美国超声心动图学会指南及标准

超声心动图在左心室辅助装置管理中的应用

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缩写

2D =二维
3D = 三维
A = 二尖瓣口舒张晚期峰值流速
AR = 主动脉瓣返流
Ao = 主动脉/主动脉根部
AS = 主动脉瓣狭窄
ASD = 房间隔缺损
ASE = 美国超声心动图学会
AV = 主动脉瓣
BiAV = 双心室辅助装置
BP = 血压
BTT = 心脏移植前过渡治疗
CCT = 心脏计算机断层扫描
CF = 恒流
CMS = 医疗保险和医疗补助服务中心
CPB = 心肺流转术
CT = 计算机断层扫描
CW = 连续波频谱
DT = 最终治疗
E' = 二尖瓣环组织速度
E = 二尖瓣口舒张早期峰值流速
ECMO = 体外膜肺氧合
FAC = 面积变化率
FDA = 美国食品及药物管理局
HF = 心力衰竭
HM-II = HeartMate II 左心室辅助装置
HVAD = HeartWare 左心室辅助装置
IABP = 主动脉内球囊反搏
IAC = 跨学会认证委员会
INR = 国际标准化比值
INTERMACS = 机械辅助循环跨部门注册组织
IV = 经静脉
LA = 左心房
LV = 左心室
LVAD = 左心室辅助装置
LVEDV = 左心室舒张末期容积
LVEF = 左心室射血分数
LVIDd = 左心室舒张末期内径
LVOT = 左室流出道
MAP = 平均动脉压
MCS = 机械辅助循环
MR =二尖瓣返流
MS = 二尖瓣狭窄
MV =二尖瓣
PFO = 卵圆孔未闭
PDA = 动脉导管未闭
PI =搏动指数
PR = 肺动脉瓣返流
PS = 肺动脉瓣狭窄
PT = 凝血酶原时间
PVAD = 经皮心室辅助装置
RA = 右心房
RCA =右冠状动脉
rPA = 右肺动脉
RV = 右心室
RVAD = 右心室辅助装置
RVOT = 右室流出道
STE = 斑点追踪超声心动图
TAH = 全人工心脏
TAPSE =三尖瓣环收缩期位移
TEE = 经食管超声心动图
TR = 三尖瓣返流
TS = 三尖瓣狭窄
TTE = 经胸超声心动图
VC = 射流紧缩
VSD = 室间隔缺损
VTI = 速度时间积分

介绍

本指南强调了超声心动图在植入左室辅助装置（LVADs）患者，在不同时期的的管理以及应用连续多普勒（CF）评价装置功能的重要作用。终末期顽固性心力衰竭患者，内科药物治疗效果不理想，LVADs 可以作为患者心脏移植前的过度手段（BTT）、最终治疗手段（DT）、等待心脏移植受体的过渡，抑或作为心脏恢复期的过渡手段。在过去的数十年当中，机械辅助循环系统（MCS）得到极大改进，全球愈 3 万人长期

依赖 LVADs。近期，不同的指南均强调了超声心动图在 LVADs 不同时期的重要作用，包括术前患者选择，围手术期的成像，术后的检测，以及 LVADs 功能的优化，LVADs 故障的处理，评价自体心肌的恢复情况。尽管 LVADs 在临床当中日渐增多，超声心动图在患者管理中的核心作用逐渐被人们所认识，LVADs 出院随访患者的呈指数增长，与移植中心数量并不成比例，仍旧亟待出台关于 LAVDs 的超声心动图指南。

美国超声心动图学会（ASE）基于已经发表的数据（目前有限的数据资料），结合大量机械辅助循环支持中心专家的建议，提供在 LVADs 患者选择、装置植入以及术后管理中超声心动图检查时机的专家共识及模板。作者旨在提供一个总体框架，供超声心动图医生以及机械辅助循环团队之间进行沟通对话。尽管临床当中使用的 LVADs 种类繁多，甚至有的仍处于研发阶段，本文主要针对美国食品药品监督管理局（FDA）批准的临床当中成人长期使用的恒流式 LVADs 装置。先天性心脏病的儿童及成人患者，是需要机械辅助循环的重要亚组人群。关于先天性心脏病的儿童或成人患者的心脏辅助装置的专家建议或共识，将会在儿童 LVADs 章节中探讨。超声医师对于外科植入的心室辅助装置、经皮植入的 LVADs，右室辅助装置（RVADs）以及双心室辅助装置（BiVADs）。关于以上装置的讨论及应用，详见附录 A。其他的 MCS 包括心肺转流泵（CPB）、体外膜肺氧合（ECMO）、主动脉球囊反搏（IABPs）以及全人工心脏，本指南不再赘述。

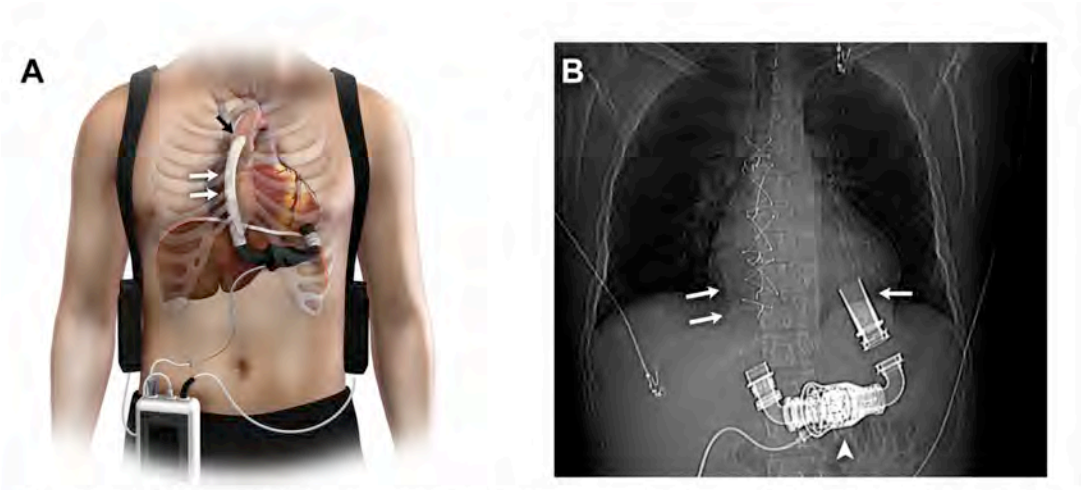


图 1 （A）HM-II LAVD 示意图，膈下为泵装置的位置，右侧胸骨旁为流出道位置（双白色箭头）以及流出道至升主动脉接合处（黑色箭头）。（B）CT 断层成像显示左心室与辅助装置流入道（单箭头）的解剖关系，叶轮壳（三角形），和流出管道（双箭头），控制装置（白色盒子）以及电池盒（黑色盒子）。

要点

- 本文旨在阐述 FDA 批准的外科恒流式 Ds 患者管理中，不同阶段的超声心动图的作用。
- 不同阶段患者的管理，主要涵盖术前患者的选择，术中 TEE 成像，术后监测，LVAD 功能的优化，针对问题的检测（植入 LVAD 的患者出现相关症状及体征，或自体心脏功能不全），评价自体心肌的恢复情况。
- 其他类型的 MCS 可以通过超声心动图

进行评价，详见附录 A。

- 尽管超声心动图常用于指导 LVAD 的治疗，已知数据倾向于指导 LVAD 植入的时机，必要的临床数据仍有待完善。本指南中的部分建议，来自于大量 MCS 中心的专家建议。
- 多数 LVAD 受体是扩张性心肌病的成年患者。本文中阐述的其他 LVAD 植入患者，包括心脏较小的患者，例如限制性心肌病，以及儿科和先天性心脏病患者。
- 作者意图提供总体框架供超声心动图团队及 MCS 团队的沟通。

左心室辅助装置

LVADs 患者的选择是一个复杂的过程，需要根据患者的情况进行个体化，因此不在本文讨论范围内。建议读者参考近期关于长期外科植入的体内 LVADs 的的结构和功能的综述，而短期、外科或经皮植入的体外 LVADs 的内容参考附录 A。目前，FDA 批准了 2 种恒流式 LVADs 用于成人患者，即 HeartMate II(HM-II)左室辅助装置（Thoratec Corporation, Pleasanton, CA）（图 1）和 HVAD 左室辅助装置（HeartWare International，Inc., Framingham,MA）（图 2）。2008 年 4 月，HM-II 得到 FDA 的批准用于 BTT 治疗，2010 年，批准用于 DT 治疗。2012 年 11 月，FDA 批准 HeartWare HVAD 用于 BTT 治疗，而 DT 治疗的临床试验仍在进行当中。简言之，文中所有 LVAD 的简写，均指这两种恒流式 LVADs。

HM-II 和 HVAD 的共同特点就是有三个组成部分：（1）左室近心尖部的流入管道，（2）机械涡轮，（3）与升主动脉吻合的流出管道（见图 1 和 2）。超声心动图可以用于探查流入管道及流出管道的血流，但是无法评价机械涡轮。HM-II 的涡轮及其外壳植入于膈肌之下，而 HVAD 的涡轮及其外壳，植入于膈肌之上、心包腔内。文后将有详细阐述，涡轮的位置是超声心动图评价两种装置的流入管道血流特点的主要鉴别点。其他方面的超声心动图评价，两种装置基本相似。HM-II 和 HVAD 都是通过胸外的控制器进行驱动。除了作为动力来源，控制器还能连续测量和计算 LVAD 功能相关的参数指标。当这些参数超过预设值或者正常范围，控制器即报警，病人及 HF 团队即可知晓装置存在异常。文后将详细阐述控制器报警的超声心动图表现。

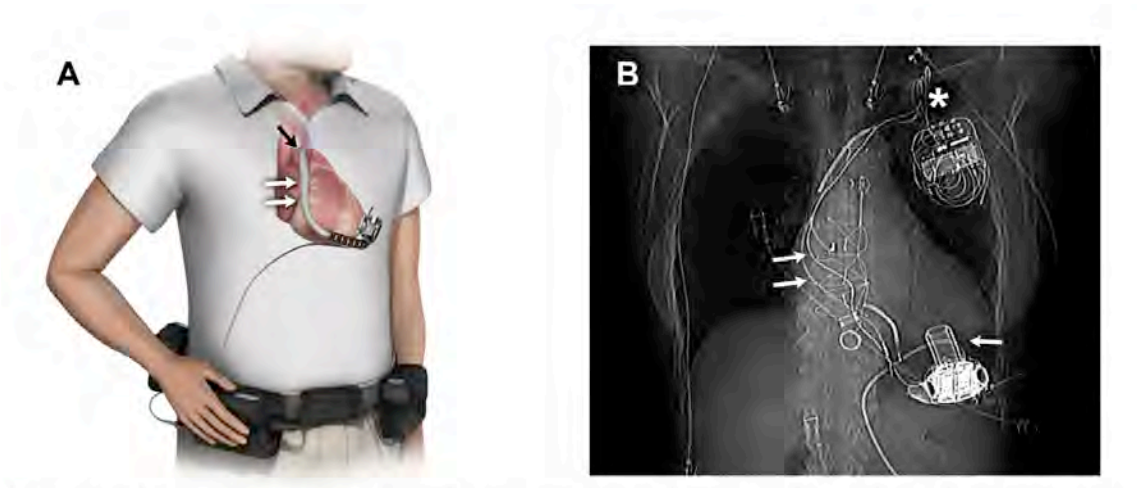


图 2（A）HVAD 示意图，提示心包内泵装置位置，右侧胸骨旁流出管道位置（双白色箭头所示）和流出管道与升主动脉吻合（黑色箭头）。（Heartware 公司提供）。（B）CT 断层成像提示左心室与流入管道的解剖关系，后者与心包内泵装置（单箭头）相连。尽管不可见，典型的流出管道应在右侧胸骨旁区域（双箭头）可见。星号提示是心脏植入式电子装置。

要点

- 目前恒流式 LVADs 有 3 个主要胸内结构：左心室流入管道，机械涡轮以及与升主动脉吻合的流出管道。
- 机械涡轮与胸外控制器通过驱动线相连。控制器检测几种 LVAD 相关参数并可以报警。这些报警需要通过超声心动图进一步证实，并提供明确的诊断。
- 超声心动图对于不同类型装置的评价总体相似，除了某些重要不同。

超声心动图在患者选择中的作用

理想的患者选择，是辅助装置的成功植入良好远期转归的决定因素之一。经胸超声心动图（TTE）是 LVAD 入组患者初筛的一线成像模式，评价患者的心脏结构、功能异常，是否存在装置植入的绝对或相对禁忌症。有些患者需要急诊外科植入 LVAD。在该情况下，全面充分的经胸超声心动图检查（TTE）可能受到条件限制甚至无法完成。而该情况之下（导管室、急诊室、重症监护室或手术室）的经食管超声心动图（TEE）需要完成经胸超声心动图（TTE）所评价的全部指标。由于超声心动图在 LVAD 患者选择的核心作地位，根据跨学会认证委员会（IAC），须行术前 TTE 或 TEE（必要时）评价，并由具有评价进展性心力衰竭（HF）和机械辅助循环支持（MCS）的经验的超声心动图医生监督和解释。LVAD 患者的术前 TTE 评价，需要包括 ASE 推荐的所有参数，尤其是针对表 1 中总结的高危发现重点扫查。全面、逐项的术前 TTE 检查模板详见附录 B 的高危标记。如果术前 TTE 无法定论，需要进一步 TEE 检查，详见后文。如果患者近期曾经有过高质量的 TTE 检查，其包括大部分参数但非全部检查的必要参数，而患者的临床状况无明显变化，那么有针对性的额外随访检查仍然可行。

左室功能不全

LVAD 受体多为扩张性心肌病引起的严重左室收缩功能不全患者。因此，超声心动图医师必须精通左室大小、射血分数（LVEF）

和心输出量的测量。

左室射血分数。医疗保险和医疗补助服务中心（CMS）将 LVEF 低于 25%，作为 LVADDT 治疗的标准。此外，LVEF 还作为西雅图心衰模型（seattle heart failure model）和心力衰竭生存得分组成部分，两种临床危险评分工具为心力衰竭专家广泛应用于计算患者预期存活时间，同样适用于 LVAD。LVEF 显著下降，并非患者是否需要 MCS 的唯一临床决定因素。因此，超声心动图对该参数的准确评价至关重要。早期 ASE 指南推荐了左室心腔内径的测量方法。基于该指南，具有技术条件及经验的超声心动图室，在患者图像质量允许的情况下，常规应用三维超声心动图评价左室容积及 LVEF；否则，应用双平面法（改良 Simpson 法）评价 LVEF。当心内膜边界显示欠清晰时，强烈推荐使用声学造影剂，从而提高 LVEF 测量的准确性。

左室舒张末期内径。除 LVEF 外，胸骨旁长轴切面测量的左室舒张末内径（LVIDd）也是评价 LVAD 的重要参数。最终植入 LVAD 的患者，对比植入前、后 LVIDd 用于评价 LVAD 植入后的去负荷程度。然而，对比植入前、后左室舒张末期容积（LVEDVs）能够更好的定量左室去负荷状态。由于患者术后平卧位、机械通气、近期胸骨切开术后、绷带缠绕以及其他物理屏障，导致标准的超声心动图声窗受到诸多限制，以上参数在植入术后早期极其难于测量。当 LVIDd 和 LVEDV 中至重度增加时，考虑植入 LVAD；有限的数据提示，当左室腔内径 LVIDd 小于 63mm 时，其植入 LVAD 后 30 天内的发病率和死亡率增加。左室腔内径偏小的患者，主要包括身材较小的老年女性患者，或伴有浸润性心肌病的人群（如心肌淀粉样变）。后者往往同时合并右室心力衰竭，另外术前高危因素将在文后详述。但是，左室腔较小的患者，亦非 LVAD 植入的绝对禁忌症，该阳性所见仍需与心力衰竭医生组沟通商榷。

心内血栓。心内血栓不是 LVAD 的绝对禁忌症，但是在 LVAD 管道植入过程中，会增加卒中风险。当患者 LVEF 显著减低或有伴室壁瘤，合并心内血栓，则患者的风险进一步增加。对于此类病人，强烈建议采用微泡声学造影评价左室血栓情况。如果发现血栓，外科医生需要在术前明确血栓的位置和大小，进而在 LVAD 植入过程中除去血栓。对于不明确的患者，建议进行心脏计算机断层扫描（CCT）除外血栓。房颤患者，左心耳有形成血栓的高危因素，需要进行 TEE 检查，进一步除外血栓形成可能。

右室功能不全

右室功能不全的超声心动图表现包括，右室功能减低、和/或右室扩大、右房压力增高（下腔静脉大小及塌陷率）、中重度的三尖瓣返流（TR）。此前的 ASE 指南，有关于右室功能及大小的定量评价方法。基于该指南，三维超声心动图通过评价右室容积，能够更为理想的评价右室射血分数，但是作者认为，该方法受到技术局限，临床应用并不广泛。超声心动图评价右室收缩功能的其他指标，包括右室的面积变化率（FAC）、三尖瓣环收缩期位移（TAPSE）、右室游离壁收缩期峰值应变，在进展性心力衰竭的患者亦很难获取。但是，如有可能，仍旧建议使用以上方法正确评价右室收缩功能。在最终的报告中，至少要体现右室大小、收缩功能以及三尖瓣返流程度的定性描述。

不能单纯依赖超声心动图阳性所见判断患者的右室功能异常，需要与患者的临床症状和体征相结合进行判断。合并严重的右室心力衰竭，HF 小组会考虑对患者植入双心室 MCS 装置，这比植入 LVAD 预后会更为理想。重度以下的右室心力衰竭，部分患者在植入 LVAD 后，右心功能会进一步恶化。机械辅助循环支持跨机构的登记（INTERMACS）定义并发症为需要植入右室辅助装置（RVAD）或静脉内持续使用正性

肌力药物超过 14 天，其预期患病率约 13%-44%，具有较高的发病率和死亡率。初步的统计结果提示，术前超声心动图能够预测术后严重右室功能不全发生。包括临床参数在内的临床多变量模型研究，提示右室纵向峰值应变绝对值小于 9.6%，舒张末期 RV/LV 比值大于 0.75，可作为超声心动图的独立预测因子。Kato 等结合超声心动图多个参数[右室组织多普勒成像、右室二维斑点追踪成型（右室纵向应变）]，能够提高 LVAD 术后预测右室心力衰竭的准确性。目前，鉴于依赖某一个超声心动图参数作为预测因子尚缺乏统一意见，左心（如左房容积指数，左室大小指数）、右心测量参数（上述右室测量参数、三尖瓣返流程度、右房压力等）相结合作为预后评价更为理想。

要点

- 基本上，所有植入 LVAD 的人群，在术前都要进行超声心动图检查，评价心脏解剖结构及功能异常，是否影响 LVAD 的植入，甚至改变手术计划。
- 本指南不推荐通过单一参数评价右心功能，用于评估植入 LVAD 或双室辅助装置（同时使用右室辅助装置）的预后。
- 术前超声心动图定量评价右心功能的参数（依患者的成像质量情况，不同患者之间差异较大），须要与患者的临床症状及体征相结合，从而避免影响手术计划甚至预后。

表 1 植入前 TTE 及 TEE 阳性所见

LV 及室间隔	
左心室腔小，尤其是左室肌小梁增多	任何人工瓣膜（尤其是主动脉瓣或二尖瓣的机械瓣）
LV 血栓	轻度以上 AR
LV 心尖部室壁瘤	中度及以上 MS
室间隔缺损	中度及以上 TR 或轻度以上 TS
RV	轻度以上 PS；中度及以上 PR
RV 扩张	**其他**
RV 收缩功能不全	任何先天性心脏病
心房，房间隔及下腔静脉	主动脉瓣病变：主动脉瘤，扩张，粥样斑块，缩窄
左心耳血栓	活动性病变
PFO 或房间隔缺损	其他分流：动脉导管未闭，肺内分流
瓣膜异常	

AR，主动脉瓣返流；AV，主动脉瓣；LV，左心室；MS，二尖瓣狭窄；MV，二尖瓣；PFO，卵圆孔未闭；PR，肺动脉瓣返流；PS，肺动脉瓣狭窄；RV，右心室；TR，三尖瓣返流；TS，三尖瓣狭窄。

注: 高危所见详见附录 B 植入 LVAD 前 TTE 模板推荐。附录 C 可见围手术期 TEE 模板/检查清单，该附录包括 LVAD 术后即刻围手术期的 TEE 检查的高危所见。

瓣膜病

早期的 ASE 指南，已经阐述了如何定量评价自体瓣膜返流、狭窄以及人工瓣膜功能异常。

瓣膜狭窄。当进展性心力衰竭患者，其每搏量严重下降，应用频谱多普勒测量跨瓣压差，无法准确评价其瓣膜狭窄的真实情况。此类病人，测量其瓣口面积更为准确可靠。中重度的二尖瓣（MV）狭窄会影响 LVAD 流入管道的血流。相反，LVAD 避开了左室流出道（LVOT），因此任何程度的主动脉瓣狭窄（AS），均不影响 LVAD 的功能。但是，

必须注意，当患者合并严重 AS，需要外科缝闭主动脉瓣或矫治严重主动脉瓣返流（AR）时，如若 LVAD 梗阻性功能异常，即使患者自身左室存在收缩功能，亦不会产生前向血流。

瓣膜返流。 LVAD 植入术前，除外 AR 意义重大。严重 AR 患者植入 LVAD 后，左室内的血液流经 LVAD 泵入升主动脉，主动脉返流会将血液逆流回左室，从而“盲路”循环。超声心动图医师很难评价进展性心力衰竭且每搏量严重减少的患者，其主动脉瓣返流程度。心力衰竭合并中重度 AR 的患者，由于体循环压力低且左室舒张压增高，其彩色多普勒的返流信号并不明显。此外，即使主动脉瓣返流分数较高，但是其返流量可能相对较少。如有可能，可通过左室流出道的血流频谱及返流分数评价每搏量。当患者主动脉根部扩张、主动脉瓣偏心性返流（尤其是主动脉瓣二瓣化畸形）、风湿性心脏病累及主动脉瓣或主动脉瓣退行性变、主动脉瓣人工瓣置换术后，应高度怀疑其存在程度较重的主动脉瓣返流。如怀疑人工瓣膜存在异常，强烈建议进行经食管超声心动图检查。当发现轻度以上主动脉瓣返流时，需要与外科医生沟通，近期指南建议，在植入 LVAD 之前，需要 TEE 明确瓣膜返流的程度，并通过外科手术修复病变瓣膜。外科处理严重自体主动脉瓣返流的术式包括：生物瓣置换、瓣膜缝合（缝合所有对合缘），或中心环缩缝合。完全缝合主动脉窦能有效减少主动脉瓣返流，但是如前所述，当 LVAD 出现机械故障时，左室将无法完成射血。如果主动脉瓣自身良好，可以进行中心环缩缝合，不仅能够减少中心性返流量，而且，当逐步降低左室辅助支持或 LVAD 发生故障时，可以允许左室通过主动脉瓣残余瓣口面积完成泵血（图 3）。

在植入 LVAD 初期，由于左室容积减少，充盈压力下降，二尖瓣叶对合改善，导致原有重度二尖瓣返流（MR）程度会明显改善。因此，LVAD 术前，任何程度的二尖瓣返流都不影响植入手术。相反，中重度的三尖瓣返流，往往提示存在右心功能不全。当发现三尖瓣返流时，需要及时与植入外科医生沟通；近期指南建议，在植入 LVAD 的同时，须进行三尖瓣的修复手术。肺动脉瓣返流（PR）在先天性心脏病患者当中更为多见。中重度的肺动脉瓣返流多与右心功能不全相关，因此，在植入 RVAD 时，需要同时修复肺动脉瓣。当右心功能良好时，即使存在 PR，在植入 LVAD 后，同样能够有效减少左室的容量负荷。但是，当存在任何原因引起的肺血管阻力增加时，包括获得性肺动脉疾病或无法有效降低左室容量负荷，重度的 PR 在植入 LVAD 后，可能导致右心功能不全。

人工瓣膜。 如符合适应症，在植入 LVAD 前，TTE 和 TEE 需要对人工瓣膜患者进行严格评估。LVAD 植入术后，无论有无机械瓣，均需要进行抗凝治疗。植入机械瓣的患者，凝血酶原时间国际标准化比值（PT INR）的控制更为严格。LVAD 植入初期，由于流经人工瓣的血流减少，进一步增加了人工瓣膜或主动脉根部血栓形成及发生栓塞的风险。因此，在植入 LVAD 的同时，往往用生物瓣膜置换原有的机械瓣膜或将瓣膜完全缝闭。功能良好的主动脉瓣位生物瓣无需进行移除或置换。同理，不建议对功能良好的二尖瓣位机械瓣进行置换，即使存在明显的 MR，在植入 MCS 后，血流也会通过人工二尖瓣口。但存在中重度的二尖瓣机械瓣梗阻时，则需要在 LVAD 植入同时，置换机械瓣为生物瓣。三尖瓣或肺动脉瓣人工瓣异常尽管较为少见，但是，该异常直接影响术后右室功能。

要点

- 人工瓣膜的位置、类型及功能直接影响外科手术及术后疗效。如果存在临床适应症，建议额外进行 TEE 成像。
- 需要特殊注意主动脉瓣返流，当患者心力衰竭时，容易低估其返流程度，在 LVAD 激活后，主动脉瓣返流恶化，主动脉内血流无法有效进入 LVAD 管道，从而影响降低左室容量负荷效果。
- 当发现中重度三尖瓣返流时，结合患者的临床症状及体征，判断其是否存在右心功能不全。
- 植入 LVAD 前，需要将主动脉瓣位机械瓣进行置换。
- 重度主动脉瓣狭窄的患者可以植入 LVAD，也可以在术中缝闭主动脉瓣，其缺点是当 LVAD 发生功能异常时，无法保障左室有效射血。
- 二尖瓣返流患者可以植入 LVAD，并且其返流程度往往在术后明显改善。

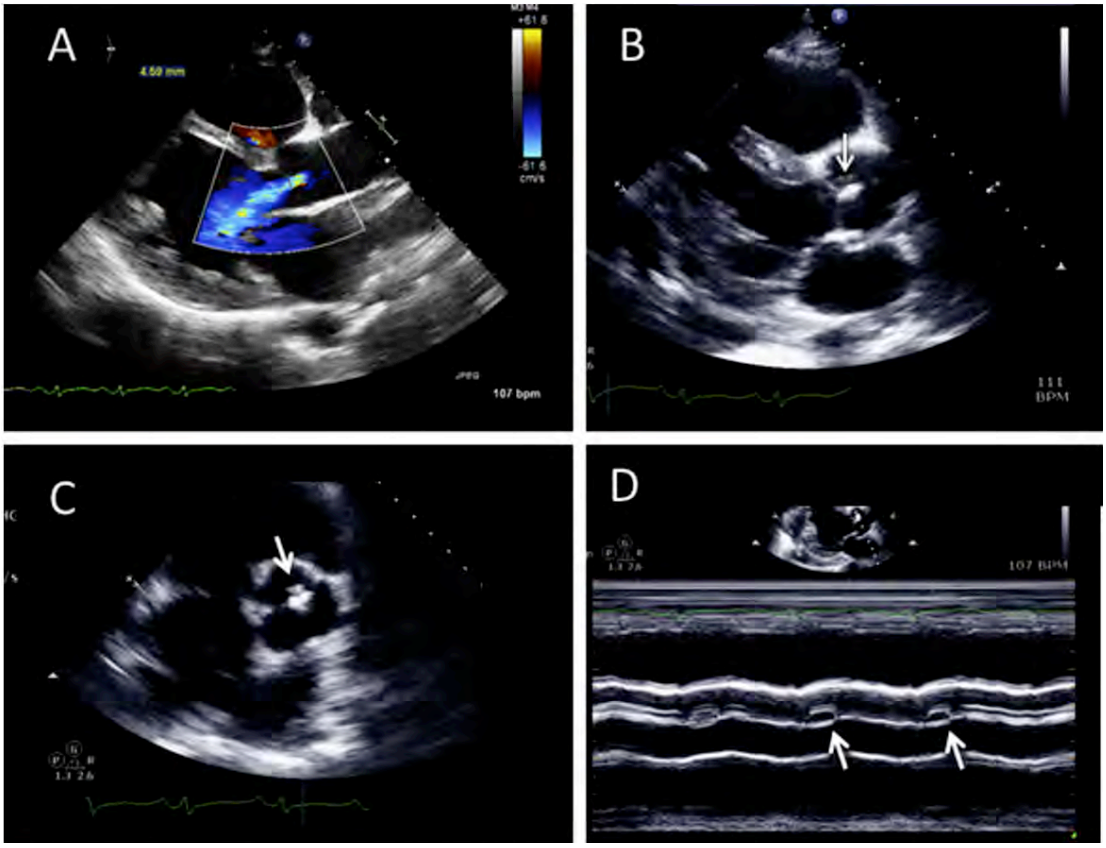


图 3（A）经胸彩色多普勒超声心动图提示 LVAD 植入术后，主动脉瓣中量返流（AR）。术中经食管超声心动图（TEE）提示主动脉瓣轻度脱垂，但瓣膜结构良好，遂行中央缝合。见视频 1。（B）经胸二维超声心动图胸骨旁长轴切面可见主动脉瓣中央缝合。（C）缝合的主动脉瓣的大动脉短轴切面。见视频 2 和 3。（D）降低 LVAD 转速，M 型超声心动图可见缝合的主动脉瓣仍有轻微开放，但无明显返流。

先天性心脏病

所有先天性心脏病患者在术前，需要全面评价心脏解剖异常、分流、侧支循环、大动脉的位置及关系。近期的研究数据提示，

包括复杂先天性心脏病在内的任何外科可以矫治的先天性心脏病，均可以通过 LVAD 作为 BTT 或 DT 治疗。某些解剖异常需要在植入 LVAD 之前进行矫治。30%人群存在卵圆孔未闭（PFO），增加了 LVAD 后低氧和矛盾性栓塞的风险。因此，卵圆孔未闭（PFO）或任何心房间交通，在 LVAD 植入前，必须进行修补或封堵。房间隔缺损（ASD）和卵圆孔未闭（PFO）合并进展性心力衰竭的患者，由于左右心房压力的增加，导致心房间压差下降，静脉注射震荡后的生理盐水，并嘱患者作 Valsalva 动作判断房水平分流，此时，单纯采用彩色多普勒或震荡的生理盐水判断房水平返流均可能发生漏诊。与房间隔缺损（ASD）相似，室间隔缺损以及心肌梗死后室间隔穿孔（VSD）的患者，在植入 LVAD 后，会出现右向左分流伴低氧血症，同时增加矛盾性栓塞风险。因此，在 LVAD 植入术前，需要彩色多普勒超声心动图全面扫查室间隔，除外室间隔缺损（VSD），一旦发现，须在 LVAD 植入术中同时修补室间隔缺损。多数病例，室间隔缺损（VSD）是 LVAD 植入的绝对禁忌症。但是，单心室患者（和未经处修补间隔缺损 VSD）的某些患者，仍旧可以植入 LVAD。

要点

- 结合其他成像模式，超声心动图是全面检出先天性心脏病重要成像方法之一。
- 超声心动图能够系统全面的检出卵圆孔未闭（PFO）和其他心内分流，在 LVAD 植入过程中同时纠正心内分流，有效避免 LVAD 术后动脉血氧饱和度下降。

其他高危因素

急性心内膜炎（或任何活动性感染）患者，LVAD 植入可能为细菌提供生存环境，因此是循环辅助装置（MCS）植入的绝对禁忌症。当发现活动性团块并高度怀疑为赘生物时，是典型的高危发现。主动脉病变（如主动脉瘤样扩张或主动脉夹层）是 LVAD 植入的相对或绝对禁忌症。因而，需要在胸骨旁长轴切面、胸骨上窝切面和剑下前面全面了解主动脉有无异常。TEE 可以用于协助诊断胸主动脉病变。如果无造影剂或磁共振成像（MRI）禁忌症，推荐进行计算机断层现象（CT）或磁共振成像（MRI），从而了解主动脉的整体情况。

要点

- 当怀疑感染性心内膜炎时，需要进一步进行评价，其为 LVAD 植入的绝对禁忌症。
- LVAD 术前，结合 CT 和 MRI 检查，全面评价主动脉的解剖情况。

术中经食管超声心动图

植入术前 TEE

需要在手术室完成 LVAD 围手术期的全面 TEE 检查，包括 LVAD 激活及稳定后的评价。当需要急诊植入 LVAD 时，术前 TEE 的评价尤其重要，是主要的筛查手段。之前的指南已经阐述了围手术期 TEE 的应用。全面、逐项的术前、术后 TEE 检查且用标记高危，详见附件 C。必须由高年资心脏超声医生或心脏麻醉医生完成该检查，其具备丰富的 TEE 及围手术期 TEE 检查经验。术前 TEE 检查的重要内容包括对 AR 程度的评价，判断是否有无心内分流、心内血栓，右室功能以

及三尖瓣返流程度的评估。以上及可能存在的其他病变（如 MS、PR 的程度，人工瓣膜功能异常，可疑赘生物和主动脉病变）在之前的检查中，很可能存在漏诊、低估等问题，甚至在手术过程中病变发生进展。以上因素可能迫使原计划的体外循环终止，而采取心肺转流术（CPB）；小的胸廓切开术转为胸骨正中切口，从而修复相关病变，甚至植入双室循环辅助装置。

如前关于 TTE 所述，由于患者处于全麻状态，动脉平均压及外周血管阻力下降，围手术期 TEE 检查可能低估 AR 程度。因此，充分评价 AR，需要通过血管收缩药物提高体循环压力完成。对于 PFO 的检出，需要降低尼奎斯特速度极限，静脉注射震荡后的生理盐水，应用彩色多普勒扫查卵圆窝位置，但仍旧存在无法确诊病例。此时，采取机械通气效仿 Valsalva 动作对诊断有益。具体方法是在中心静脉导管（如颈内静脉）内注射震荡后生理盐水，并维持 30cm 水柱的胸内压力，当右房显影后，减低胸内压力。即便采取该方法，但是由于生理盐水经上腔静脉进入右房，而个别病例，其下腔静脉血流较为丰富时，冲击卵圆窝处血流，而造成假阴性的诊断结果。因而，如若可行，采取股静脉注射生理盐水的方法，能够提高 PFO 的检出率。即便如此，仍有部分患者漏诊，在植入循环辅助装置（MCS）后，左房压力下降，出现右向左分流，方提示 PFO 存在。

要点

- 转机前的术中 TEE 检查至关重要，能够检出此前低估甚至漏诊的异常病变，直接影响外科手术计划。
- LVAD 的围手术期 TEE 检查项目清单有助于全面完成检查（见附录 C）。
- 植入前 TEE 检查包括 AR、右室功能、TR 和主动脉的评价。同时需要除外心内分流和心内血栓可能。
- PFO 的评价需要结合特殊动作，但仍旧不除外可能存在漏诊的情况。

LVAD 围手术期 TEE 检查

HM-II和HVAD两种LVAD，均在左室心尖部放置流入管道。该操作不可避免会导致左心系统进入气体。随后的TEE检查，需要协助外科医生进行排气。左房、左室（包括左室心尖部和流入管道，见图4和图5）、主动脉根部、升主动脉、流出管道与升主动脉连接（图6）、主动脉弓及降主动脉均需要逐个部位扫查。左室内的气体，常易积存于主动脉根部前右冠状动脉（RCA）开口处。急性右心功能减低或扩张，和/或三尖瓣返流程度增加，均提示可能发生右冠状动脉栓塞。因而需要密切观察，从而及时处理该并发症。在进行左室心尖开窗术时，从心肺转流术到再次恢复机械通气的一瞬间，来自肺静脉、左房及左室的气体可能再次进入心腔。此时右室功能异常可能与右冠状动脉气体栓塞有关，可能需要二次转机或重新排出心内气体。

围手术期 TEE 指导 LVAD 植入后的初始激活及速度优化

一旦LVAD激活，必须在屏幕上标注**仪器型号及初始速度**。各个中心采用的术中TEE各切面检查顺序不尽相同，但本指南建议根据文后附录C，尤其对于LVAD术后具特殊指导意义的参数，逐项进行TEE检查。表2列举出了LVAD植入术后，超声心动图的阳性异常所见。建议对植入术后早期的患者，再次应用彩色多普勒超声心动图对房间隔进

行成像，静脉注射震荡后生理盐水，明确有无房水平分流。当患者在植入LVAD后，突然发生动脉血氧饱和度下降，此前漏诊的PFO或房水平右向左分流会更易于发现，因此，此时建议再次评价有无房水平分流（见图7）。进而，评价主动脉瓣开放幅度及AR程度。短轴图像更能清晰显示主动脉瓣的开放幅度。多数病例的主动脉瓣开放程度和持续时间明显下降，甚至呈间歇性开放，其主要依赖于LVAD的转速。长轴切面，主动脉瓣M型超声心动图用于测量主动脉瓣开放的幅度（图8）。当左室流出道仅有微量血流时，奇脉或心律失常导致主动脉瓣开放呈间歇性。慢速M型超声心动图（扫描速度25mm/s，以记录更多心动周期）能更充分的显示主动脉瓣的开放情况（图8C-E）。

主动脉瓣返流。左室舒张充盈压力以 LVAD 转速升高而下降，而主动脉内压力升高，因而较术前更易出现主动脉瓣返流，因此建议在植入泵装置之前，应用彩色多普勒超声心动图再次评价主动脉瓣返流情况（图 9A）。LVAD 辅助状态下，AR（根据瓣膜开放时间）可以舒张期为主，或呈近连续性（持续至正常收缩相），或完全连续性（持续整个舒张期和收缩期）。可应用彩色 M 型和连续频谱多普勒测量 AR（图 9F-G）。AR 持续时间、AR 血流汇聚（VC）宽度，LVOT 返流束高度以及其他血流动力学参数，用以评估是否需要外科手术干预。尽管 AR 血流汇聚（VC）是定性评价指标，但是在 LVAD 支持状态下，AR 可能持续整个心动周期（图 9C），且随泵转速不同而不同（图 9D，E）。当 LVAD 故障时，如何评价 AR 严重程度将在后文阐述。但是，与此前指南一致，尼奎斯特极限为 50-60cm/s 时，汇聚血流束宽度 ≥ 0.3cm 或与左室流出道（LVOT）宽度比值大于 46%时，由于 LVAD 支持致 AR 持续时间延长，即认为至少是中度或以上 AR。无论测量 AR 压力降半时间，还是脉冲波多普勒测量主动脉舒张期逆流，在植入 LVAD 后，均无法真实评价 AR 情况。原因在于 AR 持续至收缩相。此外，这两种方法高度依赖于左室的前后负荷、主动脉脉压差，而后者在植入 LVAD 后就无法测量。但是，连续波多普勒有助于评价 AR 的时相和持续时间（图 9F，G），频谱回声强度也为定性评价返流程度提供格外信息。

右室功能不全。植入 LVAD 术后，由于右室的前负荷快速恢复正常，出现伴有或不伴有三尖瓣返流的右室功能不全并不少见。由于 CPB 等相关因素，早期出现的右心功能不全可能为一过性，也可能为右室本身功能异常而为持续性。此时，即使 LVAD 参数优化后，仍然存在明显的三尖瓣返流。LVAD 转速过高，可能加重右心功能不全的三尖瓣返流程度。当 LVAD 转速设置过高，左室腔容积过小（抽空或过度减压），导致室间隔向左室侧偏移，包括三尖瓣环在内的右室解剖结构发生形变，从而加重三尖瓣返流程度，进一步恶化右心功能。由于 LVAD 速度过高导致的一系列连锁反应最终导致“抽吸事件”，部分左室壁遮挡 LVAD 流入管道，从而被动降低了 LVAD 的血流速度。抽吸事件以及伴随的高危因素，在减低 LVAD 速度后，均会快速改善（图 10）。其他能够引起左室前负荷减少的因素，均可以引起抽吸事件。因而建议在启动 LVAD 和优化泵速后，快速评价主动脉瓣开放、左右心室大小比例、三尖瓣返流程度、流入管道的位置和血流速度。术中 TEE 检查过程中，建议调整转速的同时，重新注释屏幕上的泵转速。当泵转速较低却发生抽吸事件，或泵速较低，右心功能进行性恶化时，提示需要再次转机或植入双室辅助装置。抽吸事件亦见于其他降低前负荷（如低血容量）或后负荷过低（如败血症）等情况，其表现形式与转速过高相似。

