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Research article

AngioVac Procedures: Integration of cardiac surgeon and anesthesiologist-led transesophageal echocardiography: A preliminary report

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A R T I C L E I N F O

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A B S T R A C T

Introduction: The AngioVac system is a novel, minimally invasive, endovascular technique used to evacuate intravascular or intracardiac vegetation or thrombus. Although most AngioVac procedures are currently performed by interventionalists, this innovative procedure has been gaining attention among the surgical and anesthesia communities.

Methods: We retrospectively reviewed all patients who underwent the AngioVac procedure performed by a cardiac surgeon between August 2019 and December 2022. Fellowship-trained cardiac anesthesiologists operated TEE to navigate the AngioVac cannula during the procedure. The stored TEE images were retrospectively reviewed and independently analyzed by two cardiac anesthesiologists with specific focus on TEE-guided navigation of the AngioVac cannula towards the aspiration target.

Results: Eleven patients underwent the AngioVac procedure during the study period. In nine cases, the majority of the vegetation or thrombus was successfully aspirated. In two cases, incomplete aspiration was attributed to the mass burden being too large, firm, and chronic in etiology. Worsening tricuspid regurgitation (TR) was identified in three of the 11 cases. Intraoperative TEE provided the cardiac surgeon with simultaneous display of the AngioVac cannula shaft, its tip, and aspiration target, as well as real-time assessment of TR, facilitating the minute movements essential for successful outcomes.

Conclusions: This study details our experience and the effectiveness of the AngioVac system for treating soft, intracardiac vegetation or thrombus in a minimally invasive manner. Experienced cardiac anesthesiologists have the skillsets and knowledge to provide optimal live TEE imaging necessary for successful maneuvering of the AngioVac cannula.

1. Introduction

The AngioVac system (Angiodynamics, Latham, NY) is a relatively new innovation approved by the Food and Drug Administration in 2014 for removing soft thrombi or emboli from target vessels, including the iliofemoral vein, inferior vena cava, and superior vena

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cava, using a large-diameter aspiration cannula under veno-venous extracorporeal circulatory support (Fig. 1, Supplemental Video Clip 1). Its use has since been further extended to evacuate intracardiac vegetation or thrombus. This minimally invasive percutaneous approach may be a suitable option for patients with intravenous drug use (IVDU) and drug dependency because such patients are susceptible to reinfection where late mortality (more than 6 months) after open-heart valve repair surgery is high (nearly 18 %–25 %), due to recidivism, despite excellent short-term surgical outcomes [1]. In addition, undergoing open-heart surgery may prevent these patients from being eligible for immediate enrollment in drug rehabilitation programs due to their post-surgical opioid requirement. In contrast, the AngioVac possesses multiple qualities that circumvent many of these concerns. Because of its low perioperative risk [2], short recovery time [3], and because it preserves the opportunity to obtain immediate referral to drug rehabilitation upon discharge, this approach may be optimal for patients with IVDU-related infective endocarditis that is resistant to appropriate antibiotic treatment.

There are a growing number of case reports which detail the success and considerations for treating various conditions with the AngioVac; nonetheless, few consider the experience of cardiac surgeons as the primary proceduralist nor anesthesiologists as the provider responsible for using intraoperative transesophageal echocardiography (TEE). According to the Registry of AngioVac Procedures in Detail (RAPID), a database of patients with right heart thrombi undergoing the AngioVac procedure, interventional cardiologists were the primary proceduralist in 25.5 % of AngioVac cases and interventional radiologists in 46.8 % of cases, whereas cardiothoracic surgeons were the primary proceduralist in only 4.3 % of cases [4]. As this endovascular technique gains traction, data from diverse proceduralists with different perspectives will optimize the utility of this novel procedure for a variety of patients.

A cardiac surgeon at our academic center began using the AngioVac system in 2019. As this procedure performed by the cardiac surgeon is a new service offered to our patient population, we investigated our initial experience with the AngioVac system regarding its utility and efficacy in treating various diseases. Notably, we developed significant experience in optimizing TEE visualization for intraprocedural guidance. In this study, we report an in-depth analysis of the cardiac anesthesiologist-led intraoperative TEE, which was vital in providing real-time assessment of catheter guidance and AngioVac cannula positioning.

2. Materials and methods

We conducted a retrospective review for all AngioVac procedures performed in the operating room (OR) at our academic institution between August 2019 and December 2022. This study was approved by The University of Iowa Institutional Review Board (#201911151). All procedures were performed by the same cardiac surgeon (AKS) and intraoperatively managed by experienced fellowship-trained cardiac anesthesiologists who were diplomates of advanced perioperative TEE certified by the NBE. All AngioVac procedures were performed under general anesthesia with invasive blood pressure monitoring via an arterial line. All patients were endotracheally intubated by the cardiac anesthesia team in the OR prior to the AngioVac procedure. Prior to the start of the procedure,

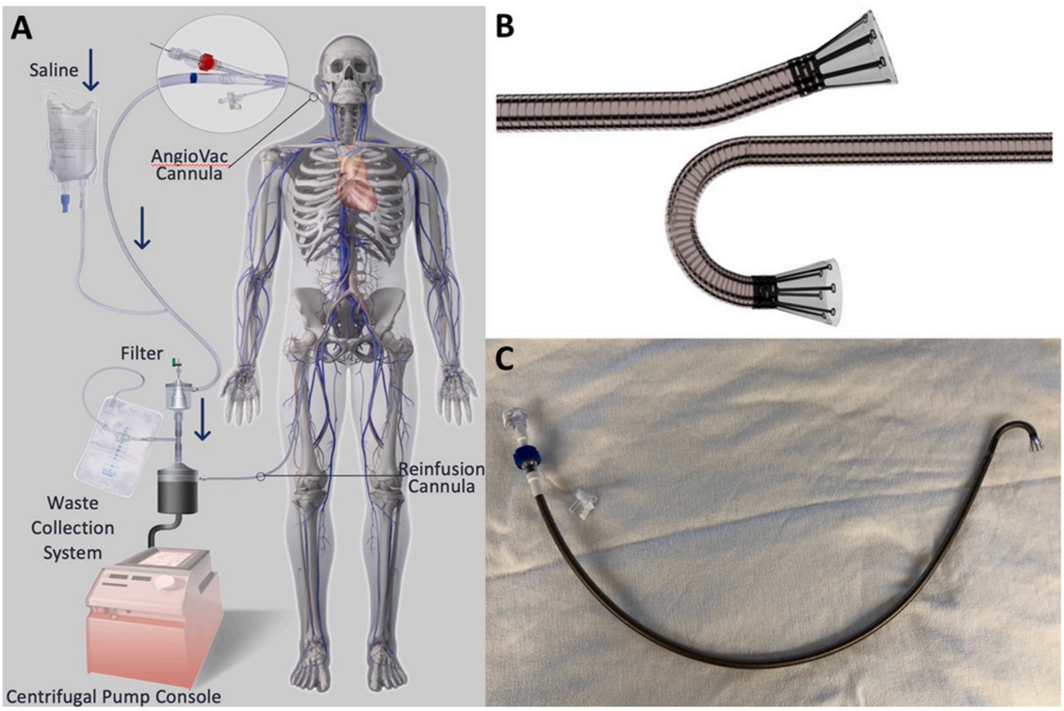

Fig. 1. A AngioVac veno-venous bypass circuit including the pump, in-line filter, and AngioVac cannula. Image courtesy of AngioDynamics, Inc. and its affiliates. Used with permission. **B** Tip of the AngioVac cannula designed to capture the thrombus or vegetation. Image courtesy of AngioDynamics, Inc. and its affiliates. Used with permission. **C** AngioVac cannula.

