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Original Article

Foetal cardiac function: assessing new technologies

Helena M. Gardiner

Department of Obstetrics, Gynaecology and Reproductive Sciences, The Texas Fetal Centre, Children's Memorial Hermann Hospital, University of Texas, Houston, Texas, United States of America

Abstract Assessment of foetal cardiac function is more challenging than in the adult, in whom emerging technologies are tested. The postnatal cardio-respiratory interaction is replaced by the cardio-placental circulation and impedance of the brain, and distal vascular beds play an important role in modulating flow to enable its redistribution in the foetal body. Prenatal specialists, comprising obstetricians and cardiologists, have tested a variety of traditional methodologies, as well as non-Doppler offline ultrasound methods in the foetus. This article reviews the development of techniques, outlines their use, and draws attention to pitfalls in adapting technologies validated in the adult heart to the small, fast beating, remote, and largely ungated foetal heart.

Keywords: Foetal cardiac function; foetal echocardiography; Doppler; strain

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Overt heart failure in the foetus is easy to recognise at echocardiography: characteristic signs include increased systemic venous pressures, an increased cardiothoracic ratio, and poor cardiac function often manifest by a "jerky" appearance during diastole. Hydrops – collection of fluid in the pleural, pericardial, and intra-abdominal spaces – may develop in the later stages and is associated with high intrauterine mortality and impaired neurodevelopmental outcome, unless a treatable cause such as foetal anaemia is found.[1,2] Quantitative measures of cardiac function are required because the unique morphological features and physiological responses of the foetal circulation make interpretation of traditional Doppler parameters[3] more difficult, particularly in the malformed heart. Prediction of functional deterioration may be difficult as systolic function is preserved in most foetuses until the time of imminent collapse, when it may be too late to reverse.[4] For example, the large heart in Ebstein malformation shows an increased cardiothoracic ratio and distended systemic veins, but systolic function may be preserved for many weeks. The pivotal question that any functional assessment must be able to answer is whether there is sufficient cardiac output to oxygenate the tissues and to maintain foetal well-being.[3,5] Non-invasive assessment requires a practical tool with which cardiac output and functional reserve are assessed; current methods pose particular challenges in the foetus.[6] Cardiac output is the product of heart rate and volume blood flow, both of which have been measured in foetal lamb models and in the human foetus, albeit indirectly.[3,5,7] Myocardial functional assessment is regulated by changes in preload, afterload, and cardiomyocyte contractility.[6,8] Myocardial performance matures during pregnancy, and parameters differ between the first and third trimesters and with abnormal foetal growth; therefore, a knowledge of these is important to allow correct interpretation of Doppler recordings.[9,10] Much of what we accept as normal human cardiac function is based on experimental invasive ovine models, which have the advantage of permitting direct recordings and can integrate information from invasive pressure measurements, volume transducers, and correlate them with non-invasive peripheral Doppler recordings.[5] Animal

Correspondence to: Professor H. M. Gardiner, MD, PhD, Department of Obstetrics, Gynaecology and Reproductive Sciences, The Texas Fetal Centre, Children's Memorial Hermann Hospital, University of Texas, 6410 Fannin, Suite 700, Houston, TX 77030, United States of America. Tel: +1 832 325 7288; Fax: +1 7133831464; E-mail: Helena.m.gardiner@uth.tmc.edu

studies are not completely applicable to the human foetus where regional distribution of blood flow in response to stress appears to differ based on recordings made using non-invasive Doppler ultrasound.[7–10]

The foetal circulation

The unique design of the foetal circulation (Fig 1) allows for ready mixing of the systemic and pulmonary circulations, even in the normally formed heart. The major site of mixing is through the oval foramen and, when there is obstruction to flow, most frequently in the arterial duct. Flow deviation away from the sites of obstruction leads to near-equalisation of pressures that would usually be elevated when using Doppler to examine a similar lesion after birth.[11] This diminishes the ability of a Doppler trace to quantify the true severity of, for example, valvular stenosis prenatally. Prenatal Doppler assessment has developed several indices to help interpret this complex foetal physiology.

