Chapter 9

Peripheral Ventricular Assist Devices in Interventional Cardiology: The Impella® Micro-Axial Pump

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Abstract

Coronary artery disease (CAD) presents an ever-growing burden on health systems especially in the Western world. While percutaneous coronary intervention (PCI) is feasible in increasingly complex CAD, certain patient groups possess a high risk for major cardiac adverse events (MACE) during PCI. Poor outcome is associated with significantly depressed left ventricular function, complexity of relevant lesions, and increasing incidence of pre-existing cerebrovascular comorbidities and poor pre-interventional status. However, these risk factors also translate into a high peri-operative risk for coronary artery bypass graft (CABG) rendering some of these patients inoperable. Peripheral ventricular assist devices (pVADs) are temporarily inserted axial or centrifugal pumps that support ventricular output during PCI. The Impella® micro-axial device (Abiomed, Danvers, Massachusetts, USA) is an easily implantable pVAD that may improve patient outcome during PCI in high-risk patients (termed "protected PCI") and in patients with cardiogenic shock (CS). pVADs in general and the Impella® system in particular play important roles in interventional cardiology and its indications and use will likely expand in the future. This chapter outlines in detail the indications, applications, and future trends concerning the Impella® system. Practical advice is given on the correct implantation of the device.

Keywords: peripheral ventricular assist device, protected PCI, Impella®, interventional cardiology

1. Introduction

The Impella® system consists of a miniaturized micro-axial pump of varying size reaching from 11 French (F) to 21 F in diameter mounted on a 9 F catheter (**Figure 1**). The propeller contained in the pump revolves at up to 50,000 rounds per minute (rpm) and draws blood into the inlet area to expel it through the outlet area of the device. The micro-axial pump itself is connected through the catheter to an automated Impella® controller (AIC) that steers the pumps output as well as the required purge fluid flow and integrates information on the pumps position (**Figure 2**). The Impella® catheter is inserted either through the femoral or axillary artery by surgical cut down or percutaneously using a modified Seldinger technique. Being forwarded into the left ventricle under fluoroscopic guidance, the Impella® is positioned to expel blood bypassing the aortic valve.