a central venous catheter was placed in the left internal jugular vein (IJV), preserving the right IJV for the procedure. Aspiration and return cannula access sites, which were any combination of the right IJV and the common femoral vein, were obtained by the surgical team. During the cannulations, fluoroscopy and TEE were used to confirm guidewire placement. Under fluoroscopic guidance, puncture sites were serially dilated to accommodate a 15–17 French cannula (16 French cannula most common) in the return cannula access site and a 24 or 26 French Gore DrySeal Introducer Sheath (26 French sheath most common) in the aspiration cannula access site. After establishing these vascular accesses, the AngioVac cannula (Fig. 1B and C, Supplemental Video Clip 1) was inserted via the introducer sheath (Fig. 2A) and guided towards the right atrium (RA) under live fluoroscopy. Heparin was administered in all cases to obtain an activated clotting time of at least 250 before initiating veno-venous extracorporeal circulatory support (Figs. 1A and 2B). All cardiac anesthesiologist assigned to the cases were diplomates of advanced perioperative TEE certified by the National Board of Echocardiography (NBE) and utilized TEE to guide the AngioVac procedure by providing real-time images.

The data presented in this study was collected from our electronic medical record system (Epic systems software). The case details of each patient were thoroughly reviewed, including the following: patient demographics, patient history, diagnosis, symptoms, indications for surgery, procedure details, type of anesthesia, airway management, intraoperative fluid therapy, intraoperative blood loss and transfusions, hemodynamic support, and perioperative outcomes, including length of stay in the intensive care unit (ICU) and hospital. Additionally, the stored TEE images, which were intraoperatively recorded by the assigned anesthesiologist in each case, were independently reviewed and analyzed by two cardiac anesthesiologists (SS and SH) at our institution who are diplomates of advanced perioperative TEE (National Board of Echocardiography, NBE) as well as Fellows of the American Society of Echocardiography. Their analysis focused on understanding how intraoperative TEE was used to navigate the tip of the AngioVac cannula to the aspiration target and produce successful outcomes.

3. Results

Eleven patients (seven male, four female) who underwent the AngioVac procedure between August 2019 and December 2022 were identified. Table 1 provides a summary of each of the 11 cases, including patient demographics, symptoms, surgical indications, success of target aspiration, and outcomes. Prior to the procedure, nine of the 11 AngioVac case patients were admitted to the hospital medical ward for treatment and optimization of medical conditions while two were admitted to the cardiovascular intensive care unit (CVICU) for stabilization.

All AngioVac procedures were performed either in a hybrid OR in the OR with C-arm fluoroscopy. After establishing the vascular accesses (Fig. 2A and B), the AngioVac aspiration cannula was inserted via the introducer sheath and guided towards the RA under live fluoroscopy. Subsequently, the cannula was navigated towards the aspiration target under anesthesiologist-led TEE (Fig. 2C). Nine of the 11 cases were of infectious etiology and two were of non-infectious etiology. Of the nine infectious cases, six were cases of tricuspid valve (TV) vegetations with pulmonary septic emboli secondary to IVDU (Case #3, 5, 6, 8, 9, 11 in Table 1); one was a case of right ventricular (RV) vegetation from the TV to the proximal main pulmonary artery (PA) secondary to chemotherapy and stem cell transplant for acute lymphoblastic leukemia (Case #1 in Table 1); one was a case of RA thrombus and plasmapheresis port vegetations

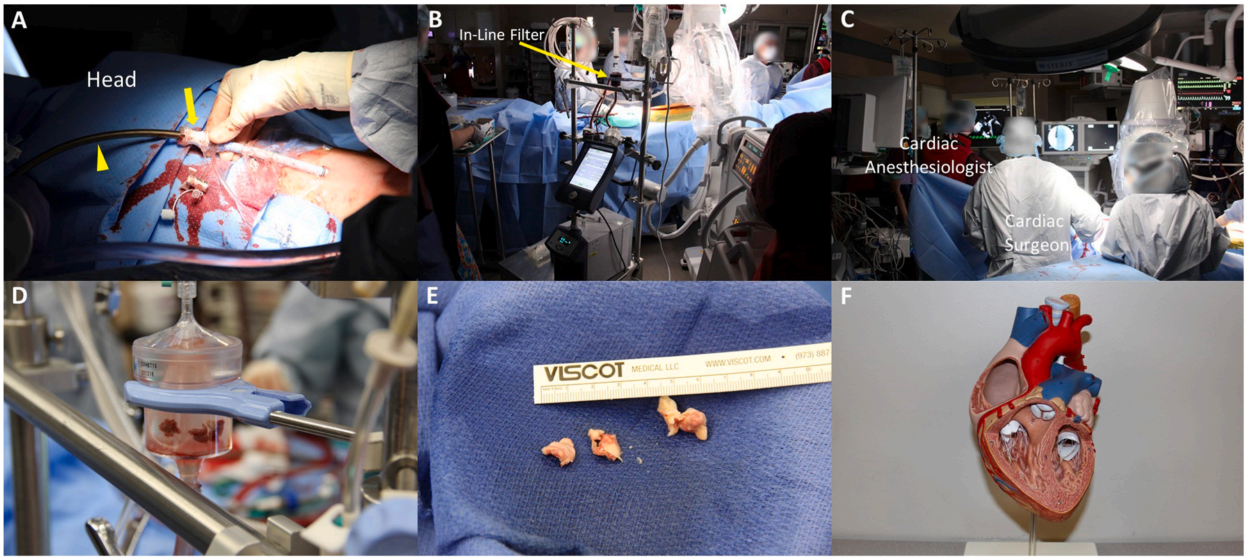

Fig. 2. A The AngioVac cannula (arrowhead) in the Gore DrySeal introducer sheath (arrow) that is in the right IJV. **B** The AngioVac system setup with the veno-venous extracorporeal circuit machine. **C** The cardiac surgeon manipulating the AngioVac cannula under TEE guidance provided by the cardiac anesthesiologist. **D** Vegetation is collected in an in-line filter. **E** Vegetative growth removed from the in-line filter. **F** An anatomical heart model in the OR helped with communication between the cardiac surgeon and anesthesiologist while reviewing TEE images during AngioVac cannula manipulation. *IJV* internal jugular vein, *OR* operating room, *TEE* transesophageal echocardiography.

