Echocardiographic Evaluation of Ventricular Assist Devices in Pediatric Patients

Ritu Sachdeva, MD, Elizabeth A. Frazier, MD, Robert D. B. Jaquiss, MD,
Michiaki Imamura, MD, PhD, Christopher J. Swearingen, PhD, and
Himesh V. Vyas, MD, Little Rock, Arkansas; Durham, North Carolina

Background: The use of ventricular assist devices (VADs) in children is challenging because of small patient size, frequent structural heart disease, and the need for biventricular assist devices. This report describes the role of echocardiography in the management of children supported by VADs.

Methods: A retrospective review of the records of all pediatric patients who underwent VAD placement between May 2005 and May 2011 was performed to collect demographics, cardiac diagnoses, details of VADs, and transthoracic and transesophageal echocardiographic findings from the time of initial diagnosis until VAD explantation.

Results: The study included 32 patients (median age, 3 years; age range, 20 days to 16 years; median weight, 12.3 kg; weight range, 3.5–60 kg), 20 with left ventricular assist devices and 12 with biventricular assist devices. Diagnoses included dilated cardiomyopathy or myocarditis (n = 27) and congenital heart disease (n = 5). The median duration of support was 12 days (range, 1–141 days). Patients with decreased right ventricular function were 8 times more likely to undergo biventricular assist device placement compared with those with normal right ventricular function (P = .026). Pre-VAD intracardiac shunts were identified in 11 patients and intracardiac thrombus in one patient. Cardiac chamber dimensions and mitral insufficiency were significantly reduced after VAD implantation. Postimplantation pericardial effusions were recognized in 16 patients and pericardial hematomas in 12 patients.

Conclusions: Echocardiography is invaluable in the management of pediatric patients receiving VADs. It is helpful in pre-VAD assessment, guiding intraoperative device placement, recognizing VAD dysfunction, and identifying postimplantation complications. (J Am Soc Echocardiogr 2013;26:41-9.)

Keywords: Ventricular assist device, Pediatrics, Echocardiography

Since their introduction for clinical use in the 1980s, ventricular assist devices (VADs) have been increasingly used to treat advanced heart failure both as a bridge to cardiac transplantation (or recovery) and as destination therapy. On the basis of its success in the adult population, this technology has increasingly been extended to pediatric patients. The use of VADs in children is more complicated because of the much wider patient size range, the presence of important congenital heart disease, and frequent need for biventricular assist devices (BiVADs). Until recently, the only VAD approved by the US Food and Drug Administration for use in small children was the DeBakey VAD Child (MicroMed Technology Inc., Houston, TX). However, this device has not gained widespread acceptance, because of significant thromboembolic complications. Moreover, its use is restricted to children aged > 5 years, with body surface areas > 0.7 m². The Berlin Heart EXCOR VAD (Berlin Heart AG, Berlin, Germany) was developed in Germany in the early 1990s and was first used in North America in 2000. It is currently the most commonly implanted pediatric-specific VAD and was recently approved by the Food and Drug Administration after the conclusion of a successful trial performed under investigational device exemption regulations. Echocardiography is the most commonly used imaging technique before, during, and after VAD implantation. The purpose of this study was to review our institutional experience with the use of echocardiography in the management of pediatric patients with Berlin Heart VAD and to introduce a protocol for echocardiographic assessment of VADs in pediatric patients.

The Berlin Heart EXCOR Device

The EXCOR device is a pneumatically driven, pulsatile VAD system that is available for either left ventricular (LV) or biventricular
support. The system consists of a paracorporeal blood pump with inflow and outflow valves, which is attached to the circulatory system by inflow and outflow cannulas that traverse the body wall. Cannulas and blood pumps are available in a range of sizes allowing support in children as small as 3 kg, up to adult-sized teenagers. Cannulation for LV support involves the placement of an outflow cannula in the ascending aorta and an inflow cannula in the LV apex, although left atrial (LA) inflow cannulation is also feasible. Right ventricular (RV) support is accomplished by means of an inflow cannula placed in the right atrium and an outflow cannula placed in the pulmonary artery (Figure 1).

