

# Left Ventricular Mechanical Support with Impella Provides More Ventricular Unloading in Heart Failure than Extracorporeal Membrane Oxygenation

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**The Impella microaxial-flow pump can directly unload left ventricle (LV) in cases of acute heart failure. Extracorporeal membrane oxygenation (ECMO) is widely used for circulatory support. Although the clinical effectiveness of ECMO has been demonstrated, insufficient LV loading reduction may not be advantageous for myocardial recovery. The objective was to compare ventricular loading reduction and reversibility of ventricular fibrillation (VF) with either Impella or ECMO. Six dogs were used. Extracorporeal membrane oxygenation was established by the femoral artery and right atrium. The Impella LD was inserted in LV by the ascending aorta. An acute failing heart was created by sequential coronary artery ligations. Pressure–volume (PV) relationships were acquired without a device and with ECMO or Impella. When VF occurred, direct cardioversion was performed while supported by either ECMO or Impella. The PV area, which is a measure of ventricular unloading and is correlated with myocardial oxygen consumption, decreased more with Impella than with ECMO. Successful defibrillation was achieved more effectively while under Impella support. Superior ventricular unloading with the Impella device may provide higher recovery potential to damaged hearts than ECMO and may have a significant impact not only on intensive care of patients with heart failure but also on resuscitation. *ASAIO Journal* 2011; 57:000–000.**

Cardiogenic shock is a condition with a miserable prognosis independent of its cause. A recent study reported that cardiogenic shock due to acute myocardial infarction has a mortality rate of approximately 50% despite a high rate of coronary revascularization.<sup>1</sup> This dismal status has stimulated the need to develop a mechanical support device to allow for native heart recovery or bridging to transplantation.

Thus, extracorporeal membrane oxygenation (ECMO) was introduced in 1977 to meet this requirement.<sup>2</sup> Extracorporeal circulation enhances coronary blood flow and reduces the time taken for restoration of spontaneous circulation in cases

of cardiac arrest.<sup>3</sup> Furthermore, ECMO supplies oxygenated blood to multiple terminal organs, preserves organ function, and increases the survival rate after cardiac arrest.

However, ECMO systems have device-related disadvantages such as hemolysis, coagulation disorders, and limited device durability. Furthermore, the efficacy of ECMO has been questioned with respect to the mechanoenergetic status of the heart.<sup>4,5</sup> Adverse effects of ECMO on a failing heart are increased in left ventricular wall stress, which is caused by increased afterload due to blood return and insufficient blood drainage to unload a failing left ventricle (LV).<sup>4</sup> In the case of intractable ventricular fibrillation (VF) concomitant with severe heart failure, physicians have seldom experienced the conversion of VF to a stable cardiac rhythm under ECMO support.

The concept of catheter-mounted axial-flow pumps in the setting of failure to wean was explored in the 1990s with the Hemopump (Medtronic Inc., Minneapolis, MN).<sup>6</sup> However, the Hemopump did not improve the survival rate of patients with severe heart failure because of hemorrhagic and thromboembolic adverse events. This device is no longer available for clinical use; however, the concept has been pursued and realized as the Impella system (ABIOMED Inc., Danvers, MA), which includes devices for both left and right ventricular support. This system has been demonstrated to be effective for various indications such as cardiogenic shock, postcardiotomy heart failure, and right heart failure.<sup>7</sup>

The purposes of this study were to test the hypotheses that Impella can unload LV more effectively than ECMO, assessed by the measurement of left ventricular end-diastolic pressure (LVEDP) and pressure–volume (PV) area (PVA), and that Impella support during cardioversion can lead to more successful defibrillation of an acute failing heart.

## Materials and Methods

### *The Impella Microaxial Flow System and ECMO Device*

The Impella support device has a motor mounted on the tip of a catheter with a cable connected to a console positioned beside the patient. The Impella system has several pump configurations, and the Impella LD with a maximal flow of 5 L/min was used in this experiment. The ECMO circuit consisted of a centrifugal pump, a hollow fiber microporous membrane oxygenator, and a percutaneous thin-walled cannula (Capiiox SP-101, Terumo, Tokyo, Japan).