Indices of foetal heart function

Arterial Doppler indices. Doppler was first used in a "blind" technique to examine placental blood flow in the 1970s.[12] Pulsed Doppler is most often used in obstetric practice today and is guided by two-dimensional images. However, it still remains a demanding technique requiring close alignment of the angle of insonation to blood flow, with the sample volume large enough to cover the diameter of the vessel to enable all velocities within the Doppler envelope to be recorded.[13] For all Doppler recordings, the foetus should be still, without breathing movements, and ideally, the mother should hold her breath during the recording. If these technical aspects are observed it is possible to record blood flow velocities, which are reproducible and may provide useful information, particularly to chart an individual's physiology over serial examinations. Measurement of volume blood flow and actual organ perfusion remains elusive.[7,13] Arterial Doppler is used to classify the degree of compromise of placental function but is not as good a predictor of timing of delivery in compromised foetuses as is venous Doppler.[12–14] Precordial venous Doppler is recognised to reflect early cardiac dysfunction with poor ventricular filling and may be abnormal, even when systolic contractility appears unaltered.[8,15,16]

Venous Doppler indices. The most useful vein seems to be the venous duct, which connects the intrahepatic portion of the umbilical vein to the inferior caval vein (Fig 1). It is a narrow trumpet-shaped structure, which acts as a conduit for oxygenated flow returning from the placenta to the left side of the

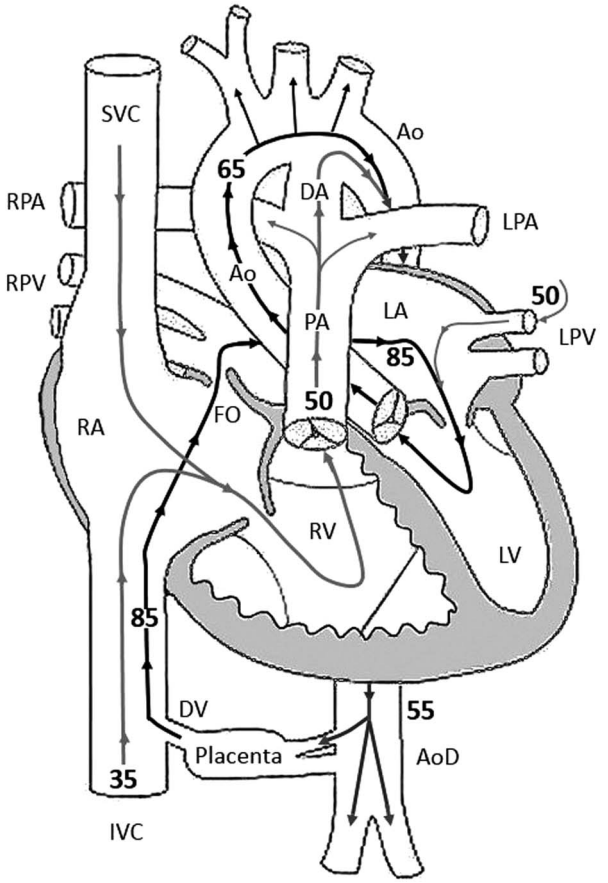

Figure 1.
Diagram of the circulation in the normal foetus showing streams of flow of higher oxygen saturation in black and lower saturation flows in grey. In particular, note the low saturation of pulmonary venous return in the foetal heart. The approximate oxygen saturations are shown in the cardiac chambers and vessels. Ao = ascending aorta and its arch; AoD = descending aorta; DA = arterial duct; DV = venous duct; FO = oval foramen (or foramen ovale); IVC = inferior caval vein; LA = left atrium; LPA = left pulmonary artery; LPV = left pulmonary veins; LV = left ventricle; PA = pulmonary artery; RA = right atrium; RPA = right pulmonary artery; RPV = right pulmonary veins; SVC = superior caval vein.

foetal heart, and also as a pressure transducer transmitting the atrial force along its walls.[15] There is normally a forward flow towards the heart during all phases of the cardiac cycle, but abnormalities of end-diastolic flow – the A wave – are manifest as absent or reversed in circumstances when foetal well-being is compromised, such as in hypoxaemia, aneuploidy, and in cases where there is increased atrial pressure.[15,16] A reversed A wave in the venous duct is seen commonly in foetuses with obstructive right heart malformations, such as pulmonary atresia with intact ventricular septum, when there is important tricuspid regurgitation or foetuses with functional abnormalities such as the recipient twin in

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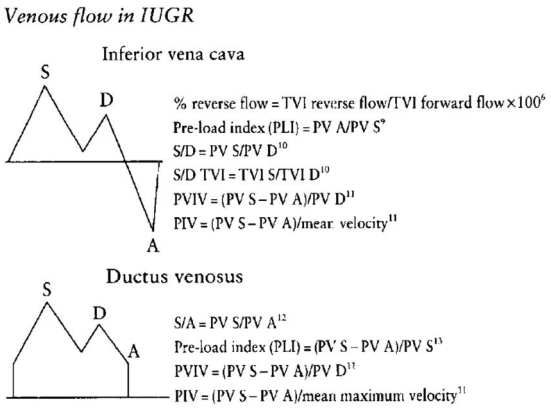