流入管道及流出管道。流入管道的位置通常临近或位于左室心尖部，管道方向朝向二尖瓣，偶见部分管道方向与室间隔成角（见图 5）。食管中段左室切面可以评价流入管道与室间隔之间的位置关系。同步多切面成像或实时三维超声心动图能更好的评价流入管道在左室腔的位置（见图 4A，B 和图 5A）。流入管道与室间隔存在一定角度不可避免，但如果启动 MCS 后，预期的左室腔容积减少过早或过晚，均提示流入管道位置异常，而需要外科手术矫正。当左室腔较小，而流入管道又与室间隔之间存在夹角时，二者之间会发生接触，从而引起室性心律失常，和/或流入管道梗阻。而且，流入管道可能影响自体二尖瓣下装置，以上阳性所见，均需与外科医生沟通。HM-II 的流入管道，彩色多普勒可见从左室至流入道单一方向的<1.5m/s 的低速层流血流信号，在收缩期角度略有变化，且无返流（见图 5B）。部分患者的流入管道血流频谱会受到二尖瓣舒张期血流或 AR 的干扰（见图 5C）。评价 HM-II 的流入管道血流，建议使用脉冲波和连续波多普勒结合评价，从而有效除外梗阻（图 5C）。HM-II 的流入管道，其彩色多普勒出现湍流或收缩期峰值流速明显增高，均提示可能存在梗阻，可能管道与室间隔、左室腔内肌小梁、或自体二尖瓣下装置接触所造成。HVAD 的叶轮位于心包内，因而，无论彩色还是频谱多普勒，均有伪像干扰，从而影响对流入管道血流的评价。仅当 HVAD 的流入管道位于扫查区域内，才会出现彩色多普勒或频谱多普勒的伪像干扰。因而，可以避免对其流入管道成像，从而评价心内的其他结构（见图 11）。因此，HVAD 流入管道是否存在梗阻，需要通过其毗邻结构和血流动力学有无异常，进行间接判断，亦将在后文详细说明。

流出管道。评价流入管道后，就需要了解流出管道是否存在异常。TEE 无法显示流出管道近心端，中段临近心脏右侧（见图 12），远端与升主动脉连接，多数病人可见。流出管道血流汇入主动脉，彩色多普勒在右肺动脉水平（如大动脉水平或食管上段）可见流出管道血流信号（图 6 和 13）。同步多切面成像或实时三维超声心动图能更好的观察吻合口情况。必须对流出管道进行频谱多普勒测量，并要保证声束与管道平行。与流入管道相似，流出管道应为低速、层流频谱，且以收缩期血流为主。但是，流出管道的血流速度却无参考范围。即使同一患者，不同转速下，其收缩期峰值流速及舒张期流速亦有所不同；不同类型的辅助装置，由于其流出管道内径不同，也导致其流出管道速度亦不相同。但是，当流出管道（包括吻合口处）血流速度超过 2m/s 时，提示存在异常，需要进行进一步检查和监测。

最后需要指出，关胸操作可能影响流入管道和流出管道的位置，使其与开胸状态时有所不同。因此，建议在关胸操作完成后，应用TTE或TEE，即刻再次评价流出管道（包括吻合口）的位置以及血流动力学状态。

泵转速。理想的泵速选择是一个较为复杂的话题。术后恢复早期，左室前、后负荷波动较大。因此，术后（手术室内）即刻设定的 LVAD 转速，主要依据术中 TEE 参数提示 LVAD 功能正常，而与术后的再评价无关。此外，理想 LVAD 转速的选择，在不同植入中心也不尽相同。有些中心以主动脉瓣间歇开放（主动脉瓣水平 M 型超声心动图）、左室舒张末容积（LVEDV）或左室舒张末径（LVIDd）最小，作为理想的转速。部分中心则采用最大程度减少左室的负荷状态，且主动脉瓣完全关闭作为最佳转速。

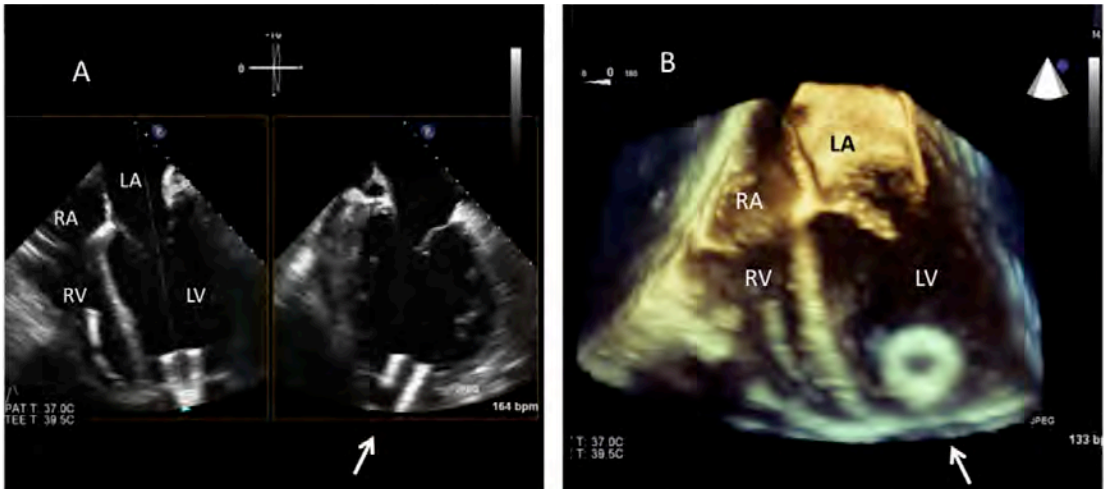


图 4　LVAD 植入术后，双平面 TEE 检查，可见左室心尖部辅助装置的流入管道（箭头所示，A、B）。同见视频 4。左右心室比例正常。右室内探及起搏导线回声。

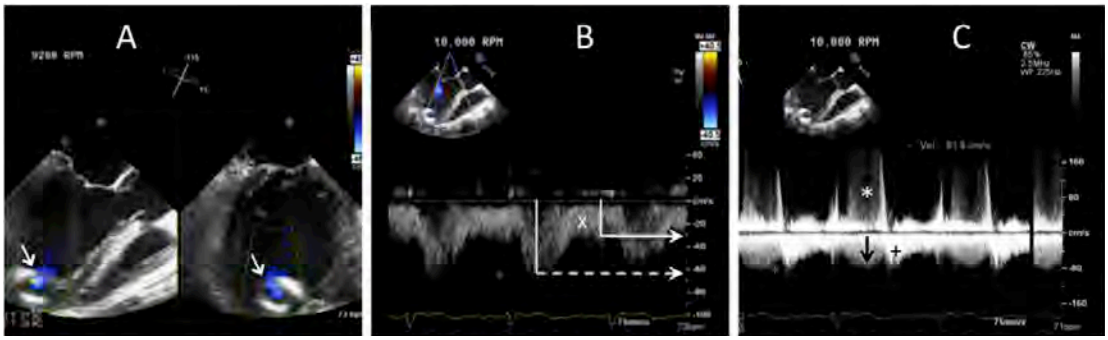


图 5（A）LVAD 植入术后， TEE 可见左室心尖部流入管道（箭头所示）开口朝向室间隔，此时未见明显梗阻，但是，在关胸后或左室容积进一步减小后，可能会导致管道梗阻。但本例患者的管道位置及流速均正常。双平面成像均未见明显梗阻，彩色多普勒显示其内血流为蓝色层流信号。见视频 5。（B）管道内脉冲波多普勒显示为连续性、以收缩期为主的典型血流频谱。虚箭头=收缩期峰值流速；X= 最低流速。（C）流入管道内连续多普勒频谱（主要用于除外有无梗阻）提示收缩期流速（黑色箭头）正常。+号为叠加血流，是流入管道内的舒张期血流频谱与二尖瓣舒张期血流的层叠。*号提示二尖瓣返流（MR）速度。

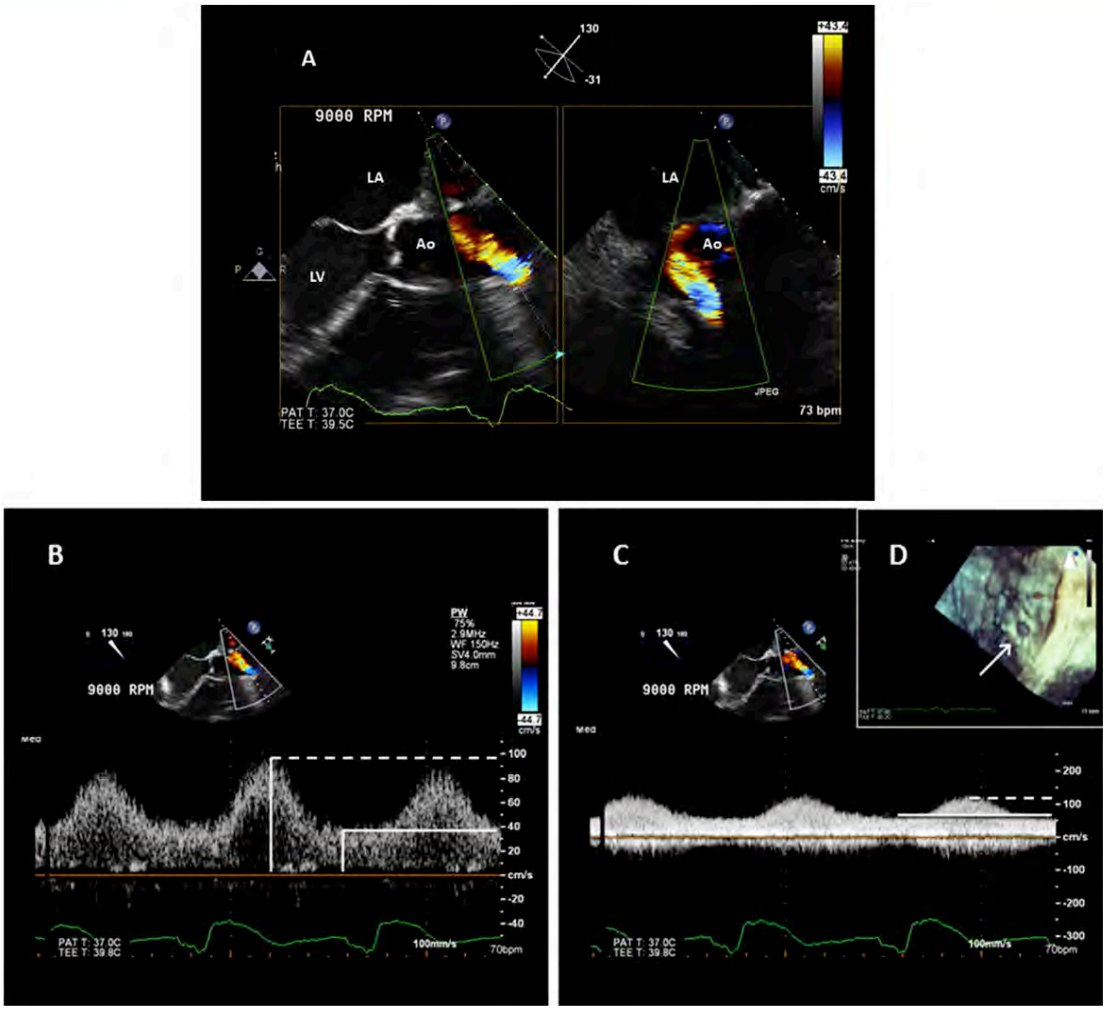


图 6 TEE 显示 LVAD 流出管道与升主动脉连接。A 多平面彩色多普勒成像显示流出管道的层流血流信号。（B）脉冲波多普勒血流频谱提示（峰值速度近 100cm/s，虚线所示）。（C）虚线所示连续多普勒测量峰值收缩速度高于脉冲波多普勒测量的 100cm/s，实线所示为舒张期低速血流频谱。（D）实时三维超声心动图可见流出道管道断面典型的圆形回声，提示无梗阻。

要点

- LVAD植入，不可避免会导致气体进入心脏，TEE有助于协助外科医生排出心内气体。
- LVAD激活后，所有图像上均应注明当时所用辅助装置型号及转速。
- 术后即刻TEE检查，在LVAD启动后及不同转速下，需要快速判断是否存在之前漏诊的PFO、主动脉瓣开放情况、左右心室大小比例关系、三尖瓣返流（TR）、室间隔位置、流出管道的位置及流速。
- 抽吸事件是指术左室部分心肌遮挡循环辅助装置的流入管道，从而导致其流速降低。该并发症常由泵转速设置过高所致（左室腔容积过小）。通过降低泵转速，通常可以有效解决抽吸事件。
- HM-II的流入管道峰值流速应低于1.5m/s。当流速过高时，提示可能存在流入管道梗阻。
- HVAD由于叶片干扰，多普勒成像存在伪像，无法评价流入管道血流速度。

- TEE可以评价流出管道及与升主动脉吻合口的形态和血流速度。
- 尽管缺少临床数据参考，但是，当流出管道血流速度超过2m/s时，提示可能存在流出管道梗阻，并需要密切观察。

表2　恒流式LVAD植入术后，超声心动图可见并发症及功能异常

心包积液

伴有或不伴有右室塌陷的心包填塞。心包填塞：血流无变化，右室流出道每搏量下降。

继发于左室部分去负荷后的左心衰竭

通过连续检查对比

a：2D/3D超声心动图：左室腔径线或容积测量提示左室增大；主动脉瓣开放时间延长，左房容积增加。

b：多普勒成像：二尖瓣口舒张期E峰流速增加，E/A 和 E/e′比例增加，二尖瓣舒张期E峰减速时间减少，二尖瓣返流（MR）增加和肺动脉收缩压增加。

右心衰竭

a：二维超声心动图：右室扩大，右室收缩功能下降，右房压力（RAP）增高（下腔静脉扩张/房间隔左移），室间隔左移。

b：多普勒成像：三尖瓣返流严重程度增加，右室流出道每搏量下降，LVAD流入和/或流出管道血流速度降低（流速低于0.5m/s提示严重心力衰竭），流入管道高流速提示可能与抽吸现象有关。注：当LVAD设置转速过高时，会导致室间隔移位，从而三尖瓣返流（TR）加重，和/或增加右室的前负荷。

左室充盈不完全或左室去负荷过度

左室腔过小（内径小于3cm或室间隔明显左移）。注：也可能是由于右心衰竭或泵转速过高所致。

LVAD的抽吸作用导致室间隔移位

左室充盈不完全，或左室心肌部分阻挡LVAD流入管道所致，降低泵转速可以解决。

LVAD相关的持续性主动脉瓣功能不全

无论LVAD流入或流入管道在正常范围内或增高，发现中重度主动脉瓣返流（AR），返流束占左室流出道面积>46%，返流汇聚内径≥3mm，左室增大，右室每搏量下降，即提示与LVAD相关。

LVAD相关的二尖瓣法流（MR）

a：原发性，流入管道受到自体二尖瓣装置的影响。

b：继发性，功能性二尖瓣返流（MR），与左室去负荷或心力衰竭有关。

注：a和b；两种情况可能并存。

心内血栓

血栓可以位于左房、右房、左室心尖部，主动脉根部。

流入管道异常

a：2D/3D超声心动图：流入管道内径减少，伴有或不伴有左室肌小梁阻挡，二尖瓣瓣下装置阻挡，或流入管道内血栓形成；流入管道位置异常。

b：彩色和频谱多普勒可见高速血流。可能是由于管道位置异常，抽吸现象或其他原因引起的流入管道梗阻：可见多普勒彩色叠加信号，连续多普勒测量流速大于1.5m/s。

c：流入管道低流速（收缩期峰值流速降低和舒张期低速血流），提示管道内血栓形成，或管道远端梗阻。多普勒血流频谱形态呈相对连续性（时相性或脉冲形态异常）。

流出管道异常

典型的是由于管道梗阻或泵停止工作。

a：2D/3D超声心动图：管道弯曲或血栓形成（少见）。

b：多普勒超声心动图：超过2m/s的血流速度，提示管道近端梗阻。远离梗阻部位的血流频谱信号减弱或消失，调整转速，右室流出道每搏量或/和左室内径无明显变。

急性高血压

与基线正常血压状态相比，患者新近主动脉瓣开放减小或消失，尤其与左室发生扩大或原扩大LV进一步恶化，二尖瓣返流量增加。注：高血压可能与泵转速过高有关。

泵功能异常或停止工作

a：彩色和频谱多普勒均提示流入管道和流出管道血流速度降低，伴有泵休止，舒张期出现逆流。

b：心衰恶化：左室扩大，MR加重，TR加重，和/或TR速度增加；泵转速变化血流动力学无明显改变：左室内径，主动脉瓣持续开放和右室流出道每搏量均无明显变化；HVAD的流入管道涡轮叶片伪像消失。

2D，二维成像；3D，三维成像；A，二尖瓣口舒张晚期峰值血流速度；AR，主动脉瓣返流；AV，主动脉瓣；BP，血压；CW，连续波多普勒；E，二尖瓣口舒张早期峰值血流速度； e′，二尖瓣环速度；HVAD，HeartWare心室辅助装置；IVC，下腔静脉；LV，左室；LVAD，左室辅助装置；LVOT，左室流出道；MR，二尖瓣返流；MV，二尖瓣；RAP，右房压力；RV，右室；RVOT，右室流出道；SV，每搏量；TR，三尖瓣返流。

*注：基于目前的观察数据。目前尚无正常流出管道峰值血流速度定义。HVAD流出管道内径比HM-II细很多。因此，HVAD流出管道血流速度均值应略高于HM-II。

LVAD 植入术后，超声心动图（TTE 和 TEE）的决策作用

LVAD植入术后，由于每个患者的临床情况不尽相同，因此超声心动图的评价也需要个体化。笔者仍旧会推荐一个评价的大体框架供参考。总体而言，LVAD的任何一次超声心动图检查，都是围绕心力衰竭展开的全面评价，不仅涵盖术前TTE的所有检查内容，而且需要包括基线转速下的LVAD特殊切面和血流动力学信息。在个别病例，还需要对某些检查参数反复测量，调整转速高于或低于基线速度。调整转速的模板，依据不同的检查适应症而有所不同。本文将LVAD超声心动图评价适应症分为三个亚类，用于指导临床决策：

1. 超声心动图监测LVAD工作状态，包括或不包括超声心动图指导LVAD的优化；
2. 针对LVAD存在问题的超声心动图检查，包括或不包括调整泵转速的超声心动图检查；
3. LVAD恢复期的超声心动图评价。

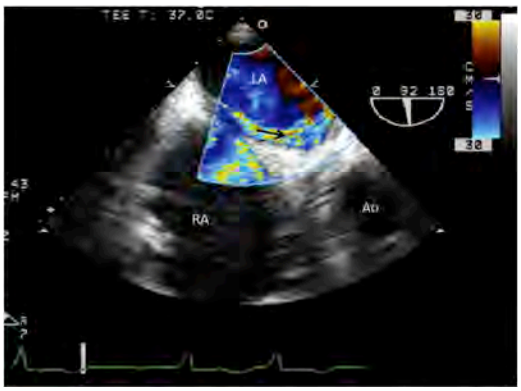


图 7　LVAD 激活后，即刻 TEE 评价，由于左室腔压力下降，可见房水平右向左分流。从而确诊此前漏诊的 PFO。尼奎斯特极限设置在 30cm/s，即可探及 PFO 的隧道样分流信号。见视频 7。

LVAD 超声心动图监测

除常规经胸超声心动图对HF的评价之外，LVAD超声心动图监测还包括在LVAD基线转速下，LVAD的特殊切面成像以及多普勒超声心动图评价。除LVAD优化模板，以基线转速基础上下调整转速，以期达到优化LVAD功能及自体心脏功能的目的。

笔者建议，如术后无明显并发症（如明显心力衰竭症状、术后14天不再依赖静脉正性肌力药物和血管活性药物、无LVAD控制器报警、无溶血或感染等血清学证据），可以定期随访TTE监测LVAD功能。建议通过**超声心动图对LVAD进行定期监测，**从而建立患者基线状态下的LVAD和自体心脏功能信息。建议LVAD植入术后2周随访超声心动图监测LVAD，或患者准备出院前，于植入术后1、3、6、12个月分别进行随访，1年以后则每6-12个月随访一次。图4总结了LVAD植入术后，TTE随访监测的时间表。对比同一患者历次随访结果，以及LVAD植入人群的同期检查结果，有助于检查者更全面的了解LVAD的有效性。并且，监测数据有助于早期诊断患者潜在的自体心脏异常（如LVAD相关性AR），或其他LVAD相关问题，早期优化转速异常。TTE监测结果与历次临床数据相结合，有助于评价患者的临床状况和制定诊疗计划。LVAD术后常规超声心动图监测（优化模板），能够早期发现和治疗相关并发症，减少再次心力衰竭的再住院率，因而认为该随访能够改善患者的预后。

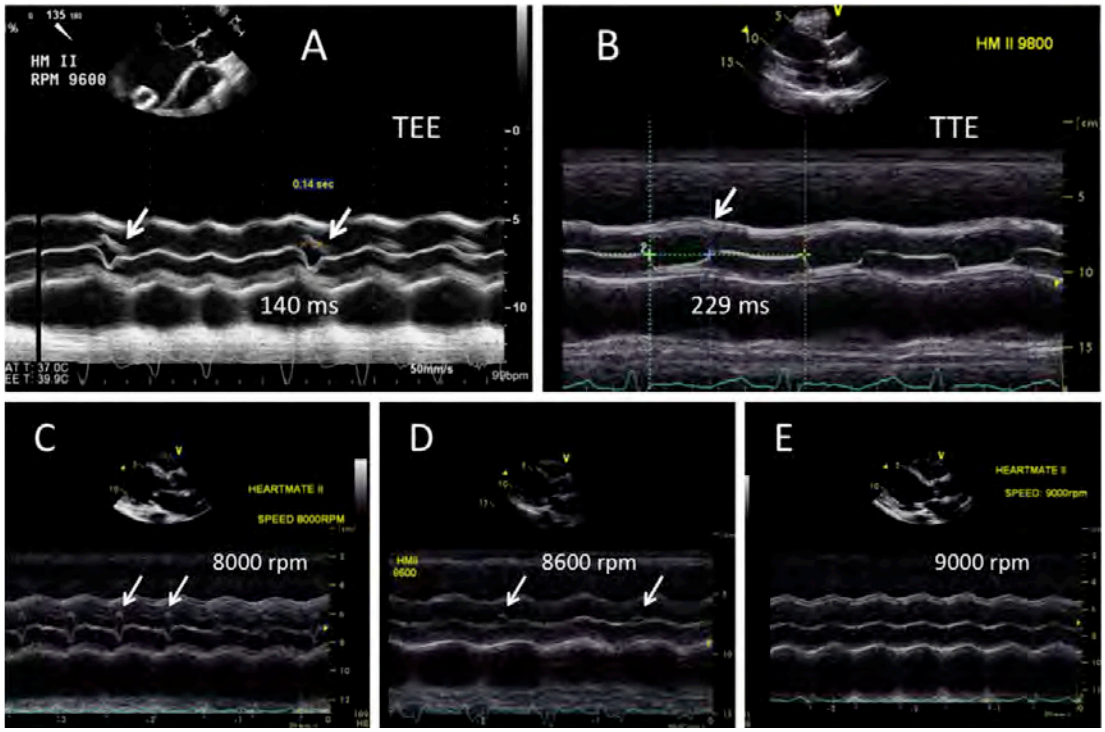
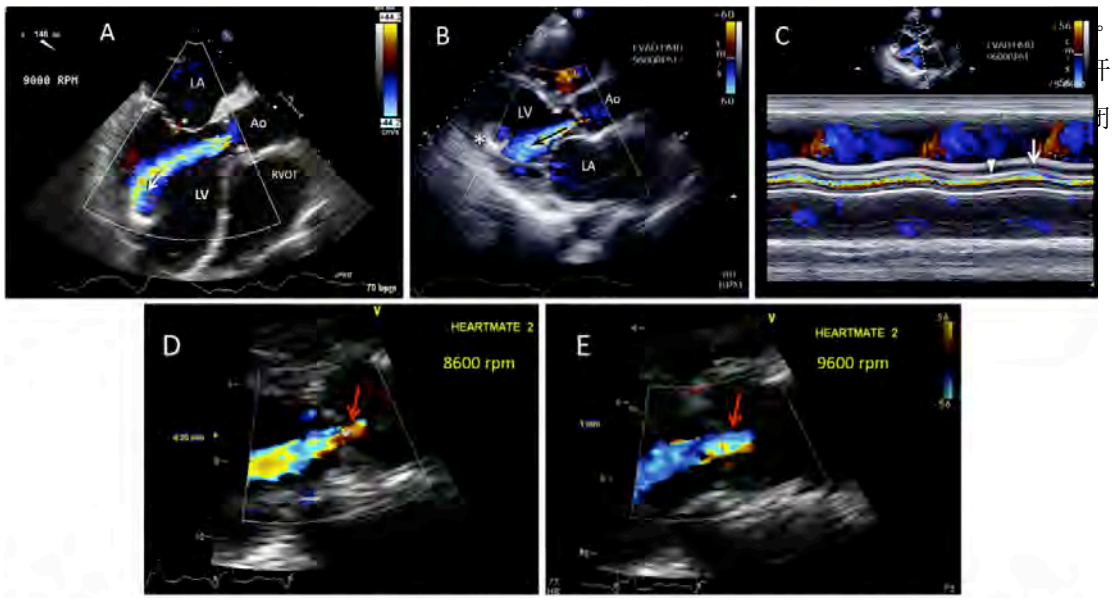


图 8　TEE（A）或 TTE（B）M 型超声心动图评价主动脉瓣口开放时间。图 A，箭头所示主动脉瓣间歇性轻微启闭活动，这可能与心律失常或正常 LVAD 转速设置在 9600 rpm 有关。图 B，近于正



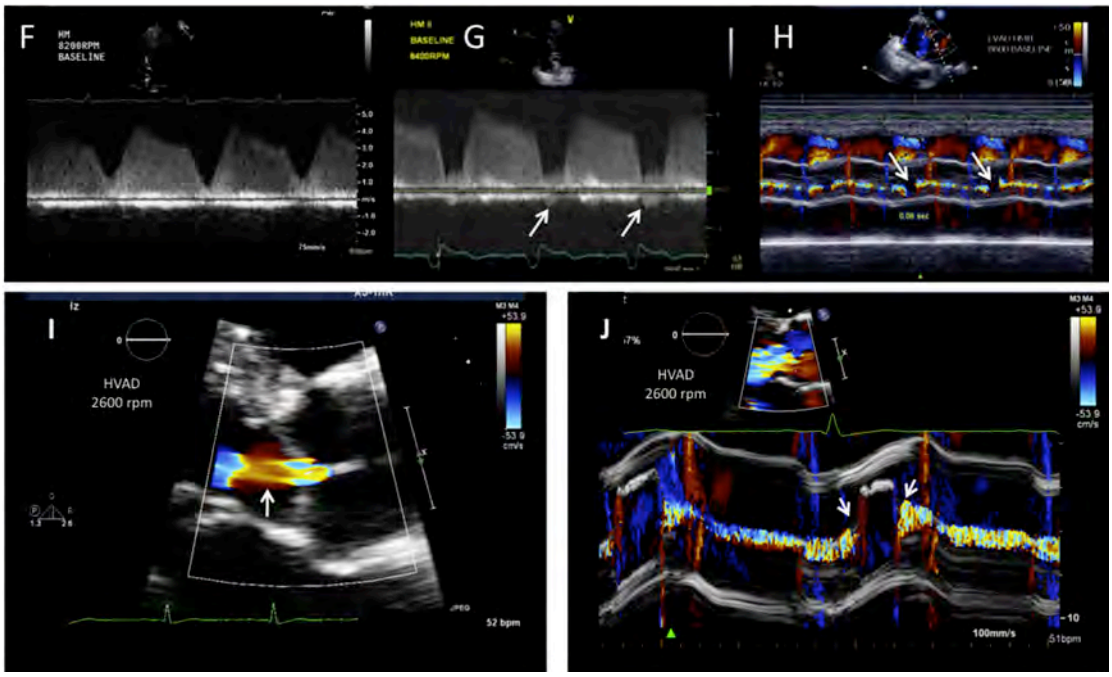


图 9 评价 AR。（A）TEE 检查，LVAD 辅助状态下，至少中度返流，甚至可能重度的持续性 AR。AR 血流汇聚>3mm，返流束宽度/LVOT 比值>46%。彩色多普勒提示返流束于收缩期进入流入管道（箭头）。二尖瓣关闭及微量的 MR （*号）也提示严重的 AR。RVOT，右室流出道。见视频 8。（B，C）LVAD 辅助状态下，胸骨旁长轴彩色多普勒（B）及彩色 M 型（C）提示至少中度持续性 AR（箭头）；星号所示为流入管道。图 C，注意彩色 M 型所示得主动脉瓣返流血流汇聚束在收缩早期（三角形所示）和收缩晚期（箭头所示）宽度变化。以上所见在不同患者表现不同，受到诸多因素影响，当泵速降低至接近主动脉瓣开放的转速时，无论是否存在 AR，都可见主动脉瓣收缩期开放。见视频 9。（D-E）随着泵速升高，主动脉瓣返流的血流汇聚束宽度随之增加。部分归因于高转速下，体循环动脉压力升高所致，进而增加了 AR 返流量。在两种转速下，VC 宽度>3mm，提示中度甚至是重度 AR。图 E 所示，HM-II 辅助装置，8600rpm 转速下，VC 宽度 4.2mm，9600rpm 转速下，VC 宽度 5.7mm。（F）TTE 心尖五腔切面，连续波多普勒提示全收缩期及全舒张期的“连续性”AR。（G）TEE 心尖五腔切面，连续波多普勒提示近连续性 AR，返流持续至电机械收缩期，主动脉瓣收缩期射血（箭头所示）。（H）彩色 M 型提示 AV 轻微开放，伴有持续收缩期前向血流（箭头所示）。（I）TTE 胸骨旁长轴切面，彩色多普勒提示 AR（箭头所示）。（J）HVAD 转速 2600rpm 下，主动脉瓣明显开放，并影响 AR。但是 AR 时相延长至电机械收缩期（箭头所示）。

要点

- LVAD术后无并发症的患者，应定期进行超声心动图随访监测，评价MCS疗效，并筛查发现亚临床并发症。
- 如果可能，超声心动图随访数据，应当与LVAD的临床随访结果相结合。

临床参数标准及超声心动图技师操作的可重复性（见表3）。在进行任何超声心动图检查之前，超声技师需要在屏幕上注明LVAD的类型以及转速，以便统计

分析。如果仪器转速有调整，需要在屏幕上重新注明当时的转速。仪器的类型和转速在超声心动图报告中也要有所体现。

血压。患者的血压状态，反应患者的外周血管阻力情况，是影响心室去负荷和超声心动图检查结果的重要参数。因此，在每次检查之前和调整转速即刻，须记录患者的血压。恒流式LVAD患者的脉压差下降且缩小，触及不到脉搏。因此，很难测量袖带血压。在重症监护室，通过有创性的动脉监测装置记录血压情况。对于无脉患者，可以用袖带和手持式多普勒探头测量肱动脉或尺动脉压力。此时注意，动脉多普勒测量的血压介于收缩压和平均压之间。实践当中，如果患者能触及脉搏（例如，主动脉瓣开放），多普勒测量的血压与收缩压等同。如果患者无脉（例如，主动脉瓣关闭），多普勒测量的血压等于平均动脉压。血压的测量，对于超声心动图的准确评价，以及调整转速，尤其是调高转速时的安全性，均至关重要。当LVAD血流量增加时，患者的血压明显增高，建议平均动脉压<85mmHg。低血压定义为平均动脉压<60mmHg，同时伴有低灌注的症状、体征。在超声心动图技师（或其他受训人员）评价植入恒流式LVAD时的一个难点就是，需要依赖于动脉多普勒测量的血压作为参考依据。为了易化恒流式LVAD的患者的管理，需要改进血压监测技术。

要点

- 尽管LVAD患者血压的测量较为困难，但是血压作为临床体征重要参数，直接影响超声心动图的评价结果。
- 无脉患者，在超声心动图检查前，需要有经验的专业人员通过可听式多普勒技术记录血压。
- LVAD泵速升高时，患者可以出现高血压。因此，每调整一个泵转速，就要测量一次血压，尤其当基线状态下，患者发生血压升高的情况。
- 建议平均动脉压应< 85mmHg。
- 低血压定义为平均动脉压<60mmHg。常伴有低灌注的症状、体征。

左室的大小和收缩功能。Lang等已经阐述过非LVAD患者，左室内径和收缩功能的径线和容积测量方法。

左室大小。如前所述，LVAD植入术后患者的二维胸骨旁长轴切面测量的左室舒张末期内径（LVIDd），具有最高的可重复性（见图15A）。正常工作的恒流式LVAD，自体心脏左室收缩功能严重减低，二尖瓣口开放变化时，很难准确判断舒张末期，从而影响测量的准确性。此时，结合心电图有助于心动周期的判断。另外，强烈建议进行声学造影，从而更好的判断心内膜边界，准确测量LVIDd。HM-II术后3个月随访，LVIDd比植入术前至少减少15%。结合心电图，对比LVIDs和LVIDd。LVIDd甚至可能小于LVIDs，该重要结果提示，患者可能存在LVAD去负荷过度和/或右心功能不全。双平面Simpson法或单平面法测量的左室容积（见图16），反应左室大小的准确性要高于M型径线测量，但是在植入LVAD术后，心尖部由于声影或放置流入管道的影响，而难以用容积法评价左室大小。这也是LVAD植入术后，超声心动图测量左室内径小于CCT测量结果的原因。LVAD植入术后，可行性测量左室舒张容积的方法应当拟合到超声随访监测中，尤其是基线泵速下的监测当中。但是，LVIDd便于获取并具

有一定的可重复性，在基线泵速和优化速度过程中，能够测量相对左室内径，用于快速对比（见图15A，15B）。LVIDd（与主动脉瓣开放程度相结合）可以作为恒流式LVAD的去负荷连续监测指标，但可供参考文献有限，且多数资料来自于HM-II的结果。但是，用于HVAD的数据参考更加有限。

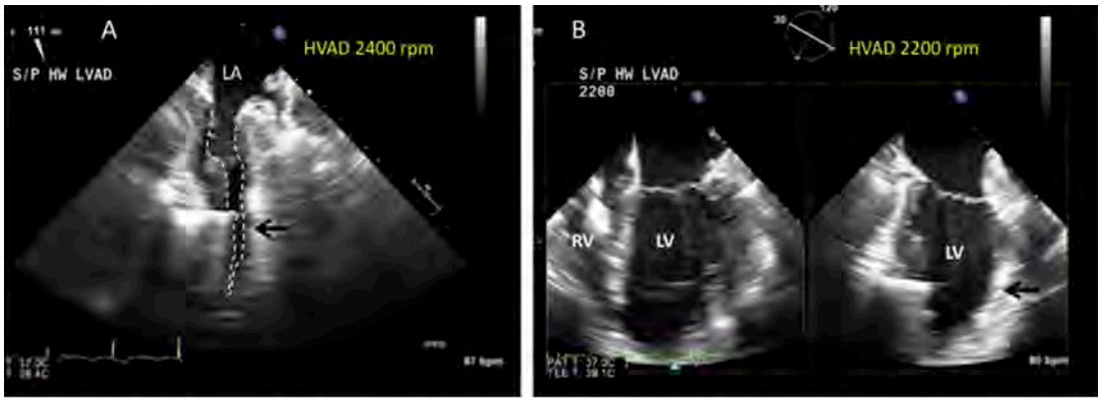


图 10　HVAD 启动后，围手术期及术后 TEE 诊断抽吸事件。最初设置的 2400rpm 转速满意，直至患者突发低血压和 LVAD 血流停滞。（A）回放图像（食管中段两腔心切面），提示左室腔近闭塞（虚线所示），左室前壁至流入管道梗阻（箭头所示）。见视频 10。（B）降低转速至 2200rpm 后，左室腔大小恢复，LVAD 正常工作。注意：该病例在停机后，左室腔过度排空，后负荷过低所致。该事件通过降低泵速，静脉输液和使用血管升压药物得以纠正。本例患者右室大小正常，未发生扩张。但是，CPB 抽吸事件可能归因于伴有右室扩张和三尖瓣返流的右室衰竭，进而左室的前负荷过低，即使降低转速纠正抽吸事件，室间隔位置仍旧可能向左偏移（见之后的 TTE 病例）。根据右室功能不全的程度，围手术期抽吸事件或右室衰竭可能或不能为一过性，内科治疗效果不确定。见视频 11。

左室收缩功能。在植入辅助装置以后，评价左室收缩功能更加困难。因此，基于LVEF之上的左室收缩功能的准确评价尤其重要。因受到图像质量（难以确定心内膜边界）以及生理因素等限制，LVEF的测量受限。由于心尖无法包罗、辅助装置造成的心尖伪影或回声失落（信号衰减），左室心内膜边界难以确认。LVAD相关的生理改变包括心室间压力变化、室间隔与左室后壁运动不协调等，而随着调整泵速，以上参数在同一患者也会发生改变。如果左室的心内膜，包括左室心尖能够充分显示，无论是否进行声学造影，推荐用双平面法（见图16）或改良Simpson法测量LVEF。尽管其他参数亦可用于评价左室的收缩功能，但是LVEF是反应左室收缩功能恶化或改善的重要指标。因而，LVAD监测和术后恢复的超声心动图应该包括LVEF，有时即使是定性评价的LVEF仍旧具有参考价值。然而，LVAD的支持明显降低了左室的前负荷，后者是决定LVEF的重要参数之一。因此，对于LVAD植入术后的患者，其LVEF必须与临床实际相结合用以评估左室的收缩功能。

其他方法：心尖部声窗欠佳的患者，但其胸骨旁图像清晰，如下方法可用于评价左室收缩功能，但其评价LVAD患者收缩功能的准确性尚未证实。

1. 左室短轴乳头肌水平二维图像测量左室面积变化率（FAC）：FAC（%）=（舒张末期面积-收缩末期面积）/舒张末期面积。
2. Quinones评价左室LVEF，该方法假设左

室心尖部不运动，而LVAD患者在心尖部植入流入管道，可以用该方法评价左室收缩功能。

3. 左室缩短（FS）（%）用于评价LVAD患者左室收缩功能：FS=（LVIDd-LVIDs）/LVIDd，LVIDs=左室收缩末期内径，上述左室收缩功能的线性和容积测量方法，因患者情况不同而需应用个体化。但是LVAD患者，由于存在节段性室壁运动异常、室间隔矛盾运动、心室间不同步或室间隔偏移等问题，且随泵转速不同而不同，不适用或建议用方法1或3作为常规评价手段。注意：LVAD患者每个心动周期每搏量不同，因此不推荐通过左室每搏量计算LVEF。之前的研究结果提示，植入HM-II的患者术后6个月，多数病情稳定的患者出现持续性中重度左室收缩功能减低。

要点

- 植入恒流式LVAD患者，LVIDd是评价左室去负荷状态可重复性最好的参数。
- LVEDV与LVIDd比值能更准确的反应左室腔大小。
- 植入LVAD后，左室容积和LVEF测量难度增加。建议使用双平面Simpson法测量LVEF（尤其建议用于左室功能恢复的患者）。

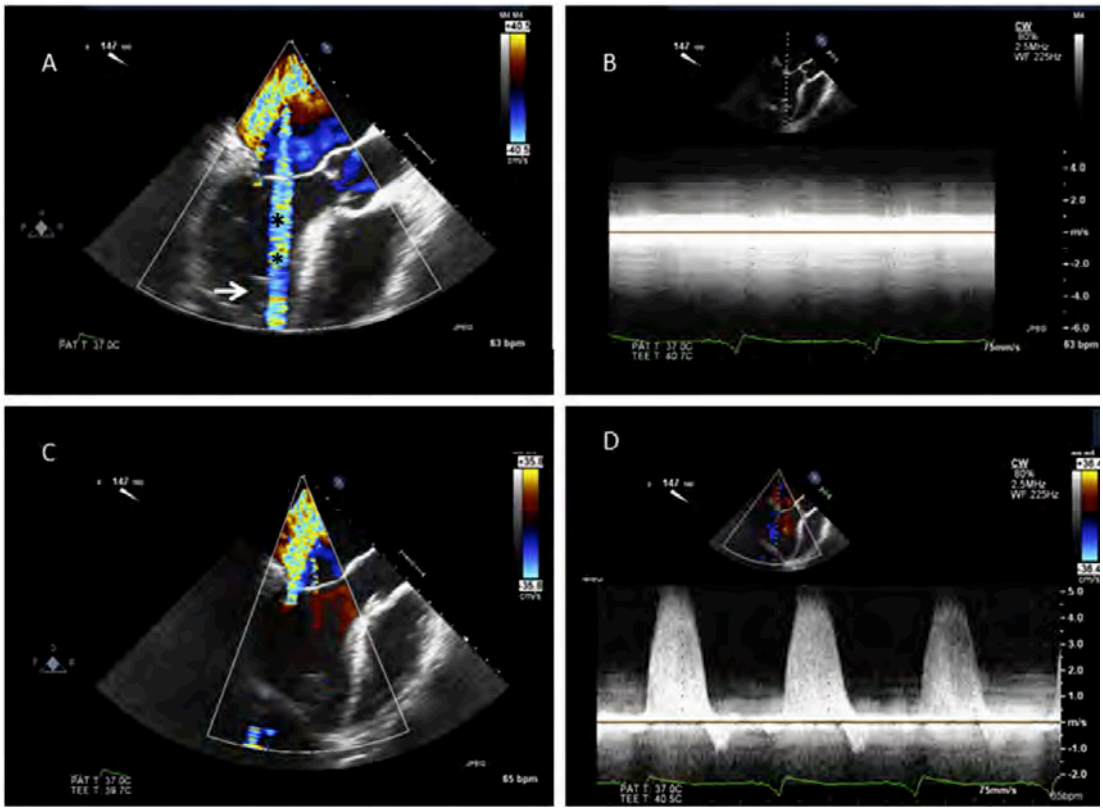


图 11 由于存在彩色（A）（**）和频谱多普勒伪像（B），超声心动图很难获得 HVAD 流入管道情况。见视频 12。当二维成像避开流入管道（C）时，伪像消失，可以获取其他结构的多普勒信息。（D）将探头稍旋转避开流入管道后，成功记录同一患者的二尖瓣返流频谱。由于二维图像（A，箭头所示）提示流入管道朝向室间隔，需要通过 TTE 或 TEE 等其他方法确定流入管道血流速度正