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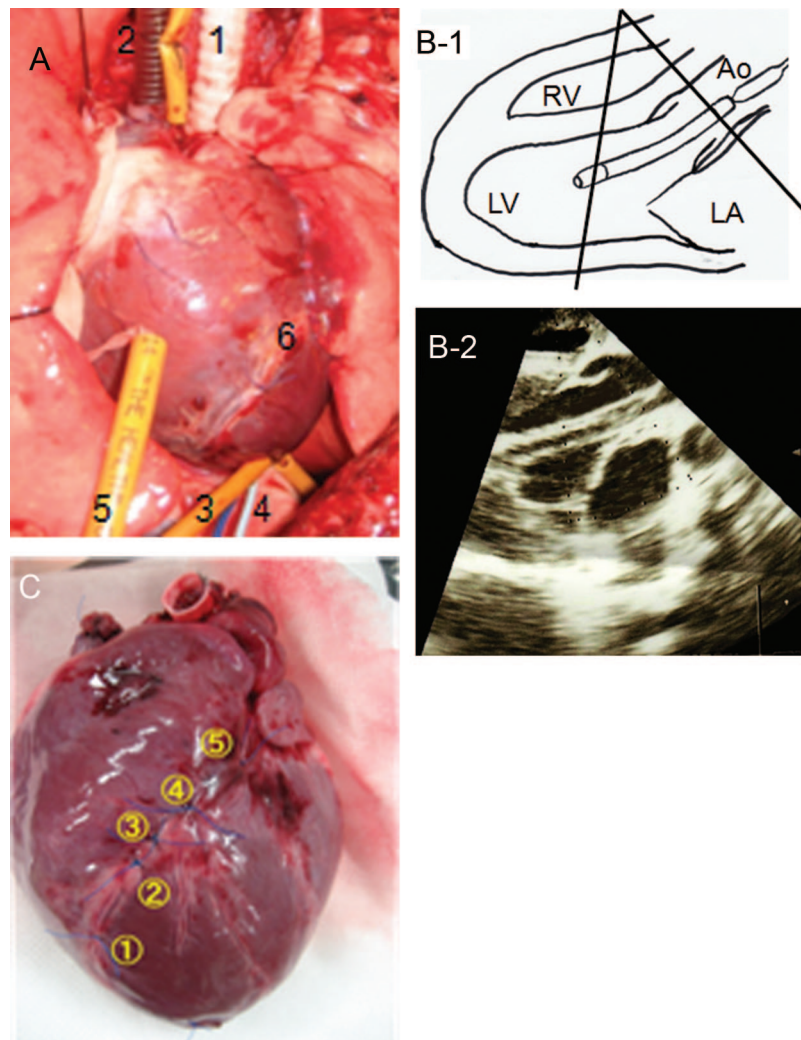
### Preparation for Surgery

All experimental procedures and protocols used in this study were in accordance with the guidelines of humane care provided in the US National Institute of Health "Guide for the Care and Use of Laboratory Animals,"<sup>8</sup> and approved by the Animal Ethical Committee at The University of Tokyo. Six healthy, breeding male dogs weighing between 20 and 24 kg (body surface area, 0.74–0.84 m<sup>2</sup>) were used in this study. Electrocardiographic (ECG) monitoring was performed throughout the experiment. An intravenous fluid route was established at the upper foreleg to maintain a given central venous pressure (CVP). After an endotracheal tube was inserted, mechanical ventilation with oxygen (2 L/min) was facilitated by an intermittent intravenous infusion of pancuronium bromide (0.08 mg/kg), and lactate Ringer's solution was infused at a rate of 5 ml/kg/h. After each ligation, CVP was adjusted to 5–10 mm Hg without a mechanical support. A

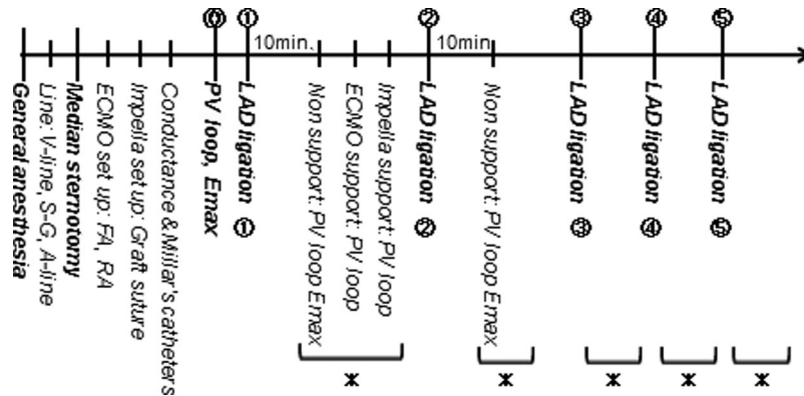
heparin-filled Swan-Ganz catheter was inserted through the right jugular vein to measure mean pulmonary artery pressure (mPAP), CVP, and cardiac output (CO). An 18-gauge catheter was inserted through the left femoral artery to measure the systemic artery pressure.

### Setup of Assist Devices and Measure Catheters

After median sternotomy, the pericardium was dissected and secured by suturing to the sternum. A 10-Fr arterial cannula was inserted in the right femoral artery, and a 28-Fr venous cannula was inserted in the right atrium, and they were then connected to an ECMO circuit. A 10-mm vascular graft (10 mm Gelsoft ERS, Terumo, Tokyo, Japan) was anastomosed to the ascending aorta for Impella insertion. Impella LD was introduced in a retrograde manner through the vascular graft under direct echocardiographic guidance in LV to ensure proper position. A 6-Fr pressure transducer-



**Figure 1.** Photographs of the operation. **A:** Preparation of the heart with the graft for Impella (1), the outlet cannula for extracorporeal membrane oxygenation (ECMO) (2), conductance (3), and pressure catheters (4), and tourniquet around the inferior vena cava (IVC) (5). The area representing left anterior descending coronary artery (LAD) ligation was distinctly blue (6). It macroscopically revealed an acute ischemic change. **B-1:** Illustration positioning Impella LD, RV, right ventricle; LV, left ventricle; Ao, ascending aorta; LA, left atrium. **B-2:** The long axis view of direct echocardiography. No aortic regurgitation, aortic stenosis, or mitral stenosis was found after Impella insertion in the left ventricular chamber. **C:** Excised heart after the experiment. The sequential ligation number of LAD is shown.