Table 1
Patient demographics, indications, diagnosis, and outcomes.

Case #	Age	Symptoms	Indication/Diagnosis	Success of Target Aspiration/Outcomes
1	30s	Failure to thrive, fatigue, weakness, nausea	History of acute lymphoblastic leukemia s/p chemotherapy and stem cell transplant complicated by disseminated fungal infection. 6.1 × 2.0 cm RV fungal mass extending from the TV to the proximal main PA.	Patient went in and out of ventricular tachycardia during the total of 4 aspiration attempts. Only a portion of the mass was removed. Patient died POD 3 due to a large PE in the left main PA.
2	30s	SOB, fever	History of myasthenia gravis on chronic plasmapheresis complicated by *S. epidermidis* bacteremia with thrombi/vegetations in the RA (3.28 × 1.75 cm, 2.18 × 1.48 cm) on the tip of the right IJ catheter, and multiple bilateral lower lobe PE.	Small residual thrombus seen on the TV that was thought to be chronic. Right IJ catheter was removed. Discharged home on a 3–4-week course of vancomycin.
3	30s	General malaise, chest heaviness, pleuritic chest pain, SOB, knee pain	IVDU with MRSA septic arthritis and bacteremia. Bacterial endocarditis with 2.3 × 1.9 cm multilobulated mass on the anterior leaflet of the TV and pulmonary septic emboli.	Initial approach via right common femoral vein did not allow significant debulking. Alternate approach with access via the right IJV produced a straighter angle and allowed a greater degree of debulking. 2 U pRBC given post-operatively in the ICU for Hb < 7 g/dL. Discharged home on a 6-week course of daptomycin.
4	70s	Generalized weakness, abdominal pain, fatigue, diarrhea, mental status change	History of CAD s/p CABG and stenting, complete heart block, and ischemic cardiomyopathy s/p ICD placement now with MRSA bacteremia refractory to antibiotic treatment. 2.0 cm RA thrombus/vegetation on a pacemaker lead, PE, and extensive thrombosis of the right lower extremity deep veins.	Small residual RA thrombus less than 0.5 cm with pacemaker lead removal and temporary pacemaker placement. 1 U pRBC administered in the ICU post-operatively. Discharged to a SNF with chronic suppressive tedizolid.
5	20s	Fever, chills, sweats, cough, SOB, abdominal pain	IVDU with MRSA bacteremia and highly mobile TV vegetation, measuring 2.7 × 2.2 cm, refractory to antibiotics and complicated by bilateral pulmonary septic emboli. Therapeutic bronchoscopy was performed to aspirate the purulence in the bilateral tracheobronchial tree.	Major burden of the TV vegetation was debulked. Discharged to a local hospital on a 6-week course of daptomycin and ceftaroline.
6	30s	Fever, palpitations, syncope, night sweats, weight loss, weakness	IVDU with MSSA and septic embolism with mobile vegetation 1.3 × 1.2 cm on the TV. Infection complicated by bilateral septic PE. Symptoms refractory to antibiotic treatment.	Significant reduction in the TV vegetation size. Symptoms resolved following procedure. Discharged to a local hospital for continued antibiotic treatment with IV cefazolin.
7	40s	SOB	RA thrombus (0.5 × 2.6 × 5.0 cm) in the free RA wall and pushing into the TV with trace TR. Thrombus of unknown etiology.	Thrombus significantly reduced in size, with trace echodensity remaining. Discharged home without antibiotics.
8	30s	Fever, chills, sweats	IVDU with MRSA bacteremia and TV vegetation (1.9 × 1.5 cm) on the anterior leaflet complicated by septic emboli in bilateral lungs and small perforation in the septal TV leaflet, refractory to antibiotic treatment.	Major burden of the TV vegetation was debulked with no residual vegetation noted. Discharged to a local hospital to complete a 6-week course of vancomycin.
9	30s	Fever, chest pain, septic shock, encephalopathy, SOB, syncope, hemoptysis	IVDU with MRSA TV infective endocarditis refractory to antibiotic treatment. Vegetations on the posterior TV leaflet measuring 1.1 × 1.4 cm. Infection complicated by septic emboli to bilateral lungs with cavitary lesions.	After multiple attempts to capture the mobile mass on the TV, no residual vegetation was seen after the procedure. Discharged to a local hospital for continued antibiotic treatment with IV ceftaroline and daptomycin.
10	20s	Abdominal pain, nausea	New diagnosis of Budd-Chiari Syndrome with chronic non-occlusive thrombus involving the hepatic veins and extending into the IVC, RA, and iliac veins. Thrombus refractory to catheter directed IR fibrinolysis and therapeutic warfarin. Mobile RA mass measuring 2.8 × 1.1 cm.	Mass in the RA was evacuated and no longer visible on TEE after the procedure. IVC clot burden was reduced by 25 %, with complete resolution at the RA-IVC junction. CTA showed bilateral segmental/subsegmental PE, prompting restart of warfarin. Discharged home to complete his antibiotic course of vancomycin, cefepime, and metronidazole.
11	20s	Headache, fever, chills, fatigue, chest pain, near syncope, SOB	IVDU with MSSA bacteremia, pulmonary septic emboli, and TV infective endocarditis. Symptoms refractory to antibiotic treatment. TV vegetation measuring 2.0 × 1.7 cm and severe TR.	The majority of the vegetation was aspirated, with the residual vegetation measuring at less than 0.5 cm. Discharged to a local hospital for continued antibiotic treatment with IV cefazolin.

CABG coronary artery bypass graft, *CAD* coronary artery disease, *CTA* computed tomography angiography, *F* female, *Hb* hemoglobin, *ICD* implantable cardioverter-defibrillator, *ICU* intensive care unit, *IJ* internal jugular, *IJV* internal jugular vein, *IR* interventional radiology, *IV* intravenous, *IVC* inferior vena cava, *IVDU* intravenous drug use/user, *M* male, *MRSA* methicillin-resistant *Staphylococcus aureus*, *MSSA* methicillin-sensitive *Staphylococcus aureus*, *PA* pulmonary artery, *PE* pulmonary emboli/embolism, *POD* post-operative day, *pRBC* packed red blood cells, *RA* right atrium, *RV* right ventricular, *S. epidermidis* Staphylococcus epidermidis, *SNF* skilled nursing facility, *SOB* shortness of breath, *s/p* status-post, *TEE* transesophageal echocardiography/echocardiogram, *TR* tricuspid regurgitation, *TV* tricuspid valve, *U* units.

