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● *Original Contribution*

THE CARDIAC STATE DIAGRAM AS A NOVEL APPROACH FOR THE EVALUATION OF PRE- AND POST-EJECTION PHASES OF THE CARDIAC CYCLE IN ASPHYXIATED FETAL LAMBS

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Abstract—The aim of this study was to investigate myocardial wall motion using echocardiography and color-coded tissue velocity imaging and to generate a cardiac state diagram for evaluation of the duration of the pre- and post-ejection phases in asphyxiated fetal lambs. Six near-term lambs were partly exteriorized and brought to cardiac arrest through asphyxia. Echocardiography measurements were recorded simultaneously with arterial blood sampling for lactate and blood gases. All fetal lambs exhibited prolongation of the pre- and post-ejection phases at the time when the most pronounced changes in lactate concentration and pH occurred. The mean change in duration of the pre- and post-ejection phases for all fetal lambs was 36 ± 7 ms ($p < 0.002$) and 77 ± 17 ms ($p < 0.019$), respectively, and the percentage change was 50% ($p < 0.001$) and 38% ($p < 0.049$), respectively. As asphyxia progressed in fetal lambs, the duration of the pre- and post-ejection phases increased. The cardiac state diagram has the potential to be a comprehensible tool for detecting fetal asphyxia. (E-mail: elle.wagstrom@karolinska.se)

Key Words: **Cardiac state diagram, Cardiac time intervals, Doppler, Fetal physiology, Myocardial motion, Asphyxia, Tissue velocity imaging, Echocardiography.**

INTRODUCTION

The recently developed color-coded tissue velocity imaging (TVI) is able to display 2-D imaging of myocardial motion velocity (Bhat and Sahn 2004; Chan et al. 2005; Comas et al. 2011; Elmstedt et al. 2010; Harada et al. 1999; Larsen et al. 2006, 2011; Lind et al. 2002; Perles et al. 2007; Steinhard et al. 2007; Tutschek et al. 2003; Watanabe et al. 2009). TVI provides supplementary information on mechanical events of the myocardium rather than information on flow, which is evaluated by pulsed Doppler.

With TVI, it is possible to register and display the common piston of the heart, which is a direct evaluation of the left and right systolic and diastolic functions. The echocardiography technique allows off-line analysis of the cardiac events.

Earlier studies reported that fetal hypoxia and acidosis and anaerobic metabolism are associated with changes in isovolumetric contraction time (Satoh et al. 2007; Yumoto et al. 2005). According to a pump principle recognized today as the dynamic adaptive piston pump (DAPP) (Lundback 1986) principle, it is now possible to visualize the mechanics of the heart through its changes in static and dynamic work. This principle, introduced over the last decade in adult cardiology, is based on the assumption that the displacement of the atrioventricular (AV) plane in relation to the apex works as a piston, with the pericardium as the closed border. Thus, rather than the ventricle squeezing, the AV piston acts as a pump. This principle has enabled us to use new software, the cardiac state diagram (CSD), which has proven to be of diagnostic value (Larsson et al. 2009) in visualizing cardiac mechanics in adults in a more intuitive way (Fig. 1).

The primary objective of the present study was to investigate myocardial wall motion as prolongation or

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shortening of the duration of the pre- and post-ejection phases using the DAPP principle and the CSD to interpret and visualize cardiac mechanics in a fetal lamb model during acute asphyxia.

METHODS

The study included six near-term fetal sheep (gestational age: 134–138 d). Gestational age was determined by early ultrasound. This experiment was performed with the approval of the regional animal ethics committee at Lund University, Lund, Sweden.