Figure 2.
Preload indices from Doppler recordings in systemic veins in the foetus. (Reproduced by permission from Rizzo et al[20]; figure 1).

twin-to-twin transfusion syndrome.[17,18] The early component and total filling time of the heart is reflected in the Doppler pattern of the venous duct and may be one practical method to distinguish twin-to-twin transfusion syndrome from selective growth restriction.[19]

Various functional indices have been described:

Preload index

Definition

This assesses the percentage of reverse flow in the precordial veins, usually the superior or inferior caval veins, or the venous duct.[20]

Method

The sample volume is placed in the superior caval vein, inferior caval vein, or venous duct in alignment with the flow, and the area under the Doppler trace is compared during forward flow and reversal with atrial contraction (Fig 2). The normal proportion of reversed flow lessens with foetal maturation, and normal ranges are available.[20–22]

Technical details

The Doppler sample must be aligned within the flow to capture the true waveform and assess the extent of flow reversal. The imaging plane of these veins will need to be parasagittal or coronal to achieve optimal alignment.

Afterload index

Definition

These are derived from arterial Doppler recordings, described as resistance or pulsatility indices[12,13] (Fig 3).

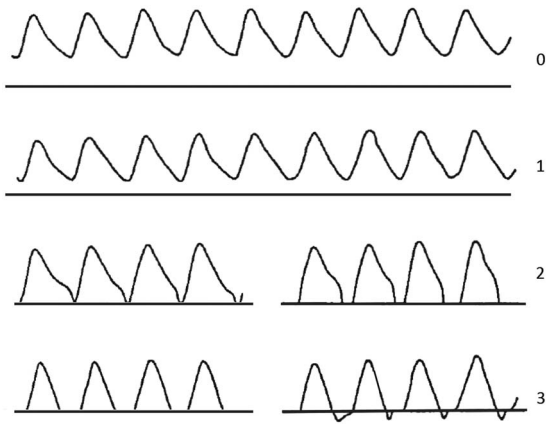

Figure 3.
Cartoon illustrating the semiquantitative blood flow classes (BFC) applicable to foetal arteries based on study by Gudmundsson and Marsál[13]: BFC 0 reflects a normal pulsatility index (PI); BFC 1 shows positive end-diastolic flow with PI > mean + 2SD; BFC 2 is when end-diastolic flow is absent; BFC 3 is when there is absence or reversal of end-diastolic flow.

Background

Doppler was first used in the assessment of blood flow to the placenta and provided obstetricians with the ability to detect pregnancies with a poorly functioning placenta. Placental dysfunction results in intrauterine foetal growth restriction and has been linked to poor perinatal outcomes.[12–14] Experimental models of placental insufficiency, where the umbilical arteries of foetal sheep have been constricted to increase foetal afterload, and have demonstrated flow reversal in the isthmus to allow preferential perfusion of the foetal brain.[23] This flow reversal can be recorded in the aortic isthmus of the human foetus, and increased diastolic flow in the middle cerebral artery has been termed the "brain-sparing" phenomenon.[14,24,25]

In contrast with the adult circulation,[6,11] intracardiac waveforms in the foetus are regulated by the more distant vascular beds, and not dependent solely on intracardiac pathophysiology. The major two influences are the distal impedances of the foetal brain and placenta that alter the balance between flow to the foetal brain and body.[23] Maturational differences in placental impedance are seen as the spiral arteries lose their thick muscular coat, resulting in an increase in diastolic flow towards the placenta.[12] This is manifest as maturational effects on Doppler waveforms.[9]

Method

The sample volume is placed in the artery of interest in alignment with flow and with a wide enough sample volume to capture all velocities.

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Technical details

The volume sample must be aligned to ensure the Doppler trace correctly demonstrates the profile of diastolic flow to enable correct assessment of impedance and resistance.[13] Although the indices are often said to be angle independent, best practice includes the recommendation that alignment is optimised to reflect true physiology, and angle correction avoided.

Cardiac M-mode: measurement of the minor and longitudinal cardiac axis

Definition

M-mode records uni-dimensional tissue motion over time.