(Case #2 in Table 1); and one was a case of vegetation on the pacemaker leads and RA thrombus secondary to right third finger abscess (Case #4 in Table 1). Of the two non-infectious cases, one was a case of large thrombus involving the hepatic veins, inferior vena cava (IVC), RA, and iliac veins secondary to Budd-Chiari syndrome (Case #10 in Table 1), and one was a case of RA thrombus of unknown etiology (Case #7 in Table 1). In nine of the 11 cases, most of the vegetation or thrombus was successfully aspirated (Fig. 3A and B). In one of the remaining two cases (Case #1 in Table 1), only a small portion of the right ventricular (RV) vegetative mass was evacuated, and the patient later died on postoperative day (POD) 3 due to a large pulmonary embolism (PE). In the other case (Case #10 in Table 1), while the RA thrombus was successfully evacuated, only approximately 25 % of the IVC thrombus was removed.

Intraoperative TEE findings for each case, as well as TEE views used for guidance in the AngioVac procedures, are summarized in Tables 2 and 3. The aspiration target was in the right heart chambers in all 11 cases, including the RA and/or RV, with or without IVC involvement. The most common TEE views used to visualize and evaluate the targets' structure, size, and location were the mid-esophageal four-chamber view with focus on the right heart chambers (Fig. 3A, B, C, D), bicaval view (Fig. 3E), modified bicaval view with focus on the TV (Fig. 3F), RV inflow-outflow view (Fig. 4A, B, C), short-axis view of the ascending aorta (Fig. 4D), trans-gastric RV inflow view (Fig. 4E), short-axis view of the TV (Fig. 4F), and long-axis view of the IVC (Fig. 5A). Live three-dimensional (3D) images were captured and recorded (Fig. 5B and C) to evaluate the aspiration target in seven of the 11 cases; however, they were not utilized during the catheter interrogation. The aspiration target was confined either entirely within the RA or in the vicinity of the TV apparatus in nine cases (Cases #2–9, 11 in Table 1), where either the four-chamber view with focus on the right heart chambers or the modified bicaval view with focus on the TV was the TEE approach predominantly used for real-time assessment of catheter interrogation. These views simultaneously provided images of both the passage of the AngioVac cannula shaft and the fine movements of the tip relative to the aspiration target (Fig. 5D, E, F, Supplemental Video Clip 2), assisting precise cannula manipulation. These views also allowed real-time assessment of the degree of tricuspid regurgitation (TR) during and immediately after evacuation of thrombus or vegetation from the tricuspid apparatus (Fig. 6A, Supplemental Video Clip 3). For Case #1 in Table 1, the RV inflow-outflow view (Fig. 6B) was predominantly used for the catheter interrogation where the RV vegetation extended from the TV to the proximal main PA. The short-axis view of the ascending aorta also helped with evaluating the evacuation of the thrombus from the main PA (Fig. 4D). For Case #10 in Table 1, the thrombus extended from the IVC to the RA, where the portion of the thrombus in the RA was successfully evacuated utilizing both the four-chamber view with focus on the right heart chambers (Fig. 3D) and the RV inflow-outflow view (Fig. 4C). The long-axis view of the IVC helped to delineate the extent of the thrombus within the IVC (Fig. 5A) and provided a post-procedural assessment of the residual thrombus.

Table 4 details the intraoperative fluids, blood loss, blood product requirements, vasoactive drug requirements, procedure time, and extubation details. There were no significant bleeding complications, except for one case with approximately 500 ml of blood loss. At least one unit of packed red blood cells was intraoperatively transfused in four of the 11 cases. Eight patients were extubated in the OR at the end of the procedure; one patient with an existing tracheostomy tube was disconnected from the ventilator in the OR and transported to the CVICU with a tracheostomy mask set at 35 % of inspired oxygen; two patients were extubated in the CVICU on POD 1. After the AngioVac procedure, all patients were transferred to the CVICU for further monitoring.

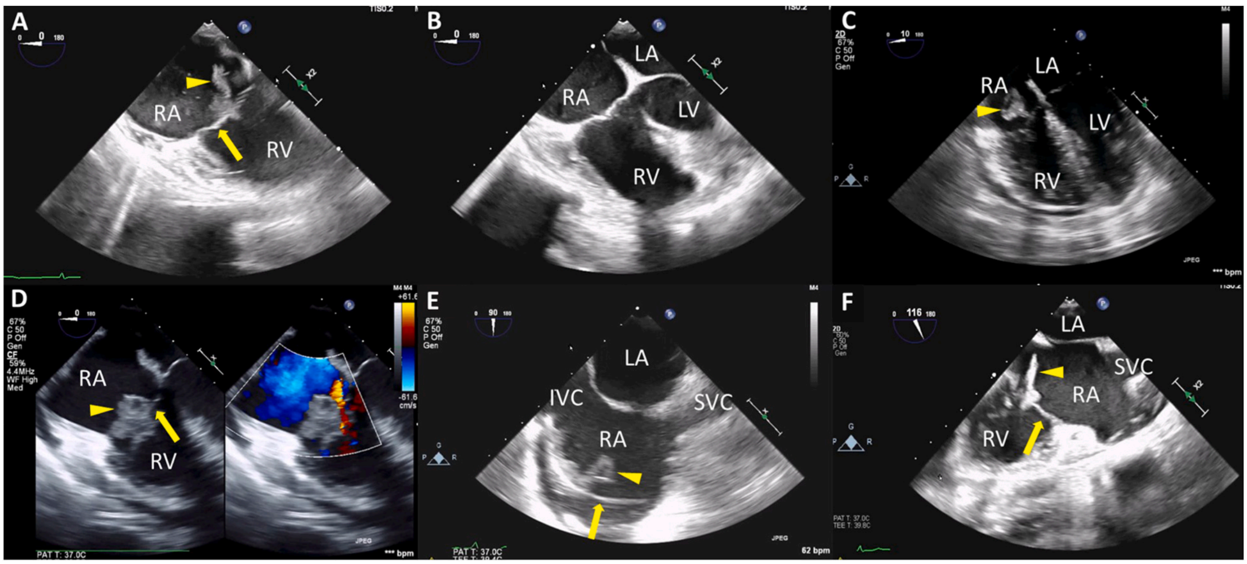

Fig. 3. A, B, C Mid-esophageal four-chamber views with focus on the right heart chambers. **A** Vegetation (arrowhead) on the TV (arrow) is **B** successfully evacuated using the AngioVac. No residual vegetation is seen. **C** Thrombus (arrowhead) extends into the RA. **D** Mass (arrowhead) is seen on the TV (arrow) with TR. **E** Bicaval view with a vegetation (arrowhead) in the RA attached to a pacemaker lead (arrow). **F** Modified bicaval view with focus on the TV shows a vegetation (arrowhead) on the TV (arrow). *IVC* inferior vena cava, *LA* left atrium, *LV* left ventricle, *RA* right atrium, *RV* right ventricle, *SVC* superior vena cava, *TV* tricuspid valve, *TR* tricuspid regurgitation.

