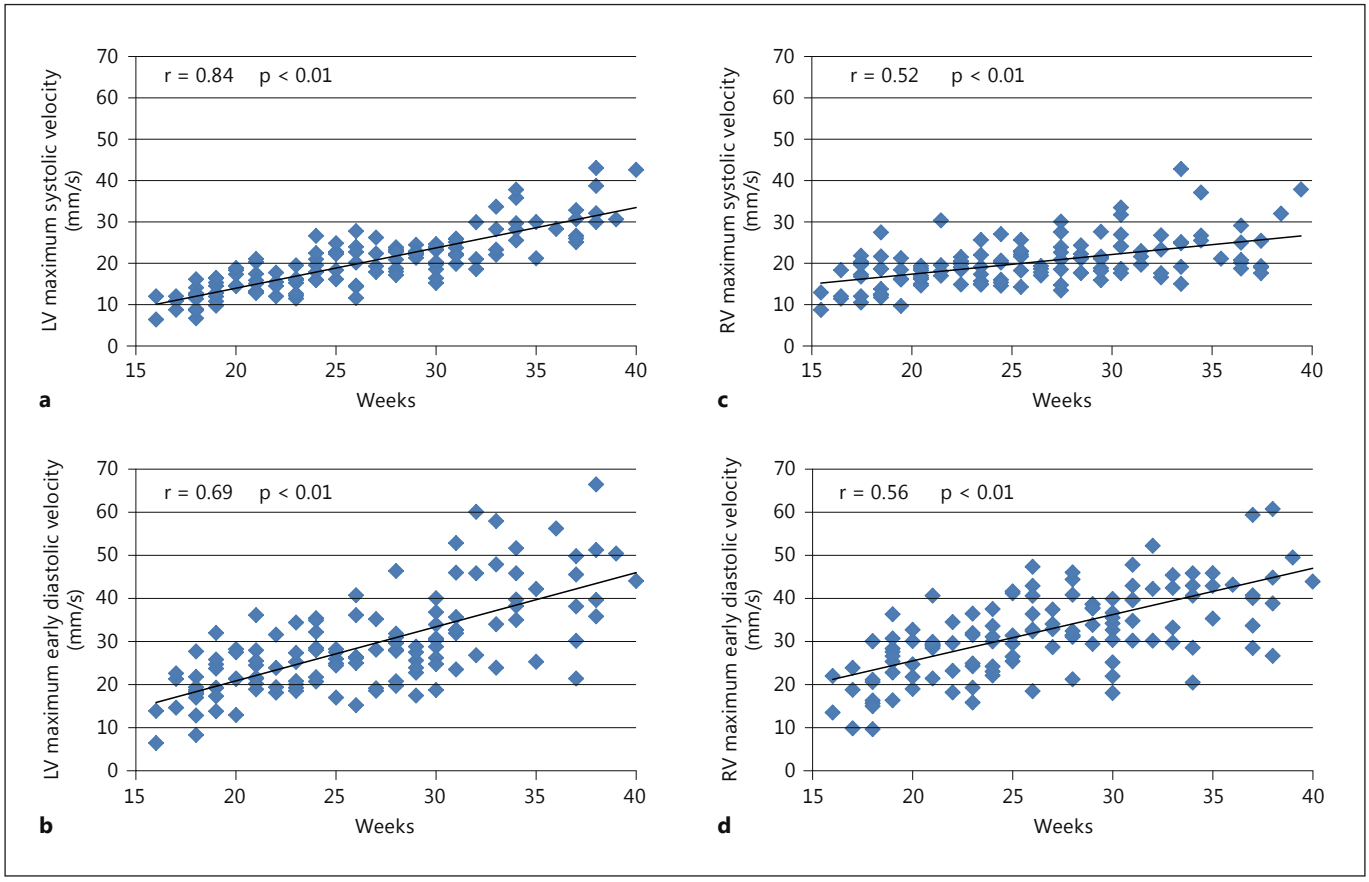

Fig. 3. Correlations of the following measurements with gestational age: maximum systolic velocity (**a**) and maximum early diastolic velocity in the LV (**b**) as well as maximum systolic velocity (**c**) and maximum early diastolic velocity in the RV (**d**). Two-way ANOVA was used to compare the LV and RV; the maximum early diastolic velocity was greater in the RV than in the LV ($p < 0.01$). r = Correlation coefficient.

