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BRIEF COMMUNICATION

Artificial Heart (Basic)

Interventricular dyssynchrony during continuous-flow left ventricular assist device support: observation using the conductance method

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Abstract

The purpose of this study was to observe and clarify the interventricular dysscynchrony caused by continuous-flow left ventricular assist device (CF-LVAD) support using the conductance method. During CF-LVAD support, the systolic phase of the left ventricle (LV) becomes shorter than that of the right ventricle (RV). Accordingly, timing of the systole and diastole during the cardiac cycle is not synchronous between the LV and RV. In this study, we evaluated this phenomenon in a normal heart model using the adult goat ($n=5$, body weight 44.5 ± 2.9 kg). A centrifugal LVAD was implanted under general anesthesia. We inserted the conductance catheter into the RV and LV to obtain the pressure–volume relationship of the two ventricles simultaneously. We defined the dyssynchronous status as the sign (plus or minus) of the LV volume-change opposite to that of RV volume-change. Dyssynchronous phase of the cardiac cycle was observed in $5.6 \pm 0.65\%$ of hearts under LVAD pump-off and $25.3 \pm 3.3\%$ under LVAD full bypass, respectively ($p < 0.05$). To the best of our knowledge, this is the first experimental report clarifying interventricular dyssynchrony during CF-LVAD support using the conductance method. Quantification of this phenomenon under various support conditions and assessment of influences on the right ventricular function will be studied in future studies.

Keywords Left ventricular assist device · Interventricular dyssynchrony · Conductance method · Pressure–volume loop

Introduction

Although the advantages of the left ventricular assist device (LVAD) on left ventricular (LV) function including LV unloading and organ function have been well documented [1, 2], one of the unsolved serious complications is the right ventricular (RV) dysfunction, which is reported to be observed in approximately 20%–50% cases after LVAD implantations. However, the complex interactions of LVAD physiology with RV performance are less researched, and controversies in understanding the mechanisms of RV failure after LVAD implantation still exist. The proposed mechanisms so far are associated with RV afterload, interventricular dependence, and RV myocardial dysfunction, or other factors [3, 4].

To understand the ventricular interaction during LVAD support more precisely, we focused on the asynchronous cardiac cycle and ventricular volume-change between LV and RV during continuous-flow (CF) LVAD support in this study [5]. In simulation studies, continuous pumping of blood directly from the LV by LVAD, independent of the phase of the cardiac cycle, results in loss of the normal isovolumic periods [6]. Thus, the systolic phase of LV becomes shorter than that of RV. Furthermore, with higher rotational speed, the aortic valve does not open and the removal of blood from the LV is not dependent on ejection through the aortic valve. In this status, the ejection period is lost and

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pressure–volume loop (PVL) of LV is transformed from its normal trapezoidal shape to a triangular shape. Accordingly, there is a gap between the phases of the cardiac cycles of the two ventricles. Moreover, the ventricular volume-change and the motion of the LV and RV is not dyssynchronous (mechanical dyssynchrony). Although this interventricular dyssynchrony may have an influence on both LV and RV functions, particularly when LV is decompressed with aggressive LVAD support, the precise mechanism has not been clarified so far.

The conductance method provides detailed online ventricular volume signals by determining the electrical conductance of blood in the ventricle. Using this method, Steendijk et al. [7] clarified and quantified the mechanical dyssynchrony. The purpose of this study was to clarify the interventricular dyssynchrony in a large animal with a normal heart model by assessing the pressure–volume relationship of the two ventricles simultaneously during the CF-LVAD support using the conductance method.

Materials and methods

Experimental animals

Experiments were conducted in five adult goats (body weight 44.5 ± 2.9 kg). All animals were handled humanely, in compliance with the ethical principles of laboratory animal care. The research protocols were approved by the ethics committee of the National Cerebral and Cardiovascular Center.

Surgical procedure

The animals were placed in the right lateral recumbent position, intubated, and mechanically ventilated under general anesthesia. Left thoracotomy was performed via the fifth intercostal space. The centrifugal LVAD (EVAHEART; Sun Medical Technology Research Corporation, Nagano, Japan) was installed as follows: the outflow graft was anastomosed with a 4–0 polypropylene running suture to the descending thoracic aorta. After systemic heparinization, the cardiac apex was incised, and the inflow cannula was inserted into the LV and fixed to the apical cuff. The pump was primed and initiated.