Table 2
Intraoperative TEE findings.

Case #	Age	LV/RV systolic function		TR severity		Vegetation/thrombus		Other findings
		Pre-AngioVac	Post-AngioVac	Pre-AngioVac	Post-AngioVac	Pre-AngioVac	Post-AngioVac	
1	30s	Normal	Unchanged	Moderate	Unchanged	Large mass extending from the RA through the TV, into the RV, and terminating in the PA	The mass appears grossly unchanged in size or mobility	Mild to moderate pericardial effusion
2	30s	LV: Normal RV: Mildly decreased	Unchanged	Mild to moderate	Severe	A mobile echodensity in the RA originates at the tip of the right IJ catheter, extending down to the TV	Small mobile echodensity remains on the TV	
3	30s	Normal	Unchanged	Mild to moderate	Unchanged	Mobile echodensity on the TV (2.0 × 1.9 cm)	Small mobile echodensity remains on the TV	
4	70s	LV: Mildly decreased RV: Mild to moderately decreased	Unchanged	Trace to mild	Unchanged	Mobile echodensity attached to a pacemaker lead within the RA with greatest dimension measuring 2.2 cm	A small residual thrombus (less than 0.5 cm) in the RA adjacent to the IVC	Biatrial enlargement Enlarged RV size Mild to moderate AS PFO with left to right shunt
5	20s	Normal	Unchanged	Moderate	Severe	A large, highly mobile echodensity (2.3 × 1.4 cm) on the TV	A small residual of mobile echodensity remains	Enlarged RA and RV
6	30s	Normal	Unchanged	Mild to moderate	Severe	A large, mobile echodensity (1.3 × 1.2 cm) on the TV	A small residual of mobile echodensity remains	Mildly enlarged RV
7	40s	Normal	Unchanged	Trace	Unchanged	Highly mobile, linear echodensity (0.5 cm wide and 2.6–5 cm in length) in the RA adherent to the atrial wall, near the IVC-RA junction	A small residual of mobile echodensity remains	PFO with left to right shunt
8	30s	Normal	Unchanged	Moderate	Unchanged	Vegetation (approximately 2.0 × 1.0 cm) is attached to the septal leaflet of the TV	No residual vegetation	
9	30s	Normal	Unchanged	Moderate to severe	Unchanged	Vegetation (1.5 × 5.0 cm) attached to the posterior leaflet of the TV	No residual vegetation on the TV	
10	20s	LV: Mildly decreased RV: Normal	Unchanged	Mild	Unchanged	A mobile mass (2.8 × 1.1 cm) in the RA, extending from RA-IVC junction into the IVC The majority of the IVC lumen is occupied by the echogenic mass	No residual mass in the RA The IVC clot burden is reduced by approximately 25 %	Large left pleural effusion Ascites
11	20s	Normal	Unchanged	Severe	Unchanged	Vegetation (2.17 × 1.9 cm) on the TV	The size of the vegetation is significantly reduced	Enlarged RA

TEE transesophageal echocardiography, *AS* aortic stenosis, *EF* ejection fraction, *F* female, *IJ* internal jugular, *IVC* inferior vena cava, *LV* left ventricle, *LVEF* left ventricular ejection fraction, *M* male, *MR* mitral regurgitation, *PA* pulmonary artery, *PFO* patent foramen ovale, *RA* right atrium, *RV* right ventricle, *TR* tricuspid regurgitation, *TV* tricuspid valve.

Table 3
TEE views used for identification and guidance of right-sided lesions in AngioVac procedures.

Position of vegetation/thrombus	TEE views
RA, TV	Mid-esophageal four-chamber with focus on right heart chambers Modified bicaval view with focus on TV
RV	RV inflow-outflow view Transgastric RV inflow view
RV, extending to PA	RV inflow-outflow view Short-axis view of ascending aorta
IVC, extending to RA	Long-axis view of IVC Mid-esophageal four-chamber view with focus on right heart chambers
Hepatic veins, IVC	RV inflow-outflow view Long-axis view of IVC

TEE transesophageal echocardiography, *RA* right atrium, *TV* tricuspid valve, *RV* right ventricle, *PA* pulmonary artery, *IVC* inferior vena cava.

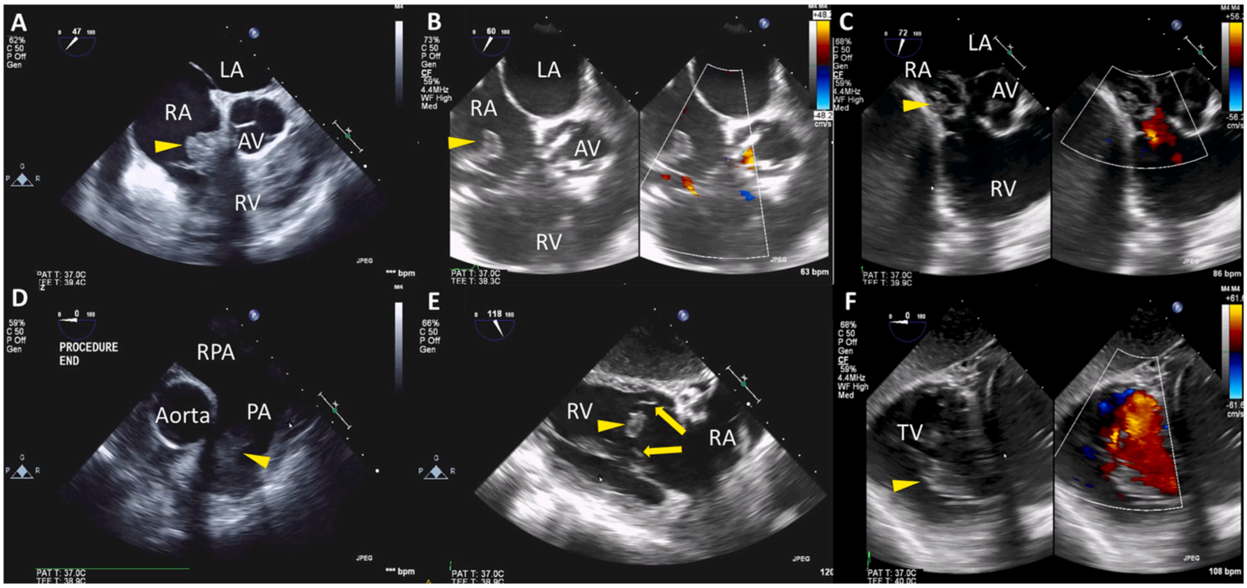

Fig. 4. A, B, C RV inflow-outflow views. **A** Vegetation (arrowhead) extends from the TV to the proximal main PA. **B, C** Vegetation (arrowhead) in the RA. **D** Short-axis view of the ascending aorta shows a thrombus (arrowhead) in the main PA. **E** Transgastric RV inflow view with a vegetation (arrowhead) on the TV (arrows). **F** Short-axis view of the TV shows a vegetation (arrowhead) on the TV. *AV* aortic valve, *LA* left atrium, *PA* pulmonary artery, *RA* right atrium, *RPA* right pulmonary artery, *RV* right ventricular, *TV* tricuspid valve.

