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Reproducibility of echocardiographic measurements of human fetal left ventricular volumes and ejection fractions using four-dimensional ultrasound with the spatio-temporal image correlation modality

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ABSTRACT

Objectives: To determine the reproducibility, both reliability and agreement, of measurements of fetal left ventricular parameters from volumes obtained by spatio-temporal image correlation (STIC) acquisition applying virtual organ computer-aided analysis (VOCAL) and Simpson's rule (method of discs). Furthermore the success rate of STIC acquisition was determined.
Study design: In 84 pregnancies between 20 and 34 weeks of gestation the fetal heart was scanned using the STIC modality. An optimal four-chamber view in end-diastole and end-systole was obtained. Left ventricular end-diastolic volume, left ventricular end-systolic volume, stroke volume and ejection fraction were determined. For calculations based on Simpson's rule only one plane was traced, whereas for VOCAL six planes were traced. To quantify the reliability intraclass correlation coefficients were calculated for both intra- and inter-observer measurements. Agreement of measurements was evaluated by Bland–Altman plots.
Results: The STIC volumes of 54 women (64%) were excluded from the study because of poor quality, leaving 30 volumes for further analysis. Intraclass correlation coefficients for intra-observer reliability for VOCAL and Simpson were 0.99 and 0.99 for left ventricular end-diastolic volume, 0.95 and 0.92 for left ventricular end-systolic volume, 0.98 and 0.97 for stroke volume, 0.76 and 0.77 for ejection fraction, respectively. Intraclass correlation coefficients for inter-observer reliability for VOCAL and Simpson were 0.97 and 0.86 for left ventricular end-diastolic volume, 0.97 and 0.86 for left ventricular end-systolic volume, 0.95 and 0.81 for stroke volume, 0.68 and 0.63 for ejection fraction, respectively. According to Bland–Altman plots, the mean percentage difference and 95% limits of intra- and inter-observer agreement for left ventricular stroke volume measurements using VOCAL were −0.2 (−25.1, 24.7)% and 2.8 (−34.2, 39.8)%, respectively. For left ventricular stroke volume measured with Simpson versus VOCAL the mean percentage difference and 95% limits of agreement were −1.8 (−22.1, 18.5)%.
Conclusions: 4D STIC enables reproducible measurements of left ventricular volumes. Reliability of the VOCAL mode is not essentially different from the single-plane method used in Simpson's rule. The large percentage of poor quality STIC volumes and the wide limits of inter-observer agreement would create obstacles for the clinical applicability of this technique.

1. Introduction

Three-dimensional (3D) and four-dimensional (4D) ultrasound allows a comprehensive analysis of left ventricular (LV) morphology and function. Since the introduction of STIC (spatio-temporal image correlation) ultrasonography, 4D imaging has increasingly been used for assessing cardiac structures and quantification of ventricular volumes because it provides rapid acquisition of data from the fetal heart [1]. Volume measurements using STIC ultrasonography have been validated in vitro using balloon models [2–4]. However, in contrast to echocardiography in adults there is no gold standard for measuring fetal cardiac output. An established method of determining cardiac ventricular volumes in adults is the so-called Simpson's rule or method of discs [5]. This geometric assumption technique method, however, is not applicable to the right ventricle

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because of a less well-defined endocardial outline (moderator band). Prenatally we can only compare the results of 3D/4D measurements with M-mode-, Doppler- and two-dimensional (2D) cross sectional measurements of fetal cardiac output. Simpson and Cook showed that these methods, including the method of discs, have wide limits of agreement [5].

Reproducibility of volume measurements in the human fetus using STIC has been studied by several research groups. Reproducibility is used as an umbrella term for the concepts of reliability and agreement [6]. Most studies evaluated the reliability of 4D measurements. Others assessed both reliability and agreement. Agreement quantifies how close two measurements made on the same subject are, and is measured on the same scale as the measurements themselves. Agreement parameters are preferable in all situations in which the instrument will be used for evaluation purposes. In publications of measurement error studies agreement is often expressed by means of Bland–Altman plots [6,7]. Reliability tells us how well patients can be distinguished from each other, despite measurement errors. Reliability parameters are highly dependent on the variation in the study population and required for instruments that are used for discriminative purposes. The reliability parameter is also known as intraclass correlation coefficient (ICC) [6,7].