**METHODS**

After approval of the study by the institutional review board of the University of Arkansas for Medical Sciences and the Berlin Heart EXCOR publications committee, a retrospective review of medical records of all pediatric patients (age < 21 years) who underwent placement of Berlin Heart VADs at our institution was performed. In all cases, the devices were placed as part of a planned bridge-to-transplantation strategy. The decision whether to place a left ventricular assist device (LVAD) only or BiVAD was made intraoperatively, by the implanting surgeon. Intraoperative transesophageal echocardiography (TEE) was performed in all patients at the time of VAD implantation.

Data collected included demographics, cardiac diagnosis, details of the VAD (pump size and configuration, LVAD or BiVAD), and findings on transthoracic echocardiography (TTE) and TEE from the time of diagnosis until the explantation of the VAD. Two physicians performed offline analysis of the TTE done before and after VAD placement. The following parameters were evaluated.

To assess chamber dimensions and function, LA and RA areas were traced in the apical four-chamber view during end-systole. LV end-diastolic diameter was measured from the parasternal short-axis view on two-dimensional echocardiography before and after VAD placement. Because the device filling and ejection are not synchronous with the native cardiac cycle, the largest LV end-diastolic diameter at the end of mechanical diastole was used. LV end-diastolic diameter Z scores were calculated according to body surface area. LV function was assessed using shortening fraction (SF) before VAD placement. However, it was not reported after VAD placement, because it does not accurately reflect intrinsic LV function while on a VAD. RV size was estimated by tracing RV area in end-diastole in the apical four-chamber view. RV function was assessed qualitatively by visual estimate. Function was categorically scored as hyperdynamic, normal, or mildly, moderately, or severely reduced to permit statistical analysis. RV systolic pressure was estimated using the tricuspid regurgitation (TR) jet velocity and adding RA pressure to it. RA pressure was either obtained directly from a central line at the time of echocardiography or assumed on the basis of the size and collapse of inferior vena cava. RV systolic pressure could not be estimated in patients with inadequate TR Doppler signals.

For valve assessment, mitral and tricuspid valve annuli were measured in the apical views before and after VAD placement. Valvular regurgitation was assessed qualitatively by inspecting the area of the color Doppler jet in the downstream chamber and classified as none, trace, mild, moderate, or severe. All transthoracic and transesophageal echocardiographic studies were additionally reviewed for intracardiac shunts, intracardiac thrombus, cannula position, pericardial effusion and hematomas, and ascending aortic aneurysms or dissection.

**Statistical Analysis**

For this review of our institutional experience, the primary analysis included the estimation of differences in measurements on TTE before and after VAD implementation as well as estimation of any association between pre-VAD RV parameters on the type of VAD used. Differences between pre-VAD and post-VAD transthoracic echocardiographic measurements were estimated using Wilcoxon’s signed-rank paired test for continuous outcomes and McNemar’s test for paired proportions for categorical outcomes. Pre-VAD measurement differences between LVAD and BiVAD patients (mutually exclusive groups) were estimated using Wilcoxon’s rank-sum test for continuous measures or Fisher’s exact test for categorical measures. The type 1 error rate was set at the accepted 5% level for statistical significance determination (i.e., P ≤ .05) for these overall and pre-VAD comparisons.

A secondary analysis was planned, estimating pre-VAD and post-VAD changes in TTE measurements within LVAD and BiVAD devices separately. For this analysis, differences between pre-VAD and post-VAD measurements on TTE were also estimated using Wilcoxon’s signed-rank test for continuous measures or McNemar’s test for proportions. However, Bonferroni’s correction was implemented for these secondary pre-VAD and post-VAD comparisons within the LVAD and BiVAD groups (i.e., statistical significance was
defined as $P \leq .025$. All statistical analysis was completed using Stata version 12.1 (StataCorp LP, College Station, TX).