常。见视频 13。

左室舒张功能。假设认为，LVAD患者，基线状态下存在严重舒张功能异常。尽管超声报告中，有关左室舒张功能参数的测量，但是其在LVAD植入术后的临床实用性仍有待证实。有些舒张功能参数，结合患者的临床症状，具有一定意义，与前次检查或不同转速相比，报告医生可以对比左室去负荷状态的改变。之前的研究结果提示，植入HM-II后3-6个月的患者，其二尖瓣口血流速度E峰（cm/s）、左房容积（ml）、肺血管阻力（wood单位）、肺动脉收缩压（mmHg）明显下降，二尖瓣减速时间（ms）明显延长。以上参数是否能够影响植入术后的临床决策及转归尚不明确。以服务于临床作为出发点，随访超声心动图应遵循该原则：植入恒流式LVAD的患者，不评价左室舒张功能不全（假设舒张功能存在异常）。

要点

- 假设认为，LVAD患者基线状态下，存在明显的左室舒张功能异常。
- 评价舒张功能的参数是否能够影响植入术后的临床决策及转归尚不明确。

右室大小和收缩功能。右室的大小和收缩功能测量的标准化方法很多，包括内径测量、右室FAC、TAPSE、右心输出量，均适用于在LVAD患者。但是，近期的研究结果提示，在外科心胸手术后，TAPSE与右室总体收缩功能之间的相关性减弱，因此，该参数评价LVAD术后临床意义有限。目前关于LVAD术后，右室收缩功能预期改善的结果彼此矛盾：一项研究结果提示LVAD术后3个月，右室FAC明显改善；而另一项研究结果则提示，术后1-6个月，右心功能无明显变化。

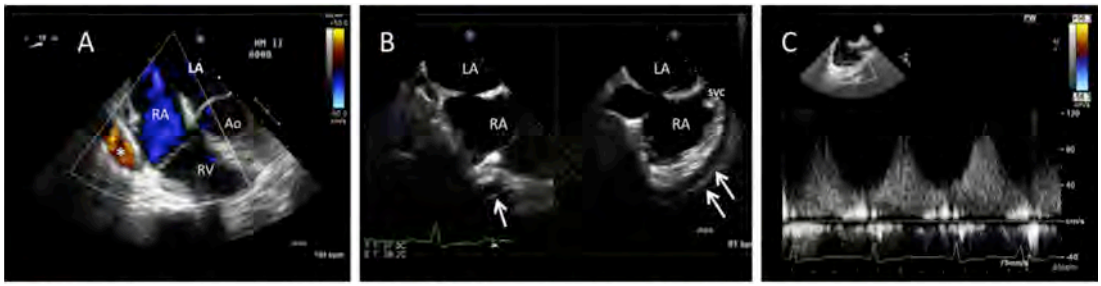


图 12　TEE 评价 LVAD 流出管道。（A，B）在改良的经食管超声四腔心切面（A），可见流入管道的近似横断面（*）。见视频 14。（B）多切面同步显像，分别可见流出管道的短轴（单箭头）和标准双腔静脉切面右房上部的流出管道长轴（双箭头）。见视频 15。（C）成功记录流出管道血流频谱（实践中并非经常能够获取）。见视频 16。

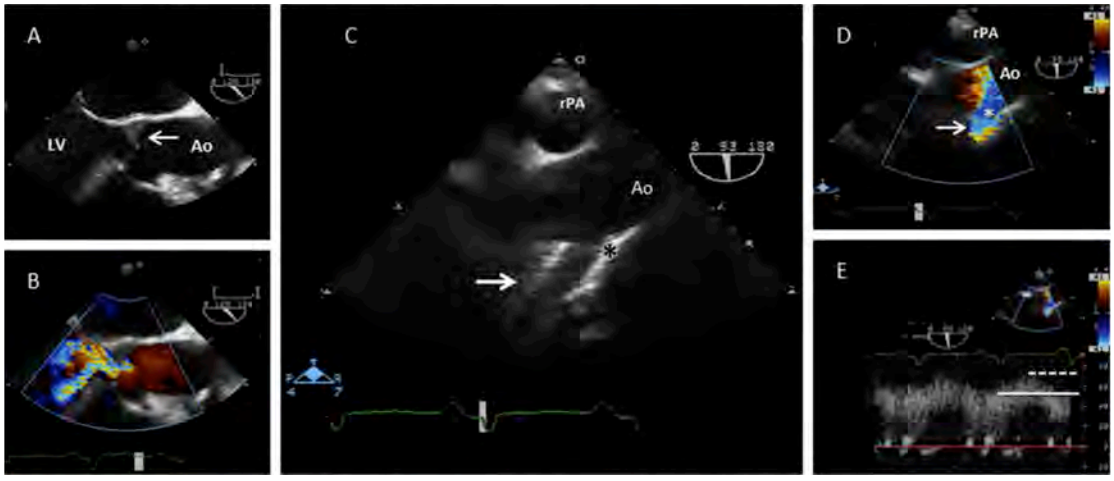


图 13 长期 LVAD 辅助的患者，TEE 检查提示由于主动脉瓣融合所致的严重 AR。（A）主动脉无冠窦探及附壁血栓（箭头所示）。见视频 17。（B）彩色多普勒提示严重主动脉瓣返流。见视频 18。（C）以右肺动脉（rPA）作为声窗，食管上段升主动脉长轴切面显示流出管道（箭头）及其与升主动脉吻合口（*）。（D）彩色多普勒评价流出管道与升主动脉吻合口情况。见视频 19。（E）流出管道与升主动脉吻合口频谱多普勒提示高流量层流信号，收缩期（虚线）与舒张期速度（实线）相似，与严重 AR 有关。

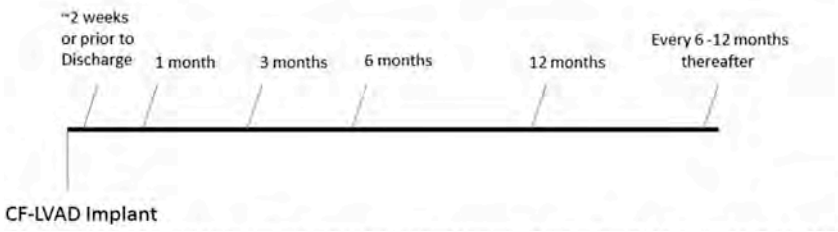


图 14 无装置功能异常的患者，初次及随访超声心动图监测的时间表示例。

瓣膜评价。*主动脉瓣*-评价主动脉瓣开放程度至关重要，主动脉瓣开放直接影响诸多参数的评价，包括LVAD的转速、自体左室功能、血容量及外周血管阻力。此外，主动脉瓣是否开放还提示其他临床意义。近期指南建议，将LVAD转速调至最低，达到主动脉瓣间歇开放的目的，但是，在自体左室功能极度受损的患者，即使转速调至最低，主动脉瓣仍旧无开放。M型扫描（扫描速度25-50mm/s）记录多个心动周期（5-6个心动周期），能最为准确评价主动脉瓣开放的频率（见图8D，E）；瓣膜可以在每个心动周期均开放，或呈间歇性开放，或呈持续性关闭。很多心力衰竭小组，要求记录M型主动脉瓣开放时间间期，该参数可能在每个心动周期都有变化，因此建议测量几个心动周期数值并取其均值。当主动脉瓣相对持续性开放，适宜用最快扫描速度（75-100mm/s）进行记录测量（图8A，B）。图17注释了M型记录主动脉瓣开放以及持续时间的缺陷。主动脉瓣半月瓣的构造、心脏的牵拉运动、轻度离轴成像，可以造成主动脉瓣开放的假阳性诊断。此时，需要结合彩色多普勒，除外主动脉瓣“假性开放”或夸大主动脉瓣开放时间的可能。有趣的是，某些主动脉瓣轻微开放的患者，其瓣膜开放时间以及收缩期前向射血速度时间不尽相同，采用彩色M型可以协助诊断（见图9G，H）。对于主动脉瓣持续关闭的患者，需要特别注意主动脉根部有无血栓，可能为一过性或与瓣膜融合有关。主动脉瓣的持续关闭可能与主动脉根部血栓形成以及LVAD引起的AR有关，详见文后。无

论是外科还是瓣膜长期关闭造成的主动脉瓣融合，超声心动图在不同转速下能够加以区别（详见文后）。

LVAD植入术后12个月，约25-33%的患者出现新的AR，直接影响是LVAD作功、致病率和死亡率。多项研究结果提示，LVAD植入术后，主动脉瓣持续关闭，即使主动脉根部无血栓形成，亦是新发主动脉瓣返流（AR）的危险因素（图18）。在术后TEE监测部分所阐述相关原因，定量评价主动脉瓣返流（AR）的标准化方法，在LVAD植入术后可能不适用。LVAD植入术后，缺乏评价轻度、中度及重度AR的明确诊断标准，需要对患者进行一个总体评价，包括时相（以舒张期为主对比连续心动周期）、AR的血流汇聚（VC）宽度、返流束所占左室流出道高度、LVAD管道及自体心脏流出道的测量，以及左室腔大小。此外，超声心动图发现明显AR时，在针对LVAD异常的筛查中，需要与装置控制参数和不同转速心脏的反应相结合，进行分析，详见后文。

要点

- 建议记录多个心动周期的彩色M型，扫描速度25-50mm/s，准确计算主动脉瓣开放的频率和时间。
- 主动脉瓣持续关闭可能与主动脉根部血栓形成及新发主动脉瓣返流有关。
- 如果主动脉根部可疑血栓形成，一定避免降低LVAD泵速（如例行检查转速调整），以免主动脉瓣突然开放。
- LVAD植入术后，主动脉瓣返流并不少见。在胸骨旁长轴切面，结合彩色多普勒成像，详细评价返流程度。

表3 超声技师检查清单：LVAD特殊人群统计数据，图像获取，改变泵速的超声心动图检查的安全性（优化，针对装置异常的筛查/泵速递增试验）

√	超声技师检查清单
	检查顺序
	● **监测，初次**（±优化，出院前/出院）
	● **监测，出院后**（±优化，术后1,3,12,18个月等）
	● **基线泵速下装置异常筛查**
	● **基线泵速下及调整泵速后的装置异常筛查**
	● **心肌恢复检查**
	相应的内科医师负责
	植入日期备案
	如存在症状需记录
	装置报警：如报警，记录报警类型

	其他主要病史/或相关适应症
	低泵速测试前充分的抗凝治疗
	在工作表单及检查屏幕记录 LVAD 型号
	在工作表单及检查屏幕记录 LVAD 泵速（基线和调整转速）
	由专业人员在每次检查时，在工作表单及检查屏幕记录血压（袖带或多普勒）
	由专业人员调整泵速
	质控：由有资质专业人员调整泵速；识别安全终点（如低血流量，抽吸事件，低/高血压）
	主动脉根部血栓形成：不再调整泵速原因（较低泵速将导致主动脉瓣开放）
	调整泵速终点： ● 完成检查 ● 低血压 ● 高血压 ● 出现新的症状 ● 装置报警 ● 抽吸事件 ○左室腔减小（典型<3cm） ○室间隔向左偏移 ○流入管道血流阻碍 ○由于室间隔偏移或右室扩张导致三尖瓣返流加重 低心输出量

AR，主动脉瓣返流； AV，主动脉瓣；LV，左心室

二尖瓣。如前所述，左室去负荷通常会导致扩张的二尖瓣环缩小、瓣叶对合改善、二尖瓣返流（MR）程度减低。LVAD激活后，持续的MR可能提示左室去负荷不足，或流入管道位置异常，影响二尖瓣下装置。如果存在MR，通过标准化方法进行定量评价。LVAD植入术后出现的MR，可能与LVAD功能异常有关，需要与临床医生沟通商榷。

三尖瓣和肺动脉瓣。同MR相似，中重度的三尖瓣返流（TR）可能与左室去负荷不足（功能性TR）、左室去负荷过度导致室间隔向左偏移（抽吸事件）、肺动脉收缩压升高、和/或右室收缩功能不全等有关。利用超声心动图区别以上病因将在后文详述。LVAD植入术后，通常采用标准化方法评价TR。LVAD植入术后，自体肺动脉瓣功能良好，当出现肺动脉瓣狭窄或返流时，可以采用标准化方法进行评价分析。如前关于围手术期TEE的描述，术前已存在明显的肺动脉瓣返流，或植入术后出现严重肺动脉瓣返流，往往与右心功能异常有关，可能需要植入RVAD。

室间隔位置。舒张末期室间隔的位置，往往取决于心室之间的压力梯度，一般描述为居中、左移或右移。室间隔左移归因于右室舒张末期压力增高，左室前负荷减少，泵速过高所致的左室过度减压；病因的鉴别诊断详见后文。室间隔右移，往往是由于泵速过低、左室舒张末期压力高、泵功能异常、严重AR或左室后负荷增加。

流入管道和流出管道吻合口。*流入管道*。-通常位于心尖部，标准或改良的

胸骨旁二维图像能够充分暴露流入管道。超声技师的主要目标是明确流入管道的位置、其与室间隔的空间关系、以及其他心内结构情况。三维超声心动图通常可以显示流入管道，有经验的医师可以通过三维超声心动图提供更多信息。围手术期TEE部分曾提及，彩色多普勒声束与流入管道平行时，能探及从心室到流入管道的层流血流信号，不存在湍流或返流。脉冲或连续波多普勒成像，在改良胸骨旁、心尖和短轴切面，通过离轴取样，使声束与管道平行，测量真正的同轴速度；测得的实际流速一般低于1.5m/s。当主动脉瓣关闭，依自身左室收缩力不同，流入管道血流呈一定程度的时相性。推荐记录至少3-4个心动周期的收缩期峰值速度和舒张期低速（图5和19）。

基线转速和不同转速下，需要用CW测量流入管道血流速度，以避免漏诊流入管道梗阻。注意：主动脉瓣返流和二尖瓣舒张期血流可能会干扰流入管道的血流频谱追踪（图20）。此外，TEE记录流入管道血流频谱，容易受到二尖瓣返流血流的干扰（图5C）。由于HVAD的叶片影响，其流入管道存在伪影，因此无论彩色多普勒还是频谱多普勒均无法评价其流入管道速度（图21）。

流出管道。-与流入管道不同，一般在非标准切面获取流出管道图像。左侧高位胸骨旁切面获取流出管道远端及与主动脉吻合口图像（图22和23）。嘱患者采取右侧卧位，在右侧胸骨旁切面，可以获取流出管道中段图像。以上切面可以结合彩色或频谱多普勒；同流入管道频谱，推荐记录至少3-5个心动周期的流出管道频谱多普勒，测量收缩期峰值流速和舒张期速度并取其均值（图24）。此时，值得注意的是，依据超声技师放置取样容积的方向（远端比近端）不同，流出管道血流速度频谱轮廓，可能位于基线之上或之下。除保证血流方向与多普勒声束同轴之外，关于流出管道血流频谱方向正负尚无标准化建议。在个别病例，依据体位不同，可以于剑下或胸骨上窝切面观察流出管道情况。在相似流量情况下，HM-II流出管道（内径16mm）流速略低于流出管道内径更小的HVAD（内径10mm）。另外，两种辅助装置的全收缩期和全舒张期流速相似。流出管道脉冲波多普勒速度时间积分（VTI）可用于直接评价LVAD流出管道流量（见图22及后文详述）。

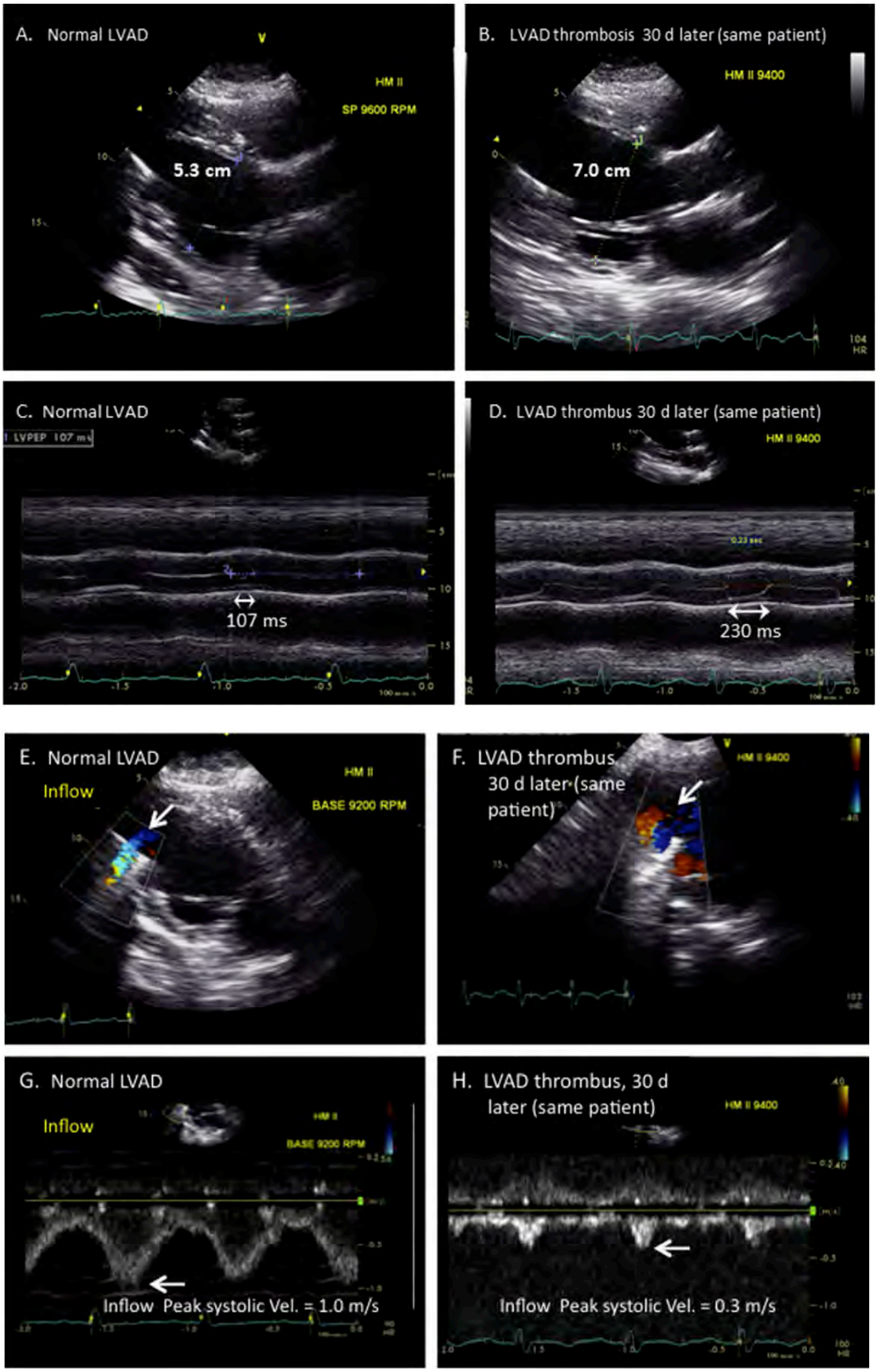
要点

- 当二维超声动图诊断不明确时，可以结合三维超声心动图，评价流出管道与室间隔的位置关系以及心内其他结构情况。
- 植入HM-II的患者，可以应用同轴脉冲波多普勒记录流出管道收缩期峰值速度、舒张期流速以及流出管道血流速度。
- HM-II的流入管道血流速度应低于1.5m/s，当流速增高时，提示流入管道可能存在梗阻。
- 由于多普勒伪影干扰，无法评价HVAD流入管道血流速度。
- 根据频谱多普勒的记录情况，采集3-5个心动周期的频谱多普勒图像，测量流入管道收缩期峰值血流速度、舒张期血流速度以及流出管道血流速度并取其均值。
- 尽管缺乏临床证据，但是当流出管道任何位置血流速度大于2m/s时，提示可能存在梗阻。

自体心脏和LVAD血流量评价。无明显肺动脉瓣返流时，心脏的净输出量（自体左室净流出量和LVAD流出量总和）等同于右心输出量。右心输出量计算参考以下公式：右室流出道输出量=右室流出道脉冲波VTI×[3.14×（右室流出道内径/2）^{2}×心率HR]（见图25）。当主动脉瓣关闭且无明显主动脉瓣返流，右室流出道算得心输出量等同于LVAD心输出量。当主动脉瓣明显开放时，脉冲波多普勒可以计算左室流出道VTI，LVAD输出量等于右室流出道输出量减左室流出道输出量。当主动脉瓣明显返流且无明显主动脉瓣开放时，由于存在LVAD至主动脉之间的盲路循环，因此LVAD的实际流量大于右室流出道计算所得心输出量。当患者存在轻度以上AR时，可以通过流出管道脉冲波频谱直接计算LVAD流量，公式如下：LVAD心输出量=LVAD流出道脉冲波VTI×[3.14×（LVAD流出道内径/2）^{2}×心率HR]（图22），但该方法尚未在HVAD中证实。应用此公式时，建议结合彩色多普勒图像，测量流出管道内径，而非采用厂家直接提供的流出管道内径进行计算，后者可能导致高估心输出量。主动脉瓣返流量=LVAD搏出量-右室流出道搏出量（见图25）。以上测量方法可以用于评价正常或异常的LVAD血流，从而在LVAD控制器报警之前（报警讨论见后文），提前知晓装置异常。

要点

- 主动脉瓣不开放，不伴有明显的 AR 或 PR，右室流出道心输出量等于 LVAD 流量。
- 如果主动脉瓣开放，则可以计算左室流出道输出量；右室流出道心输出量减去该值即等于 LVAD 流量。
- 当存在明显的 AR，而无主动脉瓣开放时，最好的方法是通过流出管道直接计算心输出量。估算出返流量，并减去右室流出道输出量。


A. Normal LVAD
HM II
SP 9600 RPM
5.3 cm
B. LVAD thrombosis 30 d later (same patient)
HM II 9400
7.0 cm
C. Normal LVAD
107 ms
D. LVAD thrombus 30 d later (same patient)
HM II 9400
230 ms
E. Normal LVAD
Inflow
HM II
BASE 9200 RPM
F. LVAD thrombus 30 d later (same patient)
HM II 9400
G. Normal LVAD
Inflow
Inflow Peak systolic Vel. = 1.0 m/s
H. LVAD thrombus, 30 d later (same patient)
HM II 9400
Inflow Peak systolic Vel. = 0.3 m/s

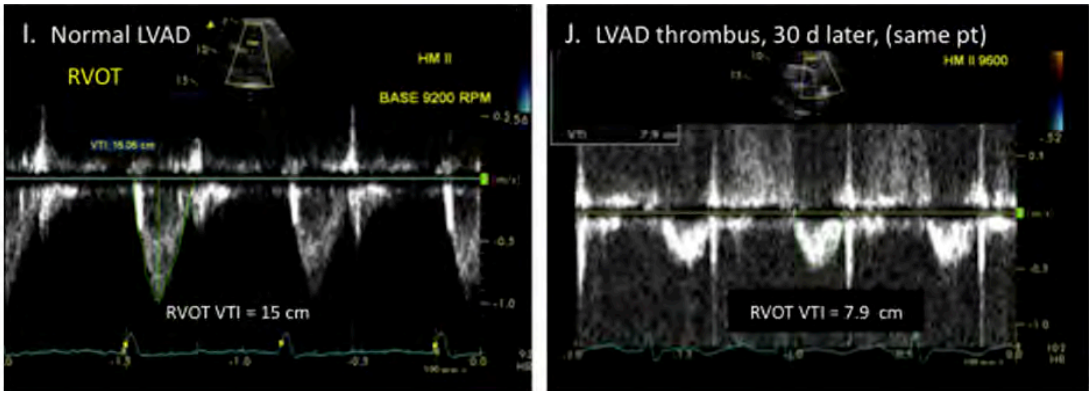


图 15　HM-II 患者，两次检查逐幅图像对比，提示涡轮叶片血栓形成。（A）LVIDd，LVAD 功能正常；（B）血栓形成后，LVIDd 增大；（C）LVAD 功能正常时，主动脉瓣 M 型超声，最小开放（107ms）；（D）诊断血栓形成后，主动脉瓣开放时间明显延长（230ms）；（E，G）功能正常的 LVAD，流入管道彩色血流（箭头）和脉冲波多普勒成像（见视频 20）；（F，H）彩色（箭头）和脉冲波成像，提示血栓形成后，流入管道收缩期血流速度极低，舒张期血流接近停滞（图 H）；（I）LVAD 功能正常时，RVOT 脉冲波多普勒 VTI=15cm；（J）LVAD 血栓形成后，RVOT 脉冲波多普勒 VTI=7.9cm。

超声心动图对左室辅助装置速度和安全的评价

在进行 LVAD 优化调整速度或装置问题检查时，需要进行速度变化测试。在调整泵速之前，推荐明确患者的抗凝状态。

达到治疗剂量的华法林或肠外抗凝治疗是泵速测试的前提。调整泵速的风险包括，未确诊的主动脉根部、泵内部和外周潜在的血栓，在主动脉瓣突然开放时（恢复了脉冲血流）导致栓塞事件，尤其在泵转速低时，更易发生。总之，在基线状态下，主动脉根部或心内可疑血栓时，慎重考虑调整泵速。在开始 LVAD 优化或针对装置问题的超声心动图检查之前，MCS 有经验的成员会立即采取解决潜在问题的方法和安全措施。在 MCS 医生或经验丰富的超声心动图医生监测下，进行 LVAD 优化检查，需要一名 HF 医生指导整个优化过程，包括具体优化的转速、每一个转速对应的超声心动图测量参数、每个病人所界定的 LVAD 优化转速、以及最终结论里应述及的泵速度（如优化速度以及基线速度）。结构性顺序模板可以引导检查过程，示范性模板见表 3，同时也概述了终止速度测试的原因。主要原因包括，（1）检查完成；（2）抽吸事件（泵速过高）；（3）出现新症状，包括但不仅限于如心悸、头晕、胸痛、呼吸苦难、头痛，可能与低灌注或血压过低有关；（4）高血压；（5）管道血液逆流。由于提高泵速会明显增加平均动脉压，因此在调整泵速时，需要再次测量血压。在泵速较低而平均动脉压反而升高（高血压）时，流出管道可能产生逆流。在调整每一次泵速后，均需要记录流入管道彩色和频谱多普勒，以期实现：（1）随着泵速逐渐增高，收缩期峰值流速和舒张期流速逐渐降低（图 24）；（2）可能出现血液逆流（流速降低或泵功能异常时）（见图 26）；（3）流入管道梗阻（图 27 和 28）（抽吸事件）；（4）由于泵管道内部血栓形成、其他机械性梗阻或明显的 AR 等原因，导致在不同泵速下，血流频谱形态消失或无变化（见图 15H）。每提高一次泵速，应用脉冲波和连续波多普勒频谱，记录流入管道的血流动力学情况，从而可以筛查流入管道梗阻。尽管在基线状态

下，多普勒成像评价流出管道血流有意义，但是在随后调整转速检查中（如 LVAD 优化，或针对装置问题检查）意义有限，除非在基线状态下，血流存在异常，或相关信息与临床异常有关。由于多普勒成像无法评价 HVAD 流入管道的血流速度，其流出管道评价尤为重要。

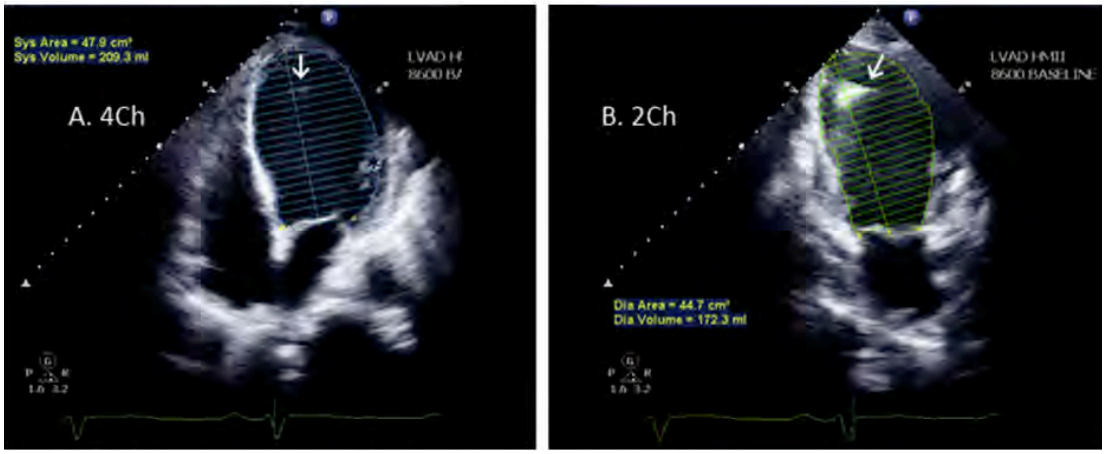


图 16 如可能，推荐使用双平面 Simpson 法测量 LVEDV 评价左室大小。单平面 Simpson 法评价 LVEDV（在四腔切面（A）或二腔切面（B））亦可满足评价左室大小的需要，优于 M 型线性测量（如图 15）。流入管道（箭头）和前外侧乳头肌（*）应勾画在心腔内。注：图 B，左室心尖部室壁瘤重构（相对左室基底），在胸骨旁长轴切面的径线测量可能导致低估左室腔大小（如图 15A，B）。见视频 21 和 22。

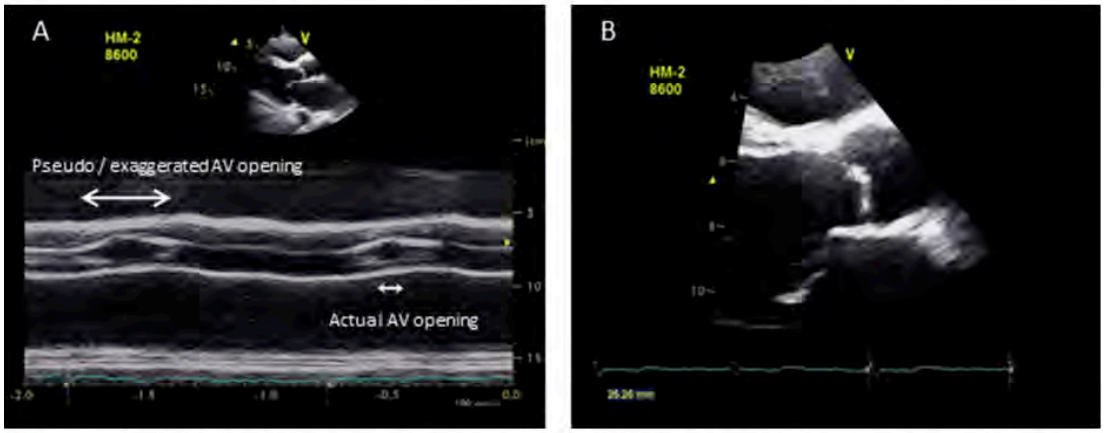


图 17 当 M 型超声心动图记录主动脉瓣形态呈纺锤形时，须怀疑主动脉瓣开放时间夸大或假性延长（A）。本例患者 M 型超声主动脉瓣开放时间> 200ms（箭头），而实际主动脉瓣仅有轻微活动或关闭。（B）该错误归因于以下几个方面，包括主动脉瓣的半月形形态，取样线放置于关闭线左侧（B：红线），主动脉根部的牵拉（见动态图像）。在 LVAD 优化模板中，单纯依靠 M 型超声记录主动脉瓣关闭速度，其意义有限。M 型超声心动图不能单独使用。假性 M 型超声心动图提示主动脉瓣开放，需要通过二维图像再次证实；彩色 M 型超声心动图（当存在 AR 时）可以证实主动脉瓣开放程度。见视频 23。

超声心动图对 LVAD 的优化

总体而言，患者无明显临床症状、或仅有轻微症状、无装置报警、无其他由于 LVAD 异常或自体心脏功能异常等临床指证，方可通过超声心动图优化 LVAD。LVAD 优化的超

声心动图检查，包括基线状态下常规全面的TTE（见附录 E），逐步提高 LVAD 泵速（rpm 为单位），每个转速条件下，采集预先设定的超声心动图参数（附录 F），从而反应 LVAD 或自体心脏的功能（如 LVIDd，室间隔位置，主动脉瓣开放频率/时间，二、三尖瓣返流程度）。

HM-II 速度。HM-II 的最低和最高速度分别是 6000rpm 和 15000rpm。转速调整范围是每次增加 200rpm。尽管存在个体差异，但是推荐转速范围 8800-10000rpm。对于 HM-II 的泵速优化，小幅度增加每一级转速在 200-400rpm 之间。

HVAD-II 速度。HVAD 的最低和最高速度分别是 1800rpm 和 4000rpm。速度每一级增加 20rpm。推荐转速范围 2400-3200rpm。其泵速优化，推荐小幅度增加每一级转速 20rpm 或 40rpm。

部分 LVAD 植入中心，在患者每次超声心动图随访监测中，均进行 LVAD 泵速优化（见图 14）。其他 LVAD 中心，仅在初次超声心动图检查（例如出院前/移植后 2 周的例行检查）时，或常规超声心动图随访监测提示泵速处于亚理想状态时，进行 LVAD 泵速优化。值得注意的是，由于超声心动图监测优化 LVAD 转速技术相对较新，因此超声心动图引导的 LVAD 泵速优化的短期和长期预后尚未明确。附录 D 总结了来自 3 个中心的三组人群，从 LVAD 植入至术后 12 个月的随访超声心动图参数。

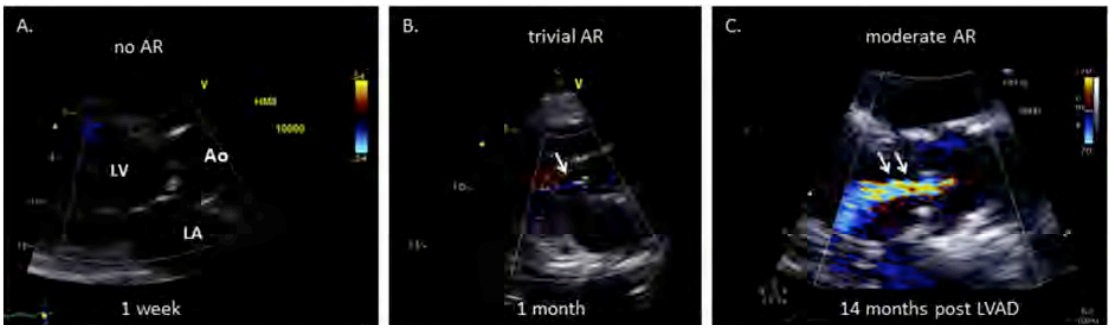


图 18　LVAD 植入后新发 AR。术后 1 周，基线状态下监测无 AR（A），术后一个月可见微量 AR（B），术后 14 个月可见至少中度 AR（箭头，VC>3mm）（C）。胸骨旁长轴切面所有图像与彩色多普勒相结合。该患者在 LVAD 辅助状态下，主动脉瓣呈关闭状态；未见主动脉根部血栓形成。见视频 24-26。

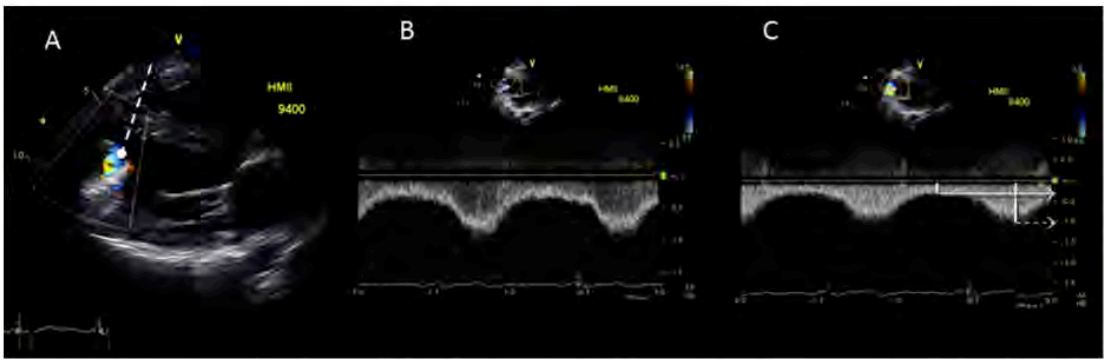


图 19　HM-II 患者改良胸骨旁长轴切面，同轴对准取样容积于流入管道，提示流入管道血流速度正常。（A）彩色血流多普勒结合脉冲多普勒取样容积放置在流入管道内。见视频 27。彩色血流多普勒和脉冲频谱多普勒形态（B）为层流信号。（C）连续频谱多普勒记录收缩期峰值流速=1.0m/s（虚箭头），舒张期流速=0.3m/s（实箭头）。（流入管道正常峰值速度<2m/s）。

“理想”LVAD 转速的决策。不同中心，对 LVAD 优化速度定义不同。但是，各中心一致共识理想转速介于最高和最低速度之间：

最低速度定义为超声心动图测量的 LVIDd（cm）相对于基线状态下略增大；室间隔可能略向右侧偏移；MR 略有增多；主动脉瓣可能开放；或偶尔抑或持续开放；右房压力或肺动脉收缩压略升高。临床当中，最低速度定义为患者出现临床症状，充血，和/或终末器官功能恶化。

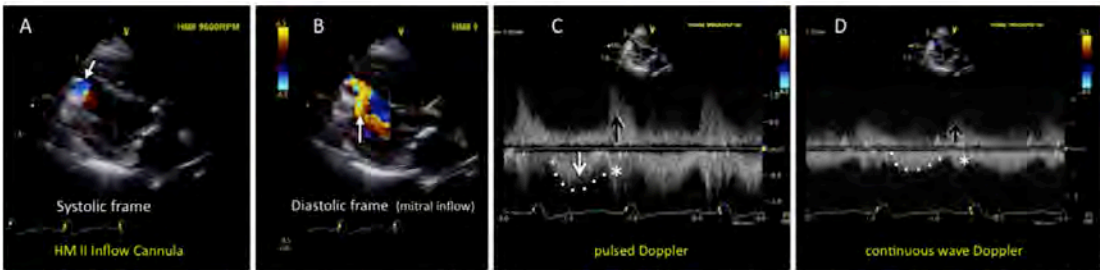


图 20（A）HM-II 流入管道收缩期正常彩色多普勒血流（蓝色，向下箭头）。（B）同一患者，曾行二尖瓣成形术，HM-II 流入管道舒张期，彩色多普勒舒张期以二尖瓣血流为主（橙色，向上箭头）。见视频 28。（C）脉冲波多普勒提示流入管道正常收缩血流（虚线）。但是，流入管道与二尖瓣舒张期血流干扰，加之临近室间隔（*），血流呈以舒张期为主的双向血流频谱形态（见动态图像）。（D）连续波多普勒记录相似形态频谱并除外梗阻。注：当存在 AR 时，流入管道的血流频谱同样受到干扰。这种低速，正常变化的被干扰的流入管道频谱多普勒形态可以通过彩色多普勒解释，而不会与高速梗阻血流信号混淆（典型>2m/s）。但是，如图 19 所示的连续舒张期低速频谱此时不可见。