**Figure 2.** The flowchart of this experiment is shown. ECMO, extracorporeal membrane oxygenation; RA, right atrium; PV loop, pressure-volume loop; LAD, left anterior descending coronary artery. \*Data acquisition were repeated.

tipped catheter (SPC 454D; Millar Instruments, Houston, TX) and a 6-Fr conductance catheter (2S-RH6-DA116; Alpha Medical Co., Mission Viejo, CA) were inserted in the left ventricular cavity through the LV apex for continuous recording of LV pressure and volume (**Figure 1A**). With respect to their positioning, these catheters were also visualized with direct echocardiography to ensure accurate position (**Figure 1B**). The conductance catheter was connected to a conductance console (Sigma 5/DF; CD Leycom, Zoetermeer, The Netherlands), which was used in the dual-frequency mode.

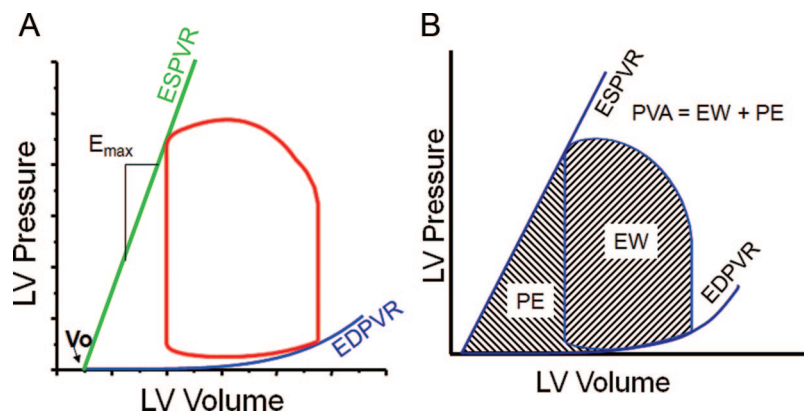
*Acute Ischemic Model and Data Acquisition*

An acute ischemic model was created by sequential ligations from the distal to proximal end of the left anterior descending coronary artery (LAD)<sup>9</sup> (**Figure 1C**) in the following order: 1) far distal of distal LAD, 2) midportion of distal LAD, 3) just distal to the second diagonal branch, 4) proximal to the second diagonal branch, and 5) just distal to first diagonal branch. Ischemic changes by these ligations were verified with immediate ST-segment elevation on ECG and obvious bluish and noncontracting acute dyskinesia of the ischemic ventric-

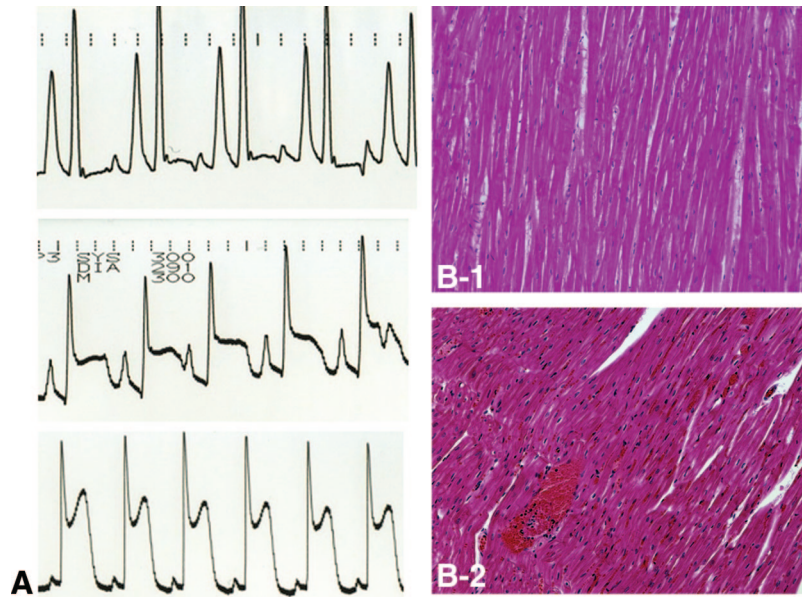
ular wall during the experiment and confirmed by pathological assessment after the experiment.

Data were acquired according to the following protocol (**Figure 2**). Data collections were started 10 minutes after each coronary ligation. Before acquiring data, hemodynamic characteristics were recorded during 20 heart beats, and the respirator was turned off to avoid respiratory influence on hemodynamics.  $E_{max}$  (**Figure 3A**) was obtained by changing the preload, such that the inferior vena cava (IVC) was occluded with a tourniquet. First, PV relationships and  $E_{max}$  were acquired without any mechanical support and then with ECMO support and Impella support. Before acquiring data with the Impella support, we checked the failing heart conditions by measuring  $E_{max}$  as the baseline. Each data acquisition was performed during steady-state conditions after the setting of each device. Five minutes of stabilization preceded the data recording for each subsequent group. A total of five sets of ligation and data acquisitions were performed (**Figure 2**). The assist flow of ECMO was maximized under a given CVP, and the Impella flow was set to be the same as the ECMO flow.