Background

M-mode was the first technology used to examine the adult heart, and in the foetus the first reports were in the evaluation of the biparietal diameter of the foetal head,[26] and later to examine the foetal heart.[27,28] More recently, assessment of foetal cardiac function has included M-mode assessment of long-axis ventricular function.[29,30]

Technique

In a parasternal long-axis view of the foetal heart, an M-mode cursor is placed at right angles to the ventricular septum and records the excursion of tissue interfaces in the heart (on the *Y*-axis) over time (on the *X*-axis) at high acquisition rates. From this, function of the minor axis of the heart is measured.[31] This measures ventricular cavity dimensions during systole and diastole used to calculate the shortening or ejection fraction of the heart.[6,11] Importantly, these mechanical events are timed relative to the electrical using an echocardiograph,[31] but this is not feasible in the foetus. In experienced hands M-mode can identify many aspects of function, but this is difficult in the absence of concurrent electrical timing of events and phonocardiography.[32]

Assessment of right ventricular function is of more interest as it is the dominant ventricle in the foetus; however, M-mode is not the optimal technique to assess right ventricular function because of its shape, and three-dimensional methods such as cardiac MRI are more suitable.[6,31,33]

M-mode has also been used to assess longitudinal myocardial function in the adult heart for many years.[34,35] Recordings of foetal long-axis function are made by placing the cursor at right angles to the atrioventricular ring in a four-chamber view to record atrioventricular ring excursion at the free wall of the left ventricle at the level of the mitral valve or tricuspid valve[22,30] (Fig 4). This method has recently been rebranded as "tricuspid annular peak systolic excursion" and "mitral annular peak systolic exertion": "TAPSE" and "MAPSE".[35] This is a simple and reproducible measurement that provides information about the displacement (in mm) of the foetal atrioventricular ring in systole, and therefore gives a measure of elasticity of the longitudinal fibres in the ventricular wall.[34]

Limitations

There are several important limitations in the use of M-mode to assess minor axis systolic function in the

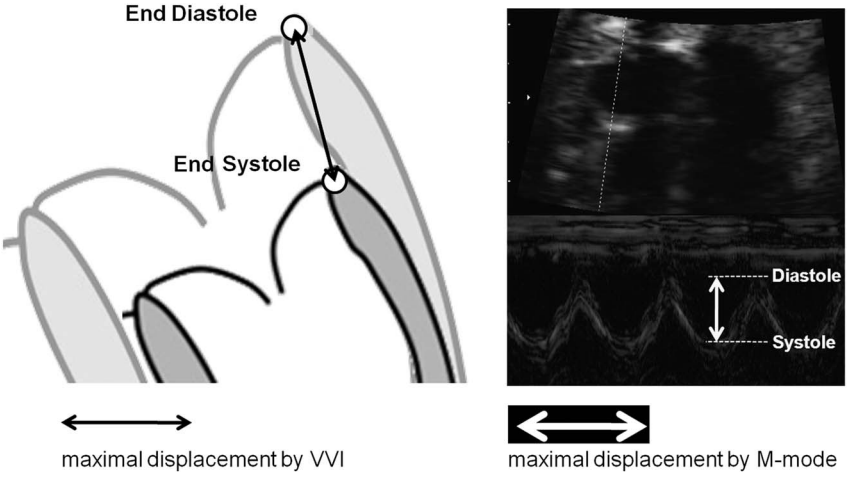

Figure 4.

Maximal displacement of the atrioventricular annulus recorded by vector velocity imaging and M-mode. Maximal displacement recorded by vector velocity imaging (left) is the distance between end-systole and end-diastole (black arrow) calculated from X–Y coordinates. Maximal displacement of the annulus recorded by M-mode (white arrow) is shown on the right-sided panel. (Reproduced by permission from Matsui et al[50]; figure 5).

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foetus: the most important is that it is recorded without echocardiograph gating, and therefore only displays the mechanical events relative to each other, but not relative to the electronic timing, which is the gold standard of activation.[31] It is also essential to place the cursor at right angles to the ventricular septum, which is not always possible because of foetal life. Anatomical M-mode has been evaluated because it can be applied in cases where the alignment is a sub-optimal alignment. In a paired study comparing this technique with conventional M-mode, values were up to 6% higher in anatomical M-mode, although it is not certain which of the two approaches provided more reliable readings, as they could not be validated against a gold standard. As the majority of foetuses were examined at insonation angles below 30° in this study, the angle independence of anatomical M-mode is not certain.[30] M-mode of the minor axis provides limited functional information in the foetus with CHD, where geometric assumptions may not be applicable and loading conditions are variable.