Different approaches have been used to calculate cardiac volume parameters from STIC volumes [8–12]. Rizzo et al., Molina et al. and Hamill et al. used STIC combined with the virtual organ computer-aided analysis (VOCAL) method. Rizzo et al. [8] found close agreement between 2D Doppler and 4D STIC measurements of stroke volume (SV). For 4D STIC measurements of SV a good reliability for both intra-observer and inter-observer measurements was found. Molina et al. [9] only determined intra-observer agreement; a poor reproducibility existed for first trimester measurements. Hamill et al. [10] used STIC with the subfeature Contour Finder: Trace. They found repeatable and reproducible calculations of ventricular volumes for both intra- and inter-observer measurements. Messing et al. [11] using STIC and inversion mode for estimating fetal cardiac ventricle volumes established a good reliability for both intra-observer and inter-observer measurements between 20 and 40 weeks of gestation. Finally, Uittenbogaard et al. [12] used STIC with a 3D slice method. Only intra-observer agreement was calculated. They found a coefficient of variation for cardiac stroke volume of 13.7%.

Although postnatally Simpson's rule is an established method of determining cardiac left ventricular volumes, no efforts have been made to compare this method prenatally with cardiac volume parameters from STIC volumes.

The objective of this study was three fold:

1. To determine the reproducibility, that is reliability and agreement, of measurements of human fetal left ventricular parameters from volumes obtained by STIC acquisition at 20–34 weeks of gestation. Both VOCAL and Simpson's rule were applied for calculating these parameters.
2. To evaluate agreement between one plane Simpson's rule and six plane VOCAL measurements of stroke volume.
3. To assess the success rate of STIC acquisition.

2. Materials and methods

A total of 84 women with a BMI under 25 consented to participate in this prospective study during the period April 2007 until August 2008. Patients were excluded from further analysis in case of inadequate 4D STIC volumes. The study was approved by the local ethics review board. All pregnancies were uncomplicated, with a normal 20 weeks ultrasound examination. No medication was used. Gestational age varied between 20 and 34 weeks of gestation as established from the last menstrual period and confirmed by first-trimester ultrasound. Inclusion of patients encompassed an equal distribution of volumes of adequate quality over the different gestational ages. The gestational age periods comprised 20–22 weeks, 23–25 weeks, 26–28 weeks, 29–31 weeks and 32–34 weeks. Inclusion of patients proceeded until six adequate 4D STIC volumes were obtained for each gestational age period allowing statistical analyses of the data collected.

3. STIC modality

The fetal heart was scanned using 4D ultrasound with the STIC modality (Voluson 730 Expert and Voluson E8, G.E. Medical Systems, Zipf, Austria). The transducer carrier frequency ranged between 4–8 and 5–9 MHz. Volume acquisition was performed during fetal quiescence and apnoea. If necessary, maternal movements were reduced by asking the woman to hold her breath during acquisition. An optimal fetal four chamber view was obtained when the fetal spine was in dorsal position [13]. The acquisition angle was selected between 20° and 25° to encompass the left ventricle and acquisition time was set at 7.5 or 10 s to minimize motion artefacts. For clinical reasons a maximum scanning duration of 20 min was adopted. On average four to six STIC acquisitions were taken. Only heart volumes without motion artefacts and a clear demarcation of the endocardial borders were accepted for further analysis.

Measurements were performed offline using specialized 3D software (4D View, GE Medical Systems). In post-processing the following parameters were determined: left ventricular end-diastolic volume (LVEDV), left ventricular end-systolic volume (LVESV), stroke volume (SV) and ejection fraction (EF). SV (ml) was calculated from LVEDV–LVESV. EF (%) was calculated from SV/LVEDV.

Volume calculations were made by means of the one plane Simpson's rule, or method of discs [5,14] and the six plane (rotational angle of 30°) VOCAL rotational method. 4D volumes were displayed in the orthogonal multiplanar mode for both methods.

4. One plane Simpson's rule

Although Simpson's rule was initially developed as a method of estimating left ventricular volumes from free-hand 2D images, we applied it to 4D STIC volumes frozen in end-systole and end-diastole.

For this approach the image was slightly rotated along the *x*-, *y*-, and *z*-axis in order to obtain an optimal four-chamber view in end-systole and end-diastole. End-systole represented the four-chamber view immediately prior to the opening of the atrioventricular valves, whereas end-diastole represented the four-chamber view immediately after the closing of the atrioventricular valves. Post-processing including adjustment of brightness and contrast was performed to obtain optimal delineation of the endocardial border. The Simpson's rule calculation method was selected from the cardio measurement application submenu in the calculations section on the Voluson ultrasound machine. Manual tracing of the endocardial border was carried out in the A-plane or acquisition plane (Fig. 1). The volume was subsequently calculated by the computer software.

Simpson's rule follows a mathematical principle. It is based on the assumption that the left ventricle has a symmetrical shape. The left ventricular volume was determined by slicing the left ventricle into 20 discs along the long axis. The area of each disc was calculated and multiplied by the disc's thickness to determine its