**RESULTS**

From May 2005 to May 2011, 32 patients (16 male) received Berlin Heart EXCOR pediatric devices at our institution. The median age was 3 years (range, 20 days to 16 years), and the median weight was 12.3 kg (range, 3.5–60 kg). Diagnoses were dilated cardiomyopathy or myocarditis in 27 patients and congenital heart disease in five patients, including recurrent subaortic stenosis ($n = 1$), atrioventricular septal defect with coarctation and LV outflow tract obstruction ($n = 1$), transposition of the great arteries ($n = 1$), pulmonary atresia with ventricular septal defect ($n = 1$), and supravalvular aortic stenosis with ventricular septal defect ($n = 1$). Eleven patients were on extracorporeal membrane oxygenation (ECMO) support before VAD placement, including five patients transferred to our institution on mobile ECMO. Aortic cross-clamping was performed in 23 patients. LVADs alone were implanted in 20 patients and BiVADs in 12 patients. Of the 12 patients who received BiVADs, 10 received the LVAD and right ventricular assist device (RVAD) in the same setting in the operating room. The other two BiVAD patients received RVADs 2 and 6 days after implantation of LVADs alone. The median duration of support was 12 days (range, 1–141 days). The pump size used for LVADs ranged from 10 to 60 cm$^3$ and for RVADs from 25 to 50 cm$^3$. Two patients were successfully weaned off the VADs, two patients died while on VAD support, and the remaining 28 patients underwent cardiac transplantation.

A total of 453 transthoracic echocardiographic studies (median, 11 per patient; range, 3–42 per patient) and 58 transesophageal echocardiographic studies (median, 1 per patient; range, 1–4 per patient) were reviewed. Table 1 shows a comparison between the transthoracic echocardiographic parameters before and immediately after VAD implantation. Some patients had inadequate images for retrospective analysis of the various parameters because of poor images related to previous cardiac surgeries, open chest, dressings, chest wall edema, mediastinal hematomas, cannulas, or significant decompression of the chambers after VAD placement.

**Left-Heart Parameters**

LA area decreased significantly after VAD implantation. LV size significantly decreased after VAD implantation. LV systolic function was severely reduced in all patients before VAD placement (mean LV SF, 9 ± 5%). In two patients with LVADs, there was complete recovery of LV systolic function: a 20-day-old patient and a 1-year-old patient with viral myocarditis. The VADs were explanted from these two patients after 13 and 56 days, respectively.

**Right-Heart Parameters**

A comparison of RV parameters in patients who received only LVADs was done to eliminate the confounding influence of right-sided decompression in the patients with BiVADs (Table 2). After VAD placement, the mean RA area did not change in those who received LVADs alone (Table 2), but it was significantly reduced when the entire study population, including those with LVADs and BiVADs, was considered (Table 1).

RV end-diastolic area significantly decreased after VAD placement. RV function was qualitatively reduced in 12 patients (mild in one, moderate in five, and severe in six). Of these 12 patients, six received BiVADs and six received LVADs initially. Of the six patients with LVADs, in three patients (one with mild and two with moderately reduced RV function), RV function was noted to be normal on TTE done 2 days after LVAD placement and remained so until cardiac transplantation. In one patient with severely reduced RV function, RV function improved but remained moderately reduced until device explantation 6 days later for cardiac transplantation. During these 6 days, despite the RV dysfunction, this patient maintained good LV filling and cardiac output. The remaining two patients required additional support with RVADs later: one patient had a severely dilated right ventricle with severely reduced function, and an RVAD was placed 2 days later; the other patient, who had moderately reduced RV function to begin with, developed signs of worsening hepatic