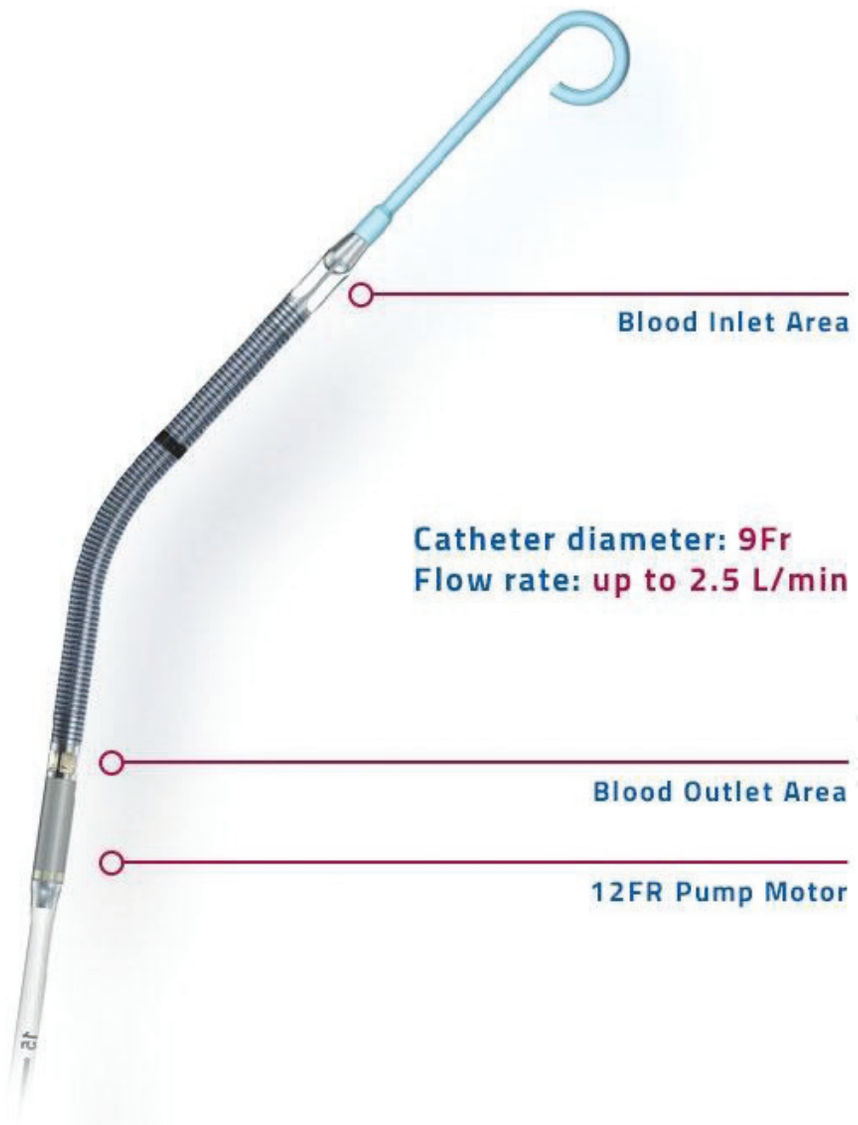

Figure 1. An Impella® 2.5 micro-axial peripheral ventricular assist device consisting of a blood inlet and an outlet area as well as the 12 Fr pump motor mounted on a 9 Fr catheter (Image courtesy of Abiomed, Danvers, Massachusetts, USA).

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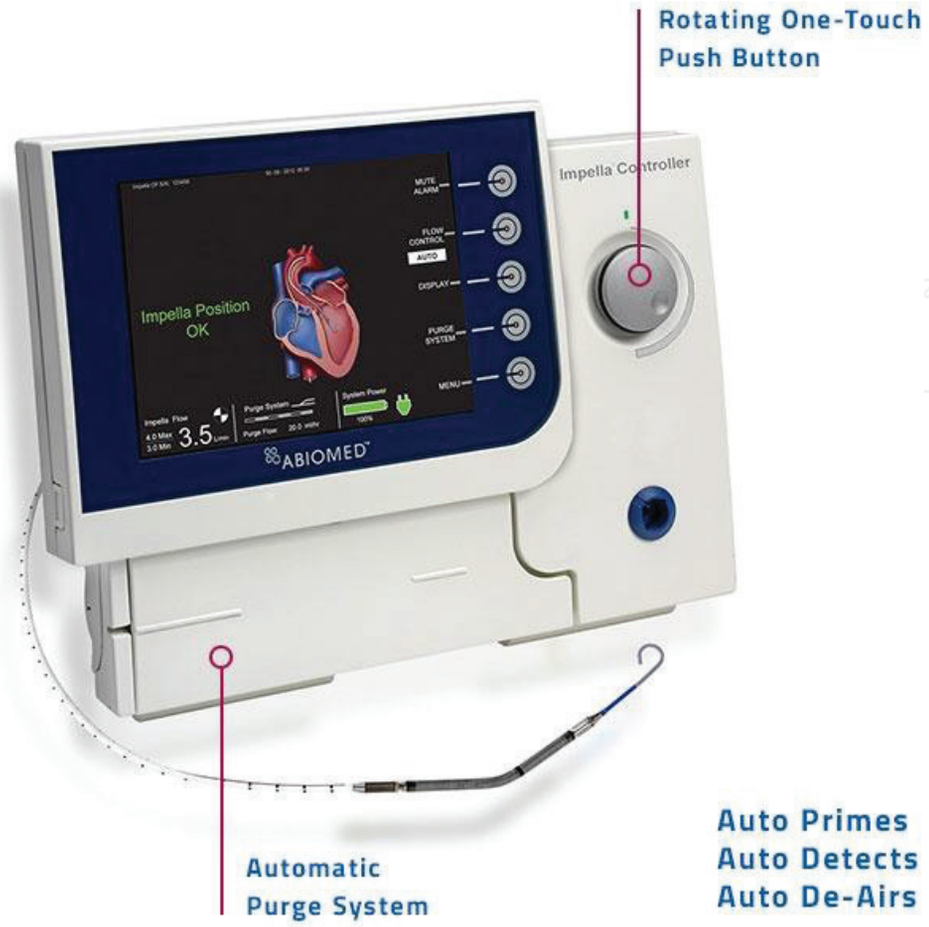

Figure 2. The Automated Impella Controller® steers the pumps output as well as the required purge fluid flow and integrates information on the pumps positions (Image courtesy of Abiomed, Danvers, Massachusetts, USA).

The Impella® platform consists of multiple devices featuring maximal output of up to 5.0 l/min and may be selected according to the required hemodynamic support. While the Impella® 2.5 (2.5 l/min of transvalvular flow) is designed to deliver support in patients mainly undergoing protected percutaneous coronary intervention (PCI), the 3.5 CP (cardiac power, 3.5 l/min of transvalvular blood flow) and 5.0 LP/LD (LP: left peripheral and LD: left direct, 5.0 l/min of transvalvular blood flow) are designed for patients in cardiogenic shock (CS). The Impella® 5.0 LD is the only device that is inserted through an open cardiac procedure into the aorta while the Impella® 5.0 LP is inserted by surgical cut down of the femoral or axillary artery.

A 3.5 l/min Impella® RP (right percutaneous) is implanted through a transvenous femoral approach into the right ventricle to support patients with right ventricular failure (RVF). The Impella® RP transports blood from an inlet in the inferior vena cava (IVC) to an outlet in the pulmonary artery bypassing the right atrium and ventricle and is currently the only device available for percutaneous hemodynamic support of the right heart. Both left and right ventricular pumps may be implanted simultaneously for support during biventricular cardiac failure [1].