Ventricular tachycardia after VF occurred frequently during the experiment and also after the last ligation. After 100 mg of



**Figure 3.** Schematic illustration of ventricular  $E_{max}$  and pressure-volume area (PVA). ESPVR, end-systolic pressure-volume relationship; EDPVR, end-diastolic pressure-volume relationship;  $V_0$ , unstressed ventricular volume. **A:**  $E_{max}$  corresponds to the slope of the line passing through the end-systolic pressure volume data points. **B:** PVA (indicated by the total shaded area) is equal to the sum of external work (EW) and potential energy (PE) and is the strongest index of myocardial oxygen demand.



**Figure 4.** Electrocardiogram (ECG) and histology. **A-1:** Before the coronary ligation. **A-2:** After the first ligation. **A-3:** After the last ligation. **B:** The right ventricle and anterior wall of the left ventricular apex were stained with hematoxylin-eosin. **B-1:** No obvious ischemic change could be observed in the right ventricle. **B-2:** Dilation of capillaries and focal bleeding around myocardial cells were observed in the left ventricular apex. These changes revealed that an acute ischemic change had occurred.

lidocaine was administered intravenously, direct cardioversion (DC) was performed in the heart without a mechanical support. In case of continuing arrhythmia, either mechanical device was switched on for 1 minute, and then DC of 20 J was applied. If the heart failed to recover, the device was exchanged, and DC of 20 J was reapplied. We counted the number of successful defibrillated dogs among those suffering from VF.

All hemodynamic data, aortic pressure, CVP, mPAP, CO, and ECG were continuously monitored on a polygraph (RMC-1100, Nihon Kohden, Tokyo, Japan) and digitized by a computer interfaced with an analog-to-digital converter (DI-720-USB, Dataq Instruments, Inc., Akron, OH). At the end of the experiment, animals were killed under an anesthetic state according to animal care guidelines.

PVA and  $E_{\max}$  were analyzed with Conduct 2000 (CD Leycom, Zoetermeer, The Netherlands)<sup>10</sup> after examination. The LV contractile state was evaluated using the ventricular end-systolic elastance,  $E_{\max}$ . The LV unloaded volume,  $V_0$ , was calculated by linear regression analysis of end-systolic pressure (ESP) and volume (ESV) data. We assumed the same  $V_0$  during each device support as the baseline in the subgroup. Pressure–volume area was the sum of the areas for the rectangular area within the PV loop and the triangular area under the  $E_{\max}$  line on the origin side of the PV loop (**Figure 3B**). The  $E_{\max}$  relative ratio was determined as the ratio of  $E_{\max}$  without a mechanical support after each ligation to  $E_{\max}$  in the native heart before ligation. Acute failing heart conditions were grouped into three groups based on the  $E_{\max}$  relative ratio. Severe, moderate, and mild failing heart conditions were defined as 0%–29%, 30%–59%, and 60%–99% of the  $E_{\max}$  relative ratio, respectively. The PVA relative ratio was determined as the ratio of PVA under ECMO or Impella support to PVA without mechanical support.

### Statistical Analysis

Data were analyzed using statistical software JMP 8 (SAS Institute Inc., Cary, NC). The hemodynamic variables in each of the failing heart conditions were compared by one-factor analysis of variance (ANOVA). If a significant difference was present among the groups, comparison between two groups was performed by the Tukey–Kramer method. A paired t-test was used for the PVA relative ratio. Two-sided  $p$  values < 0.05 were considered to be statistically significant.

## Results

### Effects of Mechanical Support Devices on Hemodynamics

We performed this experiment in six adult dogs. Electrocardiogram revealed progressive ST-segment elevations as ligations advanced to the proximal end (**Figure 4A**). Furthermore, ischemic changes such as dilation of capillaries and focal bleeding around myocardial cells in the LV apex were identified by pathological analyses (**Figure 4B**). The effects of sequential ligations of LAD on hemodynamic characteristics are summarized in **Table 1**. Mean assist flow was  $1.50 \pm 0.42$  L/min in ECMO and  $1.57 \pm 0.37$  L/min in Impella ( $p = 0.54$ ). Hemodynamic characteristics obtained from all dogs are summarized in **Figure 5**. Treatment with ECMO had no significant effect on LV ESP (LVESP), LVEDP, systolic aortic pressure, or diastolic aortic pressure. Impella support had statistically no effect on LVESP, systolic aortic pressure, diastolic aortic pressure, CVP, or mPAP. Within a subgroup, based on the degree of failing heart severity, LVESP, systolic aortic pressure, and diastolic aortic pressure did not differ significantly between ECMO and Impella. Left ventricular end-diastolic pressure did not decrease with ECMO but did with Impella; and the reduction was significant compared with that in the absence of