<table>
<thead>
<tr>
<th>Variable</th>
<th>n$^*$</th>
<th>Pre-VAD</th>
<th>Post-VAD</th>
<th>P$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEDD (cm)</td>
<td>31</td>
<td>5.1 ± 1.2</td>
<td>3.8 ± 1.3</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>LVEDD Z score</td>
<td>31</td>
<td>4.7 ± 1.7</td>
<td>1.2 ± 2.5</td>
<td>&lt;.001</td>
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<tr>
<td>LA area (cm$^2$/m$^2$)</td>
<td>30</td>
<td>18.2 ± 5.0</td>
<td>10.9 ± 4.4</td>
<td>&lt;.001</td>
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<tr>
<td>Mitral annulus (cm)</td>
<td>31</td>
<td>2.5 ± 0.7</td>
<td>2.0 ± 0.6</td>
<td>.011</td>
</tr>
<tr>
<td>Mitral regurgitation (moderate or greater)</td>
<td>32</td>
<td>24 (75%)</td>
<td>12 (37.5%)</td>
<td>.002$^5$</td>
</tr>
<tr>
<td>RV diastolic area (cm$^2$/m$^2$)</td>
<td>26</td>
<td>14.1 ± 6.0</td>
<td>10.5 ± 3.7</td>
<td>.005</td>
</tr>
<tr>
<td>RA area (cm$^2$/m$^2$)</td>
<td>27</td>
<td>14.3 ± 5.3</td>
<td>10.9 ± 4.3</td>
<td>.003</td>
</tr>
<tr>
<td>Tricuspid annulus (cm)</td>
<td>28</td>
<td>2.4 ± 0.8</td>
<td>1.9 ± 0.6</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>TR (moderate or greater)</td>
<td>32</td>
<td>9 (28%)</td>
<td>8 (25%)</td>
<td>1.000$^5$</td>
</tr>
</tbody>
</table>

LVEDD, LV end-diastolic dimension.
Data are expressed as mean ± SD or as number (percentage).
$^*$Number of patients in whom the measurement could be obtained.
$^1$P values < .05 are statistically significant.
$^5$Atrial and ventricular areas indexed to body surface area are reported.
$^5$McNemar’s test is reported; otherwise, Wilcoxon’s signed-rank test is reported.

<table>
<thead>
<tr>
<th>Echocardiographic parameter</th>
<th>n$^*$</th>
<th>Pre-LVAD</th>
<th>Post-LVAD</th>
<th>P$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA area (cm$^2$/m$^2$)</td>
<td>20</td>
<td>14.1 ± 4.8</td>
<td>11.9 ± 4.4</td>
<td>.044</td>
</tr>
<tr>
<td>RV diastolic area (cm$^2$/m$^2$)</td>
<td>20</td>
<td>13.1 ± 4.1</td>
<td>10.3 ± 3.1</td>
<td>.025</td>
</tr>
<tr>
<td>RV function (more than mildly reduced)</td>
<td>20</td>
<td>4 (20%)</td>
<td>1 (5%)</td>
<td>.250$^5$</td>
</tr>
<tr>
<td>Tricuspid annulus (cm)</td>
<td>20</td>
<td>2.2 ± 0.7</td>
<td>1.8 ± 0.5</td>
<td>.001</td>
</tr>
<tr>
<td>RVSP/SBP ratio (%)</td>
<td>12</td>
<td>47.5 ± 19.6</td>
<td>27 ± 7.1</td>
<td>.008</td>
</tr>
<tr>
<td>TR (moderate or greater)</td>
<td>20</td>
<td>3 (15%)</td>
<td>0 (0%)</td>
<td>1.000$^5$</td>
</tr>
<tr>
<td>Pulmonary insufficiency (moderate or greater)</td>
<td>20</td>
<td>9 (45%)</td>
<td>0</td>
<td>.004$^5$</td>
</tr>
</tbody>
</table>

RVSP, RV systolic pressure; SBP, systemic systolic blood pressure.
Data are expressed as mean ± SD or as number (percentage).
$^*$Number of patients in whom the measurement could be obtained.
$^1$Bonferroni-corrected $P$ values < .025 are statistically significant.$^5$Atrial and ventricular areas indexed to body surface area are reported.
$^5$McNemar’s test is reported; otherwise, Wilcoxon’s signed-rank test is reported.
dysfunction and received an RVAD 6 days after LVAD implantation. The central venous pressure was significantly elevated in both these patients (15 and 18 mm Hg respectively) before placement of the RVAD. Four patients with normal RV function received BiVADs preemptively. In patients receiving LVADs, there was a significant drop in the ratio of RV systolic pressure to systolic blood pressure.