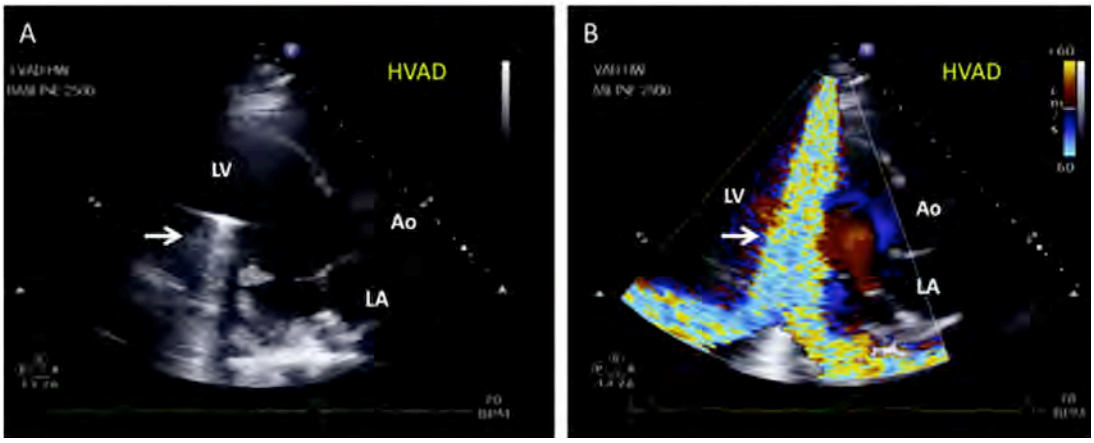


图 21（A）TTE 二维胸骨旁长轴切面，HVAD 流入管道伪像（箭头）。（B）HVAD 流入管道典型彩色血流多普勒伪像（箭头）。该伪像同样影响频谱多普勒的获取（如图 11B）。需要通过其他方法评价流入管道血流（如不同泵速下流出管道及右室流出道血流，主动脉瓣开放，左室大小等）。见视频 29 和 30。

最高速度定义为室间隔向左偏移，和/或遮挡流入管道；由于室间隔左移，导致三尖瓣环形变或/和右室扩大，三尖瓣返流程度加重；主动脉瓣停止开放，主动脉瓣返流量增加。超过泵速上限所致的以上部分或全部变化，可以引发抽吸事件，导致低流速报警（见后文）。

为确保安全，植入中心将达到 HF 患者

左室最大去负荷状态且略低于最大转速的速度，定义为理想 LVAD 泵速，主动脉瓣可以呈关闭状态（典型的，HM-II 低于最高泵速 400rpm，HVAD 低于最高泵速 40rpm）。有些植入中心，会以主动脉瓣开放作为目标之一，如可能，会以比上述定义的理想转速略低，实现主动脉瓣间歇或每个心动周期开放，结合其他超声心动图参数为临床提供充分的左室去负荷信息。部分中心会选择主动脉瓣开放最大周期作为理想优化泵速。如前所述，附录 F 提供了在 LVAD 优化过程中，每个速度级别均可以测量的参数，包括 LVIDd，室间隔位置，主动脉瓣开放频率/时间，MR 程度，和/或 TR 程度和速度，管道血流速度。

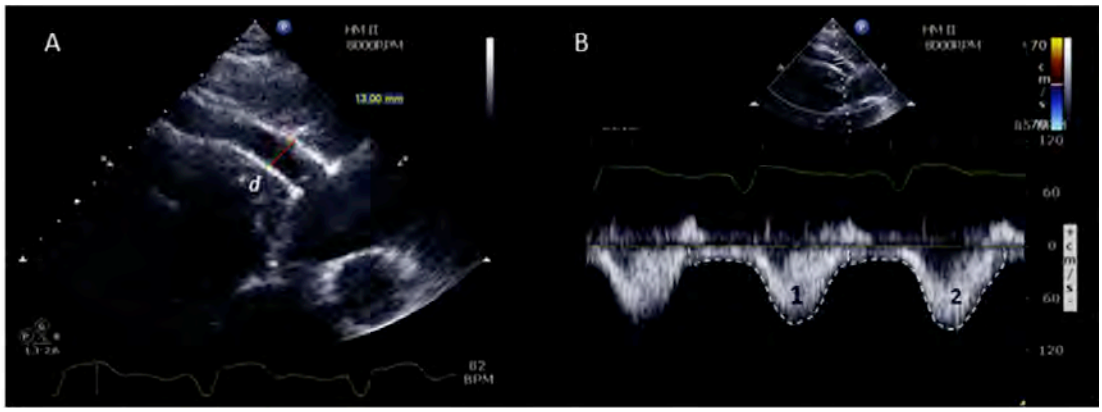


图 22 LVAD 输出量=（流出管道内径 d/2）^{2}× π ×流出管道 TVI×心率

对于心律不齐或每搏量变化的患者，采取 3-5 个心动周期取平均值。

平均流出管道 TVI = TVI（n 个心动周期）/n

由于连续血流，LVAD 速度时间积分包括收缩期和舒张期在内的曲线下面积，如图 B，此时 n=2。（π ≈3.14）。

本例：n = 2；TVI1 = 21.2cm，TVI2 = 23.6cm；心率 = 82bpm；$d_{管道}$= 1.3cm

$TVI_{平均}$=（21.2+23.6）/2 = 44.8/2 = 22.3cm

LVAD 每搏量 =（1.3cm/2）2× π ×22.4cm = 29.7ml

LVAD 心输出量 = 29.7ml×82bpm = 2435ml/min = 2.4 L/min

注：尽管存在应用价值，但是在常规检查当中很难获取图例中的图像。

针对 LVAD 异常的超声心动图筛查

一旦 HF 小组怀疑患者的 LVAD 功能异常，则需要进行有针对性的超声心动图筛查。装置异常超声心动图筛查，一般参考以下一个或多个适应症：

1. LVAD 控制器报警。
2. 新出现或持续存在异常的症状。
3. 血清学检查提示溶血或感染。
4. 基线泵速下，超声心动图检查结果异常。
5. 其他影像学检查或监测结果（如心律失常、低血压）异常，或其他临床检查提示 LVAD 功能异常。

为了最大程度的提高针对装置问题超声心动图检查的效率和实用性，HF 专家组为超声心动图医生提供相关适应症。表 3 列举了检查的典型适应症和适用于 LVAD 异常筛查检查的模板。

无论有无适应症，超声心动图检查先在基线速度下，测量常规超声心动图监测的所有指标（见附录 E）。检查开始，除非患者病情不稳定，否则无需调整泵速，一般无 MCS

成员陪同，由超声技师独立完成。此后，根据实际问题，调整转速或逐渐增加转速，实时监测超声心动图参数变化。如前文及表 3 总结，泵速变化检查，需要 MCS 医生在场，和/或培训后的超声心动图临床医生解释泵速变化反应，以及确认检查终点。

决策检查的终点，需要具有丰富的临床知识和临床判断能力，而该医生可以在或不在床旁提供必要指导。超声技师，可以先独立完成全面的、基线泵速下的针对装置异常的超声心动图筛查。而后，与 HF 专家充分解释和沟通超声心动图结果后，进而有计划性的进行泵速调整检查，此时才需要更多的专业人员参与指导。另一方面，对于临床状况不稳定的患者，需要快速检查，而忽略基线速度下的全面超声心动图检查。任何情况下，HF 医生、超声技师、超声心动图医生均必须熟知临床适应症、临床当中最常见的正常和异常情况的超声心动图典型表现。表 2 总结了除适应症（如监测，[无症状或报警]，或针对异常的筛查）外，超声心动图最常见的阳性所见。表 4 列举了 LVAD 最常见的报警原因和超声心动图可能/预期阳性所见。

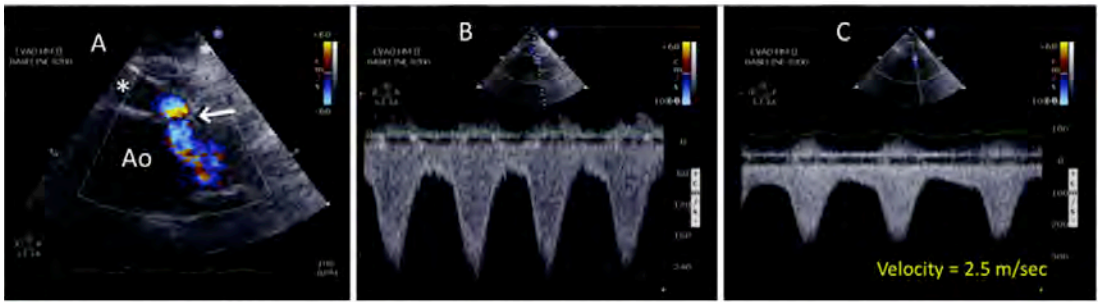


图 23 经胸超声心动图，彩色和频谱多普勒提示流出管道吻合口出轻度狭窄。（A）二维图像：流出管道（*）。混叠彩色多普勒信号提示吻合口狭窄（箭头）。见视频 32。（B）吻合口区域脉冲波多普勒提示湍流血流和异常收缩期高速血流。（C）连续波多普勒探及吻合口流速 2.5m/s。

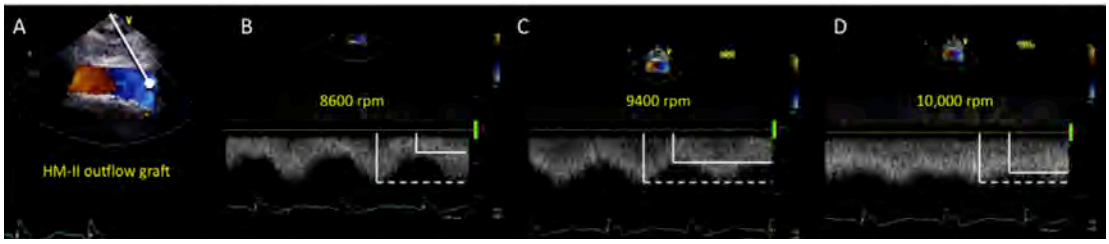


图24　TTE右侧胸骨旁切面LVAD流出管道成像。流出管道内血流为层流，随泵速提高，（降低脉压差），收缩期峰值速度（虚线）和舒张期流速（实线）典型频谱形态特点消失。注：任何原因引起的流入管道梗阻时，提高泵速，收缩期和舒张期的典型频谱特点一会消失。见视频33。

进行装置异常筛查的泵速调整策略。针对装置异常的超声心动图筛查（泵速调节试验）调整转速的目的主要是仪器报警后测试泵功能异常（如泵管道内血栓形成）、和/或查找超声心动图特异性阳性异常（如明显的AR，MR恶化，右心功能衰竭）。对于泵速调节试验，一般采取差异较大的速度梯度进行LVAD优化，同时进行常规超声心动图监测。“速度递增”形式的LVAD异常超声心动图筛查设计的初衷是评价有无泵装置内血栓形成。当然，速度递增模板亦可用于评价临床其他问题，如可疑右室功能不全，心包积液，AR，或当装置报警时协助查找问题所在（见后文列表）。在每一个速度级别，须测量以下参数（见附录F）：LVIDd、右室流出道速度时间积分（用于计算右室流

出道每搏量和心输出量）、主动脉瓣开放程度、流入管道的血流频谱特征（如可能，同时记录流出管道血流频谱）、AR和MR程度、二尖瓣流入道频谱、室间隔和房间隔位置、TR程度及估测右室收缩压。附录G列举了终止速度测试的原因。

要点

- 以泵速变化为基础的超声心动图检查，一般建立在常规超声心动图监测之上（如果LVAD泵速优化在即），或针对装置异常进行筛查，或用于患者恢复期检查。
- 泵速变化超声心动图检查，一般需要有经验的MCS相关人员同时监测参与。
- 基线和每个不同转速下，尤其在泵速提高后，需要记录当时和泵速变化后的血压。
- 泵速变化超声心动图检查，可能导致栓塞事件发生，因此，检查之前，必须明确患者的抗凝状态，以及明确心内及主动脉根部无血栓形成。
- 植入中心，需要有针对泵速调整的超声心动图检查模板，记录测量超声心动图参数，定义LVAD优化速度，提前中止原因，以及检查后的理想的LVAD转度设定。
- 典型的全面超声心动图检查，在基线转速下完成。
- 其他转速下的影像学检查，应该遵循检查适应症。
- 多普勒成像：在泵速调整的超声心动图检查中，在高速状态下，至少要结合脉冲波和连续波多普勒记录流入管道血流速度，用以除外流入管道梗阻（HM-II可能，HVAD少见）。
- 当患者出现症状，或基线超声心动图检查结果异常，通过彩色和频谱多普勒，记录每一个速度级别的AR,MR和 TR程度，胸骨旁切面（或其他可能切面）记录右室流出道血流协助诊断。
- 基线泵速或其他泵速下患者出现症状、可能泵装置功能异常时，需要记录流出道管道多普勒图像（HM-II和HVAD均可以记录）。
- 在每个不同转速状态下，根据不同需要，记录M型记录主动脉瓣开放，流入管道位置，左右心室大小，房室间隔位置，以协助诊断。
- 尽管不同植入中心对LVAD理想速度的定义不尽相同，但是超声心动图指导的最高和最低速度在各中心一致。

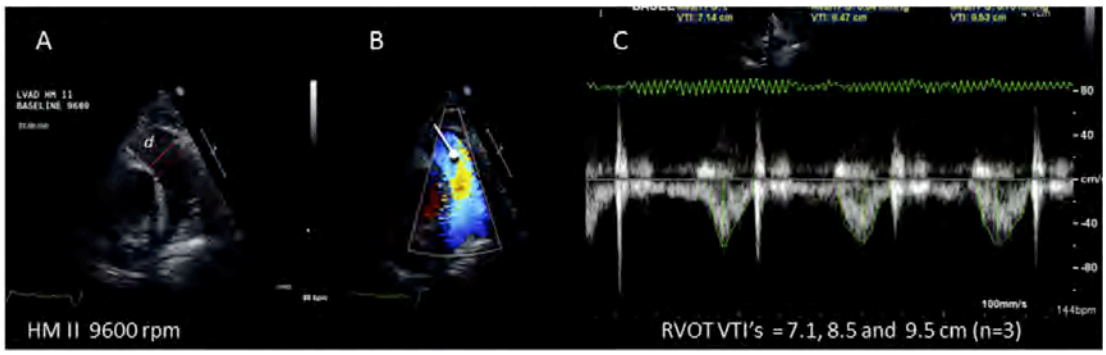


图 25 总心输出量（LVAD + 自身 LVOT ）= RVOT d/2^2× π × RVOT VTI×心率

总体心输出量，即 LVAD 与自身左室流出道输出量之和等于右室流出道心输出量。右室流出道心输出量计算包括测量 RVOT 内径（肺动脉瓣环）（d）。彩色多普勒（B）和频谱多普勒（C）除外

严重肺动脉瓣返流，并计算右室流出道 VTI。注：以本例为例，转速 9600rpm 时，右室流出道 TVI 较低（7-9cm）与低心排一致，考虑流出管道梗阻（扭曲）。根据变化情况，一般取 3-5 个心动周期 VTI 平均值。

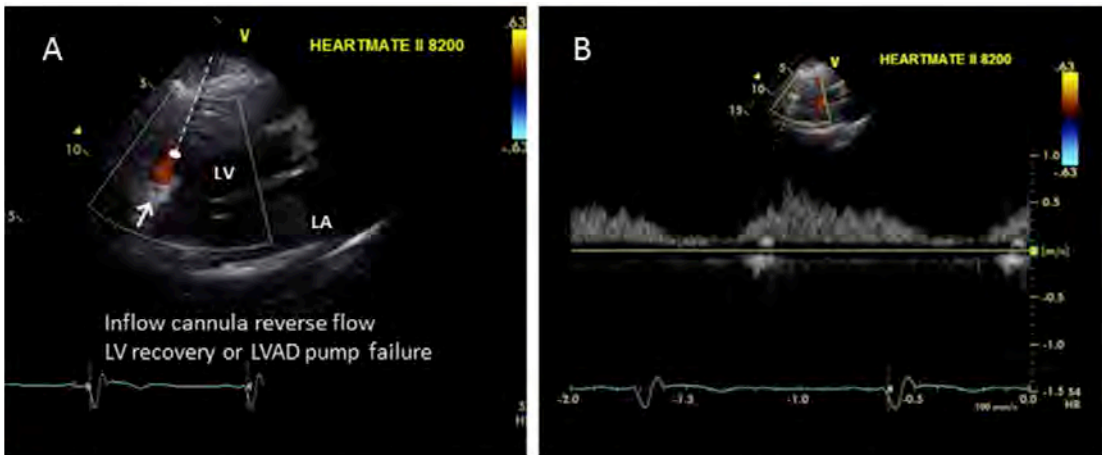


图 26 植入 HM-II 患者，自身左室功能明显恢复（见动态图像），当泵速较低（8200rpm）而 LVAD 正常工作时，TTE 改良胸骨旁长轴切面，流入管道舒张期出现逆流。（A）彩色血流多普勒成像。箭头所示为流入管道。见视频 34。（B）由于舒张改善，流入管道脉冲波频谱多普勒提示收缩期血流速度降低，但出现全舒张期逆流（主动脉至左室）。注：在 LVAD 泵功能异常时，亦可见相似频谱，但患者同时伴有 HF 症状和超声心动图其他阳性发现。

超声心动图评价 LVAD 异常报警

该部分概述控制器异常报警的类型，及其鉴别诊断，针对装置异常的超声心动图筛查和所能证实及解决的问题。通常，在控制器报警之前，LVAD 的监测及针对装置异常的超声心动图筛查往往能够提早发现可能存在的问题。而另一方面，控制器报警时，患者可能伴有或不伴有临床症状或其他临床异常发现。无论何种情况，控制器报警，需要患者或其临床医生高度重视。超声技师或超声医生需要熟知控制器报警的几种常见类型和控制器的相关参数，从而有针对性的进行相应的超声心动图检查。

速度代表叶轮每分钟转动的周数（rpm）。通过控制器调整泵转速。如前所述，HM-II 泵速范围 6000-1500rpm（临床当中多为 8800-10000rpm），HVAD 泵速范围 1800-4000rpm（临床中多为 2400-3200rpm）。泵速设置过低，可能导致血流缓慢甚至瘀滞，涡轮叶片容易形成血栓。当泵速设置过高时，以引起抽吸事件。

功率是通过泵的电机电压及电流测得，且随速度变化而不同（如泵速越高，功率越高）。在控制器上常规显示，为一定时间的平均功率，单位为瓦（通常<10w）。峰值功率是指功率增加，而无相应的转速增加，一般提示可能存在机械梗阻。HM-II 和 HVAD 的峰值功率超过基线状态下>2w 时，提示涡轮叶片可能有血栓形成导致梗阻。

流量（升/分）直接通过相应的转速（泵转速）和功率进行评估。在评估 HVAD 流量时，红细胞压积对血液粘滞度的影响需要考虑在内。对于 HVAD 而言，尤其在 LVAD 泵速较低时，当红细胞压积变化超过±5%时，即需更新系统监测，避免错误计算流量。

搏动性即最高和最低流量之间的差异，类似于动脉血流的波峰和波谷。搏动性与自体心室收缩力直接相关，与后负荷负相关。搏动指数（PI）是一个与HM-II控制器相关，

而与搏动性无关的参数。PI通过最高和最低功率之差再除以平均功率间接计算。PI与通过泵的血流量有关，随前负荷增加、心肌收缩力改善而增加，随后负荷增加而降低。总体来讲，报警分为两种，一种是低流量，另一种的高流量/高功率。泵参数偏差以及识别出的报警应与临床情况相结合（见表4），且病因不明确时，需要进一步检查证实。临床症状和体征，结合不同型号的LVAD报警参数，指导下一步诊断及治疗措施。建议参考近期LVAD特殊问题处理的指南（如泵血栓形成），根据临床表现，指导进一步治疗。HM-II的低流速报警，与以下条件相关，或者定义为以下一个或多个阳性发现：PI减低，PI参数出现异常（较前15秒PI均值变化±45%），低流速报警，或估测流量时为负值。HVAD报警时，在控制器上显示为“低流量”或“抽吸”。

要点

- 多数LVAD控制器的主要参数包括转速、功率和流量。以上参数一项或多项发生异常，即激活LVAD控制器报警。
- 结合患者的临床状况和报警的类型，可以指导超声心动图医生有侧重的获取切面（决定检查的范围）和分析图像。
- 为解决临床问题，将控制器报警分为“低流量”或“高流量”两类，其中每类都包括相应特有鉴别诊断（见表4a，b）。
- “抽吸事件”、右室衰竭、低血容量、心脏填塞、流入管道/流出管道梗阻、恶性高血压、和/或心律失常可以引起“低流量”报警。
- 泵血栓形成、体循环动脉扩张、明显的AR、和/或自身左室功能恢复均可引起“高流量/高功率”报警。对可能报警原因的鉴别诊断，需要将临床和超声心动图结果相结合。

低流量报警。对低流量报警的鉴别诊断主要侧重于患者的相关因素，包括LVAD抽吸事件、右室衰竭、低血容量、心脏填塞、心尖部流入管道或流出管道弯曲或梗阻、恶性高血压和房性或室性心律失常。

抽吸事件。-如前所述，抽吸事件是由于左室心内膜与流入管道相接触所致，直接导致流入管道流量的降低和引起相应的临床改变（如室性心律失常所致的先兆晕厥或心悸，）和/或LVAD的功能。任何引起左室充盈不足的原因，均会有引发抽吸事件的风险。这些原因包括低血容量（见图28）、右室衰竭（见图27）、心脏填塞（图29）和/或针对当时血流动力学泵速设置过高。当发生抽吸事件时，LVAD将左室排空过小，导致室间隔向左侧偏移。流入管道位置异常可能引起流入管道间歇性梗阻，或由于与心内膜机械接触造成的室性心律失常（图28）。在调整转速的模板中，监测抽吸事件是其中重要内容之一。典型的治疗建议由两点：（1）降低泵速；（2）识别和治疗相关病因。

右室功能不全。临床表现和超声心动图能够识别不同程度的右室功能不全。右室功能不全可能或不与抽吸事件有关。在LVAD和右室功能允许的条件下，应当将泵速调整至室间隔位置居中，保证右室充分的前负荷，实现有效的心输出量。进展性右室功能不全或心力衰竭的患者（基于严重增高的右室舒张末期压力和极低的右心输出量），检测是否有低流量报警，此时患者室间隔可能

明显向左偏移。超声心动图通过与基线状态结果对比，通过右室大小和功能、下腔静脉内径塌陷率、多普勒评价肺动脉压力、彩色和频谱多普勒评价三尖瓣返流程度等参数（图27），发现新出现的右心衰竭或原有右心衰竭恶化。

心脏填塞。临床当中，心包或胸腔填塞表现类似于右心衰竭，结果导致低流量报警。由于LVAD直接决定二尖瓣口的流量及心输出量，因此，当心包填塞心包腔内压力增加时，并不会增加瓣膜的返流。因此，当发现心包积液、或可疑血肿（图29）伴低流量报警和左室和/或右室容积过小时，应高度怀疑心包填塞。此时，右室流出道测量心输出量减低，且不随泵速变化而变化。

流入管道梗阻。-其他引起低流量报警的病因包括继发于血栓、巨大赘生物或心内膜接触（如抽吸事件）所致的部分性或间歇性梗阻。超声心动图阳性所见类似于泵功能异常，包括左室大小、室间隔偏移及主动脉瓣开放。然而，彩色和频谱多普勒评价流入管道速度可能异常增高、频谱形态不一致（图27和28），其严重程度随局部LVAD血流而变。频谱多普勒测得流入管道速度因近端梗阻而增加，而流出管道流速减低，和/或峰值速度变化不一。二维和三维TTE（尤其是TEE）可能检出管道或心腔内血栓或赘生物（如过多肌小梁牵拉至流入管道）。抽吸事件所致的流入管道梗阻属于“动力型”，表现为在泵速调整试验中，左室腔过小，流入管道流速增高，而降低泵速后恢复正常。

流出管道机械梗阻。-流出管道梗阻（如流出管道弯曲，移位，外部挤压或血栓形成等）的表现与LVAD后负荷增加相似（图23和30）。依据梗阻的部位和程度，除多普勒成像提示流出管道血流速度增高或降低外，超声心动图所见类似于流入管道梗阻。流入管道血流速度正常或降低（依远端梗阻的程度而不同）；若取样容积放置在梗阻部位，则流出管道血流速度可能增高，若取样容积放置在梗阻部位的近端或远端，则频谱多普勒测量的血流速度正常或减低。不同泵速下，心内血流动力学发生改变、左室腔大小及主动脉瓣开放程度等，通过泵速调整试验（如右室流出道或左室流出道VTI，收缩期和舒张期速度比值）能够协助发现异常。

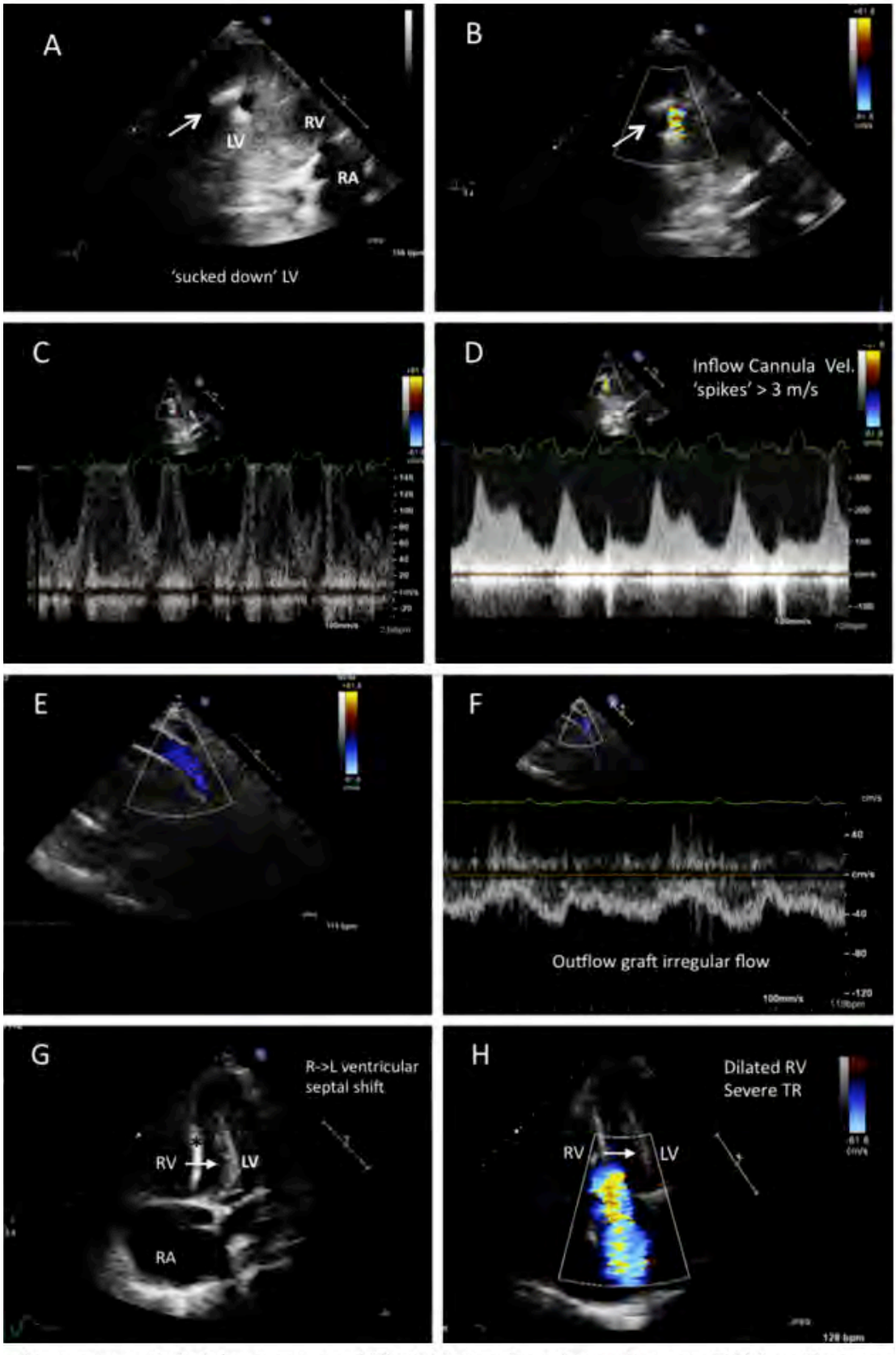


图27严重右室功能衰竭，在较低泵速下（HM-II，8200rpm），可见抽吸事件。（由于内科治疗不理想，患者植入右室辅助装置）。（A）改良右室流入道切面。左室腔明显变小，包绕流入管道（箭头），室间隔向左偏移。见视频35。（B）流入管道彩色血流多普勒信号混叠。（C）脉冲波多普勒

探及流入管道内高速血流信号。见视频36。（D）连续频谱多普勒探及流入管道内不规则血流，心动过速（心率=154次/分），收缩期最高流速达3.5m/s。（E）TTE右侧胸骨旁切面，彩色多普勒提示流出管道为低速层流血流。（F）脉冲波多普勒记录流出管道血流为不规律低速频谱波形，与严重流入管道梗阻一致。（G）心尖四腔切面提示右心严重扩大，左室腔变小，室间隔向左侧偏移（箭头），彩色血流多普勒提示伴有严重的TR（H）。见视频37和38。型号为起搏导线。

高流量/高功率（高瓦特）报警。对高功率报警的鉴别主要包括涡轮叶片血栓形成、体循环动脉扩张（如脓毒病综合征对比药理作用），和/或明显持续的AR。

恒流式LVAD泵功能异常可能由于泵装置的机械元件功能异常，但更多情况是由于涡轮叶片血栓形成所致。任何阻碍涡轮叶片转动的因素，均会导致泵耗能增加。当发生部分叶片血栓形成导致泵装置高能耗时，测量到的高速血流导致高估实际流量。与泵血栓形成相关的典型临床表现包括溶血，伴有乳酸脱氢酶、总胆红素、血清游离血红蛋白升高的血色蛋白尿。继发于血栓形成的泵功能异常，其超声心动图表现为较前次检查，左室去负荷减少。泵作功降低（左室去负荷减少）的超声心动图表现为，与前次检查相比，LVIDd增加，室间隔向右室侧偏移（取决于自身心室功能），主动脉瓣开放增加，详见表4。与前次检查相比，可疑溶血和/或泵内血栓的病人的血清学检查证据、流入和流出管道舒张期血流速度均降低，同时，伴有流入管道血流速度、流出管道收缩期舒张期速度比值增加。随后的LVAD装置异常的泵速变化检查或速度递增调整试验，可以进一步证实是否同时合并泵功能异常。任何原因引起的梗阻（如叶片血栓形成、流出管道扭曲等）均会削弱调整转速后的二维成像和流入、流出管道速度的预期变化。例如，当泵速增加时，预期的LVIDd降低、主动脉瓣开放频率和开放时间减低、二尖瓣减速时间延长以及右室流出道每搏量增加等变化均不会发生。

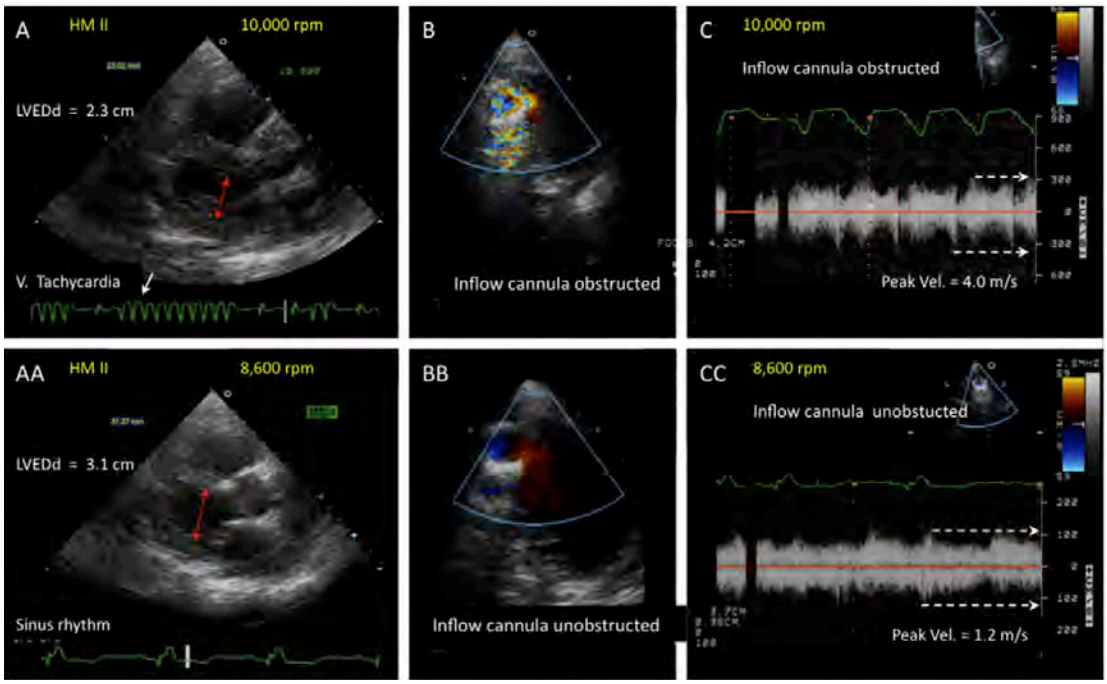


图 28 高泵速（10000rpm）及胃肠道疾病所致的低血容量引发抽吸事件，导致的机械接触所致室性心动过速。（A）左室腔小（LVEDd = 2.3cm，红色箭头），频发非持续性室性心动过速（白色箭

头）。见视频 39。（B）彩色多普勒示混叠涡流信号。见视频 40 和 41。（C）连续多普勒记录到混合，高速流入管道血流速度。（AA）泵速降低（8600rpm），LVEDd 立即增加（3.1cm，红色箭头），室性心动过速终止（如，减少了室间隔与流入管道的机械接触）。彩色血流（BB）和连续波多普勒（见视频 42）（CC）提示流入管道内正常低速血流。由于容量过低，左室仍小（3.1cm），在随后治疗改善。注：机械接触引起的室性心律失常与流入管道与室间隔形成夹角，或关胸后与心内膜接触有关，尤其在提高泵速时多见。

明显的AR与正常功率的LVAD但是流量高估有关。当二尖瓣流入道血流正常时，主动脉瓣返流量可能导致左室前负荷增加，引起自身左室流出道输出量增加，主动脉瓣开放以及间歇性AR（见图9H，9J）。亦或，由于心肌收缩力不足，收缩期仍旧存在返流，致AR呈持续性（见图9C）。当AR恶化时，与前次检查相比，LVIDd呈进行性增加，室间隔向右室侧偏移。主动脉-左室-LVAD之间形成盲路，多普勒成像评价流入管道及流出管道血流速度正常或增加。LVAD管道近端至升主动脉吻合口之间血流量明显增加，但是，通过右室流出道VIT估算的心输出量，即LVAD-升主动脉吻合口的净心输出量会降低（见图13）。由于左室容积和舒张期压力增加，二尖瓣返流量会增加（表4）。

心室功能的恢复和/或后负荷的降低。自身心室功能恢复和左室后负荷异常减低均会导致LVAD流量和功率的增加。超声心动图可以鉴别以上两种情况，尤其与前次检查结果相比时，更易鉴别。左室充盈增加（与左室功能恢复有关）或者后负荷减低（与脓毒血症或其他原因引起的体循环动脉扩张有关，或与左室充盈减少有关）时，一般会表现为血流量的增加和功率增高。心室功能的恢复表现为在基线及低泵速状态下，左室收缩功能的连续改善（如LVEF增加，左室腔减小，伴有主动脉瓣开放时间延长，右室流出道及自体左室流出道心输出量增加）。HF改善的其他指标包括功能性MR、肺动脉压力及TR均有减少。心室功能恢复后，通过自身主动脉瓣搏出的血量增加，LVAD流量相应减低。脓毒血症或其他原因（如药物因素）所致外周血管阻力异常减低（左室后负荷减少）时，即使无左室功能恢复，左室腔大小和二尖瓣返流程度也会相应减少。此种情况，多普勒超声心动图记录的左室流入管道和流出管道收缩期血流速度增高，LVEF明显改善。但是，此时室间隔明显向左侧偏移，而真正左室功能恢复时，室间隔位置居中。与前次检查相比，右室流出道估算的心输出量增加。

表4a　LVAD低流量报警的鉴别诊断及超声诊断

报警类型	HM-II* PI 减低 PI 事件 HVAD 抽吸‖	HM-II* PI 减低 PI 事件 低流量报警 血流显示“——” HVAD 低流量 抽吸‖	HM-II* PI 减低 PI 事件 低流量报警 血流显示“——” HVAD 低流量 抽吸‖	HM-II* PI 减低 PI 事件 低流量报警 血流显示“——” HVAD 低流量 抽吸‖	HM-II* PI 增加#	HM-II* PI 减低 PI 事件 低流量报警 血流显示“——” HVAD 低流量 抽吸‖	HM-II* PI 减低 PI 事件 低流量报警 血流显示“——” HVAD 低流量 抽吸‖
临床诊断	LVAD 抽吸事件†	低血容量	右心衰竭	心包填塞	恶性高血压	流入管道血栓或流出管道扭曲/梗阻	心律失常
可能超声所见‡	LV 大小：减小	LV 大小：减小	LV 大小：减小	LV 大小：减小	LV 大小：增大	LV 大小：增大	LV 大小：不变
	RV 大小：因病因不同	RV 大小：减小或不变	RV 大小：增大	RV 大小：减小	RV 大小：不变	RV 大小：不变	RV 大小：可能增大
	房间隔位置：因病因不同†	房间隔位置：无变化	房间隔位置：向左偏移	房间隔位置：无变化	房间隔位置：无变化	房间隔位置：无变化	房间隔位置：向左偏移
	室间隔位置：因病因不同†	室间隔位置：无变化	室间隔位置：向左偏移	室间隔位置：无变化	室间隔位置：无变化	室间隔位置：无变化	室间隔位置：无变化
	AV 开放：因病因不同†	AV 开放：可能减少	AV 开放：可能减少	AV 开放：无变化	AV 开放：减少	AV 开放：增加	AV 开放：增加

MV 返流：因病因不同†	MV 返流：可能减少	MV 返流：无变化	MV 返流：无变化	MV 返流：增加	MV 返流：增加	MV 返流：增加
TV 返流：因病因不同†	TV 返流：可能减少	TV 返流：增加	TV 返流：增加	TV 返流：不变	TV 返流：不变	TV 返流：增加
估测 RAP §：因病因不同	估测 RAP §：降低	估测 RAP §：增加	估测 RAP §：增加	估测 RAP §：不变	估测 RAP §：增加	估测 RAP §：增加
其他：	其他：	其他：	其他：	其他：	其他：	其他：
流入管道邻近心内膜或位置偏移#			左房/右房受压	流入管道收缩期峰值流速增加	由于部分梗阻致流出管道流速增加>2m/s¶	可能伴随抽吸事件
流入管道流速增加由于部分梗阻至流速¶			心包积液	左心充盈和肺动脉压力增加	增加泵速，以下参数变化微弱：	
室性早搏或室性心律失常					LVEDd 减小	
					ROVT VTI 增加	
					MV DT 增加	
					AV 开放减少	

AV，主动脉瓣；DT，减速时间；ECG，心电图；HM II，HeartMate II 左室辅助装置；HVAD，HeartWare 心室辅助装置；LV，左心室；LVAD，左室辅助装置；LVEDd，左室舒张末期内径；MR，二尖瓣返流； MV，二尖瓣；PI 搏动指数；RAP，右房压力；RV，右心室；RVOT，右室流出道；TV，三尖瓣；VAD，心室辅助装置；VTI，速度时间积分。

* HeartMate（HMJ-II特点。PI = 搏动指数，左心室进入泵内的血液；当发生PI事件时，45%左右的来自前15秒的平均值。

† LVAD抽吸事件可能伴随低血容量，右室衰竭和心脏填塞，并伴有心律失常（房性或室性），和/或管道移位。‡ 相同泵速下，该变化典型的与与患者自身前次超声心动图检查参数对比。

§ 基于下腔静脉内径大小和对呼吸的变化，肝静脉血流（舒张期为主或收缩期逆流）。‖ HVAD的抽吸事件特点。

¶ 可能由于完全梗阻，导致流入管道或流出管道峰值血流完全消失（很少见）。#可见不同的能量/血流和PI变化，主要与高血压的程度有关。

表4b　LVAD高流量报警的鉴别诊断及超声诊断

报警类型	HM-II*	HM-II*	HM-II*
	功率>10 瓦	PI 减低或不变	PI 事件
	血流显示“+++”	PI 事件	HVAD
	PI 减低		报警显示高瓦特 §
	PI 事件		
	HVAD		
	报警显示高瓦特 §		
临床诊断	血栓形成致泵功能异常†	低脓毒病综合征或血药收缩药物作用	明显 AR
可能超声所见‡	LV 大小：增大	LV 大小：不变	LV 大小：增大
	RV 大小：不变	RV 大小：不变	RV 大小：不变
	房间隔位置：不变或由于 LAP 增加向右侧偏移	房间隔位置：无变化	房间隔位置：不变或由于 LAP 增加向右侧偏移
	室间隔位置：不变	室间隔位置：无变化	室间隔位置：不变
	AV 开放：增加	AV 开放：增加	AV 开放：不变
	MV 返流：增加	MV 返流：不变或可能减少	MV 返流：无变化或增加
	TV 返流：不变	TV 返流：不变	TV 返流：不变
	估测 RAP‖：由于左心衰，右房压力可能增加	估测 RAP‖：不变	估测 RAP‖：由于左心衰，右房压力可能增加
	其他：	其他：	其他：
	左右心室流出道每搏量相当		彩色多普勒谈及整个收缩期和舒张期主动脉瓣持续性返流
	左心充盈压和肺动脉压力增加		典型的中重度改变：
	增加泵速，以下参数变化微弱：		血流汇聚宽度>0.3cm
	LVEDd 减小		或射流宽度/LVOT 宽度≥46%
	ROVT VTI 增加		RVOT 每搏量下降
	MV DT 增加		肺动脉收缩压增加
	AV 开放减少		
	流入管道位置偏移		
	流入或流出管道收缩期/舒张期峰值流速比值增加		