**Table 1. General Hemodynamic Characteristics**

	Mild HF			Moderate HF			Severe HF			
	Baseline	Baseline	ECMO	Impella	Baseline	ECMO	Impella	Baseline	ECMO	Impella
HR (bpm)	133.0 ± 10.2	138.0 ± 10.1	140.3 ± 23.0	136.6 ± 19.4	114.2 ± 20.6	109.4 ± 13.2	99.0 ± 18.9	136.2 ± 16.9	134.5 ± 12.2	134.8 ± 11.3
CO (l/min)	2.46 ± 0.44	2.13 ± 0.57	—	—	2.08 ± 0.76	—	—	2.08 ± 0.70	—	—
Sys Ao (mm Hg)	91.1 ± 26.8	76.6 ± 23.3	72.3 ± 33.8	68.7 ± 20.8	76.0 ± 43.2	89.2 ± 45.8	68.6 ± 39.4	68.2 ± 27.6	64.8 ± 18.9	61.7 ± 9.0
Dia Ao (mm Hg)	44.2 ± 13.4	38.6 ± 9.5	43.1 ± 23.0	49.1 ± 11.9	40.0 ± 19.0	55.2 ± 24.8	49.8 ± 25.0	29.3 ± 9.2	33.0 ± 10.2	39.2 ± 4.4
CVP (mm Hg)	4.8 ± 1.3	4.0 ± 1.5	1.4 ± 1.7 <sup>†</sup>	3.7 ± 1.3	4.4 ± 1.9	2.2 ± 2.2	4.4 ± 2.1	6.0 ± 2.1	2.5 ± 1.5*	5.3 ± 2.3
mPAP (mm Hg)	14.2 ± 1.3	13.0 ± 1.6	8.6 ± 2.9 <sup>†</sup>	12.7 ± 2.6	15.6 ± 2.9	10.6 ± 2.6 <sup>‡</sup>	16.4 ± 2.1	18.2 ± 6.4	11.3 ± 5.4	14.8 ± 4.7
LVEDP (mm Hg)	6.9 ± 3.3	8.6 ± 3.2	7.0 ± 1.6	6.1 ± 1.9	8.8 ± 2.7	7.8 ± 2.5	7.0 ± 2.0	10.2 ± 4.0	7.8 ± 5.1	6.7 ± 3.9
LVEDV (ml)	51.1 ± 7.0	58.1 ± 6.7	54.6 ± 7.5	49.8 ± 5.6	60.1 ± 8.1	56.5 ± 8.6	56.1 ± 5.7	66.4 ± 29.6	56.9 ± 23.0	53.0 ± 22.4
$E_{max}$ (mm Hg/ml)	8.27 ± 4.37	4.52 ± 1.14	—	—	2.70 ± 1.20	—	—	1.82 ± 1.08	—	—
Vo (ml)	31.8 ± 14.0	35.0 ± 9.2	—	—	16.0 ± 35.2	—	—	7.6 ± 18.0	—	—
PVA (J/min)	36.0 ± 6.9	36.9 ± 15.5	29.5 ± 23.6	19.2 ± 14.4	48.3 ± 45.3	51.8 ± 46.1	36.6 ± 34.5	62.0 ± 50.9	54.6 ± 42.0	48.5 ± 39.9

Values are mean ± SD.

\* $p < 0.05$  compared with baseline in each HF state.

<sup>†</sup> $p < 0.05$  compared with Impella support in each HF state.

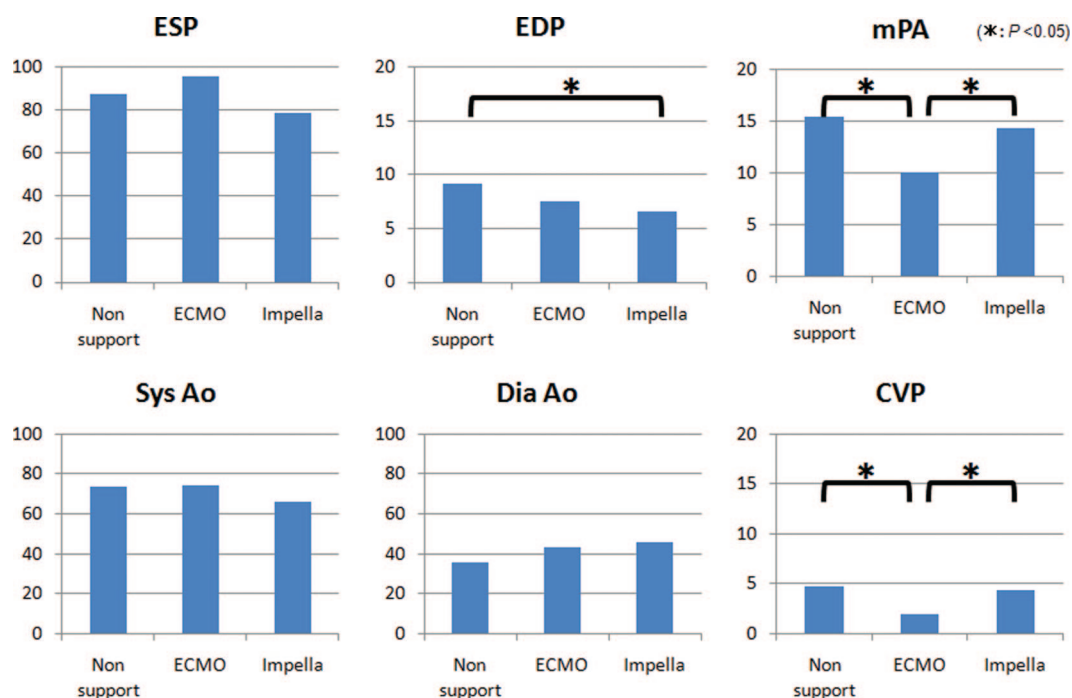
HR, heart rate; Ao, arterial pressure; CVP, central venous pressure; HF, heart failure; mPAP, mean pulmonary arterial pressure; LVEDP, left ventricular end-diastolic pressure; LVEDV, left ventricular end-diastolic volume; SD, standard deviation; ECMO, extracorporeal membrane oxygenation.

mechanical support. Central venous pressure and mPAP decreased more with ECMO than with Impella. In **Table 1**, hemodynamic characteristics are summarized based on the severity of heart failure. Left ventricular end-diastolic volume (LVEDV) and LVEDP were not significantly different between ECMO and Impella, but a trend for lower values with Impella is observed. On the other hand, mPAP with ECMO was significantly lower than that with Impella.

