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EDITORIAL COMMENT

Comparing Hemodynamics of Contemporary Mechanical Circulatory Support

Moving from In Silico to In Vivo Results*

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The degree of myocardial recovery determines the function and ultimately the survival of a patient in cardiogenic shock. Therapeutic efforts to improve myocardial function include intensive pharmacotherapy (inotropes, vasopressors), and use of mechanical circulatory support (MCS) devices, including the intra-aortic balloon pump, the left ventricular (LV)-to-aorta axial pump catheter (Impella CP [IMP]) and the left atrial (LA)-to-femoral artery pump (TandemHeart [TH]). All act through different mechanisms, and to different degrees, to unload the heart, increase blood pressure, cardiac output and systemic perfusion, while reducing myocardial work and oxygen consumption.

The hemodynamics of MCS devices are known to us predominately from computer simulations (“in silico” models) (1,2), in vivo animal studies (3,4), and series of cardiogenic shock patients (5,6). In practice, a specific device is selected based both on its presumed hemodynamic power as well as the patient’s clinical features (e.g., status of the aortic valve, peripheral vascular disease, etc.) and technical challenges of device implantation (e.g., cannula size, ease and speed of insertion, and availability of a trained team on call).

Because of the different mechanisms of action, we can expect unique hemodynamic profiles, especially involving LV unloading and other performance characteristics. To review, the intra-aortic balloon pump inflates in diastole, generating an augmented pressure pulse and deflates abruptly in systole reducing LV afterload. The net hemodynamic effects of intra-aortic balloon pump produce (to variable degrees) an increase in mean arterial pressure, coronary perfusion, and mild decrease in myocardial work. The magnitude of these effects is smaller than those of either the IMP or TH and requires a contracting heart to function effectively. The IMP works through a catheter-mounted axial pump, drawing blood from the LV and expelling it into the ascending aorta. The TH pulls blood from the left atrium through a trans-septal inserted large (22-F) inflow cannula to an external centrifugal pump, returning the blood to the arterial circulation through the femoral artery. Both IMP and TH substantially reduce LV stroke volume, LV loading, and myocardial work, and increase cardiac output and systemic pressure. Although the hemodynamics of IMP and TH have been explored extensively by computer simulations (1,2), it remains largely unknown to what degree the MCS devices perform under in vivo conditions, in the same subject with the same flow rates. Moreover, hemodynamic differences from computer simulations would be anticipated since any in silico model cannot not completely replicate the more complex behavior of the intact, in vivo animal cardiovascular system (7).

Moving from in silico to in vivo, Weil et al. (8) compared the hemodynamics of the IMP and TH from a closed chest animal model of myocardial infarction. Using a LV pressure-volume (PV) catheter, PV loops were obtained before and after a moderate-sized myocardial infarction was induced with a 2-h circumflex coronary artery occlusion.

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TABLE 1 Comparative Hemodynamic Effects of Percutaneous Ventricular Assist Devices

	IMP	TH
Heart rate (beats/min)	=	=
Mean aortic pressure (mm Hg)	=	=
Aortic pulse pressure (mm Hg), control to device activation	34 ± 2 to 27 ± 4	34 ± 2 to 14 ± 1*†
LV end-diastolic pressure (mm Hg)	15 ± 1 to 11 ± 1*	15 ± 2 to 7 ± 4*†
Pulmonary capillary wedge pressure (mm Hg)	15 ± 2 to 13 ± 2	15 ± 2 to 9 ± 1*
End-systolic elastance (mm Hg/ml)	=	=
LV stiffness constant (β)	+	+
LV dP/dt_{max} reduction	-	++
LV stroke work reduction	+	+++
LV pressure volume area reduction	+	+++
LV preload recruitable stroke work reduction	-	+

Values are mean ± SEM. *$p < 0.05$ vs. post-MI; †$p < 0.05$ vs. Impella CP (IMP). Adapted from Weil et al. (8).

+ = improved compared with control MI state; = = equivalent change between devices; - = no improvement compared to control; LV = left ventricular; TH = TandemHeart.

Although frank cardiogenic shock was not produced, myocardial infarction shifted the PV loop to the right due to an increased LV end-diastolic pressure accompanied by reduced systolic pressure with mildly reduced stroke volume. Both MCS devices were then sequentially placed, with the order randomized and the goal flow rates matched.

Both MCS devices maintained the aortic pressure but, compared to IMP, the TH had a greater reduction in LV end-diastolic pressure (but not volume), native LV stroke volume, dP/dt_{max}, stroke work, PV area, and preload stroke work slope (**Table 1**). In short and at odds with some prior reports (2–5), TH unloaded and rested the heart to a greater degree than IMP. Of particular interest and unique to this study was that the hemodynamics and PV loops of the 2 MCS devices were not only different from each other but also different from the computer model predictions (**Figure 1**).

The investigators deserve our compliments for their rigorous experimental methods. The greater decrease in native stroke work by TH suggests a more powerful volume unloading of the heart occurs despite the relative increase in native end-systolic volume compared with IMP as demonstrated by the different shapes of the in vivo PV loops (**Figure 1**). The IMP maintained end-systolic pressure, reduced stroke volume and shifted the PV loop leftward, whereas the TH increased end-systolic pressure with a pronounced reduction in stroke volume and preload. As a result, the TH produced a greater decrease in PV area (a well-validated index of myocardial oxygen consumption) than the IMP in the animal model, a contrasting observation from the computer models. Conceivably, more effective decreases in myocardial oxygen demand would lead to greater myocardial recovery after infarction, or more support during cardiogenic shock.

This well-performed study, comparing 2 commonly used MCS devices head to head for the first time in this way, suggests that, at comparable device flow rates, the degree of LV unloading depends on whether blood is withdrawn directly from the LA or the LV. The IMP draws blood from the LV and decreased LV end-diastolic volume and LV end-diastolic pressure and maintained arterial pressure, but in this study did not affect PV loop-derived indices of myocardial work significantly. In contrast, TH withdrawal of blood from the LA also reduced LV end-diastolic volume and LV end-diastolic pressure, and maintained arterial pressure while also reducing native LV stroke volume, stroke work, dP/dt_{max}, PV area, and preload-recruitable stroke work consistent with enhanced LV unloading.

Why should the findings of Weil et al. (8) differ from prior studies? Although neither a computer model nor the induced animal infarction model exactly duplicates the human cardiogenic shock state, the in vivo conditions incorporate a number of influences on myocardial function, arterial impedance and afterload, and peripheral resistance that can only be estimated in a more rudimentary fashion in computer simulations. In contrast, the present study did not truly induce a state of cardiogenic shock. Because unloading with IMP occurs most effectively when cardiac output is low and LV end-diastolic pressure and volume are increased (and poorly when these states are not present), the present model may have unfairly tilted the scale against IMP.

Why aspiration of similar flow rates from the left atrium compared with the LV would have such different hemodynamic effects remains unclear. Potentially, this result reflects the greater capacitance of the LA (compared with the LV) to release volume to the MCS device, particularly in euvolemic, nonshock states, but this would presumably have been evident from the flow rates measured. Alternatively, the authors suggest that, by decreasing the LV end-diastolic pressure to a greater extent, LA withdrawal may improve coronary blood flow. However, coronary blood flow was not measured in this study and would not explain how LV end-diastolic pressure is reduced more effectively.

The IMP and TH are powerful MCS devices that are frequently used for high-risk percutaneous coronary interventions and cardiogenic shock. In clinical practice, the selection of a percutaneous MCS device depends not only on the hemodynamic power of the device, but also and more important on the specific