AR，主动脉瓣返流；AV，主动脉瓣；HMII，HeartMate II左室辅助装置；HVAD，HeartWare心室辅助装置；LAP，左房压力；LV，左心室；LVAD，左室辅助装置；LVEDd，左室舒张末期内径；LVOT，左室流出道；MV，二尖瓣；PI，搏动指数；RAP，右房压力；RV，右心室；RVF，右室衰竭；RVOT，右室流出道；TV，三尖瓣；VAD，心室辅助装置；VTI，速度时间积分。

* HeartMate（HMJ-II特点。PI = 搏动指数，左心室进入泵内的血液；当发生PI事件时，45%左右的来自前15秒的平均值。† 如果伴有明显的溶血和其他体征，则高度可疑该诊断，并在更换泵装置之后得以确诊。

‡ 相同泵速下，该变化典型的与与患者自身前次超声心动图检查参数对比。

§ HVAD的抽吸事件特点：潜在病因导致报警。‖ 基于下腔静脉内径大小和对呼吸的变化，肝静脉血流（舒张期为主或收缩期逆流）。¶相对于正常流入管道血流，其方向偏向于二尖瓣。

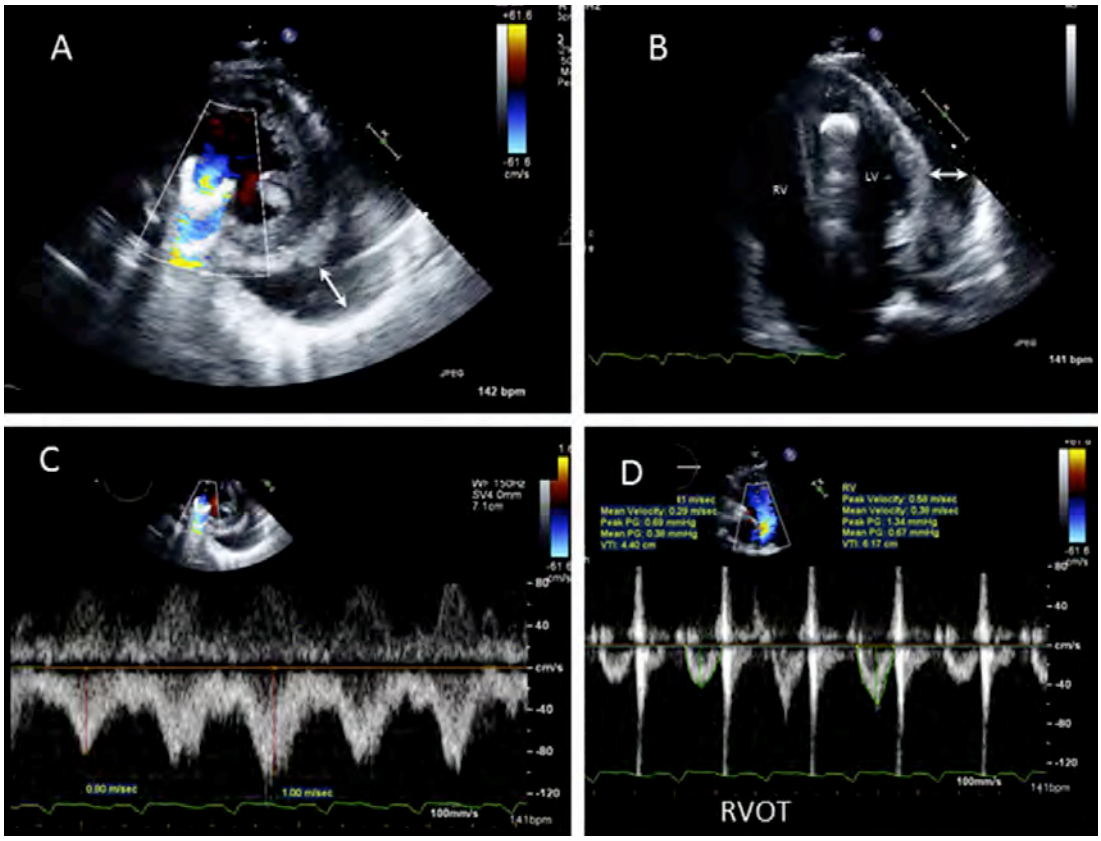


图 29 调整泵速后，LVAD 保持低流量状态，此时怀疑存在心包填塞。在左室后侧部探及较大局限性积液（箭头）。（A）胸骨旁短轴切面。见视频 43。（B）心尖四腔切面除外右室心力衰竭。视频 44。（C）频谱多普勒除外流入管道梗阻。（D）泵速为 9000rpm（HM-II），RVOT 脉冲波多普勒提示 VTI 较低（4-6cm）。如图 C 和 D 提示，LVAD 受体的血流速度常不随呼吸发生改变。

超声心动图对 LVAD 心肌恢复的评价

仅少数病例左室功能恢复，最终脱离LVAD辅助。LVAD恢复或“脱机”超声心动图模板非常关键，结合各种复杂因素决定是否适合脱离LVAD辅助。除MCS中心，很少进行LVAD心肌恢复超声心动图评价。但是，在特定地点，经常可以进行有组织的研究性的LVAD恢复性检查。考虑到LVAD管理的其他因素，关于病人治疗的潜在临床重要阶段的临床预后及专家共识的参考数据甚少。尽管本文目前无法提供关于LVAD心肌恢复超声心动图检查的具体细节，附录H及后文关于基本概念的讨论将会有助于建立基本框架。

当LVAD常规超声心动图监测结果提示自体左室功能明显改善时，可以考虑进行LVAD心肌恢复超声心动图检查。LVAD心肌恢复超声心动图检查的初始部分为在基线状体下，全面LVAD超声心动图检查。LVAD泵速极低时，可能导致装置逆流（见图26）。在基线状态检查后，逐步递减泵速至既无前向血流，又无逆流（净中位血流）。在多数的脱机模板当中，LVAD流入和流出管道的频谱多普勒有助于确定净中位血流。由于在该检查过程中，LVAD整个装置内的血流停滞，因此在典型的LVAD心肌恢复超声心动图评价之前，必须明确全身充分抗凝。在确定净中位血流的泵速后，需要进行运动试验（6分钟步行试验或其他心肺试验）测试左室功能的恢复。作为运动试验结论，需要再次评价左室功能参数，包括LVEF。若患者出现症状，基线转速心室功能的恢复可以提前结束

测试。见附录H恢复模板样板。

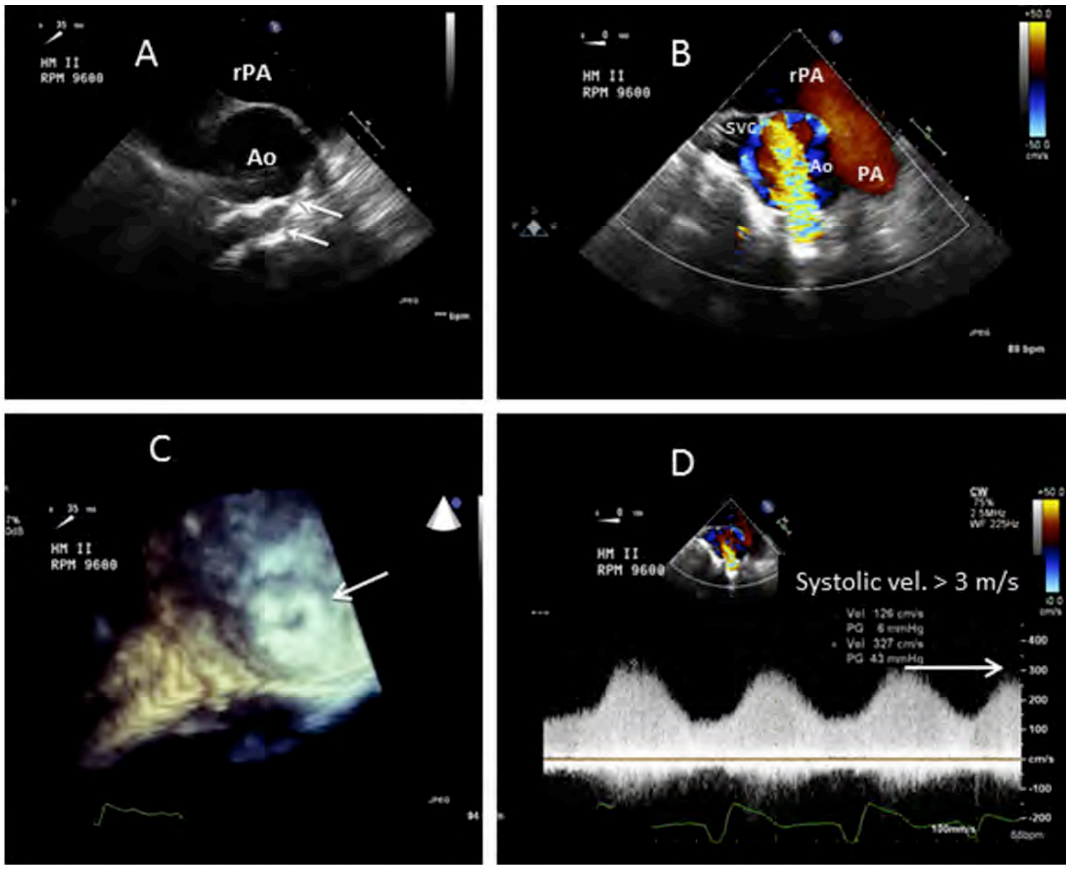


图30 在植入LVAD后，流出管道吻合口发生进行性狭窄1年以上。增加泵速以提高LVAD流量，反而增大而不是减小了左室内径，且无体循环压力增高的证据。泵装置报警尚未触发。TEE食管上段升主动脉切面：（A）流出管道远端形态不规则（扭曲和倾斜），并口径减小（箭头）。见视频45。（B）彩色多普勒见涡流/混叠信号（与正常血流相比[图6A，13C和13D]）。见视频46。（C）三维超声吻合口成像（箭头）可见纽扣孔样管道口和内膜增生（与正常相比[图6D]）。（D）连续波多普勒测量收缩期峰值流速>3m/s。注：TTE检查无法评价流出管道梗阻。

LVAD 用于儿童及青少年病人

与成人患者相比，进展性心力衰竭的儿童及青少年患者，可选择的MCS中心更少，直至最近，主要的治疗手段仍旧局限于ECMO。目前，对于体型小的患儿，尚无获批的体内VAD可用。FDA批准了两种体外VAD，包括Thoratec PediMag和Berlin Heart EXCOR（见后文详述）。目前，部分原因是每个植入中心的儿童病患数量较少，因此关于超声心动供图评价儿童VADs的相关报道甚少。而较大的儿童和青少年，可以使用成人MCS装置。本文不涉及根据患者的体型大小选择VAD型号。值得注意的是，较小儿童的VAD流入管道和流出管道的正常血流速度无参考。此外，左室腔较小，增加了流入管道梗阻的风险，个别病例甚至需要外科干预处理二尖瓣装置。

儿童患者的VAD短期支持。

CentriMag VAD的小型版本（见图A-6）、ThoratecPediMag体外离心恒流泵（曾命名Levitronix PediMag）获得FDA批准[510(k)，2009年10月]用于左室、右室或双室短期辅助（如急性恢复前过渡，等待临床决策等）。

该泵无轴承，靠磁悬浮技术驱动，最大流量1.5L/m。超声心动图测量参数较前述成人指标略小。

图 31 图示为 Berlin Heart EXCOR VAD 泵装置，流量从 10 至 60ml 不等。该图示由 Berlin Heart 公司提供。

儿童患者的VAD长期支持。

BerlinHeart EXCOR儿科心室辅助装置（Berlin Heart, Inc., TheWoodlands, TX）是唯一获批用于婴儿和小儿童的BTT辅助装置。自FDA于2011批准该装置使用，其使用量明显增加。EXCOR是体外空气驱动脉冲装置，与相似设计的成人装置完全不同，后者有更多类型的管道和泵大小供选择（10-60ml），可用于儿童及青少年患者（见图31）。美国多中心前瞻性研究入组204例儿科患者，第一年生存率75%，其中64%患者心脏移植，6%患者恢复脱离装置辅助，5%患者持续1年依靠装置辅助存活。与以往传统治疗方法相比，该结果提示患者转归明显改善。脉冲泵的超声心动图特点是，流入管道和流出管道的速度与心动周期不同步（间歇左室辅助）。“自动模式”（最大辅助状态）下，传感器能探测被动充盈，从而激发射血。该装置可以设置在低速固定转速水平进行低水平支持。关于与其他类型恒流式辅助装置不同的超声心动图特点，请咨询Estep及联合作者。

要点

- 儿童及青少年LVAD的超声心动图特点，在很多方面与成人相似，但是却存在方法学的区别。年龄、体型大小及装置标准化参数尚无参考依据。

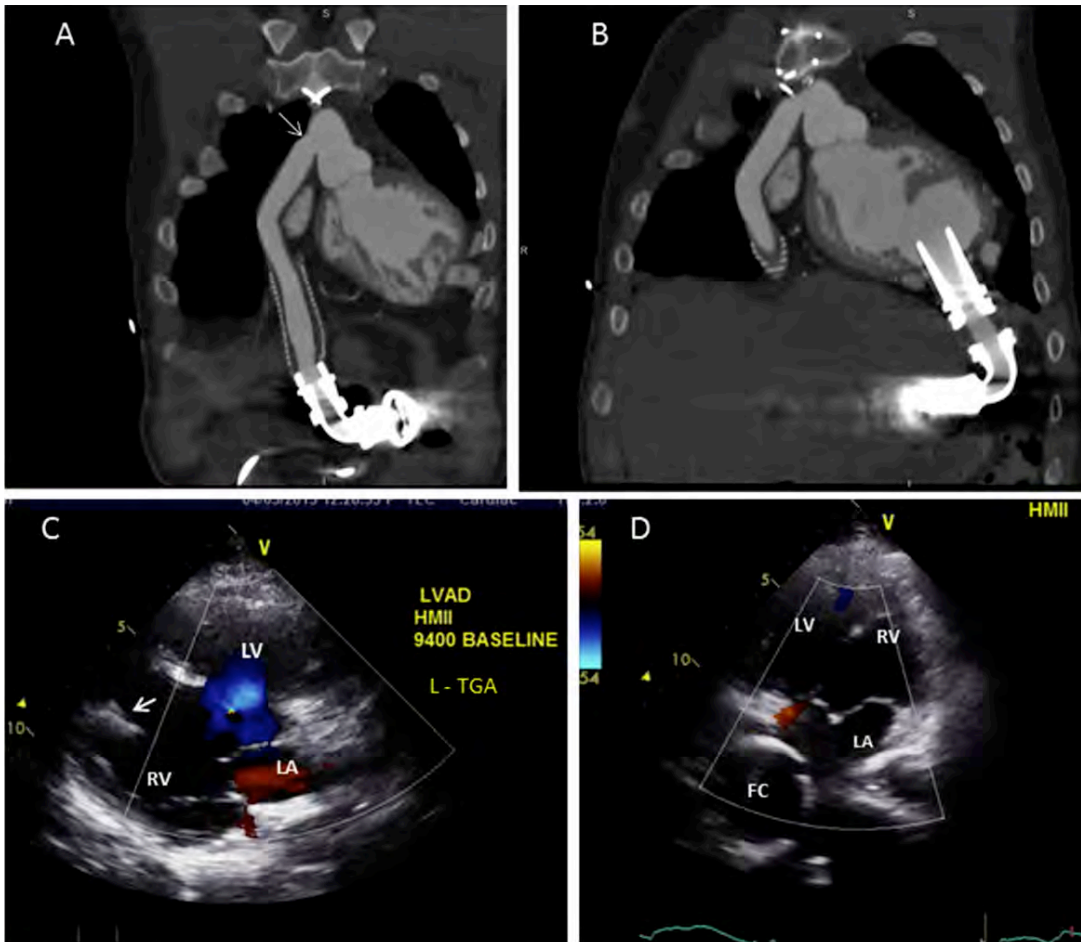


图32　25岁单心室患者CT（A，B）和超声心动图（C，D）：左位行大动脉（L-TGA），完全性心内膜垫缺损和肺动脉瓣下狭窄，5岁时植入非开孔的Fontan管道。尽管最初植入HM-II作为最终治疗，但是在辅助循环2年后，最终进行了心脏移植。（A）冠状切面CT提示包括吻合口在内的流出管道正常（箭头）。（B）近矢状切面CT提示流入管道无梗阻。（C）胸骨旁长轴切面探及非限制型室间隔缺损（蓝色血流）和心态学右室内的流入管道（箭头）。见视频47。（D）心尖四腔切面探及Fontan管道（FC）。见视频48。

其他方面的研究

目前，很多评价心脏功能研究所用参数尚未包含于本指南当中。装置植入之前，用于评价心脏收缩和舒张功能的很多传统参数，明显依赖于前后负荷，目前，其用于评价恒流式机械泵左室去负荷的效果尚属未知。植入LVAD后，反复HF的患者，其二尖瓣减速指数降低（减速时间/二尖瓣E峰），房间隔向右侧偏移提示左室部分去负荷。最近，推荐使用单一、标准化的参数（二尖瓣E/A比值，RA压力，肺动脉收缩压，左房容积指数，E/e´）作为诊断方法，能够可靠区分基线状态下正常和增高的左室充盈压力，作为左室部分去负荷的证据。尚无与泵速设置有关的超声心动图舒张参数（调整泵速后，二尖瓣E峰减低，减速时间延长）用于评价患者的症状改善。

评价心肌功能力学指标的超声心动图新参数包括心肌位移、速度、形变（应变）、应变率、扭转和非同步指数。机械指标包括纵向、轴向和径向向量，或M型斑点追踪超声心动图（STE）、频谱多普勒、背向散射积分、声学造影等静态参数。随着MCS应用逐

渐广泛，为进一步研究提供丰富的资源，用以传统和新出现的评价心脏功能的力学参数的临床实用性，预测患者的临床情况。由于目前尚无关于新的力学参数参考资料，因此推荐常规LVAD管理使用基本模板，个别中心根据需要增加方法学指标。

要点

- 随着LVAD临床应用增多，为进一步研究提供丰富的资源，传统和新的心脏功能力学参数临床实用性有待验证，可以用于进一步预测临床状况和制定诊疗决策。

LVAD 植入其他成像方法的适应症

超声心动图的一个主要局限性就是无法显示全部流出管道。而CCT能够直接显示LVAD的全部结构，包括流入管道的位置及整个流出管道（见图32）。该成像模式是评价恒流式LVAD装置并发症的较好手段，包括继发于心包血肿所致的右室受压、管道扭曲和/或异位、以及血栓等。以术中超声心动图阳性所见作为金标准，Raman等阐述了CCT检查探查管道内血栓或流入管道移位的敏感性和特异性分别是85%和100%。CCT的局限性是放射暴露和碘造影剂所致的肾脏毒性作用。然而，LVAD患者的血清肌酐水平<1.5 mg/dL，肾小球滤过率>60mL/min/1.73m，进行CCT检查仍旧是安全的。在非诊断性TTE和TEE检查，恒流式LVAD患者CCT检查的适应症包括（1）临床怀疑流入管道移位（如无法解释的抽吸事件，无LVAD控制器参数的偏倚，但反复发生的室性心律失常，或由于左室部分去负荷引起的HF）；（2）临床提示溶血证据，提示可能存在泵内血栓形成（包括流入管道或流出管道）；（3）由于流出管道扭曲造成的泵功能异常；（4）原因不明的短暂性脑缺血发作或中风，须除外心内和/或主动脉根部血栓。超声心动图作为一线成像手段，能够筛查心肌功能恢复；但是，如果声窗欠佳，影响准确评价心室的大小和功能时，可以采取门控平衡法核素心室造影 或心电门控CCT作为二线成像手段。

要点

- 超声心动图无法评价某些LVAD并发症，包括流入管道移位、泵血栓形成、流出管道扭曲或梗阻、心内或心外血栓、或继发于心包或胸腔血肿或积液引起的心脏受压。此时，CCT检查能够提供完善、明确的诊断信息。

总结/讨论

在LVAD的管理当中，超声心动图起着至关重要的作用。尚无何时及如何进行超声心动图检查的指南作为参考。由于MCS领域仍旧比较新，因此，很多建议都基于较大的LVAD中心的专家共识。文献中，需要更多的超声心动图特异性参数，建立LVAD外科手术

前禁忌症或预防措施。在LVAD植入过程中及之后，可以分别通过围手术期TEE和TTE/TEE区别装置功能正常和异常，确认自体心脏是否通过LVAD支持获益。为了建立以上推荐，我们使用了追踪管理的方法，包括（1）术前评价；（2）围手术期TEE；（3）术后超声心动图监测；（4）术后问题聚焦超声心动图检查；（5）恢复期超声心动图检查模板。

患者群体

接受LVAD植入的受体多为终末期扩张性心肌病的成年患者，我们的推荐主要应用于该类人群。超声心动图在其他方面，如年龄偏小的患者中的应用尚未确立。体型较小（但仍在生长发育）的患者，包括浸润性心肌病，扩张性心肌病的儿科及青春期患者，复杂性先天性心脏病的儿科及成人患者（见图32）。由于这些年龄小，尚未进行研究的患者群体可能从LVAD支持中获益，一般都将这类患者的问题单独列出进行讨论，除非其可以使用成人扩张性心肌病患者的LVAD，采用成人患者的入组标准、仪器选择和植入术后功能评价等推荐。但是，此类人群在个体化治疗、仪器选择及随访评价中，需要周全考虑。目前，以该患者群体为研究对象的已发表数据有限，详细建议本指南不赘述。单独的儿科患者的LVAD讨论将在文末阐述。

超声心动图的使用频率和适用范围

在过去的几年中，门诊LVAD患者数量明显增加，今后预期提高患者的生存率以及扩大植入中心规模。本指南的主要目标是为MCS动态中心提供管理框架，提高诊疗效率。图14代表植入LVAD后，一般状况稳定的患者，建立常规超声心动图监测可行性策略。常规超声心动图监测用于明确LVAD功能有无异常，评价自体心脏对循环辅助的反应性。以上检查类似于未植入LVAD的HF患者，根据指南进行内科药物治疗后，应用超声心动图评价药物疗效。很多患者能够耐受，甚至长期依靠LVAD存活。但是，仍旧推荐常规超声心动图随访监测，用以筛查可能存在的隐匿LVAD并发症（在出现症状或LVAD报警之前），包括（并不仅限于）新发或恶化的AR，根据自体心脏功能改善或恶化进行的非适当的泵速校正、泵内血栓形成、或其他管道梗阻、主动脉根部血栓、主动脉瓣融合、制动患者的进展性/隐匿性HF。理论上，早期发现并发症或早期干预隐匿且持续的HF，能够改善患者的转归，降低因HF或其他激发装置报警所引起的再住院率。出于谨慎，个别中心采取了过于密集和/或过于细致的超声心动图检查。基于此种情况，指南建议，结合患者的实际情况，制定理想的超声心动图检查频率。指南还能协助为病情稳定的患者规划常规随访合理的时间，就近进行LVAD超声心动图复查。当患者出现明显的HF或LVAD功能异常相关的症状或体征时，指南提供了指导针对装置异常的超声心动图筛查的框架。

实验室检查和使用范围

常见问题即是否结合LVAD超声心动图进行泵速校正，该检查耗时耗力。并且，每个转速下的超声心动图测量参数亦无精确界定。通常，不论监测超声心动图随访还是针对仪

器故障的超声心动图筛查，都应进行基线泵速下全面的HF超声心动图评价（不仅局限于该检查）。基线状态下，额外的LVAD超声心动图特殊成像包括（如可能）流入管道、流出管道及升主动脉吻合口（如有适应症可以应用TEE检查）的二维及多普勒成像。建议随后每级泵速下进行简单检查。每级泵速下成像的范围取决于拟解决的问题以及成像目的。在基线状态下，LVAD功能正常且无症状的患者，随后依据每个中心的不同标准，在不同泵转速下获取相关数据。最低泵速调整参数的框架详见文后附录，并根据不同情况，适用不同的患者。无症状的患者，可以定期校正泵速，从而建立患者自身参数对照，尽早识别可疑异常。泵速梯度调整试验，如果患者情况较稳定，可以作为装置异常筛查（例如，筛查溶血患者的泵功能异常和可以涡轮叶片血栓形成）和评价左室功能恢复。某些转速调整的特定禁忌症及安全终点应个体化，监测并解释，文中表格及附件已列举了相关必要信息。

门诊量比较大的LVAD中心，患者按照事先安排好的流程进行常规超声心动图随访，从而HF/MCS中心能够保证专用超声心动图室或卫星超声心动图室提供检查所用诊室和相应超声技师完成随访。当可疑异常时，根据检查的适应症，有经验的超声技师或医生依具体情况，决定检查的类型和范围。个别病例，仅能在基线泵速下进行有限的超声心动图检查用于明确诊断，入院后再进行更为详细的检查。LVAD患者检查的一个新方面就是在超声心动图检查之前，通过动脉多普勒测量患者血压，并保证在较高泵速下检查的安全性和准确性。总而言之，本文的主要目的是为超声心动图更有效的服务于常规随访及处理急诊LVAD患者提供框架模板。由于缺乏验证及转归研究，本指南推荐的大部分内容适用于各植入中心的内部标准及患者个体。但是，提供充足的受训人员，适当的仪器，保证测量质量是完成这些复杂检查所必须，但此类患者的图像质量通常较差不利于诊断。

转诊/社区医院

尽管在LVAD装置植入及随访过程中，需要有LVAD专家参与，但是，越来越多的患者因临床症状或LVAD装置报警，到经验较少的医院进行就诊。因此，本文的另外一个目的就是为经验较少的超声医师提供简单实用的参考。理想的，此类人员能够快速掌握要点及问题解决技巧，观察安全预警，与LVAD中心有效沟通。地方超声心动图室可以建立一个熟练进行随访监测的水准，并与第三方植入中心进行沟通。

其他装置

本文仅述及了FDA批准的可以长期使用的外科恒流式LVAD装置（HM-II和HVAD）。但是，实践当中，超声心动图医生可能会遇到临时LVAD，结合MCS中心的使用经验，在附录A中详细讨论。

右室辅助装置及双室辅助装置

某些情况下，需要进行右室辅助循环，在植入LVAD同时，植入RVAD，可能明显改善患者的临床转归。如文中所述，LVAD植入术后对右室心力衰竭的超声心动图预测指标的建立是临床监测的重点。遗憾的是，目前尚无法通过一个或多个超声心动图参数，可靠预测是否需要进行双心室辅助循环。相反，可以通过尽可能在植入术前及术后全面的超声心动图评价右室功能，并综合汇总超声心动图和临床关于右室功能的信息，指导

临床决策。关于RVAD的类型的讨论以及超声心动图评价辅助循环后的右室功能不在本指南中阐述，简要的信息详见附录A。LVAD植入术后，超声心动图作为右室衰竭（LVAD低流量）病因筛查具有重要意义，如除外心包填塞或胸腔积液。

综上所述，编写委员会及其相关撰写人员希望将本文作为框架，将超声心动图检查与LVAD患者的临床管理有机结合。其他的未上市的MCS装置将会在今后的更新指南中阐述。我们亦希望通过本文激发该领域的实用性及临床转归研究。

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补充数据

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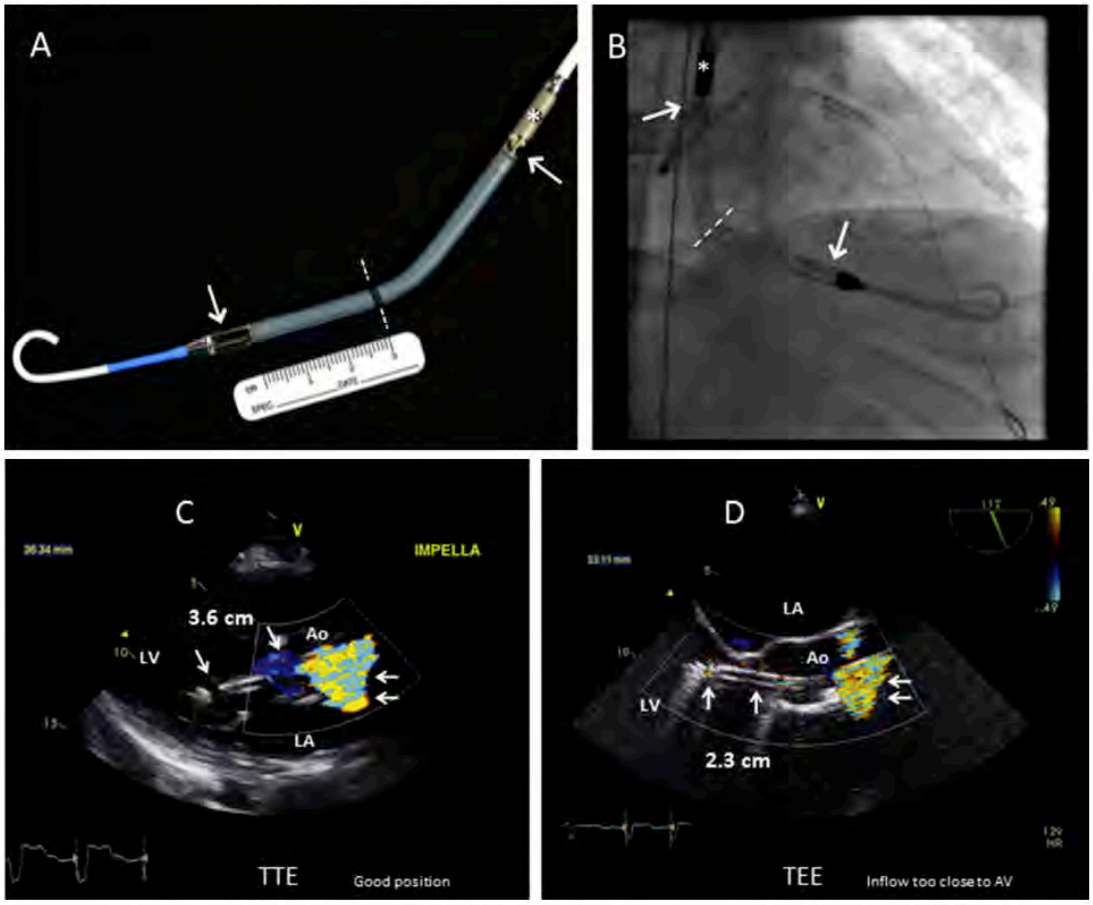
附录 A

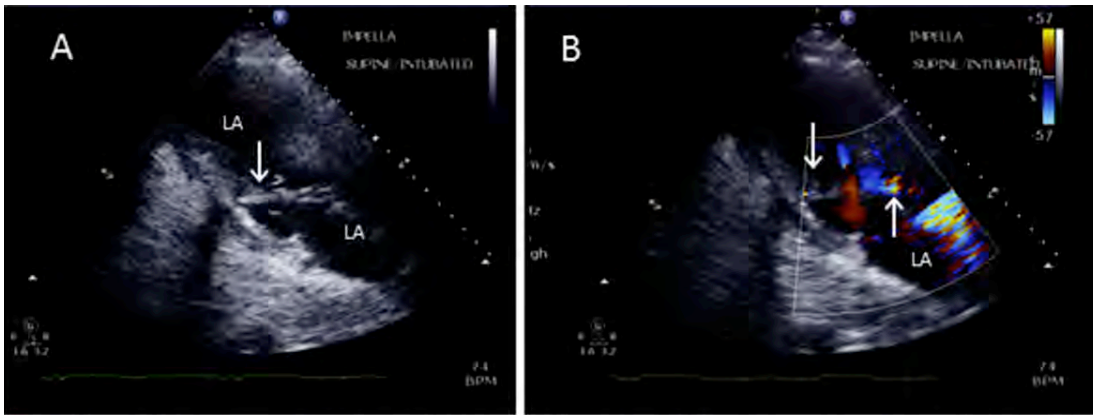
超声医生及技师在检查当中，也会遇到其他类型的辅助装置，包括经皮、胸外及右室辅助装置。

临时辅助的经皮 LVAD

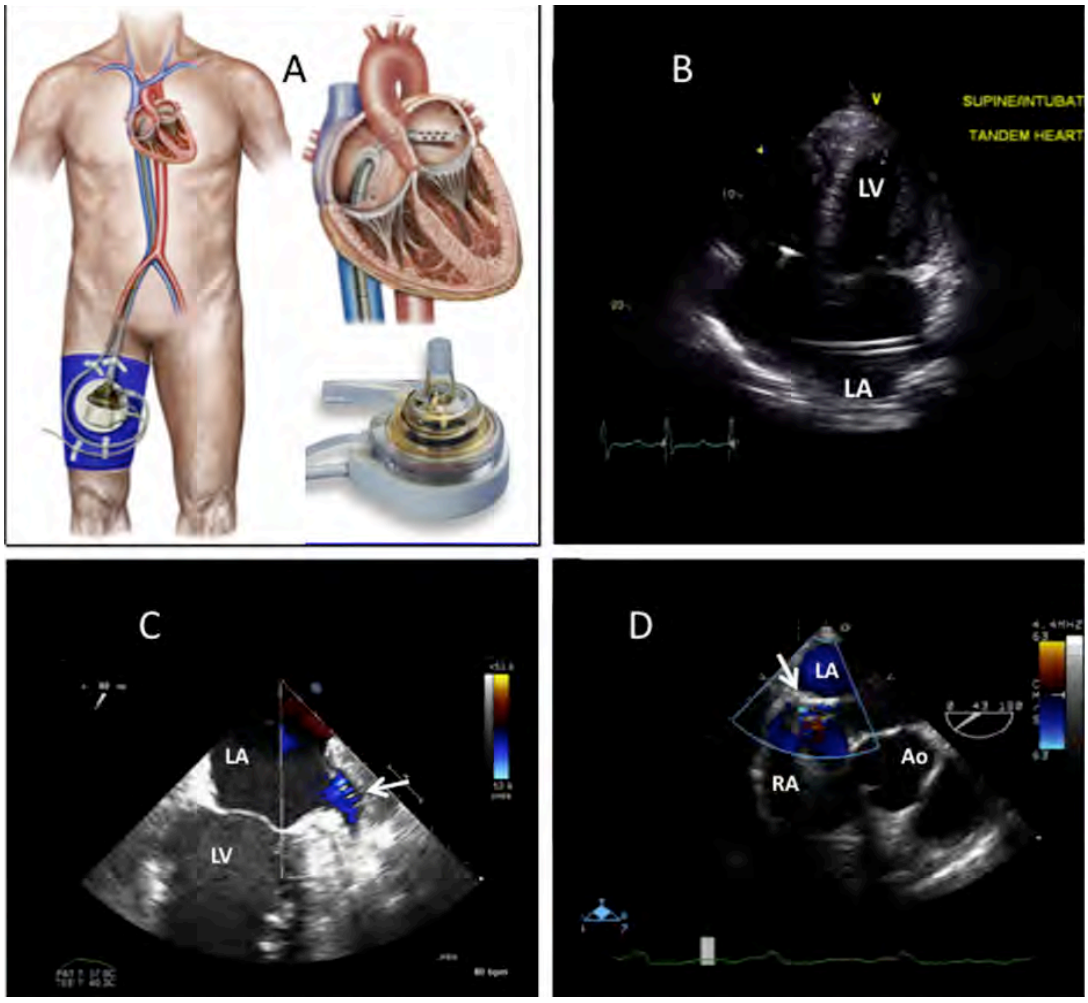
在导管室造影引导下即可完成经皮左室辅助装置（PVAD）植入，主要用于急性心源性休克或用于某些高危冠状动脉介入治疗术后患者的辅助支持。目前，FDA批准的两种PVAD包括：Impella系统（Abiomed, Inc., Danvers, MA）和TandemHeart系统（CardiacAssist, Inc., Pittsburgh, PA）。



图A1（A）经皮左室辅助装置Impella CP图片，显示Impella外壳（*号所示），血液流入区域（向下箭头）和流出区域（向上箭头），以及远端猪尾导管。（B）Impella原位X线成像，血液流入区域（向下箭头）和流出区域（向上箭头），Impella外壳（*号所示）。放射非透射区（虚线所示）为主动脉瓣环理想位置，距离流入区域约3.5cm。（C）TTE胸骨旁长轴切面。Impella装置穿过主动脉瓣。流入区域（左侧箭头）至主动脉瓣环（右侧箭头）间距约3.6cm。（D）在TEE成像中，流入区域（左侧箭头）至主动脉瓣环（右侧箭头）间距约2.3cm，尽管装置功能正常，但是为左室提供的安全区域不足。图C和D，双箭头所示为Impella典型的花彩多普勒伪像。见视频49和50。



图A2 改良TTE胸骨旁长轴切面显示经皮LVAD Impella CP装置，猪尾导管的远端接触二尖瓣下装置（向下箭头），流入区域邻近二尖瓣前叶，且与主动脉瓣环过近（向上箭头，图B）。



图A3（A）经皮辅助装置TandemHeart图例（CardiacAssist, Inc.公司提供图像）。该恒流泵为体外装置。（B）TTE心尖四腔切面可见该装置位于左房内的流入管道。见视频51。（C）TEE见左心耳内远端管道的多孔流入区域（箭头所示）。见视频53。

Impella。Impella 2.5 [FDA 510(k), 2008]及稍大型号Impella CP（Cardiac Power）（最大4 L/min）一般通过传统的股动脉途径植入。较大的Impella5.0[FDA 510(k), 2009]最大流量可以达到5L/min，并且需要外科通过左腋动脉植入。超声心动图

的重要性及其在三种辅助装置的评价参数相同。Impella远端包括微型轴连续血流泵，与左室连接的流入管道和与主动脉连接的流出管道（心内血流管道）（见图A1）。

植入前的超声心动图评价。严重的主动脉瓣返流是Impella相对禁忌症，而心室血栓和严重的AS或MS是绝对禁忌证。超声心动图可以用于筛查以上禁忌症，并评价HF的程度及病因。

植入后的超声心动图评价。装置报警或血流动力学不稳定时，可以进行急诊超声心动图检查，明确病因。患者活动（如挪床或心肺复苏）可能导致导管移位。TTE或TEE的LVOT长轴切面可以观察到Impella全貌。流入管道距主动脉瓣环约3.5-4.0cm。该泵特征性的彩色多普勒伪像在主动脉瓣环远端。管道与LVOT成45°夹角。然而，这种设计使猪尾导管远端易于与二尖瓣下装置发生缠绕（见图A2）。主要并发症包括二尖瓣返流恶化，无法继续向左室内输送装置，和/或因邻近二尖瓣叶遮挡流入管道所致低流速报警。如同其他LVADs，植入该装置后，主动脉瓣关闭或部分开放，只有结合多普勒成像通过ROVT计算净前向血流量获得每搏量和心输出量。其他关于Impella超声心动图评价的指导性信息可以在线获取。

TandemHeart。TandemHeart经皮心室辅助装置[FDA 510(k), 2006]以股静脉作为入路，并需要穿刺房间隔。该体外离心泵接受来自左房的血液，（通过心外管道）并将其泵回股动脉，依据穿房间隔流入管道内径不同，其流量介于4-5 L/min（图A2）。

植入后的超声心动图评价。左房血栓是TandemHeart植入的潜在禁忌症。该装置可以用于治疗心源性休克，包括严重的心肌梗死后室间隔穿孔、二尖瓣返流、主动脉瓣狭窄，或者伴有植入Impella的禁忌症（如严重的AR或左室血栓）。超声心动图不仅用于术前禁忌症的筛查，也用于评价HF的程度及病因。

植入后的超声心动图评价。该装置超声心动图唯一可见的结构即为穿房间隔的流入管道，在标准切面可见流入管道的全程，包括左房内、房间隔、右房内及下腔静脉的管道结构。彩色多普勒成像可以确认连续血流。此外，除确认管道的位置外，超声心动图需要评价植入后，自体心脏对循环辅助装置的反应，是否适合脱离LVAD的辅助支持。多普勒方法测量RVOT每搏量用于计算净前向血流量。穿房间隔管道一般要通过左心耳。由于管道有14个侧孔，即使管道的一端与左房或左心耳壁接触，仍旧存在正常血流（见图A3C）。由于左室可能完全被分流，当主动脉瓣关闭时，超声技师需要注意左室内（见图A4）或主动脉根部有无血栓形成。