2. Hemodynamic effects of Impella® support

Impella® hemodynamic support exhibits effects on intracardiac volumes and pressures as well as on systemic circulation, leading to augmentation of blood flow independent from heart rhythm. However, blood flow is dependent on after and preload.

During systole, the pressure gradient between aorta and LV is at its lowest, accounting for the highest pump flow and motor current. Vice versa, the increased pressure gradient during diastole between LV and aorta leads to diminished motor current and transvalvular blood flow. These periodic changes result in a sinus-like curve of motor current and blood flow on the AIC. This information is integrated and used by the AIC to control the pumps position. Accordingly, decreased preload may therefore result in reduced Impella® output.

Hemodynamic changes in patients on Impella® support are most profound in patients with CS. In CS, a decreased cardiac index leads to volume overload of the left ventricle resulting in a dilating left ventricular chamber accompanied by increased left ventricular end-diastolic pressure (LVEDP). Concomitantly, increased wall tension of the LV causes increased myocardial oxygen consumption. The increased LVEDP may also result in heart failure with lung edema, further decreasing overall oxygen supply. The positive effects of LV unloading by Impella® support are best explained using pressure-volume (PV) loops. Impella® support leads to a left shift of the PV loop resulting in a reduction of LVEDP and a reduction of area under the PV loop curve. This resembles reduced cardiac work, overall consistent with decreased cardiac oxygen consumption.

In a study by Schiller et al., cardiac index improved from 2.1 l/min/m2 to 3.8 l/min/m^2 [2]. Additionally, mixed venous saturation increased from 56 to 68% and diuresis increased from 69 ml/h at device insertion to 105 ml/h on support indicating improved systemic perfusion. Central venous pressure, lactate levels, and inotropic support, all consequently decreased.

Apart from patients in CS, a case study by Arain and O'Meallie demonstrated an increase in coronary artery circulation on Impella® support in a patient undergoing protected PCI. Fractional-flow reserve (FFR) and coronary flow reserve (CFR) were measured in a hemodynamically significant stenotic left anterior descending (LAD) coronary artery using a pressure wire. While FFR remained the same comparing on- and off Impella® support time points, CFR significantly increased. This demonstrates beneficial effects of Impella® support on coronary perfusion during protected PCI.

3. Implantation of an Impella® device

In general, the implantation of an Impella® device is comparatively easy procedure that is performed in a cath lab. However, pitfalls and limitations should be well known and implantation should be performed by an experienced team, including an interventional cardiologist, cath lab assistance, and a nurse.

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Several contraindications that include vascular pathologies reaching from the femoral artery up to the aortic valve as well as aortic valve pathologies must be observed prior to implantation. These include, but are not limited to, severe peripheral artery vessel disease (pAVD) that may increase the likelihood of vascular access complications or may render the implantation of a large sheet and thereof the Impella® impossible, as well as aortic aneurism both abdominal and thoracic. Aortic insufficiency (moderate to severe degree), severe aortic stenosis, pathologies that increase the likelihood of thromboembolic events (valve endocarditis, LV thrombus) or a mechanical aortic valve may present further contraindications. Due to the administration of aPTT-relevant doses of unfractionated heparins in the purge fluid, bleeding risk may be increased. In patients with contraindications to unfractionated heparins, such as heparin-induced thrombocytopenia (HIT), using an alternative anticoagulant through a systemic line is at the discretion of the treating physician. Furthermore, pathologies that decrease right ventricular function may concomitantly decrease left ventricular preload, leading to insufficient Impella® output.

Prior to implantation of the Impella device, we therefore recommend duplex-angiography of the respective arterial vessel considered for vascular access to: (I) measure vessel diameter and (II) exclude relevant pAVD and heavy calcifications. If bedside duplex-angiography is not available, and in case of a femoral approach, vascular access at the contralateral femoral artery and placement of a 6 F sheet may be performed. The status of the ipsilateral femoral artery may be determined via angiography through a 5 F pigtail catheter placed just above the origin of the two iliac arteries. This technique may also help to determine the location of the common femoral artery (CFA) and the best spot for needle introduction. The contralateral sheath may be left in place and later be used for introducing guide catheters and wires for coronary interventions. To exclude relevant pathologies of the aortic valve and to exclude the presence of intraventricular thrombi, echocardiography is recommended to determine whether Impella® support is feasible.

