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Review

Clinical implications of hemodynamic assessment during left ventricular assist device therapy

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ABSTRACT

Left ventricular assist devices (LVADs) significantly improve outcomes of advanced heart failure patients. However, patients continue to have high readmission rates due to complications ranging from bleeding, thrombosis, heart failure, and infection. Considering that the hallmark benefit of LVAD therapy is improvement in hemodynamics (cardiac unloading and increased cardiac output), hemodynamic assessment on LVAD support is key to better understand these difficult complications and may serve as a tool to resolving them. In this review, we will discuss the hemodynamic changes following LVAD implantation, and the implications and prognostic impact of hemodynamic optimization on outcomes and complications.

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Introduction

Left ventricular assist devices (LVADs) have become the mainstay therapy for advanced heart failure (HF) patients, both as a bridge to transplantation and as destination therapy [1]. The initial LVADs were pulsatile and extracorporeal, but current contemporary devices have continuous flow and are internally implanted. As such, they are smaller, more durable, and less invasive [2,3]. However, there are still significant complications during long-term LVAD therapy [4] with multifactorial etiologies including both patient physiology and pump performance.

LVAD therapy improves outcomes in HF patients by improving hemodynamics, unloading the left ventricle and augmenting cardiac output (CO) [5]. As a result, LVADs enhance peripheral circulation, improve end-organ dysfunction [6], increase exercise capacity, and relieve HF symptoms [7]. Hemodynamic assessment during LVAD support may clarify the role of hemodynamic derangements in the development of LVAD complications. Our group has developed echocardiographic and hemodynamic ramp tests as a tool to facilitate hemodynamic optimization by adjusting LVAD speed and medical therapy [8]. Such procedures may be key to overcoming adverse events and improving clinical outcomes.

In this review, we will discuss how to measure hemodynamics, changes in hemodynamics after LVAD implantation, hemodynamic profiles during complications, and clinical implications and prognostic impact of hemodynamic optimization with ramp testing.

LVAD types

A variety of LVADs is clinically available, and thus far, most of the LVADs currently used are implantable continuous-flow devices [1]. In Japan, paracorporeal, pulsatile-flow LVADs are still used as bridge to decision, since continuous-flow LVADs are only available as bridge to transplantation [9].

The current continuous-flow LVADs available in Japan include: EVAHEART (Sun Medical, Nagano, Japan) [10], Jarvik 2000 (Jarvik Heart, Inc., New York, NY, USA) [11], and HeartMate II (Abbott, Abbott Park, IL, USA) (Fig. 1) [2]. In the USA, the only devices that are approved for commercial use are the HeartMate II, HeartMate 3 (Abbott) [12] and HVAD (Medtronic, Minneapolis, MN, USA). The HeartAssist5 (ReliantHeart Inc., Houston, TX, USA) [13] and Jarvik 2000 are currently under investigation [14]. HVAD, HeartMate 3, and HeartAssist5 may be available in Japan shortly. In this article, we will focus on the continuous-flow LVADs.

Measuring hemodynamics during LVAD support

The hemodynamic assessment of LVAD patients starts with blood pressure measurement. Higher blood pressure has been associated with increases in intracranial hemorrhage, thromboembolic events, and progressive aortic insufficiency [15]. Unfortunately, the reduced pulse pressure during continuous-flow LVAD support limits our ability to accurately measure blood pressure with traditional oscillometric blood pressure cuffs, and Doppler opening blood pressure is commonly used as a surrogate of mean arterial pressure. Arterial lines are the gold standard for monitoring blood pressure, but are invasive and not practical for ambulatory use.

Physical examination is the most common tool to assess hemodynamics in patients with HF [16]. However, preliminary data from a prospective trial at our institution show that physical examination has low sensitivity in assessing hemodynamics compared to right heart catheterization (RHC), including central venous pressure (CVP), pulmonary capillary wedge pressure (PCWP), and cardiac index (CI) [17]. Invasive RHC remains the gold standard to assess hemodynamics in LVAD patients.

Estep et al. found that Doppler echocardiography provides an estimate of invasive hemodynamics. They demonstrated good correlation between Doppler echocardiographic and invasive measurements in mean right atrial pressure ($r = 0.863$; $p < 0.001$), systolic pulmonary artery pressure (PAP) ($r = 0.880$; $p < 0.001$), and pulmonary vascular resistance (PVR) ($r = 0.643$; $p < 0.001$) in 50 consecutive patients with HeartMate II, although optimal results require expert technique [18].

Estimation of the PCWP in patients with centrifugal continuous-flow LVAD may be achieved by analyzing the flow wave derived from the pump power. Recently, we reported that the early filling phase slope measured from the HVAD waveform (as displayed on the HVAD clinical screen) is directly correlated to the measured PCWP [19]. Our findings were corroborated by the report from Lai et al., which also demonstrated that the HVAD waveform had an excellent predictive value [20]. More studies are required to demonstrate whether waveform analysis can be routinely used as a clinical tool.

Innovative monitoring devices, such as the CardioMEMS Heart Failure Monitoring System (Abbott) [21] and Remote Dielectric Sensing (Sensible Medical Innovations Ltd., Kfar Neter, Israel) [22], are currently under investigation (Fig. 2).

Ramp test and optimization of hemodynamics

The International Society of Heart and Lung Transplantation guidelines recommend echocardiogram as an integral part of determining optimal LVAD speed, with goals including adequate LV unloading with midline LV septum and minimal mitral valve regurgitation (MR) (class I) [23]. Adjusting LVAD speed to allow intermittent aortic valve opening is currently in the guidelines as a class IIb recommendation. However, these recommendations are vague and not standardized. RHC is recommended in specific situations such as recurrent HF symptoms, pulmonary hypertension (PH), and right ventricular failure (RVF) (class I), or when LVAD explantation is considered (class IIa) [23]. Routine RHC is not recommended in the guidelines.

We recently showed in clinically stable outpatients that 57% of patients had abnormally elevated CVP and PCWP at baseline LVAD speed [8]. This finding suggests that current approaches to speed optimization are inadequate, and that measurement of hemodynamics provides significant additional information above clinical assessment. All patients may benefit from a hemodynamic-guided optimization of LVAD speed and medical therapy.

To develop a standardized approach to hemodynamic assessment and optimization, we modified our previously described echocardiographic ramp test to create an invasive hemodynamic ramp protocol [24,25]. In this protocol, LV end-systolic dimension, LV end-diastolic dimension, the frequency of aortic valve (AV) opening, and the degree of MR and AV regurgitation are measured at the baseline LVAD speed, along with hemodynamic parameters including CVP, PAP, PCWP, and CO and CI by Fick measured by invasive RHC. After these measurements, the LVAD speed is turned down to 8000 RPM in HeartMate II and 2300 RPM in HVAD. The LVAD speed is subsequently increased stepwise every 2 min by 400 RPM in HeartMate II (8000–12,000 RPM) and 100 RPM in HVAD (2300–3200 RPM). The aforementioned echocardiographic and hemodynamic parameters are measured at each LVAD speed. The study is terminated when LV end-diastolic dimension is less than 3.0 cm or a significant suction event occurs. At the conclusion, LVAD speed is set targeting CVP <12 mmHg and PCWP <18 mmHg with the secondary goal of allowing intermittent AV opening and minimal MR.

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