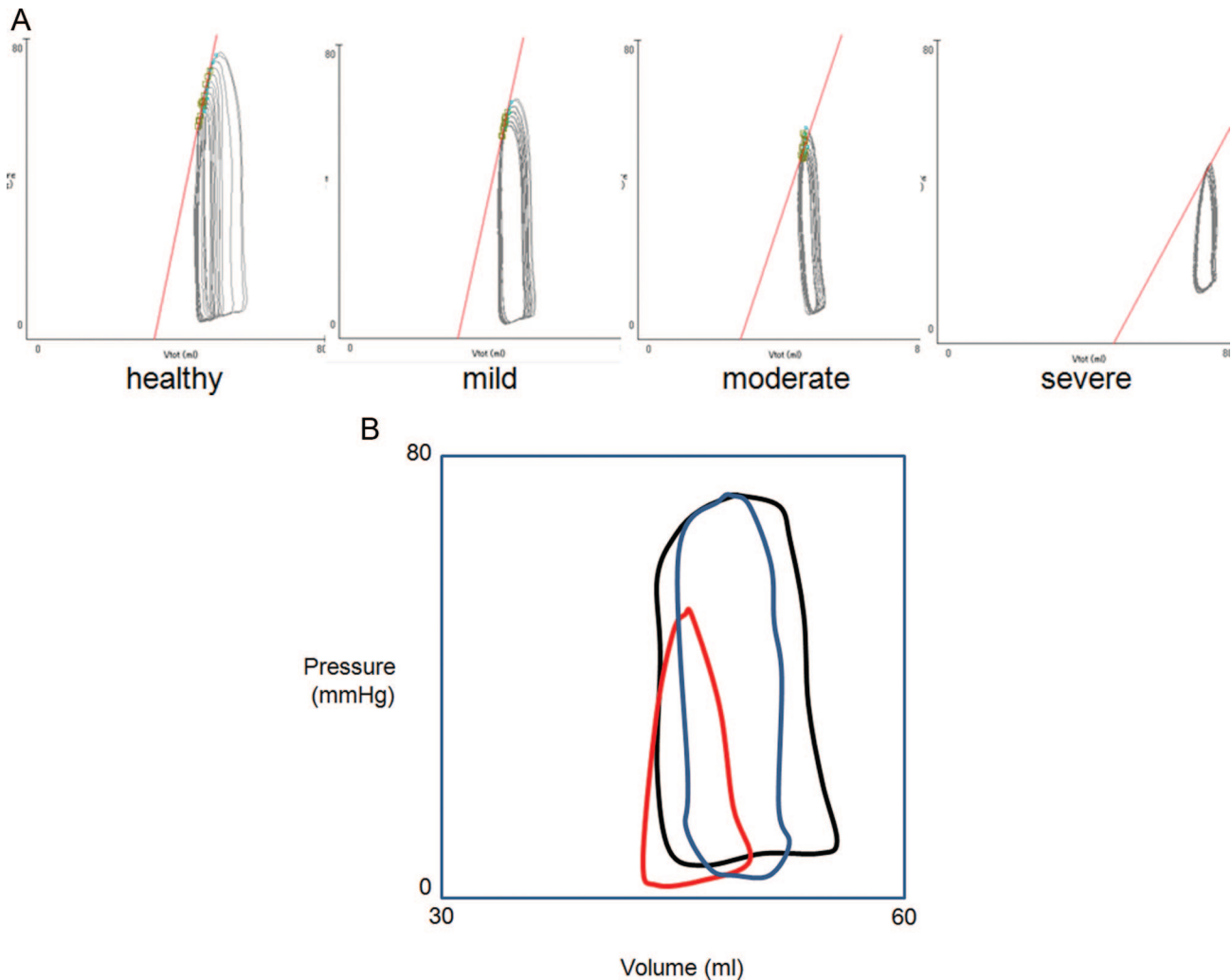
*Effects of Mechanical Supports on PVA*

Although ligation of LAD can successfully create heart failure, the extent of reduction on cardiac function was not constant with

respect to the ligation site. The failing condition was estimated based on the  $E_{max}$  value of the injured heart without any mechanical support before PV loop acquisition. Failing heart conditions were then divided into three groups, equivalent to mild, moderate, and severe heart failure in a clinical setting (**Figure 6A**). **Figure 6B** shows representative PV loops with and without any mechanical support. The pressure-volume area (PVA) relative ratio of Impella decreased more than that of ECMO in mild and moderate failing hearts. The PVA relative ratio of both mechanical devices gradually increased as the failing heart conditions exacerbated. Increase in PVA under ECMO support was more than that without a mechanical support in severe failing hearts,



**Figure 5.** Hemodynamic characteristics. LVESP, left ventricular end-systolic pressure; LVEDP, left ventricular end-diastolic pressure; mPAP, mean pulmonary artery pressure; CVP, central venous pressure. CVP and mPAP decreased more with extracorporeal membrane oxygenation (ECMO) than with Impella. LVEDP decreased significantly with Impella.