Doppler assessment of cardiac function

Background

Pulsed-wave Doppler is commonly used to assess foetal myocardial performance. The unique physiological influences on the foetal circulation make assessment of diastolic function essential. Many studies have assessed methods to measure diastolic function including the E to A ratio – the early to late filling ratio – which changes with gestational age,[9,10] timing intervals, and the volume of flow – assessed by the velocity-time interval – during atrial contraction over the whole filling period.[36]

Doppler measures include the duration of filling time and examination of the regurgitant jet that provides important practical information to the clinician. A monophasic inflow pattern is normal before 9 weeks of pregnancy and may also be seen with foetal tachycardia when it indicates there is reduced time for ventricular filling.[9] It is also seen in cases with structural malformations where there is important tricuspid regurgitation; the long duration tricuspid regurgitant jet extends through systole and into early diastole and leads to reduced cardiac output and the potential for myocardial ischaemia because of reduced filling. These are easily recorded Doppler measurements and relatively simple to interpret.[11,17,33]

The Tei index or myocardial performance index

This was first proposed by Tei[37] in 1995. It is an index of global myocardial function combining measures of systolic and diastolic performance. It has become a common measurement in the foetus as it is easy to record. However, reproducibility of the measurement is limited in the absence of a concurrent echocardiograph. Prolonged isovolumic relaxation time is considered an indicator of poor cardiac function and various technical modifications such as measuring from the valvular clicks or using tissue Doppler velocities have been investigated to improve the robustness of this measurement[38,39] (Fig 5).

Myocardial acceleration during isovolumic contraction

This is an index thought to provide a better assessment of right ventricular contractile function.[40,41] It is theoretically unaffected by the shape of the ventricle and its loading conditions. It is feasible to measure this in the foetus provided high frame rate Doppler can be obtained. It increases with increasing gestational age and the lowering of foetal heart rate.[40]

Long-axis function using tissue Doppler

More recent measures of foetal cardiac function include the assessment of long-axis function using tissue Doppler. The longitudinal myocardial fibres line the endocardium, furthest from coronary perfusion, and therefore should theoretically provide a sensitive indicator of early diastolic dysfunction.[29] Tissue motion is in the opposite direction to that of the volume of blood flow, and shortening (systolic) and lengthening (diastolic) tissue velocities can be recorded without any specialist equipment. Both Doppler and M-mode techniques may be used to record long-axis function. They are simple to use and can be recorded and measured during the clinical examination providing an immediate result, and gestational reference ranges are available for the foetus.[29,42]

Techniques

Pulsed-wave Doppler

Good-quality steady-state recordings of the inflow through the mitral and tricuspid valves may be obtained with an appropriately sized Doppler sample placed at the tips of the atrioventricular valves. In the foetus, the late diastolic component – A wave – has higher peak velocities than in early diastole – E wave – in early- and mid-gestation, reflecting the dominance of atrial contraction in filling the ventricles.[9,10] Various authors have measured peak velocities, their ratios, and the velocity-time integral of the diastolic component – A wave – over the total waveform to assess the diastolic performance of the ventricle.[36,43]

Recordings of valvular regurgitation require that the Doppler sample is placed in the jet, ideally at the place of the highest velocity and not across the valve.

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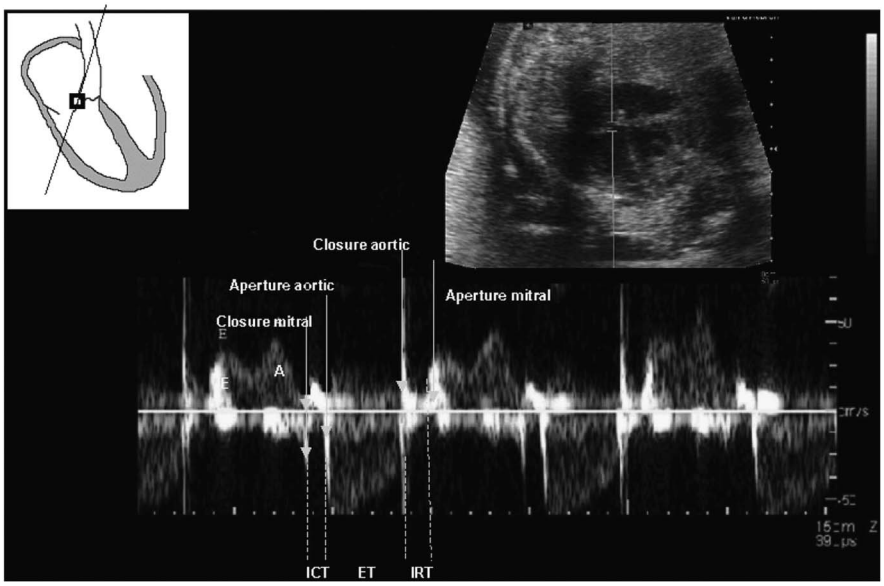