Table 3 shows a comparison of preimplantation RV parameters between patients who received LVADs versus BiVADs. Of patients with normal RV function preoperatively, 80% had only LVADs. Of the patients with any reduction in RV function, 67% received BiVADs. Patients with decreased RV function had 8 times the odds of receiving BiVADs versus LVADs alone compared with those with normal RV function (95% confidence interval, 1.25–55.42; \( P = .026 \)). There was no similar predictive relationship for either RV size or the degree of TR.

### Valvular Abnormalities

There was a significant improvement in the degree of mitral regurgitation after VAD placement. One patient with persistent severe mitral regurgitation was noted to have a large perforation in the posterior leaflet of the mitral valve when the heart was inspected after explantation. Moderate or severe TR was present in nine of the 32 patients before VAD placement. Significant TR persisted in five patients (one with persistent pulmonary hypertension, two with poorly functioning right ventricles while on LVAD support who later required RVADs, and two with significant leftward shift of the septum after LV decompensation that improved by changing the VAD settings). Two patients had more than moderate aortic insufficiency before VAD placement. The aortic valve was repaired at the time of VAD placement in one, and in the other patient, a tight band was placed on the ascending aorta while the child was on ECMO before VAD implantation because the valve was not repairable. None of the patients developed aortic insufficiency after VAD placement. The amount of pulmonary insufficiency improved in all patients with mild or greater insufficiency. One patient with severe RV–to–pulmonary artery conduit stenosis and RV failure underwent pulmonary valve replacement at the time of surgery for LVAD implantation.

### Intracardiac Thrombus

Intracardiac shunts were identified in 11 patients on TTE before VAD placement (patent foramen ovale in five, a large secundum atrial septal defect in one, a small perimembranous ventricular septal defect in one, and atrial shunt secondary to a blade-balloon septostomy in four patients who were on ECMO before placement of the VAD). All intracardiac shunts were closed at the time of surgery for VAD implantation.

### Ascending Aorta

There was no aortic dissection or aneurysm in any patient before or after VAD implantation.

### Cannula Position and Flow

Cannulas were assessed on 2D and color Doppler imaging, but spectral Doppler imaging was inadequate in most of our studies because of either poor windows or a lack of awareness during the beginning of our experience (Table 4, Figures 2 and 3). TTE identified dynamic obstruction of the LV inflow cannula in one patient with an LVAD. Adjustment of pump parameters was not effective in relieving the obstruction or improving pump filling, so the cannula was repositioned.

### Deairing

A thorough evaluation for the adequacy of deairing was done on TEE during the operation (Table 4).

### Intracardiac Thrombus

Significant spontaneous contrast was noted preoperatively in three patients with severe dilated cardiomyopathy. One of these patients had a thrombus in the aortic sinus along with five pieces of laminated clots in LV trabecular recesses that were removed during surgery (Figures 4A and 4B). After VAD placement, one patient was suspected to have a large intracardiac thrombus around the RA cannula on transthoracic echocardiographic images that were limited because of poor windows. This finding was confirmed on TEE (Figures 5A and 5B), and the patient underwent thrombectomy.

### Pericardial Effusion and Hematomas

Pericardial effusion was present in five patients before VAD placement (small in four, large in one). After VAD placement, pericardial effusion was recognized in 16 patients (small in 10, moderate or large in six) at a median duration of 5 days (range, 1–16 days) from the time of VAD implantation. Moderate and large pericardial effusions were drained. In 3 patients, the pericardial effusion was also accompanied by intraoperative hematomas. Although the effusions appeared echoluent, hematomas were echodense and highly refractile. Significant hematomas were recognized on TTE in 12 patients after VAD placement (Figures 5C and 5D). Four patients had recurrent hematomas. TEE confirmed the presence of the hematomas in three patients with poor images on TTE. Surgical evacuation of hematomas was performed in nine patients because of hemodynamic compromise.