**Figure 6.**  $E_{max}$  and pressure–volume (PV) relationships. **A:** The  $E_{max}$  relative ratio was determined as the ratio of  $E_{max}$  at each ligation to  $E_{max}$  before ligation. The representative slope of  $E_{max}$  is shown. **B:** The representative PV loop without a mechanical device and with each device is shown. The loop of the black line is the baseline. The blue line is the PV loop under extracorporeal membrane oxygenation (ECMO) support. A decrease in left ventricular end-diastolic volume and an increase in left ventricular end-systolic volume were observed. Both systolic and diastolic isovolumic phases were maintained straight. The red line is the PV loop under Impella support. Both left ventricular end-diastolic and end-systolic volumes are reduced. Isovolumic phases were not observed.

indicating overloading and dilatation of LV. In contrast, PVA increase with Impella in severe conditions continued to be less than that without a mechanical support (**Figure 7A**) indicating that beneficial unloading continued over the baseline in the unassisted state. Taken together, the PVA relative ratio of Impella was significantly lower than that of ECMO (**Figure 7B**).

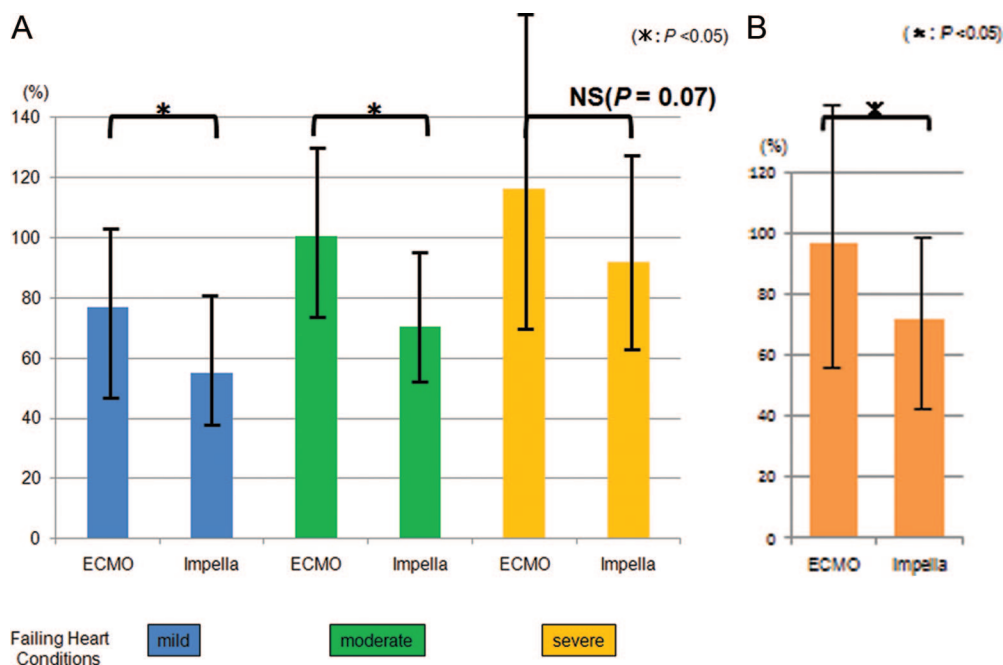
#### Reversibility of Ventricular Arrhythmia

Before the last LAD ligation, VF occurred in four dogs. However, only one dog recovered its sinus rhythm with DC under ECMO support. The other three dogs did not recover under ECMO support. All dogs recovered sinus rhythm successfully with DC under Impella and could proceed with the experiment to the final coronary ligation. After the last ligation, VF occurred in two dogs. DC did not recover sinus rhythm under ECMO support but did regain rhythm under Impella support in one dog. The other dog did not recover by DC under either support device (**Figure 8**).

#### Discussion

This study revealed that Impella could decrease LVEDP and PVA more than ECMO in an acute failing heart. Furthermore, the incidence of successful defibrillation under Impella support was significantly higher than that with ECMO. These findings suggest that left ventricular mechanical support with Impella may afford more recovery potential in failing hearts than that with ECMO.

Left ventricular performance can be characterized as time-varying elastance  $E(t)$ .<sup>11</sup>  $E_{max}$ , which is the end-systolic slope of the relationship between PV and ventricular end-systolic maximum elastance, is a reliable load-independent contractility index of a beating heart.<sup>12</sup> Pressure–volume area, which has been shown to correlate linearly with ventricular oxygen consumption ( $VO_2$ ) under various pre- and afterload conditions,<sup>13</sup> is the sum of the area for external work surrounded by the PV loop and elastic potential energy (PE) under the  $E_{max}$  line on the origin side of the PV loop (**Figure 3B**). Pressure–volume