Figure 5.
Doppler envelope of the modified myocardial performance index (Mod-MPI). The sample volume is located over the lateral wall of the aorta, close to the mitral valve. References for the time-period estimations are based on the echoes from the mitral and aortic valve movements. The E/A waveform is always displayed as positive flow. ET = ejection time; ICT = isovolumetric contraction time; IRT = isovolumetric relaxation time. (Reproduced by permission from Hernandez-Andrade et al[39]; figure 2).

Its position is ideally guided using colour Doppler, and to record the peak velocity, continuous wave Doppler should be used, as the velocity may be higher than the Nyquist limit of the usual obstetric probe, and therefore underestimate the pressure drop across the valve that allows an estimation of ventricular pressure.[11,17]

The Tei index

The Tei index can be recorded by placing a large Doppler sample between the mitral and aortic valves to record the inflow and outflow Doppler envelopes simultaneously.[37] Measuring along the *X*-axis allows measurement of the isovolumic relaxation and contraction times. The ratio of these two diastolic time intervals to the ejection time provides a measure of the amount of time the heart spends in relaxation compared with contraction (Fig 5). Longer relaxation times indicate poorer ventricular performance.[38,39,43] It is a load-dependent index, and the influence of unbalanced loading has enabled it to differentiate between early twin-to-twin transfusion syndrome and selective intrauterine growth restriction in monochorionic diamniotic twins, as is the diastolic time interval measured in the venous duct.[19,44]

Myocardial acceleration during isovolumic contraction

Myocardial acceleration is measured from Doppler tissue imaging at the base of right ventricular free wall in the four-chamber view. Myocardial acceleration is calculated by dividing pre-ejection velocity by the time interval from onset of the pre-ejection myocardial velocity to the time at peak velocity of this wave.[40,41]

Tissue Doppler

Tissue Doppler techniques may not require any specialist equipment, but do require good technique with alignment to wall motion of <20°. The volume samples should be set between 1 and 2 mm depending on gestational age, and one would not expect velocities more than 20 cm/second, and hence the scale must be increased. Ideally, they should be recorded with the highest frame rate possible, preferably more than 200 frames/second. The usual site of measurement is at the base of the heart with the Doppler sample volume placed at the mitral and tricuspid ring and in the septum. Nomenclature varies: early diastolic peaks are documented as Ea, E′, or Em; late diastolic peaks Aa, A′, or Am; and systolic peaks Sa, S′, or Sm.

Limitations

Doppler techniques, whether recording tissue motion or blood flow, share the same limitations: it is essential to be aligned <20° from Doppler flow or tissue motion to obtain good-quality representative recordings. The foetus and the mother must be still.

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There is no concurrent echocardiograph recording and therefore no gold standard for timing of mechanical events.[11] There are practical difficulties with measuring the Tei index, one of which is the difficulty in identifying the onset and the end peak systolic velocity. Modifications have been introduced making measurements from the valvular clicks.[39,43] The Tei index has become a popular measure because of the simplicity of obtaining the Doppler traces; however, values alter depending on foetal loading, and interpretation of the measurement is essential as it does not represent cardiomyocyte function. One major difficulty in recording functional measures in the foetus is the lack of temporal resolution. Very high frame rates are required for reproducible measurements of time intervals, particularly as the foetal heart rate is faster than in the child or adult. Temporal limitations affect measurement of the time intervals of the isovolumic relaxation time, the pre-ejection peak, and therefore myocardial acceleration, which are extremely short.

Advanced offline techniques to assess foetal cardiac function

Background

Newer technologies have been developed to measure deformation in the adult heart. The most commonly used technologies include strain and its time integral strain rate. Strain records the increase or decrease in length relative to its resting length when a force is applied to a material. Myocardial shortening is represented by negative strain occurring during systole and a positive strain or myocardial lengthening occurs in diastole[45] (Fig 6). Deformation is three dimensional with both longitudinal, radial, and circumferential components, both animal models and phantoms have investigated measurements of twist and torsion.[45,46] Natural and Lagrangian strain have been reported in the adult heart using a variety of technologies,[47,48] and later in the foetus with differing results, with some reporting the strain to be constant, whereas others reporting that it decreases with gestational age.[49–51]