The respective Impella® device is assembled according to the manufacturers' instructions and following the steps laid out on the AIC by the cath lab assistance. For the Impella® 2.5 and CP, the CFA is punctured and a sheath is inserted after dilatation using the provided set. Before insertion of the sheath, we recommend using a pre-close technique to facilitate sheath removal. This technique requires the insertion of two Perclose Proglide® devices prior to placing the sheaths. A needle is used to puncture the CFA and a wire is introduced into the vessel. Two 6 F Perclose Proglide® devices are then introduced. The first device is placed at a 30–45° angle and before complete removal of the first carrier device, the 0.035-inch guide wire is reinserted into the CFA. A second Perclose Proglide® device is then introduced at a 90° angle in relation to the first device and introduced. Following the end of the procedure, the sutures are cinched down after catheter removal to close the arteriotomy. This technique is only feasible in patients undergoing protected PCI, as long indwelling times render the vascular closure set unsterile.

A pigtail catheter is now advanced into the LV, followed by a 0.018-inch wire and the pigtail catheter is removed again over the wire. Under fluoroscopic guidance, the Impella® is now advanced over the wire so that the outlet area rests above the aortic valve (**Figure 3**). After removal of the guide wire, correct position should once again be confirmed using the AIC and fluoroscopy before starting the procedure. During each transfer of the patient, care should be taken to avoid Impella® movement and correct position of the Impella® should be confirmed after the transfer using bedside echocardiography.

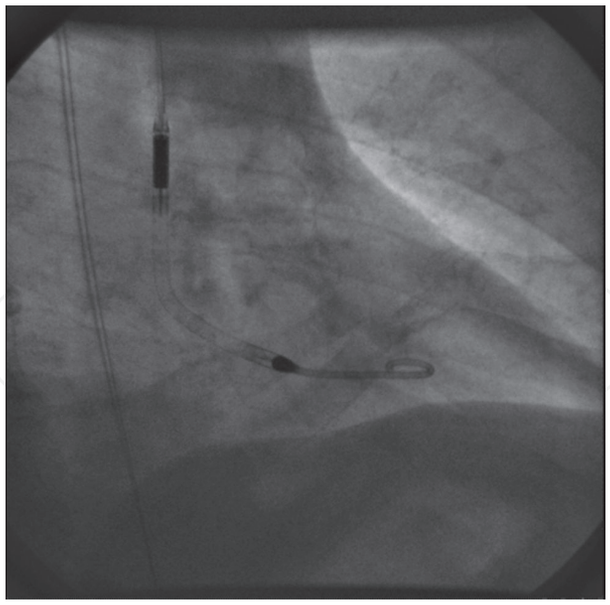

Figure 3. Correct position of the Impella 2.5 in the left ventricle with the outlet portion above the aortic valve demonstrated by fluoroscopy from an RAO (right anterior oblique) angle.

4. Adverse events

Potential adverse events following Impella® implantation or hemodynamic support with Impella® include hemolysis, functional mitral stenosis, pump displacement, malfunction and vascular site complications including bleeding and limb ischemia. Furthermore, thromboembolic events including stroke and myocardial infarction as well as acute kidney dysfunction or failure might occur. Overall incidence rate is low, seems to differ according to the indication for hemodynamic support, and is also most likely related to the duration of Impella® support. Highest rates for adverse events may accordingly be found in patients undergoing Impella® support for CS.

In 120 patients with AMI complicated by CS, The EUROSHOCK trial found major bleeding at the vascular access site in 28.6%, hemolysis in 7.5%, and pericardial tamponade in 1.7% [3]. In another study including 40 patients with end-stage heart failure and implantation of an Impella® 5.0 as bridge to transplant or bridge to left ventricular assist device (LVAD), bleeding requiring transfusion occurred in 28.0%, hemolysis in 8.0%, device malfunction in 10.0%, and limb ischemia in 3.0% [4]. Highest rates of adverse events were generally found for major bleeding at the access site and hemolysis, two complications that may usually be managed successfully while patients may remain on Impella® support.

In patients undergoing protected PCI, the frequency of adverse events is usually lower. The PROTECT trial, designed to examine the efficacy and safety of Impella® 2.5 in protected PCI, found mild, transient hemolysis in 10.0% of patients with no other major adverse events [5]. In a further study including 19 patients undergoing protected PCI, no complications occurred [6].

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Recent case reports have reported mitral valve damage possibly caused by Impella support [7]. Whether this finding warrants specific precautions needs to be further evaluated. We recommend screening for signs and symptoms of acute mitral insufficiency under Impella® support and further echocardiographic examinations on a regular basis.

Davis et al. reported a case in which a patient in CS developed acquired von-Willebrand syndrome (AVWS) under Impella 5.0 support [8]. AVWS develops in situations in which high shear stress leads to excessive proteolysis of von Willebrand factor (VWF) and loss of high molecular weight multimers, in this situation attributed to high-level Impella support. The patient suffered major bleeding under surgery for long-term LVAD and required massive substitution of blood and coagulation products. Larger trials are warranted to further evaluate alterations of VWF and the incidence of AVWS under Impella support.