外科植入体外心室辅助装置用于临时辅助

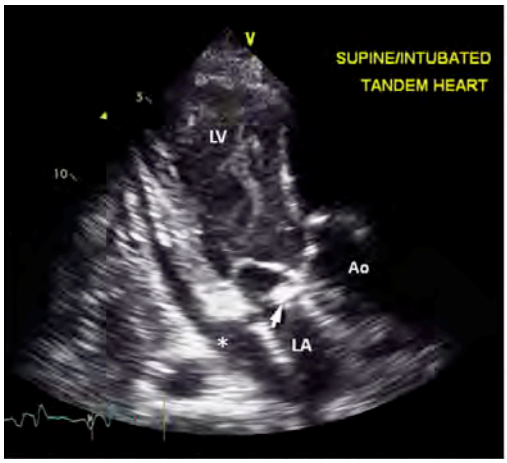
Thoratec胸外心室辅助装置（VAD）。Thoratec胸外心室辅助装置（Thoratec Corporation,
Pleasanton, CA），是第一代气动搏动泵，FDA 510(c)批准用于BTT治疗（1995年）和心脏外科术后恢复（1998年）。如图A5所示的三种泵设计，用于左室辅助，或双室辅助。流入管道植入于左心房，该入路易于非体外循环经验较少的外科医生采取急诊外科植入。尽管该装置适于植入体内作为循环辅助，但最终被第三代恒流式LVAD取代。该搏动泵的超声心动图特点是流入管道及流出管道的血流不随心动周期呈时相性（间歇左室辅助）。在自动模式下（最大支持状态），传感器感知被动心脏充盈，从而激发心脏泵血。该装置亦可设置低转速模式用于进行较

低水平支持。该泵装置与恒流式辅助装置的超声心动图鉴别特点请咨询Estep等医生。

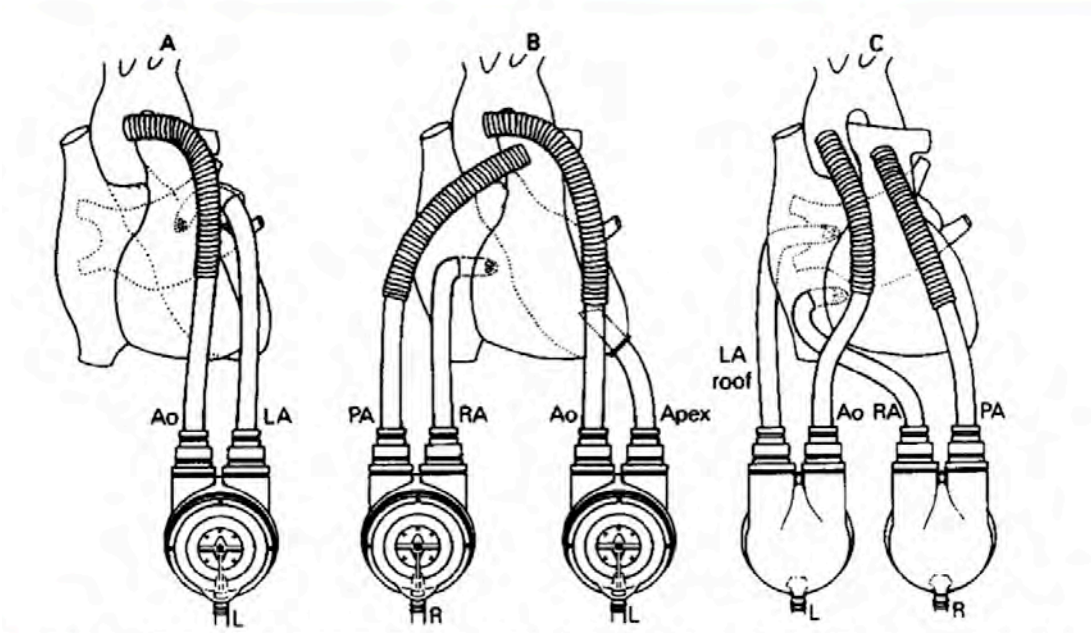
Thoratec CentriMag（曾命名Levitronix CentriMag）。CentriMag主要用于左、右室或双室的短期辅助支持。该体外离心恒流泵（见图A6）是由无轴承磁悬浮叶片驱动，最大流量达到9.9L/min。一般需要经胸骨正中切口，外科植入流入和流出管道。CentriMag适用于将患者在不同医院间输送。超声成像的难点在于胸骨缝合和患者气管插管所致成像声窗较差。当用于左室辅助时，流入管道可以置于右上肺静脉（超声几乎不可见）或左室内（超声可见）。当流入管道置于右上肺静脉时，如果主动脉瓣不开放则左心室内的血液完全被分流。如前所述的TandemHeart装置，左室内血液停滞（见图4A），增加左室血栓形成的风险，需要超声心动图进行确诊。其他的超声心动图成像特点类似于前所述的体内循环辅助装置。

右室辅助装置。

如前所述，本指南述及的多数患者仅需要植入左室辅助装置。此处仅阐述一种需要植入RVAD的情况，超声医生在临床当中常见右室辅助或双室辅助。在紧急情况下，包括LVAD植入术后，可能需要RVAD支持。右室心力衰竭的长期管理较为困难。而LVAD术后，预测右室心力衰竭的能力有限，在个别病例，即使植入术前全面评价了右心功能，患者仍旧发生右心衰竭。当优化LVAD泵速及内科药物治疗后效果仍旧不理想时，Impella,、TandemHeart、HM-II和HVAD可用于右心循环辅助（FDA未批准）；而Thoratec PVAD、 Berlin Heart EXCOR、CentriMag和PediMag等辅助装置已经获得FDA批准，可以作为RVAD。而其他较少使用的辅助装置，可以用于右心的辅助循环，目前，新一代循环辅助装置也在研发当中。对于左、右心室同时进行循环辅助的情况，本文不作详细阐述。但是，在充盈不完全及或泵速过高时，需要同时观察左、右心室大小，可能会影响流入管道血流或邻近心室形态。保证房间隔及室间隔位置居中至关重要。



图A4 TandemHeart辅助循环的患者，由于左室内的血液被完全分流，左室腔内可见严重的自发回声显影。如果无全身抗凝，发生左室内血栓的风险很高。左房（LA），主动脉根部（Ao），心包积液（*），TandemHeart流入管道（箭头所示）。视频54。



图A5 Thoratec体外循环辅助装置示意图。三种套管方式分别用于单一左室辅助（图A）和双室辅助（图B和C）。Ao=主动脉，LA=左心耳，PA=肺动脉，RA=右房， Apex=左室心尖，IAG=管道通过房间沟穿刺如左房顶。注意图C与图B前后反向为图B的背面。（图片摘自Farrar DJet al. N Engl J Med 1988; 318:333-340）

图A6 Thoratec CentriMag体外离心恒流泵。箭头所示为血流方向。

附录B　LVAD植入前推荐TTE检查模板（包括高危标记）

胸骨旁长轴切面图像获取

左室大小

高危所见：左室内径小，左室腔内肌小梁增多

整体和局部左室功能

M型超声评价左室和左房/主动脉比值

二维超声评价AV,MV,TV（在右室流入道切面观察TV）

高危所见：任何人工瓣膜

彩色多普勒超声心动图评价MV和AV

右室流入道切面

连续多普勒评价TR

左侧胸骨旁高位切面评价升主动脉

高危所见：升主动脉瘤，主动脉夹层，主动脉粥样斑块

推荐测量参数

舒张末期左室内径

收缩末期左室内径

左室后壁厚度

室间隔厚度

射血分数

左室流出道内径

主动脉根部内径

升主动脉内径

连续多普勒测量TR评价右室收缩压

胸骨旁短轴切面获取

AV及右室流出道水平二维短轴切面

左室基底段、中段及心尖水平二维短轴切面

高危所见：室间隔缺损

整体和局部左室功能

彩色多普勒超声心动图评价PV，AV和TV

频谱多普勒评价右室流出道，PV及肺动脉干

高危所见：中重度PS或PR；PDA，人工瓣膜

M型评价（如果是试验室标准化测量）

推荐测量参数

右室流出道速度

肺动脉速度

心尖四腔切面图像获取

四腔心切面二维图像（最大左室长径）

高危所见：左室血栓，左室心尖部室壁瘤，任何先天性心脏病

右室“专用”切面

高危所见：右室扩张

整体和局部左室及右室功能

高危所见：右室收缩功能不全

瓣膜流入道或返流的彩色血流多普勒成像

房间隔

高危所见：VSD，PFO或ASD

二尖瓣的脉冲波多普勒

肺静脉的脉冲波多普勒

组织多普勒成像

右室和左室的应变（可选）

连续多普勒评价自体及人工瓣膜（利用多切面获取最高流速）

高危所见：

MV：≥中度MS

AV：>轻度AR

TV：≥中度TR，或>轻度TS

PV：≥中度PS或PR

静息状态下生理盐水声震气泡结合Valsalva动作，评价心内及肺内分流。

高危所见：PFO，明显的肺内分流

推荐测量参数

左室收缩功能：计算二维/三维容积评价射血分数

左室舒张功能：二尖瓣E/A比值，减速时间，二尖瓣前后叶瓣环组织多普勒成像

右室功能：右室应变，三尖瓣环收缩期位移，三尖瓣环组织多普勒成像RV function: RV strain, TAPSE, TV DTI

左房容积指数/右房面积

心尖五腔切面图像获取

二维图像

LVOT彩色多普勒成像

LVOT脉冲波多普勒

如果存在或可疑主动脉瓣狭窄，连续多普勒测量AV血流

推荐测量参数

左室收缩功能：左室流出道每搏量，心输出量/指数

心尖二腔切面图像获取

二维图像

高危所见：左心耳血栓

整体和局部左室功能

二尖瓣彩色血流多普勒

推荐测量参数

左房容积

心尖长轴切面图像获取

二维图像

整体及局部左室功能

二尖瓣彩色血流多普勒

LVOT脉冲波多普勒

如存在或可疑主动脉瓣狭窄，连续多普勒记录主动脉瓣血流

推荐测量参数

左室收缩功能：LVOT搏出量，心输出量/指数

剑下切面

四腔切面

二维图像，包括评价房室间隔

高危所见：VSD，PFO或ASD

瓣膜流入道和返流的彩色血流多普勒

房、室间隔彩色血流多普勒评价有无分流

短轴切面

作为胸骨旁切面的完善

通过下腔静脉评价右房压力（IVC大小和随呼吸变化率）

必要时，多普勒评价肝静脉血流

胸骨上窝切面

主动脉弓长轴切面（如存在适应症，可获取短轴切面）

主动脉弓及峡部彩色多普勒血流

高危所见：主动脉病变（PDA，主动脉缩窄）

当存在主动脉瓣返流时，脉冲波多普勒记录降主动脉血流频谱

如存在或可疑主动脉瓣狭窄，连续多普勒记录主动脉瓣血流

上腔静脉

其他切面

右侧胸骨旁图像

长轴切面评价升主动脉

如存在或可疑主动脉瓣狭窄，连续多普勒记录主动脉瓣血流

右侧锁骨上窝切面

上腔静脉

当存在主动脉瓣返流时，脉冲波多普勒记录降主动脉血流频谱

2D，二维超声心动图；3D，三维超声心动图； A，二尖瓣舒张晚期血流速度； ASD，房间隔缺损；AV，主动脉瓣；CW，连续多普勒；DT，减速时间；DTI，组织多普勒成像；E，二尖瓣舒张早期血流速度；EF，射血分数；IVC，下腔静脉；LA，左房；LV，左室，LVOT，左室流出道；MV，二尖瓣；PDA，动脉导管未闭；PFO，卵圆孔未闭；PR，肺动脉瓣返流；PS，肺动脉瓣狭窄；PV，肺动脉瓣；RA，右房；RV，右室；RVOT，右室流出道；RVSP，右室收缩压；SVC，上腔静脉；TAPSE，三尖瓣环收缩期位移；TR，三尖瓣返流,；TS，三尖瓣狭窄；TTE，经胸超声心动图；TV，三尖瓣；VSD，室间隔缺损。

附录C　围手术期TEE检查模板/清单

该检查分为两部分。标准切面参考Hahn等早期指南[42]。

1. 植入术前的围手术期TEE检查

目的：明确此前超声心动图检查阳性所见（TTE或TEE）；在LVAD植入前探查突发异常。
血压：通过动脉置管；对于低血压的患者考虑使用血管加压药物评估AR严重程度
左室：大小，收缩功能，评估血栓
左房：大小，评估左心耳内及血栓
右室：大小，收缩功能，导管及电极
右房：大小，评估血栓，导管及电极
房间隔：通过二维、彩色多普勒、静脉注射生理盐水造影；高危所见：PFO/ASD
体静脉：SVC，IVC
肺静脉
主动脉瓣：高危所见：>轻度AR，人工瓣膜
二尖瓣：高危所见：≥中度二尖瓣狭窄，人工二尖瓣
肺动脉瓣：高危所见：>轻度 PS,≥中度PR，如果计划植入；人工瓣膜
肺动脉干：高危所见：先天异常（PDA,肺动脉闭锁或瘤）
三尖瓣：TR，估测肺动脉收缩压，高危所见： ≥中度TR，>轻度TS，人工瓣膜
心包：筛查心包积液，考虑缩窄性生理改变
主动脉：主动脉根部，升主动脉，主动脉弓，降主动脉胸段；筛查动脉瘤，先天异常，夹层或复合型动脉粥样斑块

2. 植入术后的围手术期TEE检查

目的：监测心内气体；除外分流；明确装置及自体心脏的功能
泵型号
泵转速：
血压：通过动脉置管；或低血压（平均动脉压<60 mmHg），考虑使用血管收缩压剂评价AR程度或其他血流动力学参数
心内气体：在停跳之前，评价左侧心腔及主动脉根部气体
左室：大小，流入管道的位置和血流速度，室间隔位置；高危所见：左室腔过小（泵速过高或右室衰竭），间隔向左偏移，左室腔增大（梗阻或泵速过低）
流入管道位置：二维/三维超声心动图评价可能的位置异常。
流入管道血流：频谱和彩色多普勒（高危所见：异常血流频谱形态/血流速度，尤其是在关胸之后）
左房：评价左心耳
右室：大小，收缩功能，高危所见：右室功能不全征象
右房：大小，评价血栓，导管/电极
房间隔：重复静脉注射生理盐水试验，应用彩色多普勒观察房间隔（高危所见：PFO/ASD）
体静脉：SVC，IVC
肺静脉：观察
主动脉瓣：主动脉瓣开放程度和主动脉瓣返流程度（高危所见：>轻度AR）
二尖瓣：除外二尖瓣下装置造成的流入管道梗阻；评价MR
肺动脉瓣：评价PR，测量RVOT每搏量
肺动脉干：（如可能，彩色多普勒评价RVAD流出管道），评价PR
三尖瓣：评价TR（高危所见：≥中度TR）；通过TR流速评价肺动脉收缩压（如不是重度

TR）

心包：筛查心包积液/血肿

主动脉：除外医源性夹层

流出管道：（如可能）通过彩色和频谱多普勒评价管道邻近RV/RA情况

流出管道与主动脉吻合口：（如可能）通过彩色和频谱多普勒评价管道血流情况，高危所见：管道扭曲或湍流，流速>2m/s，尤其在关胸后

2D，二维超声心动图；3D，三维超声心动图；AR，主动脉瓣返流；ASD，房间隔缺损；AV，主动脉瓣；CPB，心肺流转术；IAS，房间隔；IV，颈静脉；IVC，下腔静脉；LA，左房；LV，左室；LVAD，左心室辅助装置；LVOT,左室流出道；MAP，平均动脉压；MR，二尖瓣返流；PA，肺动脉；PFO，卵圆孔未闭；PDA，动脉导管未闭；PR，肺动脉瓣返流；PS，肺动脉瓣狭窄；RA，右房；RV，右室；RVAD，右室辅助装置；RVOT，右室流出道；SV，每搏量；SVC，上腔静脉；TEE，经食管超声心动图；TR，三尖瓣返流；TS，三尖瓣狭窄；TTE，经胸超声心动图

附录D　恒流式LVAD去负荷后超声心动图评价左室参数变化的量级和检查间隔

参数	LVAD 植入前	LVAD 植入术后 1 个月	LVAD 植入术后 3 个月	LVAD 植入术后 6 个月	LVAD 植入术后 12 个月
	研究 1（N=21）	研究 1（N=21）	--	研究 1（N=10）	--
	研究 2（N=63）	--	研究 2（N=63）	研究 2（N=63）	--
	研究 3（N=80）	研究 3（N=68）	研究 3（N=80）	研究 3（N=47）	研究 3（N=20）
左室参数					
左室舒张末期内径					
研究 1（mm）	66±11	55±11**	--	52±11*	--
研究 2（mm）	68±9	--	56±11*	57±12	--
研究 3（cm/m^2）	3.2（2.9，3.6）	2.8（2.3,3.2）	2.9（2.4,3.4）	2.8（2.2,3.4）	2.6（2.2,3.0）*
左室收缩期内径					
研究 1（mm）	58±10	47±12	--	43±13	--
研究 2（mm）	61±9	--	47±13*	49±13	--
研究 3（cm/m^2）	3.0（2.6，3.3）	2.6（2.0,3.1）	2.6（2.1，3.1）	2.5（1.8,2.9）	2.3（1.9,2.8）*
左室舒张末期容积					
研究 1（ml）	242±108	127±68*	--	113±45*	--
研究 2（mm）	--	--	--	--	--
研究 3（ml/m^2）	113（94,141）	77（54,109）*	86（62,106）*	86±（52,108）*	69（45,93）*
左室收缩末期容积					
研究 1（ml）	191±93	100±66*	--	82±42*	--
研究 2（mm）	--	--	--	--	--
研究 3（ml/m^2）	3.0（2.6，3.3）	2.6（2.0,3.1）	2.6（2.1，,3.1）	2.5（1.8,2.9）	2.3（1.9，1.8）*
左室射血分数（%）					
研究 1	22±5	25±13		29±10	
研究 2	19±7		26±12*	27±14	
研究 3	17（14.23）	20（15,30）	20（14,26）	25（18,33）*	22（15,31）
左室质量					
研究 1	--	--	--	--	--
研究 2（g）	383±113	--	295.9±188*	314±134	--
研究 3（g/m2）	114（93,146）	95（71,114）**	92（63,18）**	111（74,134）	77（50,104）*
左室舒张参数					
左房大小					
研究 1（mm）	47±7	37±9	--	42±13	--
研究 2（ml/m2）	69±30	--	42±15*	--	--
研究 3（ml/m^2）	46（35,54）	28（22,36）	32（23,38）	25（19,39）*	28（18,38）*
E 峰					
研究 1（cm/s）	96±23	73±27**	--	66±12**	--
研究 2（cm/s）	98±35	--	100±160	80±20	--
研究 3（cm/s）	100（80,110）	80（60,100）	80（70,100）	80（70,110）	100（60,120）

二尖瓣减速时间					
研究 1	124±39	180±53*	--	164±24	--
研究 2	132±27	--	188±70*	166±48	--
研究 3	133（112,165）	175（137,220）*	178（141,212）	172（121,220）*	170（157,225）
组织多普勒 e′（cm/s）					
研究 1	--	--	--	--	--
研究 2（室间隔 e′）	4±1	--	4±1	--	--
研究 3（室间隔 e′）	4（3,6）	6（5,9）	7（5,9）	7（4,9）	7（6,10）**
（侧壁 e′）	8（5,11）	9（7,10）	9（6,11）	10（7,13）	12（8,12）
E/e′ 比值					
研究 1	--	--	--	--	--
研究 2（室间隔 e′）	26±11	--	20±9**	13±7	--
研究 3（室间隔 e′）	23（16,30）	13（9,19）	12（9,16）*	12（9,19）	15（7,17）**
（侧壁 e′）	14（9,19）	9（16,13）**	10（6,12）	9（7,13）	10（6,11）

研究1，Lam 等，JASE 2009[52]；研究2，Topilsky等，JASE 2011[51]；研究3 Drakos等，JACC 2013;61:1985-94. 研究1和2的结果表示为均值±标准差，研究3的结果表示为中位数（第二十五，第七十五百分位数）；*$P < .01$ 对比LVAD植入前；**$P < .05$ 对比LVAD植入前。研究2仅提供了LVAD植入前与植入术后3个的测量结果。A，二尖瓣舒张晚期峰值流速；CF，连续血流或恒流；DT，减速时间；E，二尖瓣舒张早期峰值流速，e′，二尖瓣环速度;LA，左心房；LV，左心室；LVAD，左室辅助装置。

附录E　LVAD植入术后超声心动图监测模板：除LVAD特殊参数外的标准全面的TTE（或TEE）检查

血压（如无脉，应用多普勒评价平均动脉压）

泵型号及基本转速

主动脉瓣开放程度/关闭

房、室间隔位置

左室流入管道

- 位置
- 注意选取最佳切面进行观察
- 血流类型
- 血流方向
- 收缩期峰值血流速度和舒张期流速（脉冲多普勒）
- 速度频谱形态

左室流出管道

- 位置/注意选择最佳切面进行观察
- 血流类型
- 血流方向
- 收缩期峰值血流速度和舒张期流速（脉冲多普勒）
- 速度频谱形态

LVAD心输出量

- 流出管道脉冲波VTI
- 通过测量管道直径或已知参数计算管道横截面积

总体心输出量

- RVOT脉冲波VTI
- 通过RVOT内径计算横截面积

心包：心包积液/血肿

辅助装置植入术后高危超声所见

- 房、室间隔是否存在偏移
- 心内分流
- 管道内血路速度增加过快
- 管道机械梗阻
- 管道抽吸事件
- 主动脉瓣或二尖瓣返流加重
- 心内血栓形成
- 心包血肿/积液，伴有或不伴有心包填塞
    - ○ 右室功能不全（综合多个参数）

○右室增大

○右室收缩功能不全（如可能，定量评价）

○中重度TR

○右房压力增高

LV，左心室；LVAD，左室辅助装置；RA，右房；RV，右室；RVOT，右室流出道；TEE，经食管超声心动图；TR，三尖瓣返流；TTE，经胸超声心动图；VTI，速度时间积分。

参考表2中关于可能的异常并发症/高危所见

附录 F　LVAD优化/速度调整超声心动图模板

在基线状态下，进行常规超声心动图监测随访（注明血压，泵型号，基线转速）

在基线状态下，需要测量以下参数：

- 在胸骨旁长轴切面测量LVIDd
- 胸骨旁短轴切面测量右室VTI
- 胸骨旁长轴切面二维及M型超声评价主动脉瓣开放（如必要使用彩色多普勒）
- 胸骨旁长轴及短轴二维图像
- 胸骨旁长轴及心尖切面彩色多普勒评价AR及MR
- 右室流入道济心尖四腔切面彩色多普勒评价TR
- 标准脉冲波多普勒评价二尖瓣流入道参数
- 评价房、室间隔位置

HM II将泵速降低至8000rpm

或

HVAD将泵速降低至2400rpm

- 等待2分钟
- 重复测量以上参数

HM II每个速度级别增加400rpm

或

HVAD每个速速级别增加20-40rpm

- 等待2分钟
- 重复测量以上参数

HM II：

以**400rpm**为一级别，逐级增加转速至**12000rpm**，或直至获取一下参数作为终点

HVAD:

以**20-40rpm**为一级别，逐级增加转速至**3200rpm**，或直至获取一下参数作为终点

终点：

- 完成速度测试
- 抽吸事件：左室腔明显减小（典型的<3cm），伴有或不伴有心室异位，伴有或不伴有间歇性梗阻，室间隔向左偏移，TR加重
- 出现以下甚至更多症状，如心悸，眩晕，胸痛，气短，头痛等
- 高血压（如平均动脉压>100mmHg或伴有症状）
- 低血压（如平均动脉压<60mmHg或伴有症状）

2D，二维超声心动图，AR，主动脉瓣返流；AV，主动脉瓣，BP，血压；HM-II, HeartMate II; HVAD, HeartWare心室辅助装置；LV，左心室；LVAD，左室辅助装置；LVIDd，左室舒张末径；MAP，平均动脉压；MR，二尖瓣返流；PLAX，胸骨旁长轴；PW，脉冲波多普勒；RV，右心室；TR，三尖瓣返流；TV，三尖瓣；VTI，速度时间积分。

注：需要在每级泵速下，应用彩色和频谱多普勒（包括频谱多普勒）评价流入管道血流，以除外梗阻可能。如装置功能正常，基线状态下的流出管道多普勒评价是必须，在其他转速下的评价则为可选项。在异常情

况下，如可能，可增加额外参数，如流出管道血流速度形态和搏出量（例如梗阻或评价AR容量）和流出管道与主动脉吻合口，用以评价梗阻和血液回流。

附录 G　速度变化：LVAD 优化或问题聚焦（速度递增）超声心动图列表

速度变化：LVAD 优化或问题聚焦（速度递增）超声心动图列表

恒流型 LVAD 型号：　植入时间： [**患者 INR** = _____ **PTT** = _____]

前次超声心动图检查日期及异常发现：

●**优化模板。**根据 MCS 中心自身标准进行速度优化；样板参数如下：（a）至少达到主动脉瓣开放或（b）达到室间隔位置居中，和或 MR 轻度或更少，或（c）达到左室最大去负荷状态时，AV 完全关闭或（d）调整速度低于最大转速并 AV 关闭和最低速度并 MR 明显，且室间隔向右偏移。

●**针对装置异常的筛查**。检查适应症：样板检查内容包括如下适应症：

a. 左心衰或右心衰。

b. 在溶血或可疑泵内血栓时，筛查泵功能。

c. 其他问题引起的装置报警。

泵速（rpm）	血压	AV 开放（是/否/间歇）	LVIDd(cm)	RVOT VIT(cm)	严重 AR（是/否）	严重 MR(是/否）	严重 TR（是/否）	TR 速度（m/s）	二尖瓣 E 峰（m/s），DT（ms）	IVS 位置（左/右/居中）	a.症状（有/无）b.流入管道梗阻证据（有/无）

终止原因：（如流入管道梗阻，低血压，高血压，RV 或 LV 功能恶化等征象。）

最终泵速=____rpm

最终血压= _____mmHg

AR，主动脉瓣返流；AV，主动脉瓣；BP，血压；CF，恒流；DT，减速时间；E，舒张早期；INR，国际标准化比值；IVS，室间隔；LV，室间隔；LVAD，左室辅助装置；LVIDd，左室舒张末期内径；MCS，机械循环辅助支持；MR，二尖瓣返流；MV，二尖瓣；PT，凝血活酶时间；PPT，部分凝血活酶时间；RVOT，右室流出道；TR，三尖瓣

返流；VTI，速度时间积分。

注:在每一个速度级别下测量的参数，可依据各个植入中心的自身标准而有所不同。在基线转速检查后，随后转速下的其他测量参数可主要在胸骨旁切面获取，作为一个简要检查。

附录 H　LVAD 恢复检查模板清单

LVAD 恢复检查模板清单

恒流型辅助装置的型号：　　植入日期:

前次超声心动图检查时间及阳性所见：

患者 INR = _____ PTT = _____(如 INR <2.0 使用肝素)

基线转速=

低转速达标：

HM-II 从基线速度，每一级别增加 1000 rpm，直至 6000 rpm

HVAD 从基线速度，每一级别增加 100rpm，直至 1800 rpm

超声心动图测量参数

泵速（rpm）	血压	流入管道/流出管道血流方向：前向(f）中位（n）逆流（r）	AV 开放（是/否/间歇）比 ms（M 型）	LVEF	LVIDd（cm）	RV 收缩功能正常（是/否）	RV 大小正常（是/否）	ROVT VIT（cm）	明显 AR（是/否）	明显 MR（是/否）	明显 TR（是/否）/TR 流速（m/s）	MV E 峰（m/s），DT	运动试验（是/否）	症状（是/否）

基线泵速 低泵速 根据各中心标准自定义	以上参数在基线泵速及每个低转速级别下获取 i 低速后 5 分钟 ii 低速后 15 分钟 iii6 分钟步行试验后
血流动力学测量 （静息±运动）根据各中心标准自定义	如收缩压，舒张压，平均压，心率及导管测量一下参数： i 基线转速 ii 低速后 0 分钟 iii 低速后 5 分钟 iv 低速后 10 分钟 v 低速后 15 分钟 vi 低速后 6 分钟步行试验
终止原因：	气短，胸痛，视物模糊，眩晕，腹痛 （如胸痛，记录 12 导联心电图）
最终泵速设置=_____rpm 最终血压=____mmHg 最终临床状态：	

AR，主动脉瓣返流；AV，主动脉瓣；BP血压，CF，连续血流；DT，减速时间；E，舒张早期；ECG，心电图；HMII，HeartMate左室辅助装置；HR，心率；HVAD，HeartWare 心室辅助装置；INR，国际标准化比值；IVS，室间隔；LV，左心室；LVAD，左室辅助装置；LVEF，左室射血分数，LVIDd，舒张末期左室内径；MCS，机械辅助循环支持；MR，二尖瓣返流；MS，二尖瓣狭窄；MV，二尖瓣；PT，凝血酶原时间；PTT，部分凝血活酶时间；RVOT，右室流出道；TR，三尖瓣返流；VTI，速度时间积分。

注: 在每一个速度级别、不同型号和生理/运动试验检查的时间下，测量的参数，可依据各个植入中心的自身标准而有所不同。在基线转速检查后，随后转速下的其他测量参数可主要在胸骨旁切面获取，作为一个简要检查。如果无法定量评价LVEF，可用定性评价LVEF替代。

*各中心除自身标准外，还需要配备额外电池、第二个控制器、将报警模式关闭，并于 LVAD团队确认后开始检查。

Echocardiography in the Management of Patients with Left Ventricular Assist Devices: Recommendations from the American Society of Echocardiography

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Abbreviations

2D = Two-dimensional

3D = Three-dimensional

A = Mitral valve late peak diastolic velocity

AR = Aortic regurgitation

Ao = Aorta/aortic root

AS = Aortic stenosis

ASD = Atrial septal defect

ASE = American Society of Echocardiography

AV = Aortic valve

BiVAD = Biventricular assist device

BP = Blood pressure

BTT = Bridge to transplantation

CCT = Cardiac computed tomography

CF = Continuous flow

CMS = Centers for Medicare & Medicaid Services

CPB = Cardiopulmonary bypass

CT = Computed tomography

CW = Continuous wave

DT = Destination therapy

e′ = Mitral annular velocity

E = Mitral valve early peak diastolic velocity

ECMO = Extracorporeal membrane oxygenation

FAC = Fractional area change

FDA = Food and Drug Administration

HF = Heart failure

HM-II = HeartMate II left ventricular assist device

HVAD = HeartWare left ventricular assist device

IABP = Intraaortic balloon pump

IAC = Intersocietal Accreditation Commission

INR = International normalized ratio

INTERMACS = Interagency Registry for Mechanically Assisted Circulatory Support

IV = Intravenous

LA = Left atrial/atrium

LV = Left ventricular/ventricle

LVAD = Left ventricular assist device

LVEDV = left ventricular end-diastolic volume

LVEF = Left ventricular ejection fraction

LVIDd = Left ventricular internal dimension at end-diastole

LVOT = Left ventricular outflow tract

MAP = Mean arterial pressure

MCS = Mechanical circulatory support

MR = Mitral regurgitation

MRI = Magnetic resonance imaging

MS = Mitral stenosis

MV = Mitral valve

PFO = Patent foramen ovale

PDA = Patent ductus arteriosus

PI = Pulsatility index

PR = Pulmonary regurgitation

PS = Pulmonary stenosis

PT = Prothrombin time

PVAD = Percutaneous ventricular assist device

RA = Right atrial/atrium

RCA = Right coronary artery

rPA = Right pulmonary artery

RV = Right ventricular/ventricle

RVAD = Right ventricular assist device

RVOT = Right ventricular outflow tract

STE = Speckle tracking echocardiography

TAH = Total artificial heart

TAPSE = Tricuspid annular-plane systolic excursion

TEE = Transesophageal echocardiography

TR = Tricuspid regurgitation

TS = Tricuspid stenosis

TTE = Transthoracic echocardiography

VC = Vena contracta

VSD = Ventricular septal defect

VTI = Velocity-time integral

INTRODUCTION

This guideline addresses the role of echocardiography during the different phases of care of patients with long-term, surgically implanted continuous-flow (CF) left ventricular (LV) assist devices (LVADs). In patients with advanced heart failure (HF) refractory to medical therapy, LVADs have been used as a bridge to transplantation (BTT),[1] as destination therapy (DT),[2] as a bridge to transplant candidacy, or as a bridge to recovery.[3] Over the past three decades, tremendous progress has been made in the field of mechanical circulatory support (MCS), and more than 30,000 patients worldwide have received long-term LVADs.[4] Recent guidelines endorse the important role of echocardiography in the clinical care of LVAD patients at several stages, including preoperative patient selection, perioperative imaging, postoperative surveillance, optimization of LVAD function, troubleshooting of LVAD alarms, and evaluation of native myocardial recovery.[4] Despite increasing clinical use of LVADs,[5] recognition of the central role of echocardiography in their management, and presentation of an exponentially expanding outpatient LVAD population to healthcare facilities not directly associated with implantation centers, there is a lack of published guidelines for echocardiography of LVAD recipients.

This American Society of Echocardiography (ASE) document uses both published data (albeit of limited availability at this time) and expert opinion from high-volume MCS-device implantation centers to provide consensus recommendations and sample protocols for the timing and performance of echocardiography during LVAD patient selection, device implantation, and postoperative management. The authors' goal is to provide a general framework for the interactions between echocardiography laboratories and MCS teams. Although numerous types of LVADs are in clinical use or under development, the scope of this document is primarily limited to current surgically implanted CF-LVADs that have been approved by the United States Food and Drug Administration (FDA) for extended use in adults. Pediatric and adult patients with congenital heart disease represent a smaller but important and increasing subpopulation of patients receiving extended-use MCS devices. Comments or recommendations specifically relating to pediatric and congenital heart disease patients will be noted within the text and within the pediatric LVAD discussion section. Surgically implanted LVADs for short-term use, percutaneously implanted LVADs, right ventricular (RV) assist devices (RVADs), and/or biventricular assist devices (BiVADs) may also be encountered by echocardiographers. A brief discussion of these devices and their applications is included in Appendix A. Other MCS devices, including cardiopulmonary bypass (CPB) pumps, extracorporeal membrane oxygenation (ECMO), intraaortic balloon pumps (IABPs), and total artificial hearts (TAHs), are not covered in this report.

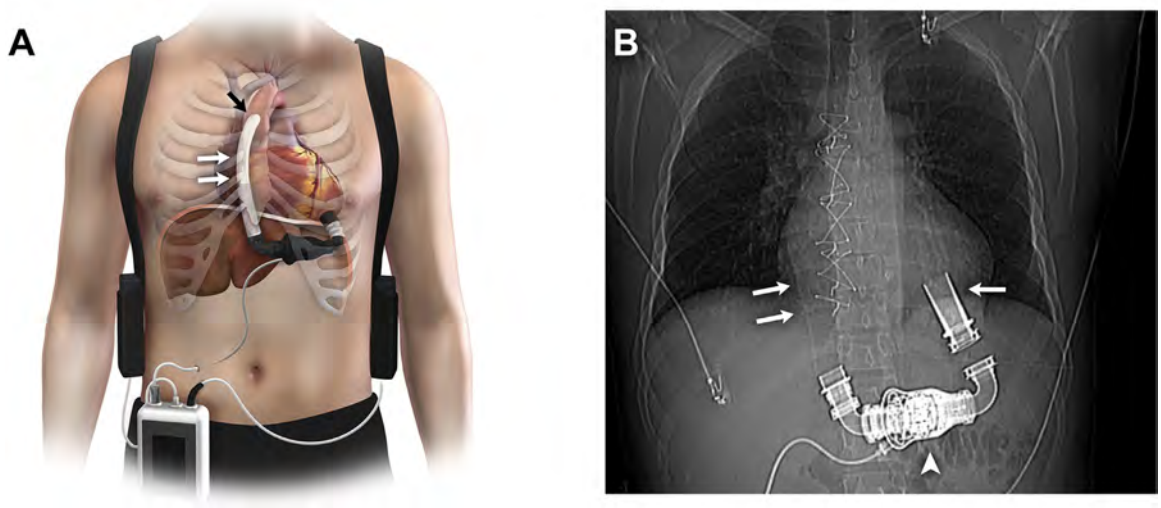


Figure 1 **(A)** Drawing of the HM-II LVAD, showing the subdiaphragmatic pump location, right parasternal outflow-graft position (*double white arrows*), and outflow graft-to-ascending aorta anastomosis (*black arrow*). **(B)** X-ray CT scout image showing the anatomic relationship between the left ventricle and the device inflow cannula (*single arrow*), impeller housing (*arrowhead*), and outflow graft (*double arrows*), controller (*white box*), battery packs (*black boxes*).

KEY POINTS

- This document addresses the role of echocardiography during the different phases of care of patients with FDA-approved long-term, surgically implanted CF-LVADs.
- The phases of patient care addressed include preoperative patient selection, perioperative TEE imaging, postoperative surveillance, optimization of LVAD function, problem-focused exams (when the patient has signs or symptoms of LVAD or native cardiac dysfunction), and evaluation of native myocardial recovery.
- Suggested protocols, checklists, and worksheets for each of these phases of care are located in the Appendices.
- Other types of MCS may also be encountered by echocardiographers, and these devices are discussed in Appendix A.
- Although echocardiography is frequently used for managing LVAD therapy, published data intended to guide timing and necessary data collection remain limited. Some of the recommendations provided herein are based on expert consensus from high-volume MCS implant centers.
- Most LVAD recipients are adults with dilated cardiomyopathies. Other LVAD patient populations addressed within this document include those with smaller hearts (eg, resulting from restrictive cardiomyopathies) and those with pediatric and congenital heart disease.
- The authors' goal is to provide a general framework for the interactions between echocardiography laboratories and MCS teams.

LEFT VENTRICULAR ASSIST DEVICES

Selection of a particular LVAD for an individual patient is a complex decision-making process and is beyond the scope of this document. Readers are referred to recent reviews for a comprehensive explanation of the structure and function of long-term, surgically implanted, intracorporeal (pump inside the body) LVADs[6] and of short-term, surgically or percutaneously implanted, extracorporeal (pump outside the body) LVADs[7] which are described in Appendix A. Currently, two CF-LVADs are approved by the FDA for surgical implantation in adults—the HeartMate II (HM-II) Left Ventricular Assist System (Thoratec Corporation, Pleasanton, CA) (Figure 1) and the HVAD Ventricular Assist System (HeartWare International, Inc., Framingham, MA) (Figure 2). The HM-II received FDA approval for BTT therapy in April 2008[8] and for DT in January 2010.[9] The HeartWare HVAD received FDA approval for BTT therapy in November 2012,[10] and a DT trial of this system is ongoing. For brevity, the abbreviation "LVAD" will be used here when referring to either of these CF-LVADs.

Common to both the HM-II and the HVAD are three components in series: (1) an inflow cannula positioned in the left ventricle near the apex, (2) a mechanical impeller, and (3) an outflow graft anastomosed to the ascending aorta (Figures 1 and 2). Echocardiography allows direct visualization of the proximal inflow cannula and the distal outflow graft but not of the mechanical impeller. The HM-II impeller and its housing structure are implanted below the diaphragm, whereas the HVAD impeller and its housing structure are implanted above the diaphragm, within the pericardial sac. Discussed in further detail below, impeller positioning is the primary differentiating factor in the echocardiographic evaluation of the inflow-cannula flow of these two devices. In other respects, echocardiographic evaluation of the two pumps is similar. Furthermore, both the HM-II and the HVAD are powered by a driveline connected to an extracorporeal controller. In addition to serving as a power source, the controller continually measures and calculates a number of parameters related to LVAD function. When these parameters fall outside predetermined normal ranges, the controller alerts the patient and the HF team that there is a problem. The implications of controller alarms for echocardiography are further discussed below.

KEY POINTS

- Current CF-LVADs have three intracorporeal (inside the body) components: an LV inflow cannula, a mechanical impeller, and an outflow graft that is anastomosed to the ascending aorta.
- The mechanical impeller is attached to an extracorporeal (outside the body) controller device via a driveline that provides power and a data link. The controller monitors several LVAD-related parameters and may generate device alarms. In turn, these alarms may indicate the need for an echocardiogram to validate the alarm and provide a definitive diagnosis.
- Echocardiography techniques for different devices are generally similar, except for important differences noted in the text.