### Endocarditis

None of the patients were diagnosed with VAD endocarditis.
DISCUSSION

Although there has been an explosive expansion of the use of VADs in adults, as both bridge to transplantation and destination therapy, it is only recently that this support modality has been used extensively in adults, as both bridge to transplantation and destination therapy, it is only recently that this support modality has been used extensively in children.7 Reports from adult patients with VADs refer to a wide range in pediatric patients, and different device types in children requiring VAD support. The only previous report focused on the use of echocardiography in pediatric patients with VADs is that by Scohy et al.,17 describing the usefulness of TEE in intraoperative hemodynamic stabilization of five pediatric patients with Berlin Heart EXCOR cannulas connected to a Levitronix centrifugal pump. To our knowledge, ours is the first report describing the role of TTE and TEE in pediatric recipients of Berlin Heart EXCOR VADs. On the basis of our institutional experience, we have implemented a checklist for guiding the echocardiographers imaging children with VADs (Table 4). If TTE is suboptimal and there are clinical concerns, TEE should be performed without any hesitation.

Assessment of Cardiac Chambers and Function

Assessment of intrinsic LV function in patients on VAD support is important to recognize recovery of function. However, this is a challenging task because the routinely used measures, such as SF and ejection fraction, are not truly reflective of intrinsic LV function because the left ventricle has been unloaded by the VAD. Strain measurements performed using Doppler tissue imaging or speckle tracking may be more reflective of the intrinsic cardiac function. However, these techniques may be limited in the post-VAD setting by the poor acoustic windows. Ideally, VAD flow should be turned down to assess intrinsic LV function. This was not done in any of our patients, except the two who had successful explantation. We have therefore not analyzed or discussed LV function while our patients were on VAD support. Additional limiting factors include paradoxical septal motion, shadowing or attenuation artifacts from the cannula, and poor imaging windows. Despite these limitations, previous studies in adult patients have reported ejection fraction using the method of disks from apical views or SF from the parasternal short-axis view.18,19 Echocardiography plays an important role in post-VAD patients in ensuring that the left ventricle is decompressed well with a septum in the neutral position and no significant TR. In the operating room, monitoring with TEE is useful to ensure that the VAD is turned on quickly enough so that the right ventricle does not experience high pressures due to a lack of LV decompression. It is important to continue monitoring with TEE until the chest is closed, especially in infants and toddlers, to make sure there are no untoward changes in ventricular size after chest closure.

RV function is an important determinant of LVAD output.20,21 On one hand, LVAD placement can improve RV function, primarily by lowering RV afterload. On the other hand, a preexisting RV myopathy can be unmasked by the increased RV preload that results from improved systemic output from the LVAD compared with a poorly functioning left ventricle. In some patients with LVADs only, good pump filling and cardiac output can be maintained despite significant RV dysfunction, as noted in one patient in our study. Reports in adult patients indicate that 9% to 30% of patients have severe RV dysfunction after LV AD placement.21,22 Interestingly, in contrast to ischemic cardiomyopathy, nonischemic cardiomyopathy has been reported to be a significant predictor of RVAD use after LVAD implantation in adults.21,23 One of the most important decisions to be made in patients requiring mechanical circulatory support is whether the LVAD alone would suffice. Currently, there is wide variation in institutional practices at the major pediatric VAD centers with regard to the use of LVADs alone versus BiVADs.24,26 This decision is mostly made in the operating room, once cardiopulmonary bypass is discontinued after implantation of the LVAD, on the basis of the acute performance of the right ventricle, echocardiographic assessment of the tricuspid valve, and measurement of RA pressure. For this critical decision, our center has followed the approach suggested by Stiller et al.,27 whereby we attempt to support the right ventricle with nitric oxide to reduce afterload, combined with the aggressive use of catecholamines and milrinone.24

Table 4 Checklist for evaluation of patients receiving VADs

<table>
<thead>
<tr>
<th>Pre-VAD evaluation</th>
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<tbody>
<tr>
<td>1. Cardiac anatomy</td>
<td></td>
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<tr>
<td>2. Chamber dimensions and function</td>
<td></td>
</tr>
<tr>
<td>3. Valvular abnormalities</td>
<td></td>
</tr>
<tr>
<td>a. Degree of regurgitation or stenosis</td>
<td></td>
</tr>
<tr>
<td>b. Annular dilation</td>
<td></td>
</tr>
<tr>
<td>4. Intracardiac shunts: level, direction, and amount of shunt</td>
<td></td>
</tr>
<tr>
<td>5. Intracardiac thrombus or spontaneous contrast</td>
<td></td>
</tr>
<tr>
<td>6. Assessment of the ascending aorta</td>
<td></td>
</tr>
</tbody>
</table>