in the IUGR group and 661 ± 324 g in the control group. In the IUGR group, absent end-diastolic velocity of the umbilical artery was observed in 5 subjects and a cerebroplacental ratio of ≤1.0 was obtained for 7 subjects. The MPI was 0.44 ± 0.12 in the LV and 0.48 ± 0.14 in the RV in the IUGR group, and no significant difference was observed when comparing the IUGR group with the control group. Similarly, the fractional shortening was 29.2 ± 6.6% in the LV and 25.7 ± 7.9% in the RV in the IUGR group, and no significant difference was observed in comparison with the control group. In the PT measurements, the maximum early diastolic velocity of the RV was significantly lower in the IUGR group than in the control group (24.5 ± 6.2 vs. 32.1 ± 7.0 mm/s, $p < 0.01$).

Third, the myocardial maximum velocities were compared between the TTTS recipient and control groups. The gestational age at the time of examination was 19.0 ± 1.4 weeks in the TTTS recipient group and 19.4 ± 1.7 weeks in the control group (table 2). The estimated body weight at the time of examination was 265 ± 112 g in the TTTS recipient group and 291 ± 104 g in the control group. In the TTTS recipient group, absent or reverse end-diastolic velocity of the ductus venosus was observed in 2 subjects, tricuspid regurgitation was observed in 4 subjects, and monophasic tricuspid valve inflow was observed in 1 subject. Since 1 fetus did not have antegrade blood flow in the pulmonary artery, it was not possible to measure the MPI in the RV. In the TTTS recipient group, the MPI was 0.60 ± 0.15 in the LV and 0.58 ± 0.11 in the RV; both values were significantly higher than those observed in the control group (LV, $p < 0.01$; RV, $p = 0.04$). Similarly, fractional shortening was 26.6 ± 9.6% in the LV and 20.4 ± 7.9% in the RV in the TTTS recipient group. RV fractional shortening was significantly lower in the

Table 1. Comparison of background factors, MPI, fractional shortening, and myocardial maximum velocity measurements using PT in the IUGR and control groups

	IUGR group (n = 10)	Control group (n = 20)	p
Gestational age, weeks	23.4±3.8	23.3±3.0	0.93
Estimated fetal body weight, g	458±296	661±324	0.10
Absent umbilical artery end-diastolic flow	5	0	<0.01*
Cerebroplacental ratio <1.0	7	1	<0.01*
Ductus venosus absent atrial contraction wave	0	0	1.00
MPI			
LV	0.44±0.12	0.44±0.08	0.98
RV	0.48±0.14	0.48±0.13	0.91
Fractional shortening, %			
LV	29.2±6.6	32.6±7.1	0.22
RV	25.7±7.9	30.4±7.6	0.13
Maximum systolic velocity, mm/s			
LV	15.2±5.5	18.0±3.9	0.12
RV	17.5±6.6	21.1±5.0	0.10
Maximum early diastolic velocity, mm/s			
LV	25.6±9.6	27.8±8.5	0.52
RV	24.5±6.2	32.1±7.0	<0.01*

Data are expressed as means ± SD or numbers. Calculated by ANOVA and Fisher's exact test. * $p < 0.05$.