Techniques

Strain is usually an offline assessment and can be performed using one of several different technologies in the foetal heart. Colour Doppler myocardial imaging records velocities measured at two points a distance apart and their change within the cardiac cycle. It records a strain rate from which it derives strain in the longitudinal plane.[49] Speckle tracking or vector velocity imaging is a technique that tracks the acoustic markers observed following constructive and destructive interactions of the ultrasound beam from frame to frame. It is a non-Doppler technique and does not require the close alignment of Doppler techniques, but still requires capture at high frame rates of 140 Hz or more.[50] Image acquisition should be set up using high frequency, without harmonics if possible, and the image should ensure good contrast between the cavity and the endocardium. Ventricular wall strain can be assessed by summating the small strain values calculated by the software along the ventricular wall, natural or point strain, or by summing the distances during the mechanical event and calculating strain along the whole length of the wall – Lagrangian strain. The Lagrangian strain is likely the better methodology and current software packages are being altered to enable automatic calculation using this method.

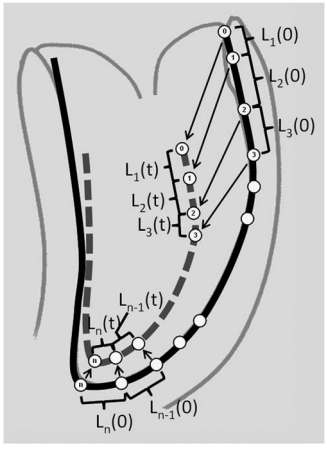

Figure 6.
The black line shows the tracking line in end-diastole, and the dashed line shows the tracking line at time t. In vector velocity imaging analysis, the software provides tracking points (white circle 0 – n) in each frame of the two dimensional echo image. The length of the free wall is calculated from the summation of the small segments between consecutive tracking points ($L_1(t)$–$L_n(t)$). Lagrangian myocardial strain is calculated from the ratio of change of the free wall length. (Reproduced by permission from Matsui et al[50]; figure 3).

Limitations

Tracking of acoustic markers is more difficult in the foetal heart because of small size, fast heart rate, the variable scanning depth, and no echocardiograph gating to aid recording of the original frame rates. Assessment of the strain recorded using colour Doppler myocardial imaging requires high frame rates of more than 200 frames/second and may be limited in later gestation if harmonic imaging is required to image the foetal heart.[49–51] It requires close alignment parallel to the wall motion because it

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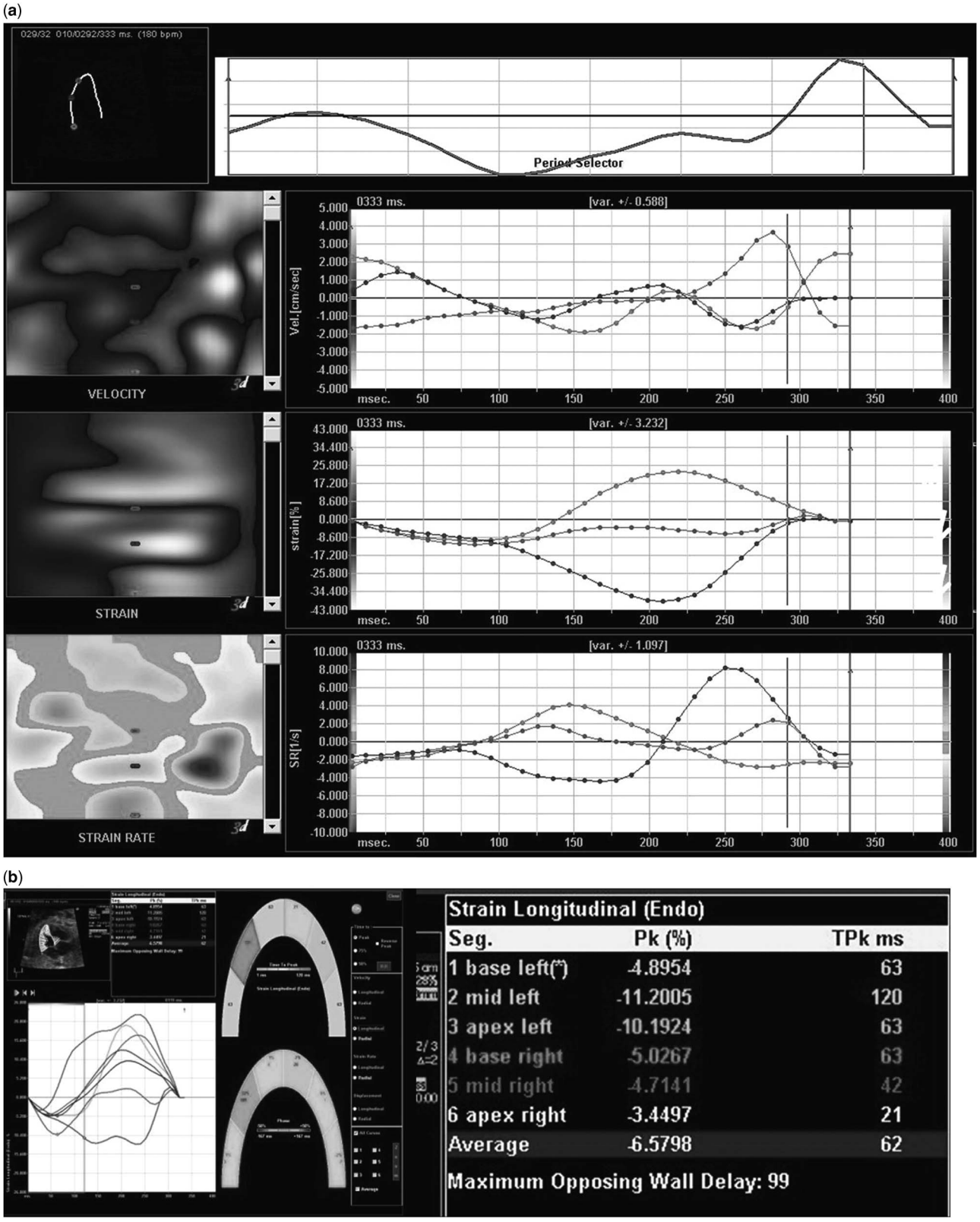