5. Indications

5.1. Protected PCI

Poor outcome in patients undergoing PCI is associated with depressed left ventricular function, higher complexity of lesions, multi-vessels disease, and poor pre-interventional status [9]. In these patients, even limited episodes of myocardial ischemia caused by intracoronary application of contrast medium, inflation of balloons, implantation of stents, or more sophisticated maneuvers like rotablation may provoke hypotension resulting in a vicious cycle of impaired coronary perfusion, malignant cardiac arrhythmias, and cardiac arrest. The pre-interventional implantation of an Impella® device, referred to as protected PCI, may provide hemodynamic support in case of hemodynamic compromise and augment intracoronary blood flow.

The PROTECT I trial (A Prospective Feasibility trial Investigating the Use of the IMPELLA RECOVER LP 2.5 System in Patients Undergoing High Risk PCI) was the first trial designed to evaluate the safety and feasibility of the Impella® 2.5 system in patients undergoing protected PCI [5]. Including 20 patients in a prospective, multi-center fashion, this study demonstrated that the Impella® 2.5 is safe and easy to implant with only two patients showing signs of mild hemolysis. All patients included had a poor left ventricular function and underwent PCI of an unprotected left main coronary artery or last patent coronary conduit. None of the patients developed hemodynamic compromise during PCI.

The PROTECT II trial represents the second landmark study for protected PCI via Impella® 2.5, comparing the Impella® device with intra-aortic balloon pump (IABP) in a randomized, controlled design [10]. Although the study was terminated early on grounds of futility (the study was underpowered for the primary endpoint of superiority of Impella® 2.5 compared to IABP in terms of MACCE), trends for improved outcomes were observed for Impella® 2.5-supported patients at 90 days.

Besides the mentioned trials, multiple individual experiences with the device and protected PCI, case studies, and case reports have been published [6, 11–16]. In general, the concept has

been described as safe and feasible, resulting in hemodynamic improvement. Data from the USpella registry have further demonstrated the feasibility of protected PCI through Impella® 2.5 in a real-world setting [17].

5.2. Cardiogenic shock

Mortality of patients suffering from acute myocardial infarction (AMI) complicated by CS remains high. Given the potential benefits of pVADs in this specific scenario, short-term circulatory support seems to be a promising therapeutic option. Hypoperfusion caused by cardiogenic shock triggers the so called "shock spiral" by systemic hypoxemia leading to dismal systemic regulatory efforts. The implantation of a pVAD may halt this downward spiral by increasing cardiac output, decreasing LVEDP by unloading of the left ventricle, and therefore reducing oxygen consumption of the myocardium. As appealing as this approach may sound, there is currently no randomized, controlled trial available that may prove the benefit of pVADs in this scenario. The IMPRESS (IMPella versus IABP REduces mortality in STEMI patients treated with primary PCI IN SEVERE and deep cardiogenic SHOCK) trial, a recent controlled, randomized, multi-center study by Ouweneel et al. has found no difference in short-term and 6-month mortality in patients undergoing pVAD support through the Impella® CP in cardiogenic shock compared to Intra-aortic balloon pump (IABP) [18]. Furthermore, a recent meta-analysis from the same authors evaluating the three available randomized trials of Impella® usage in CS patients and comparing it to IABP also revealed no survival benefit at 30 days and 6 months [19].

Interestingly, there seems to be differences in survival in-between men and women. Data from the cVAD registry (catheter-based ventricular assist device registry), a database retrospectively enrolling patients that underwent pVAD support with Impella®, showed that early initiation of hemodynamic support in patients with AMI complicated by CS was associated with a greater survival benefit in women compared to men [20]. These data are encouraging, as women usually suffer higher unadjusted mortality rates and experience the use of guideline-recommended therapies to a lesser extent.

Although the concept of pVADs in CS seems convincing and there is ample data showing improved hemodynamic parameters, there is still no evidence from RCTs that pVADs improve survival in these patients. One issue is certainly identifying patients that might profit from pVAD implantation and selecting the appropriate pVAD. Future trials should therefore focus on identifying the "right" patient and the "right" time for Impella® implantation in CS.

5.3. Right ventricular failure

The Impella® RP received FDA approval in 2015 upon completion of the RECOVER RIGHT (The Use of Impella RP Support System in Patients with Right Heart Failure: A Clinical and Probable Benefit Study) trial, resembling the first percutaneous right ventricular assist device [21]. This prospective, multi-center, single-arm study included 32 patients from 15 institutions

in the USA. Of these patients, 18 were included with right ventricular failure (RVF) after left ventricular assist device (LVAD) implantation and 12 patients presented with RVF after cardiotomy or myocardial infarction. All patients included exhibited life-threatening RVF with three vasopressors/inotrops installed and a mean cardiac index of 1.8 l/min/m^2.