Table 2. Comparison of background factors, MPI, fractional shortening, and myocardial maximum velocity measurements using PT in the TTTS recipient and control groups

	TTTS recipient group (n = 10)	Control group (n = 20)	p
Gestational age, weeks	19.0±1.4	19.4±1.7	0.53
Estimated fetal body weight, g	265±112	291±104	0.53
Ductus venosus absent or reverse atrial contraction wave	2	0	0.10
Mitral regurgitation	0	0	1.00
Tricuspid regurgitation	4	1	0.03*
Monophasic mitral valve inflow	0	0	1.00
Monophasic tricuspid valve inflow	1	0	0.33
MPI			
LV	0.60±0.15	0.45±0.10	<0.01*
RV	0.58±0.11	0.47±0.13	0.04*
Fractional shortening, %			
LV	26.6±9.6	33.0±8.3	0.06
RV	20.4±7.9	34.3±6.4	<0.01*
Maximum systolic velocity, mm/s			
LV	10.1±3.6	13.8±3.2	<0.01*
RV	11.8±4.3	18.2±4.6	<0.01*
Maximum early diastolic velocity, mm/s			
LV	16.5±4.6	22.5±6.6	0.01*
RV	17.3±8.5	24.9±5.8	<0.01*

Data are expressed as mean ± SD or numbers. Calculated by ANOVA and Fisher's exact test. * $p < 0.05$.

TTTS recipient group than in the control group ($p < 0.01$), and LV fractional shortening also appeared to be lower in the TTTS recipient group, but the difference was not statistically significant ($p = 0.06$). In the PT measurements, the maximum systolic velocities and maximum early diastolic velocities of the RV and LV were significantly lower in the TTTS recipient group than in the control group (LV maximum systolic velocity, 10.1 ± 3.6 vs. 13.8 ± 3.2 mm/s, $p < 0.01$; LV maximum early diastolic velocity, 16.5 ± 4.6 vs. 22.5 ± 6.6 mm/s, $p = 0.01$; RV maximum systolic velocity, 11.8 ± 4.3 vs. 18.2 ± 4.6 mm/s, $p < 0.01$; RV maximum early diastolic velocity, 17.3 ± 8.5 vs. 24.9 ± 5.8 mm/s, $p < 0.01$).

Discussion

Maximum systolic and maximum early diastolic velocities exhibited positive correlations with gestational age in both ventricles. It has been reported that the maximum systolic velocity of the myocardium correlates well with dP/dt, a systolic performance indicator [2], and that the maximum early diastolic velocity correlates well with the catacrotic time constant τ of the ventricular pressure curve, a diastolic performance indicator [3]. The results of this study suggest that the systolic and diastolic performances of both ventricles increase with gestational age.

Although we observed no difference between the maximum systolic velocities of the LV and RV, the maximum early diastolic velocity was higher in the RV than in the LV. We believe this is because the RV is larger in size and has a higher cardiac output than the LV in the fetal heart. In reports published thus far, longitudinal velocity is greater in the fetal RV than in the fetal LV, as measured by tissue Doppler imaging [16, 17]. However, no reports have been published on radial velocity. The myocardium is a complex three-dimensional network of myocytes in a matrix of fibrous tissue in both ventricles. However, there is a predominant longitudinal orientation to the myocytes, forming the myofibers in the RV. Although the longitudinal function of the RV is predominant prenatally, the radial systolic function may have no difference in both ventricles. The present study has clearly shown that fetuses have greater early diastolic radial velocity in the RV than in the LV.

The RV maximum early diastolic velocity was lower in second-trimester IUGR subjects than in healthy fetuses. The decreased RV diastolic performance in the IUGR subjects suggests the possibility that the afterload and the end-diastolic pressure of the ventricles increase in IUGR, owing to the increasing vascular resistance of the placenta [18, 19]. Furthermore, the RV has a larger preload than the LV because it ejects more blood flow. Moreover, as compared with the LV, the RV may have an anatomical structure that is more easily affected by the afterload. The LV mainly ejects blood flow to the brain, and the RV ejects to the placenta through the ductus arteriosus. Although increased resistance of placenta effects afterload is found in both ventricles, brain sparing leads to a decreased afterload in the LV. In our IUGR group, a cerebroplacental ratio of ≤1 was obtained for 7 subjects, and a ratio close to 1.0 was obtained for the others. In reports published to date, systolic and diastolic longitudinal velocities in the fetal heart are lower in fetuses with IUGR than in normal fetuses, as measured by tissue Doppler imaging [20]. In this study, no difference in the MPI or fractional shortening was seen between the IUGR and control groups. This finding is explained by the many mild cases that were included in our IUGR group. It has previously been reported that early stages of IUGR more typically affect the longitudinal function than the radial function of the fetal heart [4]. However, the results of the present study suggest that radial diastolic dysfunction in the RV may occur in fetuses with early stages of IUGR.