We used an electromagnetic flow meter (EMF-1000: 16–22 mm in diameter; Nihon Kohden, Tokyo, Japan) for the pulmonary artery. A 6 Fr conductance catheter (Taisho Biomed Instrument, Osaka, Japan) was inserted into the LV from the descending thoracic aorta and into the RV from the pulmonary artery to obtain data on the pressure–volume relationships of both ventricles.

Measurements

The conductance catheter enables continuous measurement of five segmental volume slices perpendicular to the ventricular long axis. The catheters were connected to a PowerLab (AD Instruments, Australia) for data acquisition of segmental and total LV volume (LVV), RV volume (RVV), LV pressure (LVP), RV pressure (RVP), and ECG. Nonuniform performance between LV and RV was determined from the conductance signals of these two ventricles and characterized by the following indexes.

Interventricular dyssynchrony

A ventricular volume signal was defined as dyssynchronous if the change in the total RV volume (i.e., $dRVV/dt$) was opposite to the simultaneous change in the total LV volume (i.e., $dLVV/dt$). Accordingly, the two ventricles were labeled dyssynchronous if $(dLVV/dt) \times (dRVV/dt) < 0$.

Interventricular dyssynchrony was assessed under LVAD pump-off and full bypass. Support conditions were set by bypass rate (BR), which were calculated by dividing the pump flow by the main pulmonary artery flow presenting the total systemic flow (i.e., full bypass of LVAD was observed with BR of 100%).

Results

Figure 1 shows the typical pressure–volume relationship of LV and RV under LVAD pump-off and full bypass. In full bypass, the PVL of LV was triangular (aortic valve closed throughout the cardiac cycle), while that under LVAD pump-off was trapezoidal (aortic valve opening maintained). The PVL of RV was trapezoidal under both conditions.

Figure 2a and b shows the sample waveform of the volume-change under LVAD pump-off and full bypass. While the RV and LV volume-changes were almost synchronous under LVAD pump-off, the phase with dyssynchronous status increased dramatically during LVAD full bypass condition. The dyssynchronous status was mainly observed at the end systole of each cardiac cycle. Dyssynchronous duration in the cardiac cycle was $5.6 \pm 0.65\%$ under LVAD pump-off and $25.3 \pm 3.3\%$ under LVAD full bypass ($p < 0.05$) (Fig. 2c).