Figure 7.
*(**a**) Software calculates natural strain by placing points at very short distances along the free walls of the foetal heart and calculating point strain. (**b**) Point strain shows marked segmental variation and the values are summed to provide an average point, or natural strain. (Reproduced by permission from Germanakis and Gardiner[52]; figures 4a and 4b).*

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is a Doppler technique and one of the more difficult aspects of this methodology is to ensure that the Doppler sample remains within the area of interest.[45–48] As with all Doppler-based measurements in the foetus, it is prone to artefacts from foetal or maternal movement, or maternal aortic pulsations. The differences in reports using vector velocity imaging may be explained by several technical factors specific to using speckle tracking in the foetal heart.[52] Speckle tracking is not suitable on stored clips – unless they are stored in digital imaging and communications in medicine – because the video capture rate of these is between 25 and 30 Hz. One pitfall of the current measures of vector velocity imaging is that the offline software analysis provides the user with parameters such as velocity, strain, and strain rate. The strain produced by these techniques is calculated from individual very short segments – known as "point strain" – and the mean or average of all of these small point strains is used to provide global strain values. An alternative method is to measure Lagrangian strain, which assesses the deformation of the entire free wall of the myocardium, rather than summation of individual deformations.[50,52] This may be less prone to error and more physiological than the natural strain values generated by the software (Fig 7).

Comparison of Doppler, M-mode, and newer techniques

Application of newer techniques to the foetus are limited by technical issues, particularly in the time domain.[43] From paired studies on vector velocity imaging comparing high and low frame rate recordings, it is clear that the peak diastolic velocities and peak positive strain rates are reduced when lower frame rate recordings are analysed.[50] Moreover, the detection of biphasic diastolic waveforms require at least 29 frames/heartbeat and are rarely detected using speckle tracking, although they are invariably seen with tissue Doppler techniques.[49–51] It is important to understand the differences between the techniques; the velocities recorded by speckle tracking are lower than those recorded using tissue Doppler because instead of measuring the maximum velocity, speckle tracking calculates the mean of the X and Y coordinate velocities.[50] Correlation of myocardial displacement measurements made using M-mode and vector velocity imaging is good. In comparative studies, vector velocity imaging or speckle tracking correlates better with traditional Doppler or M-mode in the spatial parameters such as displacement or strain, but more poorly in those requiring temporal parameters such as strain rate and velocities.[50]

Conclusions

Many newer techniques are not yet suitable for day-to-day assessment of foetal cardiac function. It is probably wise to use the simplest and most validated techniques and to gain experience with these for clinical assessment. However, good-quality research is essential to evaluate newer techniques, and technology will undoubtedly continue to increase our ability to assess function in the foetal heart.

Acknowledgements

None.

Conflicts of Interest

None.

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