Intraoperative evaluation

1. RV size and function (if LVAD alone)
2. LV unloading
3. Valvular abnormalities
4. Intracardiac shunts: level, direction, and amount of shunt
5. Inflow and outflow cannula position and Doppler
   a. LV inflow cannula (Figures 2A and 2B): in LV apex
   - View in midesophageal four-chamber and long-axis views
   - Parallel to septum and aligned with mitral inflow
   - Unidirectional flow from left ventricle into the cannula
   b. LV outflow (Figures 2C and 2D): in ascending aorta
   - View in midesophageal long-axis view
   - View in midesophageal short-axis view and bicaval view
   c. RV inflow (Figures 3A and 3B): in the right atrium
   - View in midesophageal short-axis view and bicaval view
   d. RV outflow (Figures 3C and 3D)
   - View in midesophageal 20°-70° view

6. Cannula position before and after chest closure
7. Deairing during the following phases of surgery
   - From cannula placement until release of aortic cross-clamp
   - From release of aortic cross-clamp to the end of cardiopulmonary bypass
   - From the termination of cardiopulmonary bypass to the end of the operation

Assessment while on VAD support

1. Biventricular size and function and septal position
2. Valvular abnormalities
3. Cannula position and Doppler
   - Malposition or obstruction
4. Pericardial effusion and hematoma
   - Chamber collapse (an important marker of tamponade)
5. Intracardiac thrombus
6. Ascending aorta dissection

ASD, Atrial septal defect; PFO, patent foramen ovale; VSD, ventricular septal defect.
Some studies from adult patients have reported preoperative echocardiographic predictors of RV AD placement. One such study noted that compared with LV AD-only patients, those patients who received biventricular support had larger RV end-diastolic volumes, higher RA pressures, and higher pulmonary vascular resistance. Another study suggested that RV fractional area change < 20% may have RV failure after LV AD insertion. We were unable to evaluate the utility of RV fractional area change in this study, because of suboptimal images of the right ventricle after VAD placement. Moreover, the role of this method in assessing intrinsic RV function in a patient on BiV AD support is questionable. In the present study, only reduced RV function, but not RV size, amount of TR, or RV systolic pressures, was associated with placement of a BiVAD versus an LVAD alone. It is important to note that there were only a small number of patients in each category for comparison, so that besides being retrospective, the study was very underpowered. At the beginning of our experience, there was a much higher use of BiVADs. In addition, a high incidence of aortic cross-clamping may have contributed to increased use of RVADs. In this retrospective study, it is hard to know if the patients who had received BiVADs preemptively would have done well on LVADs alone.

Valvular Abnormalities
In patients on VAD support, valvular function is influenced by the loading conditions of the heart, preexisting annular dilation, and, very rarely, damage by the cannula. In this study, we noted that the area of the color Doppler jet of mitral regurgitation in the downstream chamber was smaller after VAD placement compared with baseline. This could possibly have resulted from reductions in LV volume and systemic driving pressure. After LVAD insertion, the amount of TR may decrease with the drop in RV afterload. On the other hand, TR may actually worsen once the left ventricle is decompressed, because of a distortion of the tricuspid annulus by the leftward shift of the ventricular septum, pulmonary hypertension, and RV dysfunction, as seen in some of our patients. Significant aortic insufficiency can be detrimental, as it can result in poor LVAD output into the systemic circulation. Adults on long-term LVAD therapy have been reported to develop insufficiency of the native aortic valve, but this was not seen in any of our patients.

Intracardiac Shunts
Although many adult patients may have persistent foramen ovale, pediatric patients can additionally have atrial and ventricular septal defects that will need to be addressed at the time of VAD placement, as seen in our study. Active diastolic suction by the LVAD pump can cause right-to-left shunting once the left heart is decompressed, resulting in cyanosis and increased risk for paradoxical embolization.