Cardiac index increased to 3.3 l/min/m^2 and central venous pressure decreased from 19.2 to 12.6 mmHg under Impella® RP support. In total, 73.3% of patients survived more than 30 days after an average hemodynamic support of only 3.0 days. RECOVER RIGHT was not designed to compare Impella® RP to standard medical treatment; however, the safety and hemodynamic efficacy of the device were shown. The device is approved for a period of 14 days, warranting more durable solutions in patients that do not recover.

Besides above-mentioned causes of RVF included in the RECOVER RIGHT study, further indications for temporary right ventricular support seem appealing. Hansen et al. presented a case of a patient with sepsis induced RVF on grounds of pulmonary hypertension that initially recovered after Impella® RP implantation [22]. Again, markedly improved hemodynamic parameters were reported after initiation of hemodynamic support.

The Impella® RP therefore may serve as a valuable therapeutic option in patients presenting with life-threatening RVF of a variety of causes and under already applied standard of care. Again, patient selection plays a crucial role for the success of the treatment.

5.4. Impella® as a bridge to decision or bridge to next therapy

A growing number of patients with a severely reduced LV require temporary mechanical support to bridge time to multidisciplinary assessment of best therapeutic strategy or bridge to next therapy. Lima et al. reported their single-center experience with Impella® 5.0 for either bridge to heart transplant or bridge to durable left ventricular assist device in 40 patients [4]. The primary endpoint survival to next therapy was reached in 75.0% of patients. Compared to the predominant bridging strategy employing Extracorporeal membrane oxygenation (ECMO), this reveals a significantly higher likelihood of survival. Furthermore, critical complications are significantly lower in patients undergoing Impella® support compared to ECMO. In summary, Impella® may serve as a valuable therapeutic alternative in patients being bridged to next therapy overcoming some of ECMOs limitations.

6. Future trends

A multitude of case reports has reported potential indications for Impella. For example, Deshpande et al. reported a case of acute embolic myocardial infarction and heart failure in a Fontan patient resolved by Impella support followed by successful transplantation [23]. These descriptions on a case-by-case basis highlight promising future indications for the Impella system. However, clinical data in terms of randomized and controlled trials are missing for all of the mentioned indications. **Table 1** further reported the indications for Impella® support.

Authors	Indication for Impella® implantation	Year
Cena et al. [26]	Non-ischemic cardiomyopathy and cardiogenic shock	2016
Deshpande et al. [23]	Acute myocardial infarction and cardiogenic shock in a Fontan patient	2016
Stottrup et al. [27]	Cardiac arrest	2016
Ancona et al. [28]	Post-infarct ventricular septal rupture	2016
Burzotta et al. [29]	Bail-out use as bridge to TAVI in cardiogenic shock	2016
Desai et al. [30]	Cardiac arrest after neuraxial anesthesia	2015
Rashed et al. [31]	Cardiogenic shock secondary to takotsubo cardiomyopathy	2015
Burns and Quantz [32]	Viral myocarditis	2015
Khaliel et al. [33]	Toxic cardiomyopathy	2014
Miller et al. [34]	Hemodynamic support during VT ablation	2013

Table 1. Emerging indications for Impella® support.

6.1. Combination of ECMO and Impella

Multiple authors have introduced the concept of multi-device approaches in patients with cardiogenic shock [24, 25]. By using different pVADs either simultaneously or in a sequential order, negative effects of one individual device may be balanced by the use of another system.

This concept seems especially efficient for the simultaneous implantation of VA-ECMO and Impella. Pappalardo et al. compared in a recent study 21 patients undergoing VA-ECMO and Impella with 42 propensity-matched patients undergoing VA-ECMO alone for cardiogenic shock [24]. Hospital mortality was significantly lower in patients implanted with both devices (47.0 vs. 80.0%, $P < 0.001$).

The implantation of an Impella® device may address one of the important pitfalls of VA-ECMO, hence explaining the reported improved outcomes. VA-ECMO leads to an increased afterload due to retrograde blood flow impairing unloading of the left ventricle and increasing LVEDP. Overcoming these dismal effects and supporting unloading of the left ventricle by Impella® may therefore prove a valuable concept in the future.

7. Summary

The Impella® platform resembles a pVAD system that augments the repertoire of modern interventional cardiology. The landmark PROTECT II study presented evidence that in patients undergoing protected PCI, hemodynamic support with Impella 2.5 leads to improved outcomes at 3 months when compared to IABP. With the Impella® being easy

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and safe to implant and its overall low rate of adverse events, the system provides interventional cardiologists with a tool for patients at high risk for adverse events during complex PCI procedures.

Adding more powerful (up to 5.0 l/min) and right cardiac support devices to the platform, the range of indications have expanded to cardiogenic shock, right ventricular failure, and a multitude of conditions that result in impaired left ventricular output. Although the principal physiological benefits of left ventricular support of unloading of the left ventricle with Impella® have been examined extensively, there are currently no randomized, controlled trials demonstrating improved survival of patients supported with Impella® in cardiogenic shock. A promising new strategy is combining ECMO with Impella. Further studies should answer the questions of (I) what cohort of patients at (II) what time and stage of cardiogenic shock (III) profit from what respective pVAD.