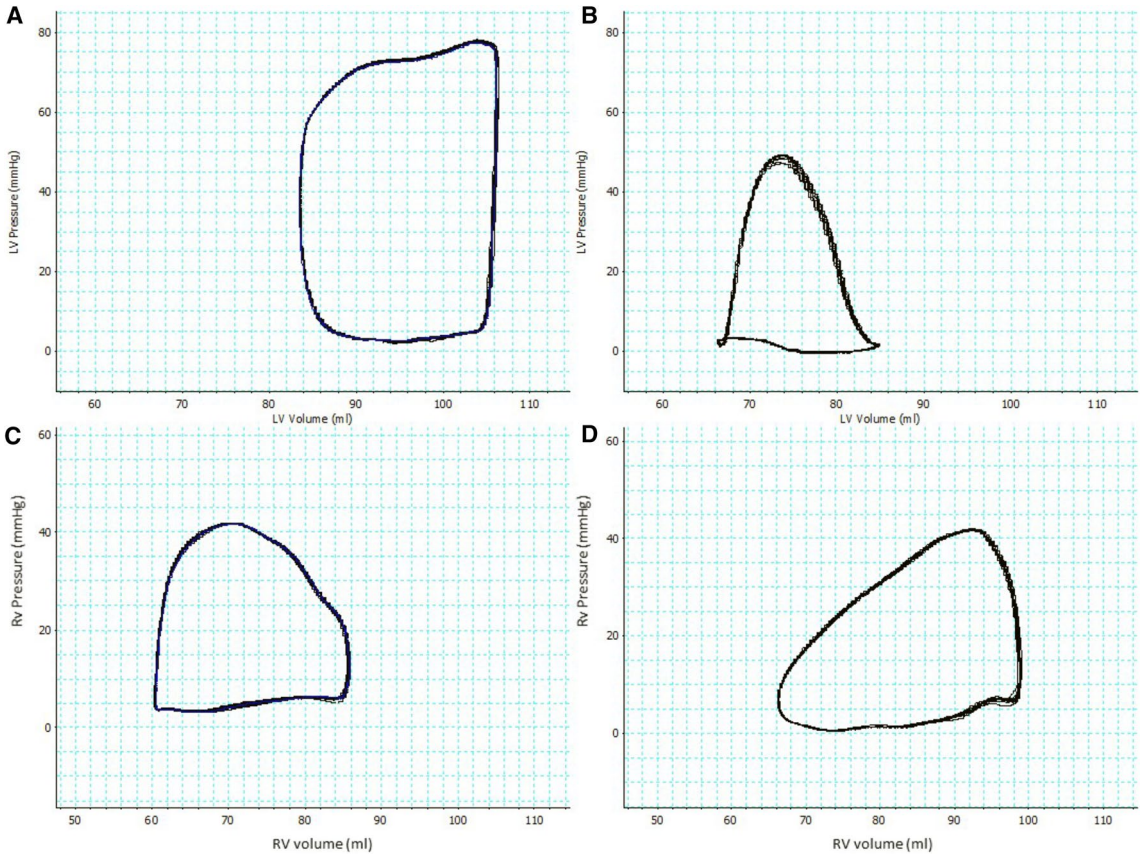

Fig. 1 Pressure–volume loop of left and right ventricles. **a** Pressure–volume loop of left ventricle under left ventricular assist device (LVAD) pump-off. **b** Pressure–volume loop of left ventricle under LVAD full bypass. **c** Pressure–volume loop of right ventricle before LVAD pump-off. **d** Pressure–Volume loop of right ventricle under LVAD full bypass

Discussion

This study demonstrated and clarified the interventricular dyssynchrony during CF-LVAD support by assessing the ventricular volumes of LV and RV in the normal heart condition. To the best of our knowledge, this is the first report clarifying this phenomenon using the conductance method.

Our primary findings were as follows:

1. The PVL of LV was trapezoidal under LVAD pump-off and triangular under full bypass of LVAD support. On the other hand, the PVL of RV showed similar shape under LVAD pump-off and full bypass.
2. Interventricular dyssynchrony was not evident under LVAD pump-off, but was clearly observed under the full bypass.

The mechanism of the change in PVL observed during LVAD support was presumed to be as follows: As the LV was increasingly unloaded with higher pump flow rate, the gap between LV pressure and arterial pressure increasingly dissociated. When the aortic valve did not open, the continuous blood drainage, independent of the cardiac cycle, resulted in loss of normal isovolumic periods and changed the PVL from a trapezoidal to triangular shape. In the RV, the increased preload and intraventricular septum shift toward LV by LVAD suction increased the RV end-diastolic volume and subsequently the stroke volume [8, 9].

In general, interventricular dyssynchrony was observed in some cardiac etiologies, such as cardiopathy, heart failure associated with structural abnormalities of ventricular myocardium, or irregular electrical ventricular activation [10, 11]. The diagnostic or prognostic value of ventricular dyssynchrony using the QRS duration measured via surface ECG has been known and other diagnostic modalities, such as cardiac ultrasound, three-dimensional echocardiography, color kinesis, or tissue doppler imaging [12–16] have been proposed to evaluate myocardial dyssynchrony more precisely.