Ascending Aorta
In older populations, screening for atheromas is important, but this is not an issue in the pediatric population. When the outflow cannula ejects blood with high velocity into the aorta, it increases the shear stress of the aortic wall and can result in aortic dissection in adult patients, but this has not been reported in children. A thorough evaluation of the ascending aorta is warranted in patients with congenital
lesions with associated aortic wall abnormalities, such as bicuspid aortic valve, connective tissue disorders, and hypoplastic left heart syndrome.

Cannula Position and Flow

We have not been able to provide information regarding Doppler-derived velocities across various cannulas due to suboptimal spectral-Doppler imaging. Data from adults indicate that a peak velocity of >2.3 m/sec across the inflow cannula and >2.1 m/sec across the outflow cannula suggests cannula obstruction.16,29 These absolute cutoffs are not applicable to younger patients, and we anticipate that these velocities will be much higher in children given the smaller cannula size and the faster heart rates.

Deairing

During the implantation of an LVAD, significant amounts of air may be accumulated within the blood pump and the cannulas. To prevent air embolism, close attention must be paid to a thorough deairing, the adequacy of which is best assessed echocardiographically.33 Areas prone to air entrapment are the upper pulmonary veins, the left atrium and its appendage, the LV apex, the right coronary sinus of Valsalva, and the anastomotic sites of cannulas.14

Intracardiac Thrombi

LV thrombus has been observed in 9% to 16% of patients receiving VADs.29,15 The apex of a poorly functioning left ventricle is

Figure 3  Bicaval view on transesophageal echocardiography showing 2D (A) and color Doppler (B) images of the RVAD inflow cannula (arrow) positioned in the right atrium (RA). The outflow cannula (arrow) is seen in the main pulmonary artery on 2D (C) and color Doppler (D) images. Ao, Aorta; LA, left atrium.

Figure 4  Transesophageal echocardiogram in a patient with dilated cardiomyopathy before VAD placement showing (A) spontaneous contrast (“smoke”) in the left ventricle (LV) and (B) thrombus in the aortic sinus (arrow).
particularly predisposed to thrombus formation. Dislodgement of such thrombi at the time of cannula insertion may cause embolic stroke. These thrombi can also obstruct the cannula orifice. After VAD placement, the areas surrounding the cannulas are prone to thrombus formation.

Pericardial Effusion and Hematomas

Patients with VADs are highly prone to bleeding and can develop tamponade related to hemopericardium or hematoma that may cause extrinsic compression. Regional tamponade should be suspected if there is a decline in output in an extrinsically compressed chamber.

Endocarditis

Patients with VADs are at increased risk for endocarditis given the prosthetic material and externalized cannulas used in them. If trans-thoracic echocardiographic images are inadequate, TEE should be used to detect vegetations on VAD cannulas and native or prosthetic valves. However, it is important to remember that in a patient on VAD support with positive blood cultures, the diagnosis of VAD endocarditis is made irrespective of echocardiographic findings, if all other sources of infection are excluded. VAD endocarditis can be associated with obstruction of the cannulas, malfunctioning of their valves, or very rarely cannula rupture.

Limitations

This descriptive study was limited by its retrospective nature. For this reason, some of the more novel and sophisticated quantitative measures of analysis of cardiac function could not be applied. RV function was assessed qualitatively in our study, rather than using quantitative measures. Intrinsic LV function could not be reported given the limitations of the techniques available to assess this while a patient is on VAD support. The assessment of TR was limited by the fact that it was qualitative and did not account for eccentric jets. Moreover, it could not be controlled for uniformity in technical factors such as instrument gains and filters, because of its retrospective nature. The decision to implant LVADs versus BiVADs was clinical and not randomized.

CONCLUSIONS

Echocardiography plays a vital role in the management of pediatric patients receiving VADs. It is helpful in defining cardiac anatomy and function before VAD insertion and recognizing other problems, such as intracardiac shunts, thrombi, and significant valvular regurgitation, that will need to be addressed at the time of implantation surgery. Frequent echocardiographic evaluation of patients on VAD support is recommended for the evaluation of cardiac function and screening for complications such as device malfunction, intracardiac thrombi, endocarditis, pericardial effusions, and hematomas.
REFERENCES