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References

[1] Aghili N, Bader Y, Vest AR, et al. Biventricular circulatory support using 2 axial flow catheters for cardiogenic shock without the need for surgical vascular access. *Circulation. Cardiovascular Interventions*. 2016;9(6):e003636.

[2] Schiller P, Vikholm P, Hellgren L. The Impella(R) recover mechanical assist device in acute cardiogenic shock: a single-centre experience of 66 patients. *Interactive Cardiovascular and Thoracic Surgery*. 2016;22(4):452-458.

[3] Lauten A, Engstrom AE, Jung C, et al. Percutaneous left-ventricular support with the Impella-2.5-assist device in acute cardiogenic shock: results of the Impella-EUROSHOCK-registry. *Circulation. Heart Failure*. 2013;6(1):23-30.

[4] Lima B, Kale P, Gonzalez-Stawinski GV, Kuiper JJ, Carey S, Hall SA. Effectiveness and safety of the Impella 5.0 as a bridge to cardiac transplantation or durable left ventricular assist device. *The American Journal of Cardiology*. 2016;117(10):1622-1628.

[5] Dixon SR, Henriques JP, Mauri L, et al. A prospective feasibility trial investigating the use of the Impella 2.5 system in patients undergoing high-risk percutaneous coronary

intervention (The PROTECT I Trial): initial U.S. experience. JACC. Cardiovascular interventions. Feb 2009;2(2):91-96

[6] Henriques JP, Remmelink M, Baan J, Jr., et al. Safety and feasibility of elective high-risk percutaneous coronary intervention procedures with left ventricular support of the Impella Recover LP 2.5. *The American Journal of Cardiology*. 2006;97(7):990-992.

[7] Elhussein TA, Hutchison SJ. Acute mitral regurgitation: unforeseen new complication of the Impella LP 5.0 ventricular assist device and review of literature. *Heart, Lung & Circulation*. 2014;23(3):e100-e104.

[8] Davis ME, Haglund NA, Tricarico NM, Keebler ME, Maltais S. Development of acquired von Willebrand syndrome during short-term micro axial pump support: implications for bleeding in a patient bridged to a long-term continuous-flow left ventricular assist device. *ASAIO Journal*. 2014;60(3):355-357.

[9] Peterson ED, Dai D, DeLong ER, et al. Contemporary mortality risk prediction for percutaneous coronary intervention: results from 588,398 procedures in the National Cardiovascular Data Registry. Journal of the American College of Cardiology. May 04 2010;55(18):1923-1932.

[10] O'Neill WW, Kleiman NS, Moses J, et al. A prospective, randomized clinical trial of hemodynamic support with Impella 2.5 versus intra-aortic balloon pump in patients undergoing high-risk percutaneous coronary intervention: the PROTECT II study. Circulation. Oct 02 2012;126(14):1717-1727.

[11] Valgimigli M, Steendijk P, Serruys PW, et al. Use of Impella Recover(R) LP 2.5 left ventricular assist device during high-risk percutaneous coronary interventions; clinical, haemodynamic and biochemical findings. *EuroIntervention: Journal of EuroPCR in Collaboration with the Working Group on Interventional Cardiology of the European Society of Cardiology*. 2006;2(1):91-100.

[12] Dens J, Meyns B, Hilgers RD, et al. First experience with the Impella Recover(R) LP 2.5 micro axial pump in patients with cardiogenic shock or undergoing high-risk revascularisation. *EuroIntervention: Journal of EuroPCR in Collaboration with the Working Group on Interventional Cardiology of the European Society of Cardiology*. 2006;2(1):84-90.

[13] Minden HH, Lehmann H, Meyhofer J, Butter C. Transradial unprotected left main coronary stenting supported by percutaneous Impella Recover LP 2.5 assist device. *Clinical Research in Cardiology: Official Journal of the German Cardiac Society*. 2006;95(5):301-306.

[14] Cohen R, Domniez T, Elhadad S. High-risk left main coronary stenting supported by percutaneous Impella Recover LP 2.5 assist device. *The Journal of Invasive Cardiology*. 2007;19(10):E294-E296.

[15] Hatch J, Baklanov D. Percutaneous hemodynamic support in PCI. *Current Treatment Options in Cardiovascular Medicine*. 2014;16(4):293.

[16] Spiro J, Venugopal V, Raja Y, Ludman PF, Townend JN, Doshi SN. Feasibility and efficacy of the 2.5 L and 3.8 L Impella percutaneous left ventricular support device during high-risk, percutaneous coronary intervention in patients with severe aortic stenosis. *Catheterization and Cardiovascular Interventions: Official Journal of the Society for Cardiac Angiography & Interventions*. 2015;85(6):981-989.