Surgical procedure and data acquisition

The pregnant ewes were intubated after induction with 30–80 mg intravenous ketamine (Ketaminol Vet, Intervet International, Unterschleissheim, Germany) and 600–800 mg thiopental (Thiopental inresa, Inresa Arzneimittel, Freiburg, Germany), and the position of the tube was verified by capnography. Continued anesthesia was provided with a mixture of 0.5%–0.8% isoflurane (Isoflurane Baxter, Baxter Medical AB, Kista, Sweden) and 50%–70% nitrous oxide. It was complemented by an infusion of remifentanil (Ultiva, 50 μg/mL at 5–18 mL/h). Cesarean section was performed under aseptic conditions. Polyurethane catheters were introduced into the external carotid artery and the jugular vein of the partially exteriorized fetal lambs. Fetal mean arterial blood pressure (MAP) and heart rate were monitored continuously, and the electrocardiogram was recorded *via* direct electrodes attached to the fetal lamb. After completion of preparatory procedures, baseline measurements were made and were monitored throughout the experiment. The partially exteriorized fetal lamb's head was covered in a surgical glove to prevent gasping and breathing. After the baseline period, the umbilical cord was gently extracted through the uterine incision and gradually and progressively clamped with a rubber hose every 5 min until cardiac arrest occurred, which was defined by the absence of pressure waves. Arterial blood sampling for lactate and blood gas measurements was performed before the start of cord occlusion and every 5 min thereafter until cardiac arrest. Lactate was analyzed using a Lactate Pro (KDK, Kyoto, Japan), and blood gases were analyzed using ABL 300 (Radiometer Medical, Bronshoj, Denmark).

Echocardiography acquisition

Echocardiography images and TVI were recorded for all lamb fetuses using the Vivid-i Dimension ultrasound system (GE Vingmed Ultrasound, Horten, Norway) with a standard 2-D transducer (3S-RS) with a frame rate varying between 100 and 150 frames/s.

Blood sampling and echocardiography measurements were performed simultaneously, and the images

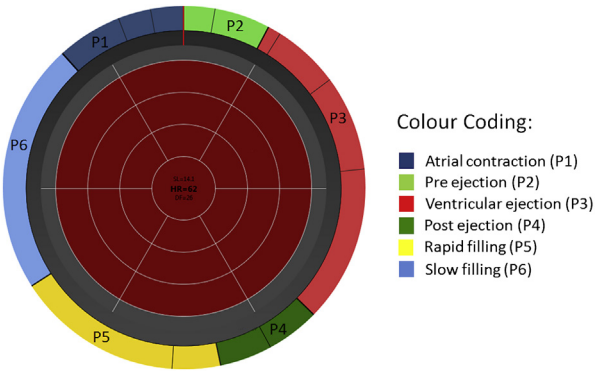

Fig. 1. Cardiac state diagram for a healthy adult. One heartbeat corresponds to 360° in the diagram, starting with atrial contraction and ending with slow filling.

were imported to EchoPAC software, Version BT 110 (GE Vingmed Ultrasound). In the TVI mode, a circular region of interest (ROI) of 2 × 2 mm was positioned in the basal segment of the left ventricle, septal, and right ventricle walls as part of the common piston of the heart according to the DAPP principle (Fig. 2). The velocity curve for each wall was exported to GHLab software, Version 2.10 (Gripping Heart, Stockholm, Sweden) for analysis.

Definition of pre- and post-ejection phases

Velocity curves for each wall recorded by TVI were analyzed in GHLab during the procedure and presented in a new visualization diagram, the cardiac state diagram (CSD), which is based on temporal events in the myocardium. The duration of the temporal events is presented in

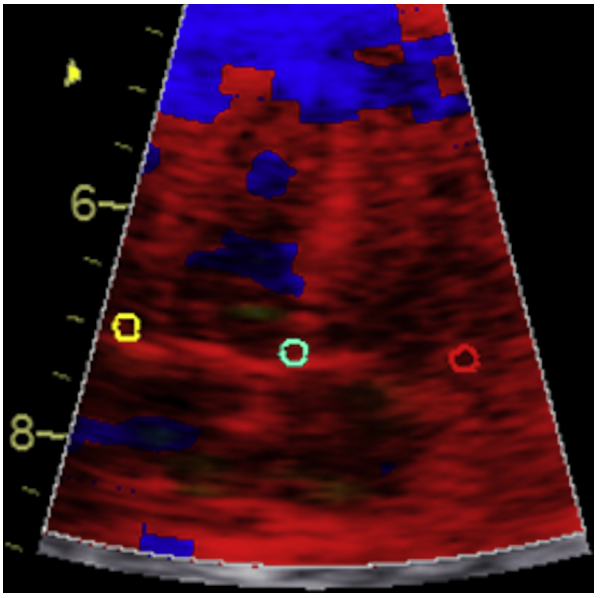

Fig. 2. Tissue velocity imaging indicatingplacement of the region of interest in the left (yellow), septal (blue) and right (red) heart walls.