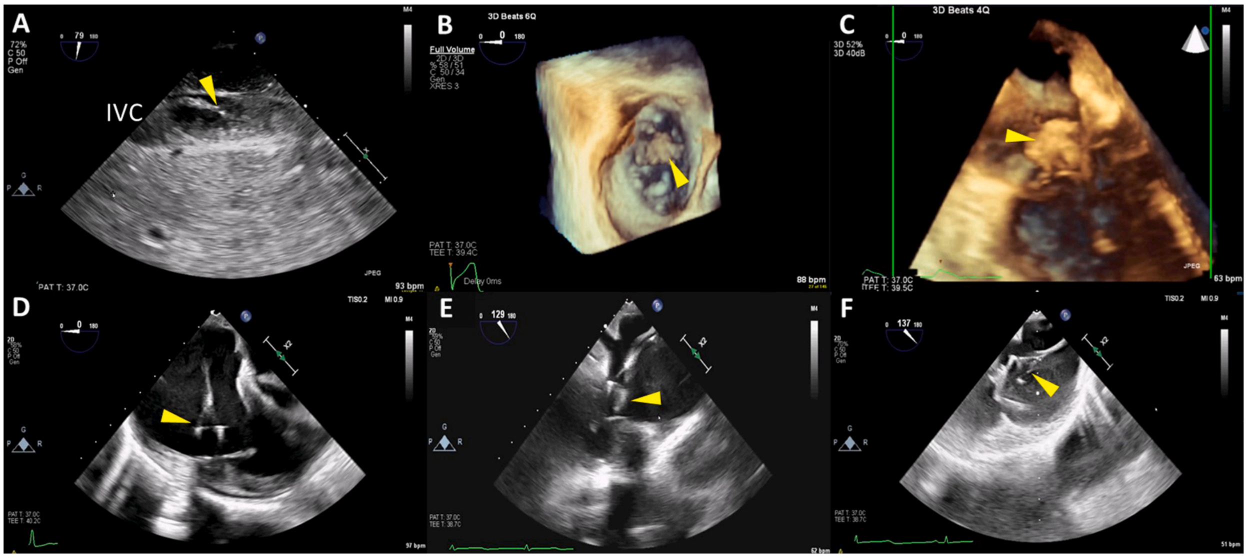

Fig. 5. A Long-axis view of the IVC shows a thrombus (arrowhead) in the IVC. **B, C** 3D images of the TV and vegetation (arrowhead). **D** Four-chamber view with focus on the right heart chambers shows the AngioVac cannula tip (arrowhead) approximating the aspiration target. **E, F** Modified bicaval view shows the AngioVac cannula tip (arrowhead) approximating the aspiration target. **D, E, F** In all views, simultaneous visualization of both the AngioVac cannula tip and shaft is preserved, facilitating catheter guidance by the proceduralist. *3D* three-dimensional, *IVC* inferior vena cava, *TV* tricuspid valve.

4. Discussion

The 11 AngioVac cases described in this study indicate that the procedure is an effective technique for removing vegetation or thrombus, particularly those that are soft and with minimal adhesion to adjacent tissue. Intraoperative TEE is a vital tool for assisting the procedure and evaluating intraoperative complications [5–8]. Fellowship-trained cardiac anesthesiologists who are NBE-certified in TEE are adequately qualified to provide TEE guidance during AngioVac procedures. Successful TEE guidance and close communication with the cardiac surgeon allowed for the precise navigation of the cannula to aspirate the target safely and successfully.

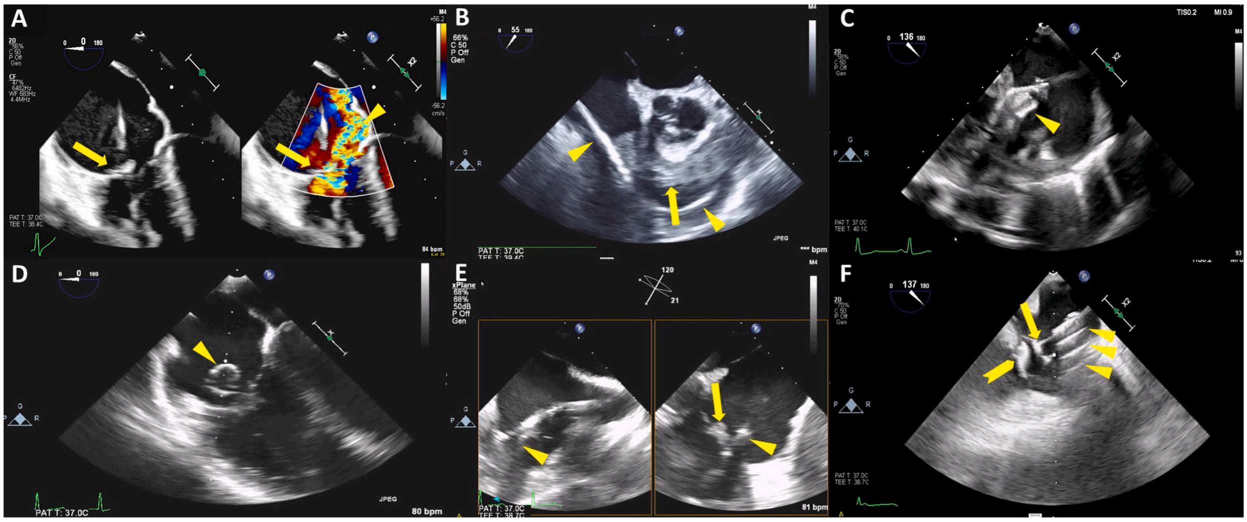

Fig. 6. A Mid-esophageal four-chamber view with focus on the right heart chambers shows real-time assessment of the degree of TR (arrowhead) during evacuation of the aspiration target through the AngioVac cannula tip (arrow). **B** RV inflow-outflow view shows the AngioVac cannula (arrowhead) approximating a vegetation (arrow) which extends from the RV to the PA. **C** AngioVac cannula tip (arrowhead) capturing the aspiration target. **D** Visualizing both the cannula shaft and tip simultaneously was occasionally difficult to achieve as seen in this image where only the cannula tip (arrowhead) is visualized. **E** X-plane imaging is useful in identifying the positional relationship between the AngioVac cannula tip and the aspiration target. In this X-plane image, the cannula tip (arrowhead) and the aspiration target (arrow) are misaligned as the target is situated medially relative to the AngioVac cannula tip. **F** Reverberation artifacts (arrowhead) did not interfere with the image quality of the cannula tip (arrow) or the aspiration target (chevron). *PA* pulmonary artery, *RV* right ventricular, *TR* tricuspid regurgitation, *TV* tricuspid valve.