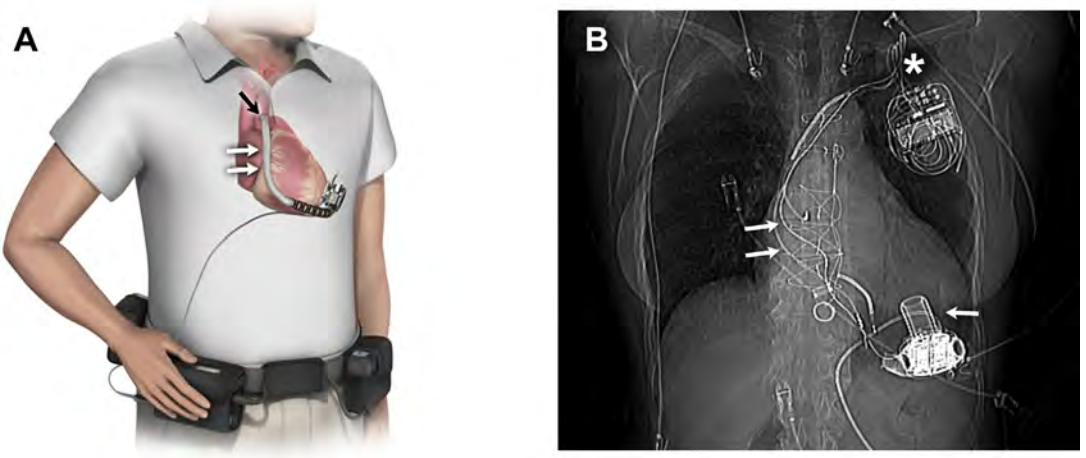


Figure 2 **(A)** Drawing of the HVAD, showing the intrapericardial pump location, right parasternal outflow graft position (*double white arrows*), and outflow graft-to-ascending aorta anastomosis (*black arrow*). (Courtesy of Heartware, Inc.). **(B)** X-ray CT scout image showing the anatomic relationship between the left ventricle and the device inlet cannula with its attached intrapericardial pump (*single arrow*). Although not visible here, the outflow graft would typically be imaged in the right parasternal area (*double arrows*). The asterisk denotes a cardiac implantable electronic device.

THE ROLE OF ECHOCARDIOGRAPHY IN CANDIDATE SELECTION

Optimal candidate selection is one of the most important determinants of a successful operative and long-term outcome for LVAD recipients.[4] Transthoracic echocardiography (TTE) is generally the first-line imaging modality used to screen LVAD candidates for structural and/or functional abnormalities that represent absolute or relative contraindications to device implantation. In some cases, patients require urgent or emergent surgical LVAD placement. In these acute situations, adequate TTE information may be technically limited or unavailable. Therefore, transesophageal echocardiography (TEE) performed in the acute setting (catheterization laboratory, emergency department, intensive care unit, or operating room) should address all of the factors mentioned below with regard to TTE. Given its central role in LVAD candidate selection, preimplantation TTE or TEE (when necessary) should be performed in a laboratory that has been accredited by the Intersocietal Accreditation Commission (IAC)[11] and should be supervised and interpreted by a skilled echocardiographer[12] who is experienced in advanced HF evaluation and the hemodynamic assessment of MCS devices. Preimplantation TTE in LVAD candidates should include all the elements of a comprehensive examination as recommended by the ASE,[13] with a particular focus on the high-risk or "red-flag" findings detailed below and summarized in Table 1. A comprehensive, checklist-based preimplantation TTE protocol with the notation of red-flag findings is available in Appendix B. If preimplantation TTE yields inconclusive findings, TEE may be performed, as described below. If a recently performed high-quality TTE exam includes most but not all of the required preimplantation exam elements and there has been no interval change in the patient's clinical status, a limited, focused follow-up exam to obtain the additional necessary information may be acceptable.

LV Dysfunction

Severe LV systolic dysfunction resulting from a dilated cardiomyopathy characterizes the majority of LVAD recipients. Accordingly, echocardiography laboratories must be proficient in techniques for measuring LV size, ejection fraction (LVEF), and cardiac output.

LV Ejection Fraction. Demonstration of an LVEF of <25% is a Centers for Medicare & Medicaid (CMS)-qualifying condition for LVAD implantation as DT.[14] Additionally, the LVEF is a component of both the Seattle Heart Failure Model[15] and the Heart Failure Survival Score,[16] two clinical-risk scoring tools that are widely used by HF specialists to calculate patients' expected survival times and, by extension, their suitability for an LVAD. A severely decreased LVEF is by no means the only clinical parameter used for determining whether or not a patient is referred for MCS. However, its accurate measurement by echocardiography is of paramount importance. Previous ASE guidelines describe the recommended methods for echocardiographic LV chamber quantification.[17-19] On the basis of those guidelines, laboratories with the ability and expertise to perform three-dimensional (3D) assessment for determining LV volumes and the LVEF should routinely do so when imaging conditions permit; otherwise, they should use the biplane method of disks (modified Simpson's rule) from two-dimensional (2D) images. Strong consideration should be given to the use of a microbubble contrast agent when indicated to enhance endocardial definition and improve the precision of LVEF measurement.[20]

LV Internal Dimension at End-Diastole. In addition to the LVEF, the LV internal dimension at end-diastole (LVIDd) from 2D parasternal long-axis images is a critical measurement in LVAD candidates. For patients who eventually undergo LVAD implantation, comparison of the preoperative LVIDd to the postoperative LVIDd is the primary clinical measure of the degree of LVAD-mediated LV unloading. Whereas a comparison of pre- and postoperative LV end-diastolic volumes (LVEDVs) would better quantify LV unloading, these measurements can be extremely challenging to obtain in the immediate postoperative period, when standard echocardiographic windows are limited by supine positioning, mechanical ventilation, a recent sternotomy, bandages, and other physical barriers. While the LVIDd and LVEDV are moderately to severely increased in most patients considered for an LVAD, limited data suggest that a smaller LV cavity, defined by an LVIDd of <63 mm, is associated with increased 30-day morbidity and mortality rates after LVAD implantation.[21] Patients who tend to have smaller LV cavities include elderly women with a smaller body habitus and persons with

Table 1 Preimplantation TTE/TEE "*red-flag*" findings

Left Ventricle and Interventricular Septum
Small LV size, particularly with increased LV trabeculation
LV thrombus
LV apical aneurysm
Ventricular septal defect
Right Ventricle
RV dilatation
RV systolic dysfunction
Atria, Interatrial Septum, and Inferior Vena Cava
Left atrial appendage thrombus
PFO or atrial septal defect
Valvular Abnormalities
Any prosthetic valve (especially mechanical AV or MV)
> mild AR
≥ moderate MS
≥ moderate TR or > mild TS
> mild PS; ≥ moderate PR
Other
Any congenital heart disease
Aortic pathology: aneurysm, dissection, atheroma, coarctation
Mobile mass lesion
Other shunts: patent ductus arteriosus, intrapulmonary

AR, Aortic regurgitation; *AV,* aortic valve; *LV,* left ventricular; *MS,* mitral stenosis; *MV,* mitral valve; *PFO,* patent foramen ovale; *PR*, pulmonary regurgitation; *PS*, pulmonary stenosis; *RV,* right ventricle; *TR*, tricuspid regurgitation; *TS*, tricuspid regurgitation.
Note: These red-flag findings are found within the Recommended Pre–LVAD-Implantation TTE Protocol (Appendix B). They are also found within the Perioperative TEE Protocol/Checklist (Appendix C), which contains additional immediate post-LVAD-implantation perioperative TEE red-flag findings.

infiltrative cardiomyopathies (eg, amyloidosis). The latter group may also have concomitant right-sided HF, another preoperative high-risk finding that is discussed below. Whereas a small LV cavity is not an absolute contraindication to LVAD implantation, the presence of this finding should be communicated to the HF team.

Intracardiac Thrombi. An intracardiac thrombus is not an absolute contraindication for LVAD implantation but may increase the risk of stroke during the LV cannulation portion of the procedure. At particularly increased risk for LV thrombus are patients with a severely decreased LVEF and/or an LV aneurysm. In these patients, strong consideration should be given to the use of a microbubble contrast agent during assessment for LV thrombus. If such a thrombus is identified, the implanting surgeon should be made aware of its size and location so that the thrombus can be carefully removed during device implantation. In borderline cases, cardiac computed tomography (CCT) may be adjunctively used to rule out an LV thrombus.[4] In patients with atrial fibrillation, who are at increased risk for thrombus in the left atrial appendage, adjunctive TEE may be required for complete intracardiac thrombus assessment.

RV Dysfunction

Echocardiographic signs of RV dysfunction include impaired RV systolic function and/or RV dilatation, increased RA pressure (ascertained by inferior vena cava size and collapsibility), and moderate or greater tricuspid regurgitation (TR). Previous ASE guidelines describe the recommended methods for echocardiographic evaluation of RV function and chamber quantification.[17,18,22] On the basis of those guidelines, 3D echocardiographic assessment of RV volumes to calculate the RV ejection fraction would be ideal, but the authors realize that this approach is technically challenging and not widely available. Measurement of other secondary echocardiographic surrogates of RV systolic function, including RV fractional area change (FAC), tricuspid annular-plane systolic excursion (TAPSE), and RV free-wall peak longitudinal strain, can be difficult in patients with advanced HF. Nonetheless, quantitative measures of RV function are recommended for use whenever possible, but only when able to be properly measured in a given patient. At a minimum, a qualitative assessment of RV size and systolic function and of TR severity should be performed and communicated in the interpretation.

Echocardiographic signs of RV dysfunction should not be considered in isolation. They should be integrated with a patient's clinical signs and symptoms of possible right-sided heart failure syndrome. Clinically severe preoperative RV dysfunction may prompt the HF team to consider planned biventricular MCS, as this may lead to better outcomes than delayed conversion of an LVAD to biventricular MCS.[23] Some patients with less than severe RV dysfunction at preoperative assessment will develop severe RV dysfunction after LVAD implantation. This complication, defined by the Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS)[24] as the requirement of an RV assist device (RVAD) or >14 consecutive days of intravenous (IV) inotropic support, has an estimated prevalence of 13% to 44% and is associated with significant morbidity and mortality.[25,26] Preliminary data suggest that there may be preoperative echocardiographic parameters predictive of severe postoperative RV dysfunction. In studies that included clinical parameters in their multivariable models, an RV absolute peak longitudinal strain of <9.6%[27] and an RV: LV end-diastolic diameter ratio of >0.75[28] were identified as potential independently predictive echocardiographic parameters. More recent data by Kato and colleagues[29] suggests that the accuracy for predicting post LVAD RV failure may be improved when more than one RV echocardiographic parameter (in this case RV tissue Doppler imaging and RV speckle tracking imaging [RV longitudinal strain]) are used in aggregate. Given the lack of consensus thus far regarding the predictive value of any single echocardiographic parameter, an aggregate assessment utilizing relevant left-sided parameters (eg, indexed left atrial volume, indexed LV size) and right-sided parameters (eg, RV parameters described above, TR severity,[30] and right atrial [RA] pressure estimation) is likely the optimal approach for now.[4,31]

KEY POINTS

- Nearly all LVAD candidates undergo echocardiography to screen for structural and/or functional abnormalities that preclude LVAD implantation or that may alter surgical planning.
- At this time, the literature does not support the use of any single echocardiographic RV parameter for predicting the post-LVAD prognosis or the need for biventricular support (RVAD use).
- Quantitative echocardiographic parameters of RV function (which may vary among patients, depending upon imaging conditions), should be integrated with clinical signs and symptoms to determine the degree of preoperative RV dysfunction, which may impact the operative plan and/or postoperative prognosis.

Valve Disease

Previous ASE guidelines address detection and quantitation of valvular regurgitation,[32] valvular stenosis,[33] and prosthetic valve dysfunction.[34]

Valve Stenosis. In patients with advanced HF and a severely reduced stroke volume, spectral Doppler-derived valve gradients in isolation may not accurately reflect the degree of valvular stenosis. In these patients, calculation of the valvular orifice area may be more accurate. Moderate or severe mitral valve (MV) stenosis can prevent adequate LVAD cannula inflow. Accordingly, significant mitral stenosis (MS) must be corrected before LVAD implantation. In contrast, aortic stenosis (AS) of any severity may be present without affecting LVAD function, because LVADs completely bypass the native LV outflow tract (LVOT). It is important to note, however, that patients who have critical AS or who undergo surgical aortic valve (AV) complete closure to correct aortic regurgitation (AR) will have no forward flow in the event of obstructive LVAD failure, even if residual LV function is present.

Valve Regurgitation. Exclusion of significant AR before LVAD implantation is critical and sometimes challenging. When present at LVAD implantation, significant AR enables a "blind" loop of flow in which blood enters the LVAD from the left ventricle, is pumped into the ascending aorta, but then flows back into the left ventricle through the regurgitant aortic valve. It may be difficult for echocardiographers to determine the degree of AR present in patients with advanced HF and a severely reduced LV stroke volume. Heart failure patients with moderate or severe AR may have unimpressive color-flow Doppler images and low AR velocities due to low systemic pressures and high LV diastolic pressures. Additionally, the aortic regurgitant volume may be relatively low, despite a high regurgitant fraction. Accordingly, the Doppler-derived LVOT stroke volume and regurgitant fraction should be calculated routinely when possible.[32] Furthermore, there should be a high level of suspicion for significant AR in the presence of aortic root dilatation, eccentric AR (particularly if associated with a bicommissural AV), rheumatic or calcific AV degeneration, or an aortic prosthesis. TEE should be strongly considered when there is any degree of suspected abnormal prosthetic valve regurgitation. The presence of more than mild AR should be communicated to the implanting surgeon, because recent guidelines advise confirmation by perioperative TEE and surgical correction of AR before LVAD implantation.[4] Surgical treatment options for significant native valve AR include replacement with a bioprosthesis, completely oversewing the valve (by suturing along all coaptation zones) or by performing a central coaptation (Park) stitch.[35] Completely over sewing the AV cusps effectively eliminates AR, but (as mentioned above) leaves the patient with no fail-safe means of LV ejection in the event of LVAD failure. When the aortic cusp integrity is good, a central coaptation (Park) stitch technique can treat central AR while allowing aortic forward flow through the residual commissural zones to occur during reduced LVAD support (Figure 3) or in the event of LVAD pump failure.

Mitral regurgitation (MR) that is significant preoperatively is often markedly improved after initiation of LVAD support, because of reduced LV size, reduced filling pressures, and improved coaptation of the MV leaflets. For this reason, any degree of MR is acceptable in LVAD candidates. In contrast, moderate or greater TR is a potentially ominous finding, which may indicate RV dysfunction as mentioned above. It is important to communicate the presence of significant TR to the implanting surgeon; recent guidelines recommend that surgical tricuspid valve repair be considered at the time of LVAD implantation.[4] Pulmonary regurgitation (PR) may be more commonly encountered in patients with congenital heart disease. In any patient, moderate or greater PR could contribute to preoperative RV dysfunction and would require repair in the event of RVAD implantation. However, PR may be well tolerated in the setting of successful LVAD implantation with adequate RV function and successful LV unloading. However, significant PR could potentially contribute to RV dysfunction after LVAD implantation if pulmonary vascular resistance were increased for any reason, including acquired pulmonary disease or an inability to adequately unload the left ventricle.

Prosthetic Valves. When indicated, prosthetic valve assessment by TTE and TEE is critical for surgical decision-making. LVAD-supported patients must receive systemic anticoagulation, regardless of the presence of mechanical prosthetic valves. However, a higher target prothrombin time international normalized ratio (PT INR) may be necessary if a mechanical valve is present. After initiation of LVAD support, the inherent reduced flow through a mechanical AV prosthesis further increases the risk of postoperative valvular or aortic root thrombosis and subsequent thromboembolic events. For this reason, replacement of even a normally functioning mechanical AV prosthesis with a bioprosthesis or valve closure should be considered at the time of LVAD implantation. Adequately functioning bioprosthetic AVs do not require removal or replacement. Similarly, surgical replacement of a normally functioning mechanical MV prosthesis is typically not recommended, even if significant MR is present, as obligatory forward transmitral flow will occur during MCS. An important exception is the presence of moderate or worse mechanical MV stenosis. In these cases, consideration should be given to MV replacement with a bioprosthesis at LVAD implantation.[4] Although not frequently encountered, tricuspid or pulmonary valve prosthesis dysfunction is an important finding, as it could adversely affect postoperative RV function.

KEY POINTS

- The position, type, and functioning of any prosthetic valve can have an important impact on surgical and postoperative management, and adjunctive TEE imaging should be performed if clinically indicated.
- Aortic regurgitation warrants special attention, as it can easily be underestimated in HF patients, generally worsens after LVAD activation, and impairs LV unloading due to a "blind loop" of aorta→LV→LVAD flow.
- Moderate or greater TR is an ominous finding, especially if accompanied by other signs or symptoms of RV dysfunction.
- A mechanical AV should be replaced before LVAD implantation.
- Severe AS and even complete AV closure can be tolerated after LVAD implantation, although either of these conditions results in the lack of a fail-safe mechanism for LV output in the event of LVAD failure.
- Mitral regurgitation is generally well tolerated and may improve after LVAD implantation.

Congenital Heart Disease

For all patients with known congenital heart disease of any severity, previous imaging studies documenting cardiac morphology, shunts, collateral vessels, and/or the location and course of the great vessels should be reviewed.[4] Recent data suggest that with amenable cardiac anatomy, even patients who have complex congenital heart disease can undergo implantation of an LVAD as a BTT or as DT.[36] Some common anomalies require correction before LVAD implantation. A patent foramen ovale (PFO), present in up to 30% of the general population, increases the risk of hypoxemia[37,38] and paradoxical embolization in patients receiving LVAD support. For this reason, PFOs or any other interatrial communications should be closed at the time of device implantation.[4] In evaluating patients with advanced HF for atrial septal defects (ASDs) and PFOs, the use of IV agitated saline combined with an appropriately performed Valsalva maneuver is necessary, because

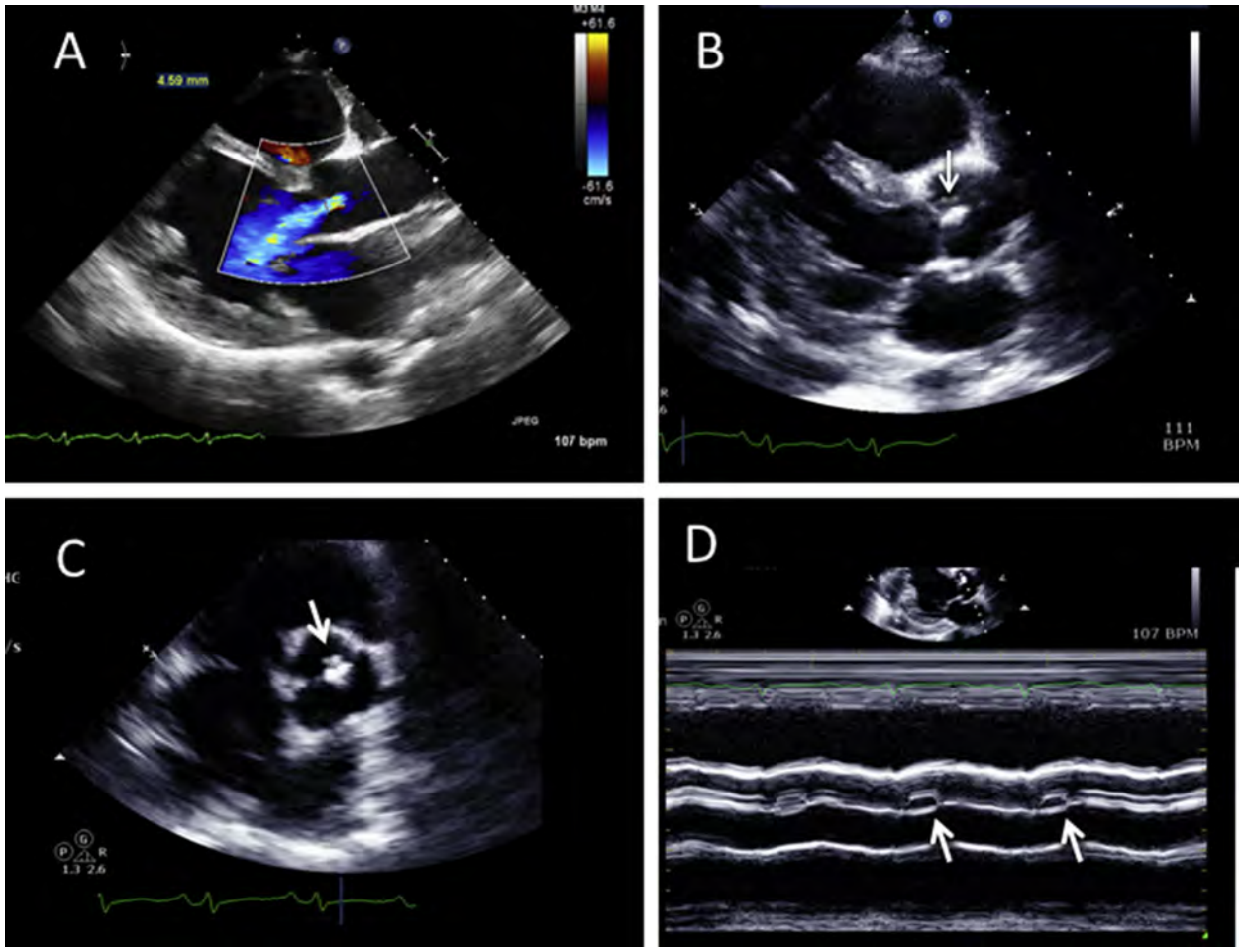


Figure 3 **(A)** TTE color Doppler shows moderate central AR before LVAD implantation. Intraoperative assessment revealed subtle cusp prolapse with good tissue integrity, so a central coaptation (*Park*) stitch was placed. See also Video 1. **(B)** TTE 2D imaging of the AV shows the central coaptation stitch in the parasternal long axis **(B)** and short axis **(C)** (*arrows*). See also Videos 2 and 3. M-mode imaging **(D)** shows residual cusp separation near the cusp commissures during reduced LVAD pump speed, but no residual AR was present.

elevated left and/or RA pressures may reduce interatrial pressure gradients and preclude detection of the defect by color Doppler imaging or agitated saline injection alone.[39] Like ASDs, congenital and post–myocardial infarction ventricular septal defects (VSDs) can also result in immediate postimplantation right-to-left shunting with hypoxemia and a risk of paradoxical embolization during LVAD support. The presence of VSDs should be systematically excluded by color Doppler interrogation of the entire ventricular septum; if identified, VSDs should be closed at LVAD implantation. In most cases, an unrepaired VSD is an absolute contraindication to device implantation.[4] However, selected patients with single ventricle physiology (and an unrepaired VSD) may be considered for an LVAD.

KEY POINTS

- In patients with congenital heart disease, echocardiography is an important complementary imaging modality after other, previous imaging studies have been reviewed.
- The echocardiography exam should systematically exclude the presence of a PFO or other intracardiac shunt, which should be electively repaired at the time of surgery to avoid sudden arterial oxygen desaturation after LVAD activation.

Other High-Risk Findings

Acute endocarditis (or any other active infection) is an absolute contraindication to MCS-device implantation because of the risk of bacterial seeding of a newly implanted LVAD.[4] As a result, a mobile mass lesion suggestive of a possible vegetation is a high-risk finding. Diseases of the aorta that are relative or absolute contraindications to LVAD implantation (eg, significant aneurysmal dilatation, dissection) may be discovered on TTE. For this purpose, high parasternal long-axis, suprasternal notch, and subcostal views of the aorta should be attempted. TEE may be very useful for the diagnosis of thoracic aorta pathology. However, in the absence of contraindications to contrast agents, computed tomography (CT)[4] or magnetic resonance imaging (MRI)—barring MRI contraindications[40]—are preferred modalities for comprehensive imaging of the aorta before LVAD implantation.[4]

KEY POINTS

- Any findings suspicious for endocarditis should be further evaluated, as this is an absolute contraindication to LVAD implantation.
- Adjunctive CT and MR imaging may be necessary to adequately evaluate for aortic disease before LVAD implantation.

PERIOPERATIVE TRANSESOPHAGEAL ECHOCARDIOGRAPHY

Preimplantation TEE

Comprehensive perioperative TEE should be performed in the operating room before LVAD implantation, with additional imaging performed at the time of LVAD activation and after a period of stabilization. Preimplantation TEE is particularly important when urgent or emergent LVAD placement is required, in which case this modality may serve as the primary screening echocardiography examination. Previous guidelines describe the recommended approach for perioperative TEE[41,42] A comprehensive; checklist-based pre- and postimplantation perioperative TEE protocol with notation of red-flag findings is included in Appendix C. The physician performing the examination should be a highly trained cardiologist with significant advanced TEE and perioperative TEE experience[42,43] or a cardiovascular anesthesiologist with advanced perioperative TEE training.[42,44,45] Among the most important aspects of preimplantation TEE are reevaluation of the degree of AR, determination of the presence or absence of a cardiac-level shunt, identification of intracardiac thrombi, assessment of RV function, and evaluation of the degree of TR. These and potentially other important conditions (eg, degree of MS, PR, prosthetic dysfunction, possible vegetations, aortic disease, etc.) may have been undiagnosed or underappreciated on previous imaging exams or may have progressed in the intervening time. Their presence may necessitate conversion of a planned "off-pump" case into one that requires CPB, a change from a limited thoracotomy to a sternotomy to enable needed repairs, or possibly biventricular MCS.

For the same reasons discussed above for TTE, the degree of AR on perioperative TEE may be underappreciated on color Doppler imaging during general anesthesia, because low mean arterial pressure and/or systemic vascular resistance may be present. As a result, adequate AR assessment may necessitate systemic blood pressure (BP) augmentation by vasopressor agents.[4] With regard to PFO detection, thorough color Doppler scanning of the fossa ovalis margins at a low Nyquist-limit setting and IV injection of agitated saline may be inconclusive. In these cases, IV injection of agitated saline combined with a "ventilator" Valsalva maneuver may also be useful. This maneuver involves injecting agitated saline into a central IV line (eg, internal jugular) during a briefly sustained application of up to 30 cmH_2O of intrathoracic pressure and, on opacification of the right atrium, release of the intrathoracic pressure.[46] Even with this maneuver, in some cases, significant competitive inferior vena cava "negative contrast" flow in the fossa ovalis region can cause a false-negative PFO evaluation after saline injection into the superior vena cava. Injection of agitated saline into a femoral vein may increase PFO detection[47,48] if such access is available. Despite all efforts, a PFO may not become apparent in some cases until MCS is initiated and the left atrial pressure is decreased.

KEY POINTS

- The preimplant perioperative TEE is an important confirmatory imaging study, which can identify previously underappreciated or undiagnosed pathologic conditions that may influence the surgical procedure.
- An LVAD perioperative TEE checklist can be useful for laboratory personnel (see Appendix C).
- Preimplantation TEE should include reevaluation of AR, RV function, TR, and the aorta. Cardiac-level shunts and intracardiac thrombi should be excluded.
- Evaluation for PFO may require special imaging maneuvers as outlined in the text. Despite best efforts, a PFO may not be able to be diagnosed prior to LVAD implantation.

Perioperative TEE During LVAD Implantation

Both the HM-II and the HVAD require coring in the region of the LV apex for inflow-cannula insertion. This part of the procedure is inevitably accompanied by some degree of entrained air on the left side of the heart. Subsequent de-airing maneuvers require continuous TEE guidance.[4] The left atrium, left ventricle (including the LV apex and inflow cannula (Figures 4 and 5), aortic root, ascending aorta, outflow graft-to-ascending aorta anastomosis (Figure 6), and transverse and descending aorta should all be directly visualized and carefully inspected for signs of air.[39] The ostium of the right coronary artery (RCA) is situated anteriorly in the aortic root and is a common destination for air ejected from the left ventricle.[4] Acute RV dysfunction or dilatation and/or an increase in the severity of TR should suggest the possibility of air embolization to the RCA, and this complication may resolve with watchful waiting. As during the LV coring procedure, the period immediately after separation from cardiopulmonary bypass and reinstitution of mechanical ventilation can be accompanied by the sudden appearance of new air bubbles originating from the pulmonary veins, left atrium, or left ventricle. This finding, if associated with signs of RV dysfunction from a presumed coronary air embolism, may signal the need for reinstitution of CPB and/or repeat de-airing maneuvers.[4]

Perioperative TEE During Initial LVAD Activation and Speed Optimization

Upon LVAD activation, the **device name** and the **initial pump speed** should be annotated on the imaging screen. Although the exact order of perioperative TEE views obtained after LVAD initiation may vary among centers, it is recommended that physicians follow an LVAD checklist-based protocol (Appendix C) to include all of the important components unique to postoperative LVAD assessment. Table 2 lists possible abnormal findings detectable by echocardiography after LVAD implantation. Early imaging of the interatrial septum with color Doppler and with IV injection of agitated saline contrast to confirm the absence of an **atrial septal communication** is recommended. This is particularly important if initiation of LVAD support results in a sudden decrease in arterial oxygen saturation, the hallmark of an "unmasked" PFO or other right-to-left shunt (Figure 7). Next, the degree of AV opening and the degree of AR (if any) should be assessed. When there is no AV opening, this may be apparent with standard planar imaging. In many cases, the extent and duration of aortic cusp separation may be markedly reduced or only intermittent, depending upon the degree of LVAD support (pump speed). M-mode imaging of the AV in the long-axis view can be helpful for measuring and reporting the degree of AV opening (Figure 8). When there is minimal residual native LVOT forward flow, AV opening may be intermittent due to pulsus alternans in regular sinus rhythm or because of arrhythmias. A slow M-mode sweep speed (eg, 25 mm/sec to acquire more cardiac cycles) may be needed to adequately display intermittent AV opening (Figure 8C-E).

Aortic Regurgitation. A pump speed–dependent reduction in LV diastolic filling pressures and increased central aortic BP can lead to the appearance of more prominent AR on color Doppler imaging than was appreciated before pump implantation (Figure 9A). During

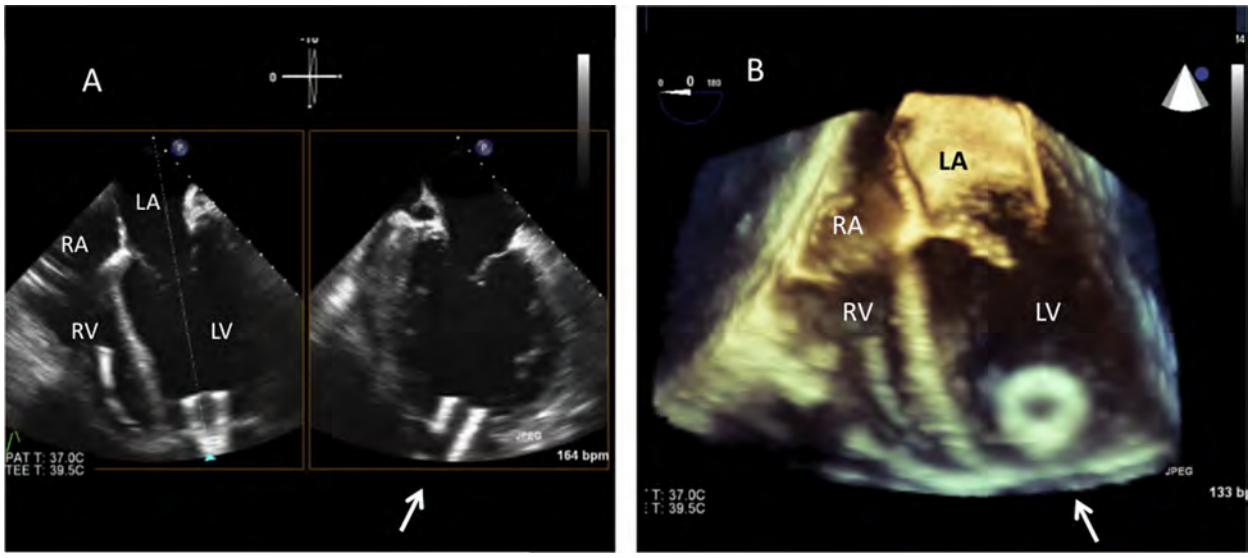


Figure 4 After LVAD implantation, TEE reveals a typical unobstructed inlet-cannula position (*arrow*) by means of simultaneous orthogonal-plane 2D **(A)** and real-time 3D imaging **(B)**. See also Video 4. The relative RV to LV size appears normal. The right ventricle has a pacing lead.

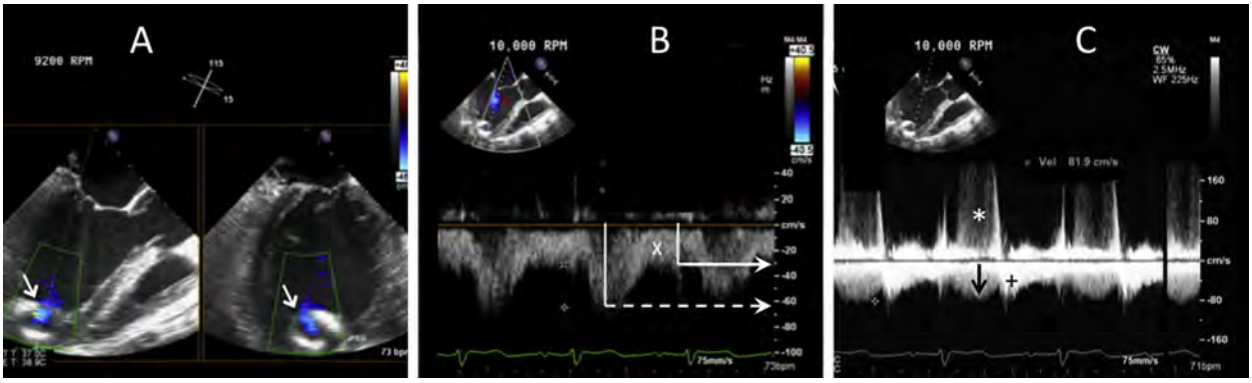


Figure 5 **(A)** After LVAD implantation, TEE shows that the inflow cannula is somewhat directed towards the ventricular septum (*arrow*). This can be acceptable but may predispose to inflow-cannula obstruction after sternal closure or later reduction in LV size. However, cannula position and flow velocities are shown to be acceptable (*normal*) in this case. Simultaneous orthogonal plane imaging reveals unobstructed, laminar inflow-cannula flow on 2D and color-flow Doppler (*blue*) examination. See also Video 5. **(B)** Pulsed Doppler interrogation of the inflow cannula shows a typical continuous, systolic dominant inflow pattern. Dashed arrow = peak systolic velocity; X = nadir diastolic velocity. **(C)** Continuous-wave spectral Doppler interrogation of the inflow cannula (to screen for inflow obstruction) shows normal inflow-cannula systolic flow (*black arrow*); "+" indicates a hybrid signal that results from overlapping of continuous diastolic inflow-cannula flow and diastolic MV inflow; "*" indicates MR velocity.

LVAD support, AR can be intermittent (depending upon the valve opening duration), predominantly diastolic, nearly continuous (extending into the normal systolic phase of the cardiac cycle), or continuous (holosystolic and holodiastolic). Measuring the temporal occurrence of AR can be achieved with color M-mode and continuous-wave (CW) Doppler (see Figure 9F-G). The AR duration, AR vena contracta (VC) width, LVOT AR jet height, and other evidence of hemodynamically significant AR (discussed in further detail, below) should guide the need for possible surgical intervention on the AV. Although the AR VC width may be useful in a qualitative sense, during LVAD support, the width may vary throughout the cardiac cycle with continuous AR (Figure 9C) and at different pump speeds (Figure 9D,E). Methods for assessing AR severity in the context of an LVAD problem-focused exam are further discussed below. However, in keeping with previous guideline recommendations, a VC width of ≥0.3 cm or a jet width/LVOT width of >46% at a Nyquist limit of 50-60 cm/s[32] should be considered to indicate at least moderate (and possibly severe) AR, owing to the prolonged (if not continuous) duration of AR during LVAD support. Neither the AR pressure half-time method nor pulsed Doppler evaluation of aortic diastolic flow reversal is a reliable method for AR severity assessment after LVAD implantation. This is because the AR duration extends into the systolic ejection period. In addition, both of these methods are highly affected by LV preload, LV afterload, and aortic pulse pressure, which is diminished during LVAD support. However, CW spectral Doppler imagining may be useful for evaluating the timing and duration of AR (Figure 9F, G), and it's pixel intensity may be additive to the qualitative assessment.

RV Dysfunction. Poor RV performance, with or without significant TR, immediately after LVAD initiation is not uncommon due to rapid normalization of the RV preload by the pump. Early RV dysfunction may be transient, due to CPB-related factors, or refractory, due to

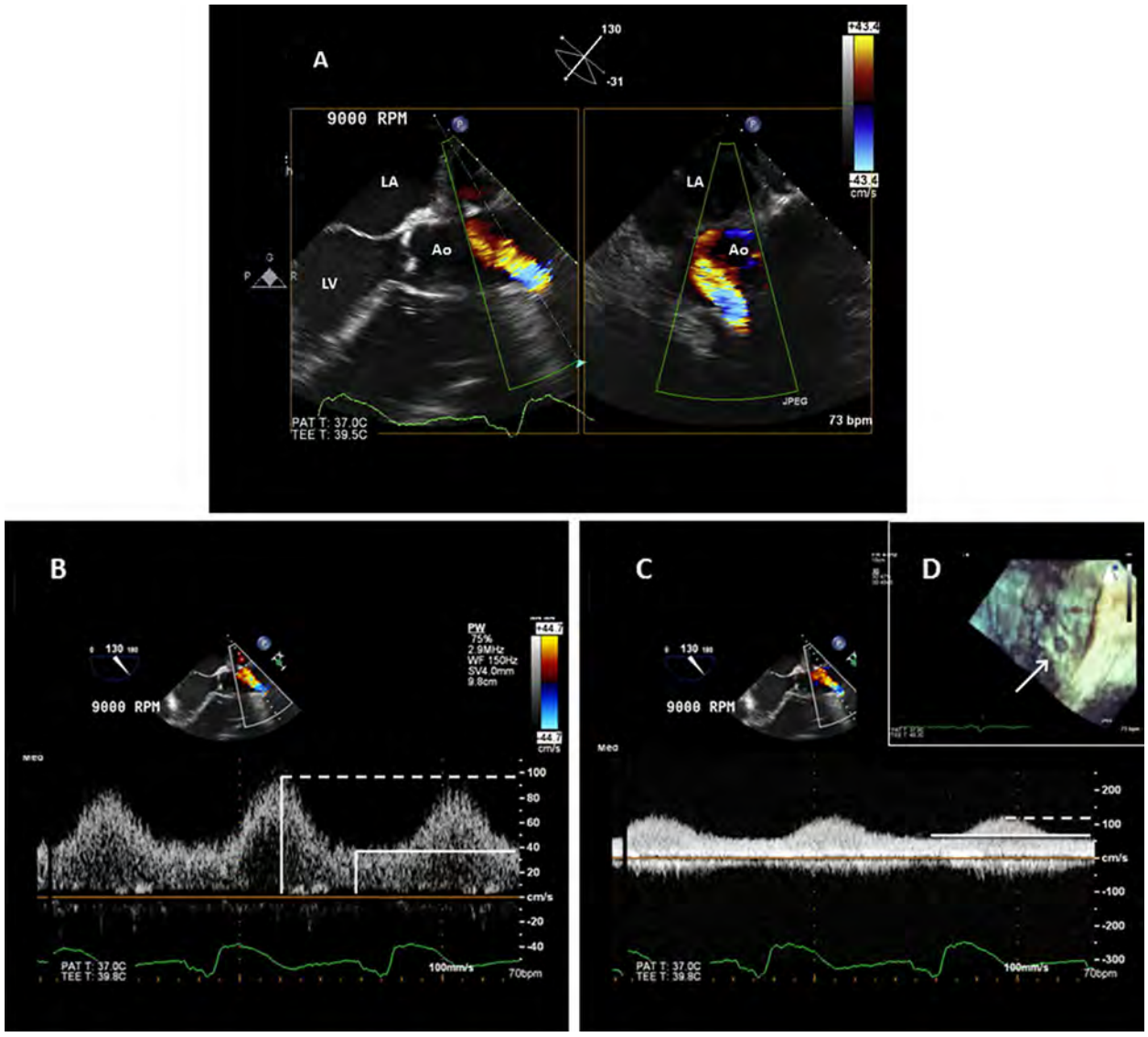


Figure 6 TEE of the outflow graft-to-ascending aorta anastomosis. **(A)** Simultaneous orthogonal plane 2D imaging with color-flow Doppler shows normal laminar color Doppler inflow. See also Video 6. **(B)** Pulsed Doppler profile (peak velocity approximately 100 cm/s, dotted line). **(C)** Continuous-wave Doppler with a peak systolic velocity (*dotted line*) that, as expected, is somewhat higher (just >100 cm/s) than that revealed by pulsed Doppler. The solid line indicates the nadir diastolic velocity. **(D)** Typical circular appearance of unobstructed outflow graft-to-aorta anastomosis (*arrow*) using real-time 3D TEE, en face view.

underlying RV dysfunction. In this setting, significant TR may be present despite an "optimal" LVAD pump speed. However, an excessive LVAD pump speed may precipitate acute severe RV dysfunction with acute severe TR. When the LVAD pump speed is set too high, the left ventricle may become small ("sucked down" or "over-decompressed"), resulting in an abnormal RV-to-LV septal shift that causes distortion of the RV geometry, including the tricuspid valve annulus; this alteration precipitates or worsens TR, which, in turn, causes or exacerbates RV dysfunction. The cascade of events resulting from an excessive LVAD pump speed may ultimately result in a "suction event," a condition in which a segment of the LV myocardium partially occludes the inflow cannula and reduces pump inflow. Suction events, along with the noted high-risk findings, can be quickly corrected by lowering the pump speed (Figure 10). Suction events can be related to other causes of reduced LV preload relative to the pump speed setting. Accordingly, rapid assessment of AV opening, the relative LV and RV sizes, degree of TR, ventricular septal position, inflow-cannula position, and flow velocities is recommended after initiation of LVAD support and after changes in the LVAD pump speed. It is important that the updated pump speed is always reannotated on the screen during the course of the perioperative TEE exam. A suction event that occurs at a relatively low pump speed or ongoing severe RV dysfunction at low levels of LVAD support is an ominous sign that may indicate the need for a return to CPB or for biventricular support. Suction events can be related to other causes of a reduced LV preload (eg, hypovolemia) or a low afterload (eg, sepsis) relative to the pump speed setting.