As compared with the healthy fetuses, the TTTS recipient fetuses exhibited low maximum systolic and low maximum early diastolic velocities of both the LV and RV. Further, the two groups were observed to have different MPIs and fractional shortenings. In previous reports, increased MPI and decreased fractional shortening have also been noted in both ventricles of recipient fetuses with TTTS [21]. Moreover, a study has found that myocardial diastolic function measured by tissue Doppler imaging is lower in recipient fetuses with TTTS than in healthy fetuses [22]. However, no report has included measurements of myocardial radial velocity in recipient fetuses with TTTS. The present study has clearly shown that the myocardial radial velocities of both the LV and RV are lower in recipient fetuses with TTTS than in normal fetuses.

This study investigated the radial velocity of the ventricular free walls. Ultrasound-based measurements of cardiac velocities can be divided into the following three directions: longitudinal, circumferential, and radial. Tissue Doppler imaging has been used to measure the longitudinal velocity of the fetal myocardium [23]. However, very few reports have considered the radial velocity of the fetal myocardium [8]. Fractional shortening is an indicator of radial-direction systolic performance, and the movement of the myocardium in the radial direction ef-

ficiently changes the ventricular volume [24]. We therefore think that the radial velocity of the fetal myocardium is one of the most important indicators for evaluating cardiac function. However, because the radial velocity is smaller than the longitudinal velocity, it requires more precise measurements. In the present study, we used the PT method to obtain precise measurements of radial velocity.

PT has many advantages for the measurement of myocardial velocity in fetuses. Because of the very small size and fast beating rate of the fetal heart, excellent spatial and temporal resolutions are required to measure fetal myocardial velocity with high precision. Currently, fetal myocardial velocity is measured using tissue Doppler and speckle tracking methods. Studies using tissue Doppler and speckle tracking have evaluated cardiac function in IUGR and TTTS recipient fetuses [25, 26]. Although speckle tracking has less angular dependence, it may nonetheless be difficult to obtain a sufficient frame rate when examining fetuses [8]. PT has much greater spatial and temporal resolutions than those offered by conventional ultrasonographic techniques [9]. In conventional ultrasonographic techniques, deviations of a point of interest cannot be detected if they are smaller than the wavelength. However, the PT method can be used to detect displacements of a point of interest that are smaller than the wavelength, based on an evaluation of the phase difference between two ultrasonic pulses. Accordingly, PT provides improved spatial and temporal resolutions. In water tank testing, the velocity measurement precision of PT was found to be 0.1 mm/s [10]. PT can measure myocardial velocity with higher precision than tissue Doppler or speckle-tracking methods.

However, PT measurements are dependent on angle. Since the heart moves with three-dimensional distortion, the measurement of myocardial velocity in one direction may not capture the systolic and diastolic performances of the entire heart. It is also possible that the measurement of radial velocity at a single point on the endocardium side of the ventricular free wall does not reflect the movement of the entire ventricle. In addition, myocardial velocity is affected by the pre- and afterload of the ventricles. Furthermore, the number of pathological fetal subjects in this study was small, and it must be increased to achieve more precise findings.

In this study, the evaluation of cardiac function involved precise measurements of myocardial radial velocity, which were performed separately for the contraction and expansion of the two ventricles in fetuses. We demonstrated that, in healthy fetuses, ventricular systolic and diastolic radial performances increase with gestational age. By measuring myocardial radial velocity using PT, we found diastolic dysfunction of the RV in fetuses with IUGR as well as systolic and diastolic dysfunctions of both the LV and RV in TTTS recipients. PT may provide a useful method of measuring the maximum radial velocity in the fetal myocardium, and thereby assessing systolic and diastolic performances in fetuses.

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