In nine of the 11 cases, the majority of the vegetation or thrombus was successfully aspirated. In the two cases with unsuccessful complete aspiration of the target, the mass or thrombus was too firm and large, which prevented complete evacuation despite multiple attempts. In one of these cases (Case #1 in Table 1), the patient suffered from fungal endocarditis, which is associated with dense heterogeneous vegetations [9]. The fungal mass was likely highly developed and chronic, measuring at 6.1 $\times$ 2.0 cm, precluding complete aspiration (Figs. 4A and 6B). In the other case (Case #10 in Table 1), 75 % of the thrombus in the IVC remained (Fig. 5A). Given the diagnosis of Budd-Chiari Syndrome, the thrombus may have been chronic in etiology, causing it to be more solid and difficult to remove. The AngioVac is designed and primarily used for removing soft material [10], such as fresh thrombi and, thus, the lack of success removing huge dense heterogenous vegetations or chronic-appearing clots in these cases is not necessarily an unexpected outcome.

While fluoroscopy plays an important role in the AngioVac procedure to provide initial guidance of the cannula towards the target, it does not produce the precise images of the aspiration target required to facilitate fine catheter movements. Studies have demonstrated TEE to be safe and effective in thoracic and cardiovascular surgeries [8,11,12] and superior to fluoroscopy in providing greater details of tissue, thrombi, and other material [12]. Consistently, in AngioVac procedures, the aspiration target is more readily identifiable by TEE, allowing navigation of the aspiration cannula towards it with high accuracy. Once the cannula tip approximates or captures the target (Fig. 6C, Supplemental Video Clip 4), the final positioning also needs to be confirmed by TEE immediately before and during the aspiration process. The procedure requires fine-tuning of the cannula manipulation and positioning under the guidance of simultaneous real-time TEE imaging; thus, communication between the proceduralist (cardiac surgeon in our case) manipulating the AngioVac cannula and the echocardiographer (cardiac anesthesiologist in our case) obtaining precise live TEE images is key for success. Notably, we discovered that visualizing the information by using a physical anatomical heart model in the OR (Fig. 2F) during cannula manipulation was particularly helpful for the proceduralist (cardiac surgeon) and echocardiographer (anesthesiologist) to more accurately and efficiently convey and translate what is being displayed on the TEE images.

Identification of both the catheter passage and tip of the cannula simultaneously on the TEE images (Fig. 5D, E, F and Supplemental Video Clip 2) provided greater depth of information for the proceduralist to direct the cannula successfully; however, visualizing both the cannula shaft and tip on the same image was occasionally difficult to achieve (Fig. 6D), which made appropriate cannula direction a challenge for the proceduralist. In such cases, fine adjustment of the TEE probe and/or the angle of the ultrasound beam or utilizing an alternate TEE view was helpful in providing better images. X-plane imaging was also useful in identifying the relationship between the cannula tip and the aspiration target (Supplemental Video Clip 5A). Fig. 6E and Supplemental Video Clip 5B show the misalignment of the cannula tip with the target while this target was actually more medial relative to the tip in the X-plane image. The simultaneous modified bicaval view seemingly but misleadingly displayed the catheter passage directly aligned with the target. With the additional information that the X-plane images provided, the cannula was redirected medially to capture the target in this case. Of note, the cannula shaft often created a reverberation artifact when its passage was aligned perpendicularly to the ultrasound beam. However, the artifacts rarely interfered with the image quality of the cannula tip, aspiration target, nor the catheter manipulation as the areas of interest were not in close proximity with the image artifacts (Fig. 6F). In seven out of 11 cases, the location, quantity, and

Table 4
Intraoperative and postoperative course.

Case #	Intraoperative Fluid Administration	Intraoperative EBL and Blood Transfusion	Intraoperative Vasoactive Drug Requirement (Total dosage)	Post-Procedure Vasoactive Drug Requirement	Procedure Time (minutes)	Extubation Date, Location	LOS in CVICU (days)	LOS in Hospital (days), Disposition
1	Crystalloid: 2000 ml	EBL: 100 ml 2 U pRBC (650 ml) 2 U platelets (500 ml)	PHE Bolus: 0.3 mg PHE Infusion: 11.51 mg	NE infusion	211	POD 1 CVICU	3	3 died POD 3
2	Crystalloid: 2000 ml	EBL: Minimal No blood products	EPH Bolus: 5 mg NE infusion: 0.28 mg PHE Infusion: 0.51 mg	None	102	POD 1 CVICU	3	11 Home
3	Crystalloid: 1000 ml 25 % Mannitol: 12.5 g	EBL: 100 ml No blood products	NE Infusion: 0.34 mg	None	204	Extubated in OR	1	6 Home
4	Crystalloid: 2000 ml	EBL: Minimal 1 U pRBC (325 ml)	NE Infusion: 0.83 mg	None	136	Extubated in OR	1	19 SNF
5	Crystalloid: 1200 ml 5 % Albumin: 250 ml	EBL: Minimal No blood products	PHE Bolus: 0.5 mg EPH Bolus: 15 mg NE Infusion: 1.28 mg	None	120	Extubated in OR	1	1 OSH
6	Crystalloid: 1500 ml	EBL: Minimal No blood products	NE Infusion: 4.44 mcg	None	91	Extubated in OR	1	7 OSH
7	Crystalloid: 1100 ml 5 % Albumin: 500 ml	EBL: 25 ml No blood products	NE Bolus: 0.008 mg NE Infusion: 0.55 mg	None	86	Trach mask in OR	2	2 Home
8	Crystalloid: 1500 ml	EBL: Minimal 1 U pRBC (325 ml)	NE Infusion: 0.24 mg	None	105	Extubated in OR	1	1 OSH
9	None recorded	EBL: Minimal No blood products	NE Infusion: 0.16 mg	None	128	Extubated in OR	1	1 OSH
10	Crystalloid: 1000 ml	EBL: 500 ml 2 U pRBC (650 ml)	NE Infusion: 1.36 mg EPI Infusion: 0.35 mg Vasopressin Infusion: 8.48 U	NE, EPI, vasopressin infusion	313	Extubated in OR	11	25 Home
11	Crystalloid: 2000 ml 5 % Albumin: 250 ml	EBL: Minimal No blood products	EPH Bolus: 5 mg NE Infusion: 0.61 mg	None	196	Extubated in OR	1	3 OSH

CVICU cardiovascular intensive care unit, *EBL* estimated blood loss, *EPH* ephedrine, *EPI* epinephrine, *LOS* length of stay, *NE* norepinephrine, *OR* operating room, *OSH* outside hospital, *PHE* phenylephrine, *POD* post-operative day, *pRBC* packed red blood cells, *SNF* skilled nursing facility, *U* units.

quality of the aspiration target were evaluated by live 3D images (Fig. 5B and C); however, none of them was used during the actual catheter interrogation. Although using live 3D images to navigate catheter manipulation effectively is more complex and requires additional skillsets and training, such images may have been superior for the purpose of catheter interrogation in some occasions [13]; hence, incorporating this 3D tool during AngioVac procedures may be considered in future practice.