[17] Maini B, Naidu SS, Mulukutla S, et al. Real-world use of the Impella 2.5 circulatory support system in complex high-risk percutaneous coronary intervention: the USpella Registry. *Catheterization and Cardiovascular Interventions: Official Journal of the Society for Cardiac Angiography & Interventions*. 2012;80(5):717-725.

[18] Ouweneel DM, Eriksen E, Sjauw KD, et al. Impella CP versus intra-aortic balloon pump in acute myocardial infarction complicated by cardiogenic shock: the IMPRESS trial. *Journal of the American College of Cardiology*. 2017 Jan 24;69(3):278-287.

[19] Ouweneel DM, Eriksen E, Seyfarth M, Henriques JP. Impella versus intra-aortic balloon pump for treatment of cardiogenic shock: a meta-analysis of randomized controlled trials. *Journal of the American College of Cardiology*. 2017 Jan 24;69(3):358-360.

[20] Joseph SM, Brisco MA, Colvin M, et al. Women with cardiogenic shock derive greater benefit from early mechanical circulatory support: an update from the cVAD registry. *Journal of Interventional Cardiology*. 2016;29(3):248-256.

[21] Anderson MB, Goldstein J, Milano C, et al. Benefits of a novel percutaneous ventricular assist device for right heart failure: the prospective RECOVER RIGHT study of the Impella RP device. *The Journal of Heart and Lung Transplantation: The Official Publication of the International Society for Heart Transplantation*. 2015;34(12):1549-1560.

[22] Hansen LN, Berg H, Schmidt H, et al. Percutaneous right ventricular assist device in sepsis due to right ventricular failure and pulmonary hypertension. *Acta Anaesthesiologica Scandinavica*. 2016;60(10):1470-1472.

[23] Deshpande SR, Dalal A, Kim DW, Babaliaros V, Jokhadar M. Acute embolic myocardial infarction and heart failure in a fontan patient: recovery with Impella device and successful transplantation. *ASAIO Journal*. 2016;62(6):e52-e54.

[24] Pappalardo F, Schulte C, Pieri M, et al. Concomitant implantation of Impella(R) on top of veno-arterial extracorporeal membrane oxygenation may improve survival of patients with cardiogenic shock. *European Journal of Heart Failure*. 2017 Mar;19(3):404-412.

[25] Pieri M, Contri R, Winterton D, et al. The contemporary role of Impella in a comprehensive mechanical circulatory support program: a single institutional experience. *BMC Cardiovascular Disorders*. 2015;15:126.

[26] Cena M, Karam F, Ramineni R, Khalife W, Barbagelata A. New Impella cardiac power device used in patient with cardiogenic shock due to nonischemic cardiomyopathy. *The International Journal of Angiology: Official Publication of the International College of Angiology, Inc*. 2016;25(4):258-262.

[27] Stottrup NB, Jakobsen L, Krusell LR, Terkelsen CJ. Utility of Impella(R) left ventricular assist device during cardiac arrest: a case report. *International Journal of Cardiology*. 2016;225:111-112.

[28] Ancona MB, Regazzoli D, Mangieri A, Monaco F, De Bonis M, Latib A. Post-infarct ventricular septal rupture: early Impella implantation to delay surgery and reduce surgical risk. *Cardiovascular Intervention and Therapeutics*. 2016 Sep 7. [Epub ahead of print].

[29] Burzotta F, Nerla R, Trani C. Bail-out use of Impella CP as a bridge to TAVI in a cardiogenic shock patient: the "pump-rewiring" technique. *The Journal of Invasive Cardiology*. 2016;28(1):E1-E5.

[30] Desai N, Chaudhry K, Aji J. Impella left ventricular assist device in cardiac arrest after spinal anaesthesia for caesarean section. *BMJ Case Reports*. Oct 28;2015.

[31] Rashed A, Won S, Saad M, Schreiber T. Use of the Impella 2.5 left ventricular assist device in a patient with cardiogenic shock secondary to takotsubo cardiomyopathy. *BMJ Case Reports*. May 7;2015.

[32] Burns DJ, Quantz MA. Use of the Impella 5.0 device as a bridge to recovery in adult fulminant viral myocarditis. *Innovations*. 2015;10(4):279-281.

[33] Khaliel F, Moss E, Demers P, Bouchard D. A bailout approach: transaxillary Impella implantation in toxic cardiomyopathy. *Asian Cardiovascular & Thoracic Annals*. 2014;22(6): 722-724.

[34] Miller MA, Dukkipati SR, Chinitz JS, et al. Percutaneous hemodynamic support with Impella 2.5 during scar-related ventricular tachycardia ablation (PERMIT 1). *Circulation. Arrhythmia and Electrophysiology*. Feb 2013;6(1):151-159.