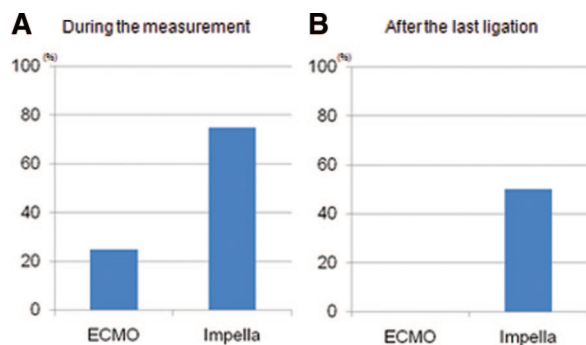
**Figure 7.** Pressure–volume area (PVA) relative ratio. **A:** The PVA relative ratio of Impella decreased more than that of extracorporeal membrane oxygenation (ECMO) in mild and moderate failing hearts. The PVA relative ratio of both mechanical support devices gradually increased as the failing heart conditions exacerbated. **B:** The PVA relative ratio in all cases was compared between ECMO and Impella. The PVA relative ratio of Impella was significantly lower than that of ECMO.

area could be calculated under some assumptions.  $V_o$  was determined by linear regression of ESP and ESV data at end systole by changing the preload due to IVC occlusion after each sequential ligation of LAD without a mechanical support. Pressure–volume areas were calculated using this  $V_o$  and end-systolic PV relationship in a subgroup. In addition, our laboratory performed an experiment to develop the best assist mode of a centrifugal pump and ensured the correlation between PVA using these assumptions and myocardial oxygen

consumption ( $MVO_2$ ) using blood gas data.<sup>14</sup> Furthermore, assumptions of PVA were justified under various mechanical ventricular device and supporting mode, including partial support of a centrifugal pump.<sup>15</sup> Myocardial PE is related to the amount of wall tension,<sup>16</sup> and maximum wall tension is associated with LVEDP and LVEDV. In this experiment, the decreases in PVA, LVEDP, and LVEDV were more with Impella than with ECMO, indicating superior LV unloading with Impella.

A promising strategy for functional recovery of the severely injured heart is to reduce the inherent oxygen demand of the myocardium. Reducing oxygen demand could place the muscle in a more protected state in the event of an ischemic insult in the acute phase and attenuate the proinflammatory status in the chronic phase under a mechanical circulatory support.<sup>17</sup> Reduced oxygen demand under Impella support has been demonstrated in other acute animal models.<sup>18</sup> Our results that Impella decreased PVA more than ECMO may indicate a larger reduction in  $VO_2$  in the failing status, therefore leading to a higher recovery potential than ECMO, but direct measurements of  $VO_2$  would be necessary to substantiate this conclusion.

Furthermore, coronary flow depends on both the pressure gradient across the coronary artery and the vascular resistance. Given that venous pressure and resistance of the primary artery are fixed, coronary flow will be proportional to the ratio of aortic pressure to microvasculature resistance. Reductions in LV volume and pressure decrease myocardial wall tension and microvascular resistance. In our experiment, LVEDP and LVEDV decreased with Impella, which may result in augmenting coronary flow and increasing oxygen supply. This effect had been demonstrated in patients under Impella support.<sup>19</sup>



**Figure 8.** Successful defibrillation rate: Number of successful defibrillated dogs/number of dogs who suffered from ventricular fibrillation (VF)  $\times$  100 (%). **A:** During the experiment (before the last left anterior descending coronary artery [LAD] ligation), VF occurred in four dogs. Although only one dog recovered heart beats with direct cardioversion (DC) under extracorporeal membrane oxygenation (ECMO) support, the other three recovered heart beats successfully with DC only under Impella support. **B:** After the last LAD ligation, VF occurred in two dogs. DC effectively recovered heart beats under Impella support in one dog but not in any dog under ECMO support.

Reduction in oxygen demand and increase in coronary flow could contribute in minimizing the damage after ischemic insult, and reduction of infarct size under Impella support has been demonstrated in animal models.<sup>18,20</sup>

Despite optimal hemodynamics in each device, successful defibrillation rates differed between Impella and ECMO. One explanation for this is the hypothesis of coronary flow competition. It could cause flow turbulence causing insufficient microcirculatory flow with subendocardial ischemia, which is responsible for lethal arrhythmia. Another explanation is that this difference in rate may be associated with  $MVO_2$  as mentioned previously. Our results strongly recommend LV unloading at DC to intractable ventricular arrhythmia due to cardiogenic shock. To our knowledge, no percutaneous modality has been used to achieve LV loading reduction. In the early period after cardiopulmonary resuscitation using ECMO, the first priority is to maintain blood flow and perfusion pressure to the terminal organs, and the heart is left as it is. Impella could fulfill both requirements, LV unloading and systemic hemodynamic support, which ECMO could not.

However, the increase in CVP and mPAP may indicate a drawback of Impella in the case of right ventricular failure. A right-sided Impella device may be a good indication for this condition. Our data did not show a significant reduction in PVA under Impella in the severe damaged status. Impella flow was set to be the same as that of ECMO, although the flow of Impella was not maximal. This is because our objective was to evaluate which device is more effective in LV loading reduction with the same assist flow. If Impella had been allowed to run at its maximal flow during the experiment, PVA may have been significantly reduced.

In summary, Impella unloads LV more than ECMO, while maintaining systemic hemodynamics in an acute failing heart. Favorable successful defibrillation from VF in a severely failing heart may be achievable with Impella. This study provides more information on not only intensive care of patients with heart failure but also resuscitation.

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