In terms of the safety of the AngioVac system, there was no single major catastrophic event encountered in this current study. This is consistent with literature describing the safety of the AngioVac [14,15]. One of the most common complications during the procedure was worsening TR, a known complication of this procedure [16,17], particularly when the AngioVac was used to debulk vegetations on the TV. Of the nine cases involving debulking of TV vegetations or thrombi, three (Case #2, 5, 6, in Table 1) resulted in higher grade TR following the procedure. Of note, in these three cases, there was already preexisting TR categorized as at least mild to moderate. Due to the susceptibility to worsening TR, it is necessary to be especially careful while manipulating the AngioVac cannula near the TV. Utilization of TEE allows the proceduralist to maintain proper visualization of the cannula and avoid unnecessary damage to the surrounding structures. Because both the four-chamber view with focus on the right heart chambers and the modified bicaval view with focus on the TV allowed for real-time assessment of the degree of TR during evacuation of the target thrombus or vegetation (Fig. 6A and Supplemental Video Clip 3), these views were particularly useful for the vigilant observation required during critical moments of catheter interrogation.

The AngioVac system requires veno-venous extracorporeal circulatory support. The aspirated material via the AngioVac venous drainage cannula is collected in an in-line filter system within the extracorporeal circuit while the aspirated blood is reinfused back to the patient, minimizing blood loss (Fig. 2B–D, E). This is consistent with the current study findings as there was no significant blood loss complications apart from one procedure with an estimated blood loss of 500 ml. Despite the minimal blood loss, packed red blood cells were administered in four of the 11 cases, even in those with minimal to no blood loss. This incongruity may be explained by the hemodilutional effect of the priming volume upon initiation of veno-venous extracorporeal circulatory support, which could lead to increased hemodynamic support requirements in an already critically ill patient under general anesthesia.

Previous literature suggests a variety of different surgical treatments for patients with IVDU, including complete excision of the valve and delayed valve replacement when the patient was infection free [18]. With decreased perioperative risks and shorter recovery time, however, the AngioVac procedure may be superior to traditional surgical interventions in such patients. In this current study, the average procedure time for AngioVac was 154 min (Table 4), which is likely much shorter than that of traditional open-heart surgery for removing intracardiac vegetations or thrombi. Additionally, the utilization of blood products (Table 4) is also likely much lower in AngioVac procedures. These factors may result in reduced medical costs and benefit both the patient and society.

In the current study, there was a high proportion of patients with IVDU who were less than 35-years-old and given antibiotic therapy as first-line treatment for infective endocarditis, yet their disease progressed despite appropriate antibiotic treatment due to their large infectious burden. Debulking of the vegetations to reduce the infectious burden using the AngioVac led to quickly resolving symptoms as the patients became more amenable to antibiotic therapy. Our success with the AngioVac system in treating severely ill patients by the cardiac surgery and anesthesia teams is congruent with data presented in published case reports and studies provided by other specialties, such as cardiology, radiology, and vascular surgery, demonstrating positive patient outcomes [14,17,19,20]. Notably, our study uniquely focused on the role of cardiac anesthesiologists in navigating the AngioVac cannula using TEE in coordination with a cardiac surgeon as a proceduralist, adding a novel perspective to the existing literature. This highlights the multidisciplinary nature of this procedure and the importance of skilled anesthesiologists in its success.

AngioVac procedures are often performed by interventional cardiologists or radiologists [4]. On the other hand, all AngioVac cases were performed by a cardiac surgeon in this study. Although the procedure has been shown to be safe, unexpected serious events can occur. The case discussed in a previous report [21], where emergent open embolectomy was required, highlights one advantage of having a cardiac surgeon immediately available. In this case, because the cardiac surgeon was already present in the room when the patient developed unexpected cardiac arrest due to acute PE, the surgeon could perform emergent sternotomy in a timely manner and treat the life-threatening condition. Currently, cardiac surgeons are not the primary proceduralist in most AngioVac cases; however, their unique skillset is a valuable asset in cases of emergencies. Therefore, it may be prudent to adopt a multispecialty team approach and for the primary proceduralist, whether it be an interventional cardiologist or radiologist, to maintain close communication with the cardiac surgeon to achieve the highest patient safety standards and successful outcomes.

Lastly, while our current study details the success of the AngioVac system, particularly in managing right heart vegetations and thrombi with minimal complications, it is important to consider its broader applications in the field. Although not yet common, AngioVac has been used for left-sided lesions [22], a scenario we have not yet encountered at our institution. This emerging application suggests potential areas for future research and underscores the versatility of the AngioVac system in treating a wider range of cardiovascular conditions.

We acknowledge the limitations inherent in a retrospective study design. Furthermore, the small sample size of eleven patients, though providing initial insights, may not fully capture the diverse patient demographics and clinical scenarios encountered in wider clinical practice. Although our findings are encouraging, the limited number of cases and the specific patient cohort, predominantly consisting of individuals with a history of intravenous drug use, may limit the generalization of our results to all patient populations. While our findings contribute to the growing body of evidence supporting the AngioVac system, further research with larger and more diverse patient samples is necessary to validate our results.

In summary, the AngioVac system is a novel procedural technique designed to treat intracardiac thrombi, emboli, and vegetations percutaneously. The minimally invasive nature of the procedure is one of its most enticing characteristics, and the current study indicates this technique is safe and effective for treating soft thrombi and vegetative growths. TEE guidance in each case provided by the fellowship-trained cardiac anesthesiologist and close coordination with the cardiac surgeon facilitated precise navigation of the AngioVac cannula towards the aspiration target, resulting in successful outcomes.

Data availability statement

Data will be made available on request.

Ethical declaration

This study was approved by the University of Iowa Institutional Review Board (#201911151) on October 18, 2022.

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CRediT authorship contribution statement

Cory Y. Lin: Writing – original draft, Methodology, Data curation. **Arun K. Singhal:** Writing – original draft, Methodology, Conceptualization. **Nicholas B. Cavanaugh:** Writing – review & editing, Methodology. **Sudhakar Subramani:** Writing – review & editing, Methodology. **Jarrod K. Bang:** Writing – review & editing, Methodology. **Satoshi Hanada:** Writing – original draft, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fig. 1 A, B: Images courtesy of AngioDynamics, Inc. and its affiliates. Used with permission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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