On the other hand, the mechanism of interventricular dyssynchrony under LVAD support proposed here is a mechanical phenomenon in which LV systolic time decreased following LVAD suction. Thus, in this study, we applied the

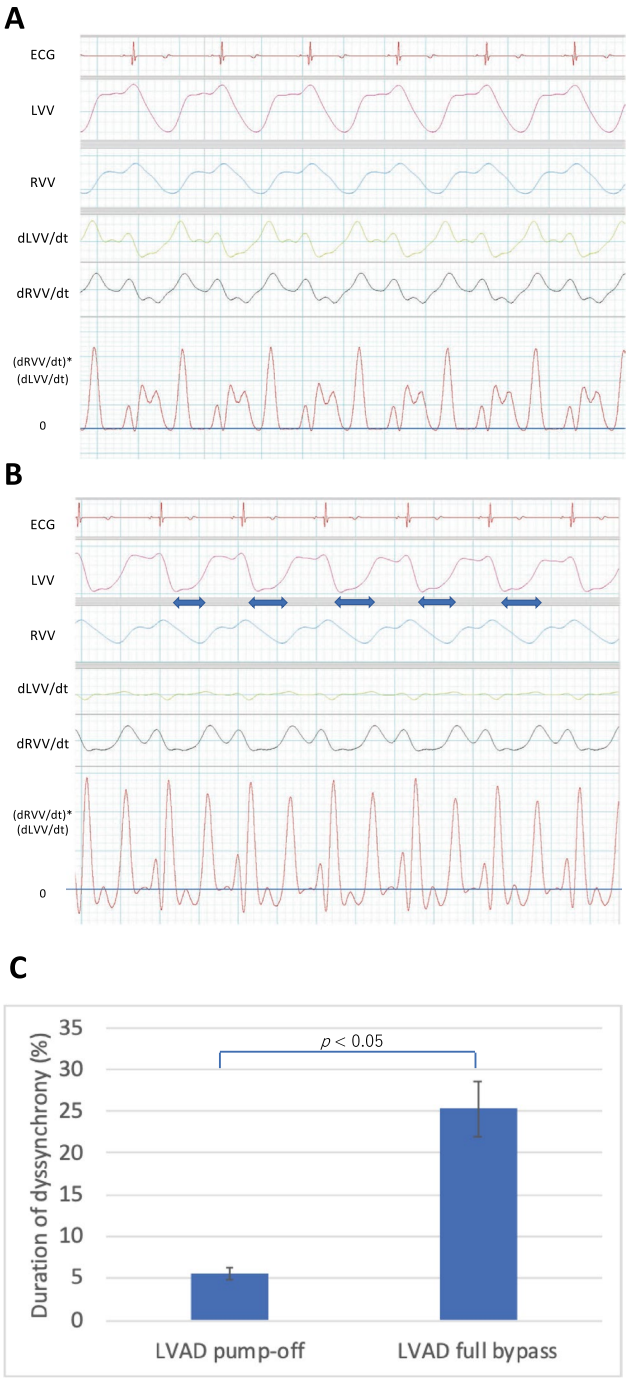

Fig. 2 Typical wave form obtained from conductance catheter measurements. *LVV* total left ventricular volume, *RVV* total right ventricular volume, *LV* left ventricle, *RV* right ventricle, *LVAD* left ventricular assist device. **a** Waveform obtained under LVAD pump-off. The volume changes are almost synchronous between LV and RV. **b** Waveform obtained under LVAD full bypass. Interventricular dyssynchrony is clearly observed as the area where $(dLVV/dt) \times (dRVV/dt) < 0$. Volume changes of this phase in LV and RV are opposite, as indicated by arrows. **c** Dyssynchronous duration of each cardiac cycle observed under left ventricular assist device (LVAD) pump-off and full bypass

conductance catheter to obtain the real-time pressure–volume relationships between the two ventricles, which successfully clarified the interventricular dyssynchrony.

As one of the hemodynamic effects of the CF-LVAD supports in the native heart and interactions between the two ventricles, we believe that interventricular dyssynchrony is important when seeking to understand the physiology of the CF-LVAD treatment.

Limitations

The findings observed in this study were obtained in a normal heart condition model. In practice, the dyssynchronous phenomenon may be influenced by cardiac dysfunction caused by heart failure. Accordingly, we would like to assess this phenomenon in a heart-failure model in further studies. Additional study of the chronic phase is also necessary to assess the influence of interventricular dyssynchrony on cardiac performance, including right ventricular function.

Conclusion

Interventricular dyssynchrony during CF-LVAD support was observed using the conductance method. Dyssynchrony became significant when LV was unloaded with high rotational speed of CF-LAD. Its influences on right ventricular function in heart failure models warrant further study.

Compliance with ethical standards

Conflict of interest None declared.

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