Inflow Cannula and Outflow Graft. *Inflow Cannula.*—An appropriately positioned inflow cannula lies near or within the LV apex and is directed towards the MV, although some angulation towards the ventricular septum may be observed (Figure 5). Assessment of the relationship of the inflow cannula to the ventricular septum is generally performed by

Table 2 Continuous-flow LVAD postimplant complications and device dysfunction detected by echocardiography

Pericardial effusion
With or without cardiac tamponade including RV compression. *Tamponade*: respirophasic flow changes; poor RVOT SV.
LV failure secondary to partial LV unloading
(by serial exam comparison) a. 2D/3D: increasing LV size by linear or volume measurements; increased AV opening duration, increased left atrial volume. b. Doppler: increased mitral inflow peak E-wave diastolic velocity, increased E/A and E/e′ ratio, decreased deceleration time of mitral E velocity, worsening functional MR, and elevated pulmonary artery systolic pressure.
RV failure
a. 2D: increased RV size, decreased RV systolic function, high RAP (dilated IVC/leftward atrial septal shift), leftward deviation of ventricular septum. b. Doppler: increased TR severity, reduced RVOT SV, reduced LVAD inflow cannula and/or outflow-graft velocities (ie, <0.5 m/sec with severe failure); inflow-cannula high velocities if associated with a suction event. Note: a ‘‘too-high’’ LVAD pump speed may contribute to RV failure by increasing TR (septal shift) and/or by increasing RV preload.
Inadequate LV filling or excessive LV unloading
Small LV dimensions (typically <3 cm and/or marked deviation of interventricular septum towards LV). Note: May be due to RV failure and/or pump speed too high for loading conditions.
LVAD suction with induced ventricular ectopy
Underfilled LV and mechanical impact of inflow cannula with LV endocardium, typically septum, resolves with speed turndown.
LVAD-related continuous aortic insufficiency
Clinically significant—at least moderate and possibly severe—characterized by an AR proximal jet-to-LVOT height ratio >46%, or AR vena contracta ≥3 mm; increased LV size and relatively decreased RVOT SV despite normal/increased inflow cannula and/or outflow graft flows.
LVAD-related mitral regurgitation
a. Primary: inflow cannula interference with mitral apparatus. b. Secondary: MR-functional, related to partial LV unloading/persistent heart failure. Note: Elements of both *a* and *b* may be present.
Intracardiac thrombus
Including right and left atrial, LV apical, and aortic root thrombus
Inflow-cannula abnormality
a. *2D/3D*: small or crowded inflow zone with or without evidence of localized obstructive muscle trabeculation, adjacent MV apparatus or thrombus; malpositioned inflow cannula. b. *High-velocity* color or spectral Doppler at inflow orifice. Results from malposition, suction event/other inflow obstruction: aliased color-flow Doppler, CW Doppler velocity >1.5 m/s. c. *Low-velocity* inflow (markedly reduced peak systolic and nadir diastolic velocities) may indicate internal inflow-cannula thrombosis or more distal obstruction within the system. Doppler flow velocity profile may appear relatively ‘‘continuous’’ (decreased phasic /pulsatile pattern).
Outflow-graft abnormality
Typically due to obstruction/pump cessation. a. 2D/3D imaging: visible kink or thrombus (infrequently seen). b. Doppler: peak outflow-graft velocity ≥2 m/s* if near obstruction site; however, diminshed or absent spectral Doppler signal if sample volume is remote from obstruction location, combined with lack of RVOT SV change and/or expected LV-dimension change with pump-speed changes.
Hypertensive emergency
New reduced/minimal AV opening relative to baseline exam at normal BP, especially if associated with new/worsened LV dilatation and worsening MR. Note: hypertension may follow an increase in pump speed.
Pump malfunction/pump arrest:
a. Reduced inflow-cannula or outflow-graft flow velocities on color and spectral Doppler or, with pump arrest, shows diastolic flow reversal. b. Signs of worsening HF: including dilated LV, worsening MR, worsened TR, and/or increased TR velocity; attenuated speed-change responses: decrease or absence of expected changes in LV linear dimension, AV opening duration, and RVOT SV with increased or decreased pump speeds; for HVAD, loss of inflow-cannula Doppler artifact.

2D, Two-dimensional; *3D,* three-dimensional; *A,* mitral valve late peak diastolic velocity; *AR,* aortic regurgitation; *AV,* aortic valve; *BP,* blood pressure; *CW,* continuous-wave; *E,* mitral valve early peak diastolic velocity; *e′,* mitral annular velocity; *HVAD,* HeartWare ventricular assist device; *IVC,* inferior vena cava; *LV,* left ventricular; *LVAD,* left ventricular assist device; *LVOT,* left ventricular outflow tract; *MR,* mitral regurgitation; *MV,* mitral valve; *RAP,* right atrial pressure; *RV,* right ventricular; *RVOT,* right ventricular outflow tract; *SV,* stroke volume; *TR,* tricuspid regurgitation. Adopted and modified from Estep et al.[65]

*Note: based on observational data. The ‘‘normal’’ outflow graft peak velocities are not well defined. Because the HVAD outflow graft diameter is smaller than that of the HM II device (see discussion in text). Therefore, the normal Doppler-derived HVAD outflow velocities may be somewhat higher on average than those observed for the HM II LVAD.

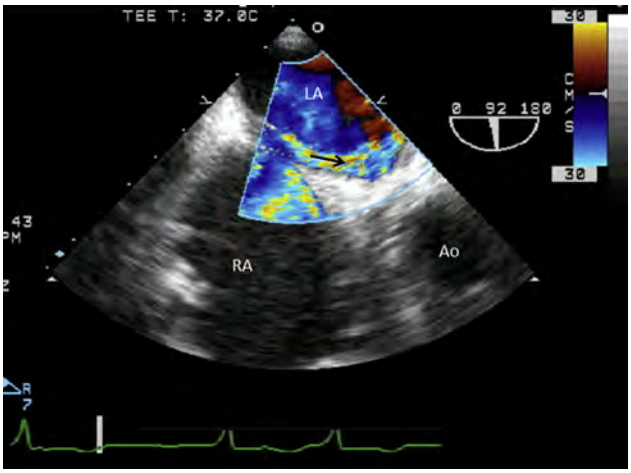


Figure 7 Perioperative TEE showing marked RA-to-LA shunting via an "unmasked" PFO, which became apparent immediately after LVAD activation. The PFO "tunnel"-defect shunt is readily apparent on color-flow Doppler (*arrow*) with a low Nyquist-limit setting of 30 cm/s. See also Video 7.

using standard planar mid-esophageal LV views.[39] Additional simultaneous orthogonal planes and real-time 3D imaging may be used to better identify the terminal portion of the cannula within the LV cavity (Figures 4A,B and 5A). Although a certain degree of inflow-cannula deviation towards the interventricular septum may be unavoidable, an excessive degree of angulation may necessitate surgical revision, given an expected decrease in LV cavity size either acutely or later in the clinical course after initiation of MCS. The combination of a smaller LV cavity and an angulated cannula can result in direct contact between the inflow cannula and the septum, which, in turn, can cause ventricular arrhythmias and/or inflow-cannula flow obstruction, as previously discussed. Additionally, the inflow cannula may directly interfere with the native submitral apparatus, and this finding should be communicated to the surgeon. Color Doppler interrogation of a properly aligned HM-II inflow cannula should reveal low-velocity (typically ≤1.5 m/sec)[49] laminar, unidirectional flow from the ventricle to the inflow cannula, with a variable degree of uniform systolic augmentation and no regurgitation (Figure 5B).[39] In some cases, the normal inflow-cannula spectral Doppler flow signal may be "contaminated" by mitral inflow and/or AR (Figure 5C). Using both pulsed and CW spectral Doppler for interrogating the HM-II inflow-cannula flow is recommended, in order to screen for obstructive velocities (Figure 5C). Any HM-II inflow cannula turbulent color Doppler or significant peak systolic velocity variability suggests the presence of mechanical obstruction by the interventricular septum, LV muscular trabeculations, or submitral apparatus. The pericardial location of the HVAD impeller results in a prominent, characteristic color and a spectral Doppler artifact that generally precludes Doppler interrogation of the inflow cannula.[49,50] The HVAD Doppler artifact occurs only when the inflow cannula appears within the imaging sector. Therefore, successful color and spectral Doppler interrogation of other cardiac structures is possible whenever the imaging plane excludes the HVAD inflow cannula (Figure 11). Consequently, HVAD inflow must be determined indirectly by correlating the inflow cannula anatomic imaging (ie, does the cannula appear unobstructed?) with downstream anatomic and hemodynamic parameters, as discussed in more detail below.

Outflow Graft.–After interrogation of the inflow cannula, attention should be directed towards the outflow graft. Whereas the proximal outflow graft is not visible with TEE, the middle portion adjacent to the right side of the heart (Figure 12) and the distal outflow graft-to-aorta anastomosis can be visualized in the majority of patients. Flow from the outflow graft into the aorta can be visualized by color Doppler interrogation near the level of the right pulmonary artery (eg, great vessel, upper esophageal view [Figures 6 and 13]). Simultaneous orthogonal-plane or real-time 3D imaging may allow better characterization of the anastomosis site. Every effort should be made to perform spectral Doppler interrogation coaxially to the direction of flow. As with the inflow cannula described above, the spectral Doppler appearance should consist of low-velocity, laminar, unidirectional flow with a variable amount of systolic augmentation. However, outflow-graft-velocity benchmarks are not available. The peak systolic and nadir diastolic Doppler-derived velocities vary with pump speed in the same patient, and these speeds may also vary with the graft cross-sectional area of the particular device type. However, an outflow-graft peak systolic velocity of >2 m/s at any level (including the that of the aortic anastomosis) may be abnormal and warrant further investigation or monitoring.

Finally, it is important to note that sternal closure can change the orientation of either the inflow cannula or the outflow graft relative to their open chest positions. Accordingly, it is critical to reevaluate the inflow cannula orientation and flow characteristics and the outflow graft and/or outflow graft-to-aorta anastomosis flow immediately after sternal closure. This can be accomplished by TEE or TTE.

Pump Speed. Optimal pump speed selection is a complex topic. The early postimplantation recovery phase may be associated with significant fluctuations in LV preload and afterload. Therefore, the immediate postimplantation (operating room) pump speed that is associated with 'normal' LVAD function by the perioperative TEE parameters discussed above may or may not be appropriate later on. In addition (as discussed in more detail, below), selection of an "optimal" LVAD speed setting varies among implantation centers. Some centers select the speed that minimizes LVEDVs and/or the LVIDd while allowing at least intermittent AV opening (assessed best by M-mode echocardiography at the AV level). Other centers maximize LV unloading, leaving the AV closed.

KEY POINTS

- Intracardiac air is a consequence of LVAD implantation, and TEE evaluation is useful for ascertaining the success of de-airing maneuvers.
- All images acquired after LVAD activation should be annotated with the device name and current pump speed.
- Postimplant perioperative TEE should include rapid assessment for possible unmasked PFO shunt, AV opening, the relative LV and RV sizes, degree of TR, ventricular septal position, inflow-cannula position, and flow velocities after initiation of LVAD support and after changes in the LVAD pump speed.
- A "suction event," is a condition in which a segment of LV myocardium partially occludes the inflow cannula and reduces pump inflow. This complication is usually related to over-pumping of the left ventricle (producing a small "sucked down" LV cavity). Suction events can often be quickly corrected by lowering the pump speed.
- HM-II inflow cannula peak systolic flow velocities are typically <1.5 m/sec. Higher velocities suggest possible inflow-cannula obstruction.
- HVAD inflow-cannula velocities cannot be measured due to a characteristic Doppler artifact.
- TEE imaging can frequently show the anatomic contour and flow velocities of the distal outflow-graft region and the outflow-graft–to–aorta anastomosis.

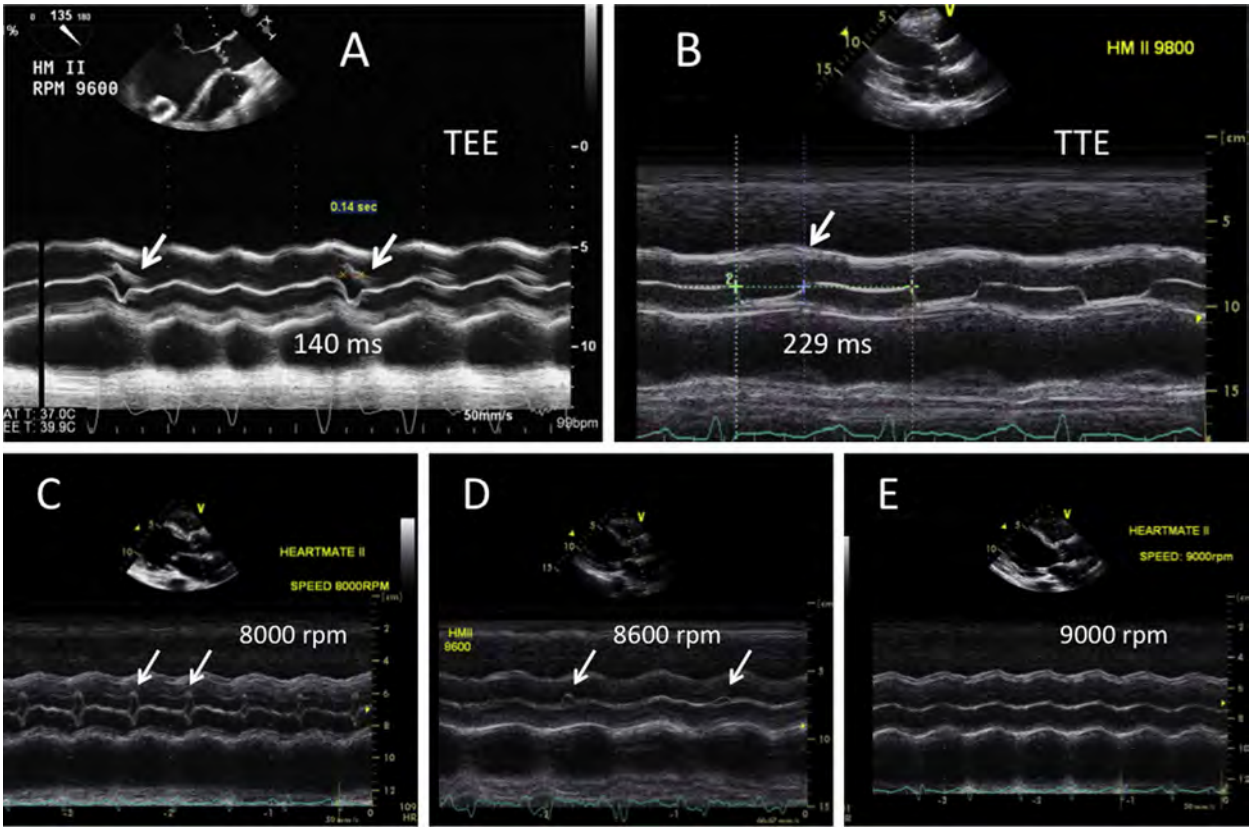


Figure 8 The duration of AV opening during LVAD support can be easily measured using M-mode during either TEE **(A)** or TTE **(B)**. In view A, the AV "barely opens" intermittently (*arrows*); this may, in part, be related to an arrhythmia and suggests normal LVAD function at a pump speed of 9600 rpm. In view B, there is near-normal AV opening, with durations of >200 ms; this may be an abnormal finding at a high LVAD pump speed (9800 rpm). **(C–E)** The expected progressively reduced duration of AV opening in the same patient during a ramp (speed-change) echo exam at different HM-II pump speeds: In view C (8000 rpm), the AV "barely opens"; in view D (8600 rpm), the AV "opens intermittently" (*arrows*); in view E (9000 rpm), the AV "remains closed."

- Outflow-graft velocities of >2 m/s at any level may be abnormal and warrant further consideration for possible obstruction, although benchmark data are lacking in this regard.

ROLE OF ECHOCARDIOGRAPHY (TTE OR TEE) AFTER LVAD IMPLANTATION

The significant variability in the clinical courses of individual patients after LVAD implantation precludes a "one-size-fits-all" approach to postimplantation echocardiography. Nevertheless, the authors believe that an overall framework can be recommended. In general, the starting point for any LVAD echocardiographic examination is a comprehensive "HF" TTE exam, which is performed at the pump's baseline speed setting and includes LVAD-specific views and Doppler flow assessments in addition to all the elements of preoperative TTE. In some cases, outlined below, the exam also includes the systematic reacquisition of selected exam components at pump speeds above and/or below the baseline speed. The exact protocol for changing pump speeds varies, depending on the indication for examination. There are three subcategories of LVAD echo protocol indications that appear to reflect real-world clinical management:

1. *LVAD surveillance echocardiography,* with or without *LVAD optimization echocardiography.*
2. *LVAD problem-focused echocardiography, with or without an LVAD speed-change protocol.*
3. *LVAD recovery echocardiography.*

LVAD Surveillance Echocardiography

LVAD surveillance echocardiography is performed at the pump's baseline speed setting and includes LVAD-specific views and Doppler flow assessments in addition to all the elements of a standard HF TTE exam. Addition of an *LVAD optimization protocol,* may involve further limited imaging at pump speeds higher and/or lower than the baseline speed to optimize LVAD and native heart function.

The authors recommend that patients with an uncomplicated postoperative course (eg, absence of HF symptoms, successful weaning from IV pharmacologic inotropic and vasopressor agents within 14 days, absence of LVAD controller alarms, and lack of serologic evidence of hemolysis or infection) undergo follow-up surveillance TTE at prespecified intervals. Periodic ***LVAD surveillance echo exams*** are recommended, to establish patient-specific "baseline" parameters for both LVAD and native heart function. An LVAD surveillance echo exam should be considered at approximately 2 weeks after device implantation or before index hospitalization discharge (whichever occurs first), followed by consideration of surveillance TTE at 1, 3, 6, and 12 months post implantation and every 6 to 12 months thereafter. Figure 14 summarizes a sample schedule

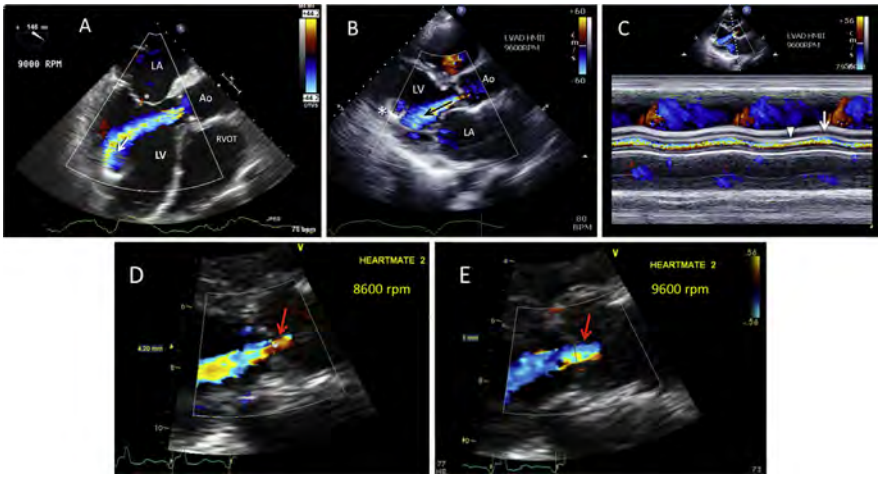


Figure 9 Assessment of AR. **(A)** TEE shows at least moderate—and possibly severe—continuous AR during LVAD support. The AR VC is clearly >3 mm, and the jet width/LVOT width is clearly >46%. Color-flow Doppler reveals inflow-cannula systolic entrainment of the AR jet (*arrow*). A closed MV and trace MR (*) are indicative of marked systolic AR. *RVOT,* right ventricular outflow tract. See also Video 8. **(B, C)** During LVAD support, at least moderate continuous AR (*arrow*) is observed in the transthoracic parasternal long-axis view with color Doppler **(B)** and color M-mode imaging **(C)**; the inflow cannula is denoted by an asterisk. In view C, note the variance in the early systolic (*arrowhead*) versus late systolic (*arrow*) AR VC width, as shown by M-mode. This finding is not consistent among different patients; it is likely influenced by several variables and by the fact that the AV cusps can exhibit augmented systolic opening, despite AR, at speeds close to (but below) the AV "opening speed." See also Video 9. **(D–E)** The AR VC width may increase at higher pump speeds in the same patient, as seen here. This may partially be due to an increased systemic arterial pressure at higher pump speeds, which presumably increases the AR volume. At both speeds, the VC is >3 mm, indicating at least moderate—and possibly severe—AR. The VC width is 4.2 mm at 8600 rpm in view D and is 5.7 cm at 9600 rpm in view E (HM-II LVAD). **(F)** "Continuous" holosystolic and holodiastolic AR, as detected by continuous-wave Doppler (TTE apical 5-chamber view). **(G)** Continuous-wave Doppler (TTE apical 5-chamber view) reveals nearly continuous AR, which significantly extends into the electrical and mechanical systolic period with a brief period of AV systolic forward flow (*arrows*). **(H)** Color M-mode shows minimal AV opening, with a brief duration of low-velocity systolic forward flow (*arrows*). **(I)** TTE parasternal long-axis view of an AR jet on color-flow Doppler imaging (*arrow*). **(J)** The AV opens widely, with forward flow that interrupts AR. However, the AR period extends into the electrical and mechanical systolic period (*arrows*) during HVAD pumping at 2600 rpm.

for timing postimplantation surveillance TTE. Comparison of serial surveillance-exam results to each other (for an individual patient) or to population-based benchmarks (see Appendix D) can also help the examiner understand a patient's response to LVAD therapy over time. Moreover, surveillance data may allow early diagnosis of occult native heart abnormalities (eg, development of LVAD-related AR) or other device-related problems, including a drift from previously optimal device speed settings. When surveillance TTE is coordinated with the patient's routine LVAD clinic visits, HF specialists can integrate the information obtained into their clinical assessments and care plans. A putative benefit of routine LVAD surveillance echocardiograms (with optimization protocols when indicated) is improved patient outcomes, including early detection and treatment of complications and reduced hospitalizations for recurrent HF.

KEY POINTS

- Patients with an uncomplicated postoperative course should undergo LVAD surveillance echocardiography at certain predetermined intervals after LVAD implantation to assess the patients' response to MCS therapy and to screen for the development of subclinical complications.
- When possible, LVAD surveillance echocardiography should be coordinated with routine LVAD-clinic visits.

Clinical Data-Acquisition Standards and Sonographer Reproducibility (see Table 3). Before initiating any LVAD echo exam, sonographers should always annotate the LVAD type and baseline LVAD speeds in rotations per minute (rpm) on the imaging screen in addition to the standard patient demographic data. If the device speed is changed, this should be reannotated during the exam. The device type and speed information should also be routinely incorporated into reporting templates.

Blood Pressure. The patient's BP, which reflects peripheral vascular resistance, is an important parameter that greatly influences ventricular unloading and the observed echocardiographic findings. Therefore, the BP should be recorded just before the exam and immediately afterward if pump speed changes were made. Patients with CF-LVADs have a reduced and narrowed pulse pressure, and a palpable pulse may be absent. Therefore, cuff-based BP assessment may be difficult or impossible to perform. In the intensive care unit, the BP may be obtained from invasive arterial monitoring devices. In other settings in which no pulse is present, the use of a BP cuff along with handheld audible Doppler evaluation of the brachial or radial artery may be required.[51] Note that the arterial Doppler-derived BP reading lies between the systolic pressure and the mean arterial BP.[52] For practical purposes, if the patient has a pulse (ie, the AV is opening), the Doppler-derived BP is the same as the systolic BP. If the patient does not have a pulse (ie, the AV is not opening), the Doppler BP is considered to be the mean arterial BP. A current BP measurement is necessary for accurate echo interpretation and for safety reasons during "speed change" protocols, particularly when changing to higher speed settings. Susceptible patients may develop clinically significant hypertension in response to increased LVAD flow, and a mean arterial pressure of <85 mmHg is recommended.[53]

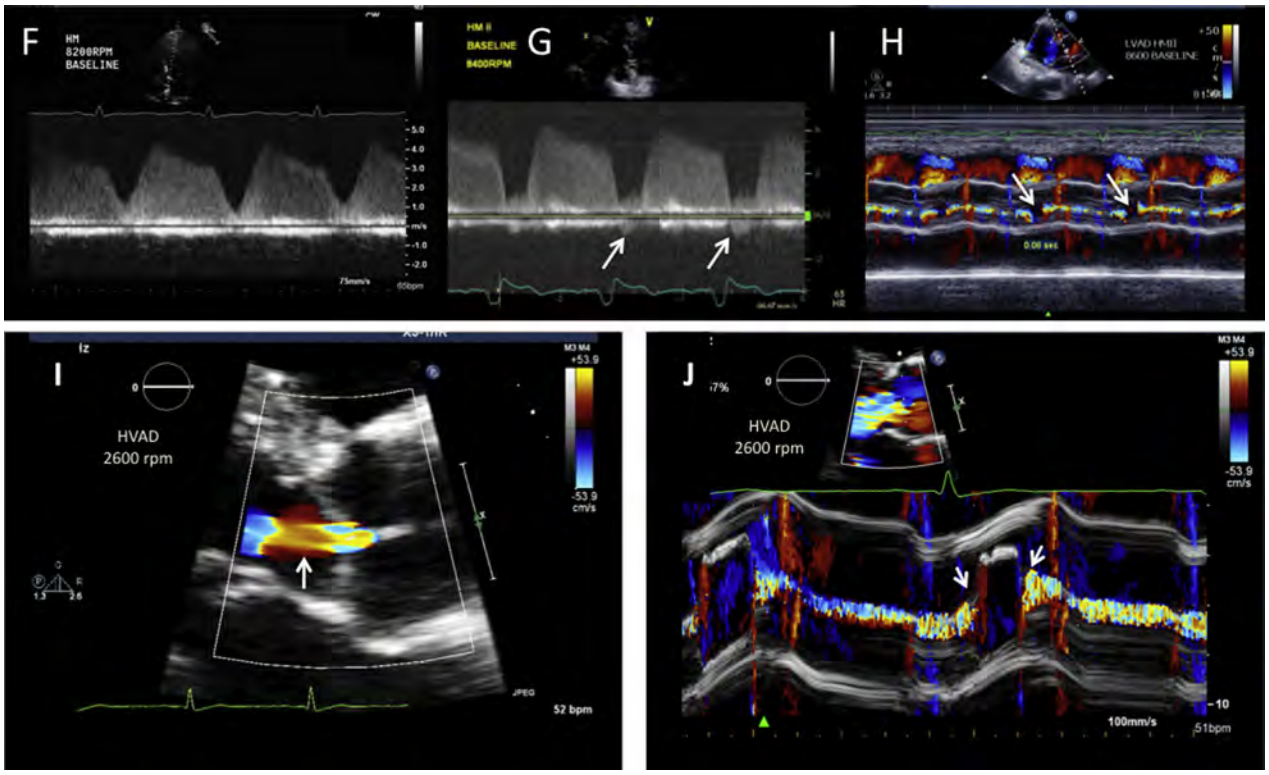


Figure 9 (*continued*).

Hypotension is generally defined as a mean arterial pressure of <60 mmHg and may be associated with traditional symptoms and/or signs reflective of hypoperfusion. With CF-LVADs, one of the challenges is that a sonographer (or some other trained and available individual) needs to be facile at obtaining an arterial Doppler-derived BP reading. To facilitate the care of CF-LVAD recipients, there may be a need for improved BP monitoring techniques.[54]

KEY POINTS

- Although BP readings can be challenging to obtain in LVAD patients, this variable is important, as it significantly influences observed echo findings and their interpretation.
- In the absence of a palpable pulse, BP measurement may require audible Doppler interrogation by an appropriately trained individual before the echo exam.
- Susceptible patients can experience marked hypertension after the LVAD pump speed is increased. Therefore, the BP measurement should be repeated after a significant pump-speed increase, particularly if the BP is elevated at the baseline pump speed.
- A mean arterial BP of <85 mm Hg is recommended.
- Hypotension is generally defined as a mean arterial pressure <60 mmHg. It may be associated with traditional symptoms and/or signs of hypoperfusion.

LV Size and Systolic Function. Methods for determining LV size and systolic function by using linear and volumetric approaches in non-LVAD patients have been described by Lang and colleagues.[17]

LV Size.–As mentioned above, the LVIDd from the 2D parasternal long-axis image is considered the most *reproducible* measure of LV size after LVAD implantation (Figure 15A). In the presence of a normally functioning CF-LVAD, severely depressed native LV function, and altered MV opening, determination of end-diastole may be difficult. In this scenario, correlating the images to the electrocardiographic signal can be helpful. Additionally, strong consideration should be given to the use of a microbubble contrast agent when endocardial definition is insufficient for accurate LVIDd measurement.[20] Previous data from HM-II outpatients in stable condition suggest that at least a 15% reduction in the LVIDd compared to preimplant values can be expected 3 months after implantation.[55,56] Care must be taken to correlate LV end-systolic versus end-diastolic diameters with the electrocardiographic signal. The LVIDd may be paradoxically smaller than the LVIDs, and this is an important finding, as it is associated with excessive LVAD unloading and/or severe RV dysfunction. Although LV volumes, as determined by Simpson's biplane or single-plane method (Figure 16), reflect the LV size more accurately than do linear measurements, the LV size by volume assessment may be technically challenging to obtain after LVAD implantation because of apical shadowing/dropout associated with the inflow cannula. This is one reason why postimplantation LV volumes assessed by echocardiography are smaller than those assessed by CCT.[57] A reasonable LV diastolic volume assessment is possible in many ambulatory LVAD patients, and this metric can be incorporated into the surveillance exam, particularly at the baseline pump speed setting. However, LVIDd measurement, being more expediently acquired and reproducible, is practical for tracking the relative LV size over time at a baseline pump speed (eg, Figure 15A vs. 15B) and in the context of a speed-change exam (see below) for quick problem solving. That the serial LVIDd measurement (combined with the degree of AV opening) can be used as a surrogate marker for the degree of LV unloading in CF-LVAD patients seems intuitive and is supported by limited available literature, which is derived primarily from HM-II

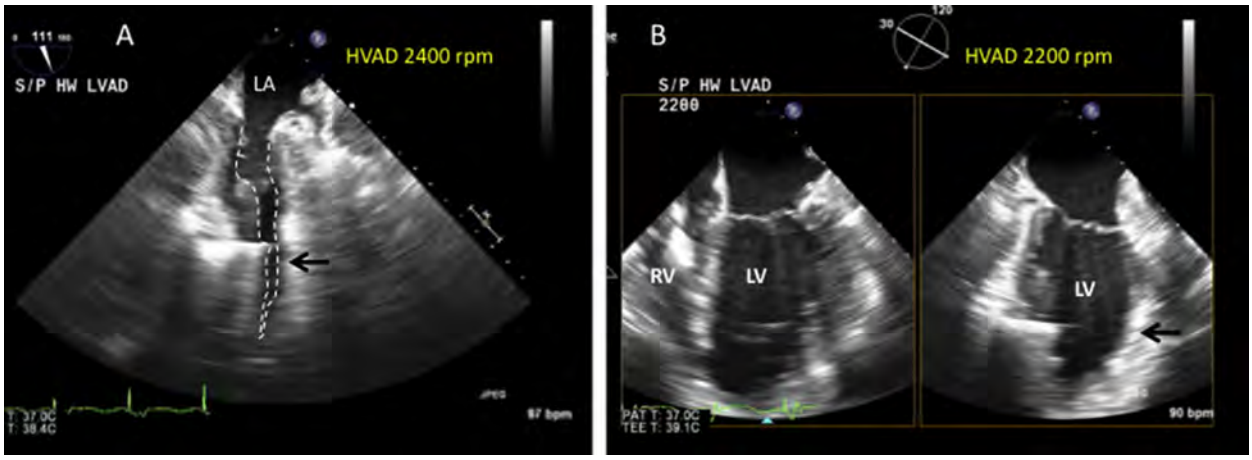


Figure 10 Suction event diagnosed with perioperative/postoperative TEE soon after HVAD activation. A 2400-rpm pump speed was initially satisfactory until the patient developed sudden hypotension and LVAD flow cessation. **(A)** Relook imaging (mid-esophageal 2-chamber view) showed LV cavity obliteration (*dotted line*) and inflow-cannula obstruction by the anterior LV endocardium (*arrow*). See also Video 10. **(B)** Restoration of acceptable LV size and normalized LVAD function seconds after pump-speed reduction to 2200 rpm. *Note*: In this case, the suction event was precipitated by intravascular volume depletion and a low afterload following weaning from CPB; the event was easily corrected by reducing the pump speed, administering IV fluids, and adjusting vasopressor infusions. In this example, the RV remained small and not dilated. However, CPB suction events can result from a low LV preload related to acute RV failure, with associated RV dilatation, TR, and a leftward ventricular septal shift that may persist despite pump-speed reduction (see the TTE example below). Depending on the degree of underlying RV dysfunction, perioperative suction events or RV failure may or may not be transient and responsive to medical management. See also Video 11.

studies. However, robust outcomes data are limited, and applicability to HVAD patients, for whom there is less evidence, has not been demonstrated at this time.[58]

LV Systolic Function.–Accurate determination of LV volumes is challenging after device implantation. So, too, is accurate and meaningful determination of overall LV systolic function, as based on the LVEF. Limitations for LVEF measurements are both technical with regards to imaging quality (endocardial border detection) and physiologic. The LV endocardium may be difficult to visualize because of apical foreshortening, apical shadowing from the device or acoustic dropout (signal attenuation). LVAD-related physiologic challenges include enhanced interventricular dependence and discordant septal and inferolateral wall motion, which may vary considerably in the same patient at different pump speeds. If the LV endocardium, including the apex, can be adequately visualized, with or without a microbubble contrast agent, the preferred method for calculating the LVEF is the biplane method of disks (Figure 16), modified Simpson rule).[17] Although other parameters for LV systolic function may be considered, the LVEF is an important surrogate for showing possible LV worsening or recovery. Therefore, surveillance and recovery LVAD exam reports should include an LVEF assessment, even if only a qualitative assessment is possible. However, LVAD support markedly reduces LV preload, an important determinate of LVEF. Therefore, the value of LVEF for determining systolic function during LVAD support must be taken into consideration during clinical decision-making.

Other methods: In patients with suboptimal apical but adequate parasternal views, the following methods for measuring LV systolic function may be considered, although their accuracy has not been validated in LVAD patients.

1. The LV fractional area change (FAC) method at the mid-papillary muscle level on 2D short-axis views: FAC (%) = [(end-diastolic area - end-systolic area)/(end-diastolic area)].[59]
2. The Quinones method for determining the LVEF,[60] with the assumption of an akinetic apex given the presence of the apical inflow cannula.
3. The LV fractional shortening (%) method: FS = [(LVIDd-LVIDs)/(LVIDd)], where FS = fractional shortening and LVIDs = the LV internal dimension at end-systole,[17] which has been applied in LVAD patients.[57,61]

The linear and volume measurements of systolic function noted above represent possible methods for tracking the course of individual patients, serving as their own controls, over time. However, routine use of methods 1 to 3, above may not be feasible or recommended for many LVAD patients because of segmental wall-motion abnormalities, exaggerated paradoxical septal motion, ventricular dyssynergy and/or ventricular septal shift, the extent of which could change at varying pump speeds in the same patient. Note that methods of calculating the LVEF based on the LV stroke volume are not recommended, because many LVAD patients have beat-to-beat variations in this parameter.[49] Previous data suggest that the vast majority of outpatient HM-II recipients in stable condition have persistent moderately to severely depressed LV systolic function during the first 6 months after device implantation.[55,56]

KEY POINTS

- After CF-LVAD activation, the LVIDd may be the most reproducible measure of LV unloading that can be tracked over time and/or at different pump speeds.
- The LVEDV is a more accurate representation of LV size than is the LVIDd.
- After LVAD implantation, measurement of LV volumes and the LVEF can be technically challenging. When the LVEF needs to be obtained (particularly to assess for LV recovery), Simpson's biplane method of disks is recommended for use when possible.

LV Diastolic Function. It is assumed that LVAD patients have markedly abnormal baseline diastolic function. Although the standard LV diastolic function parameters[62] can be measured and included in the report, there is a paucity of data validating their clinical usefulness in the setting of LVAD support. The use of certain diastolic parameters

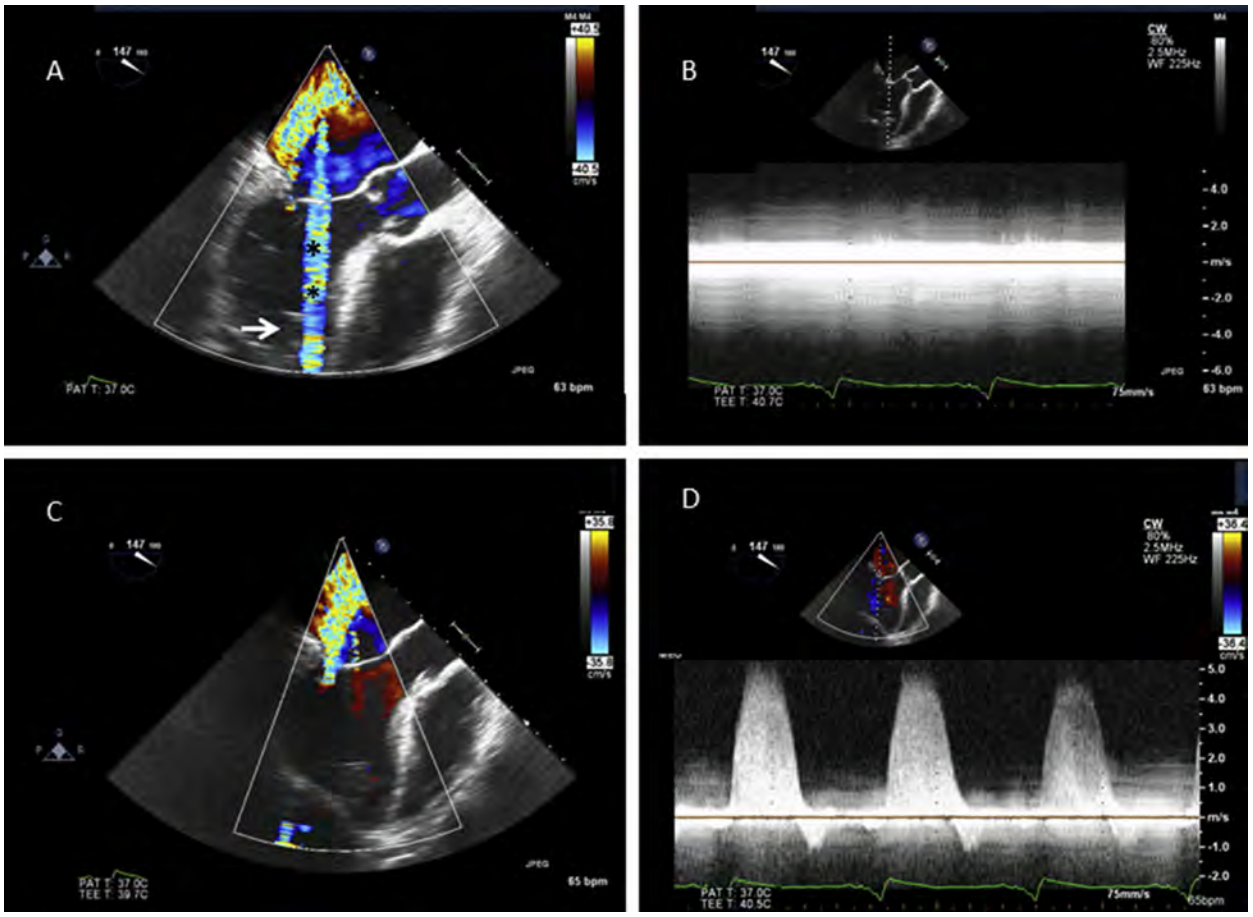


Figure 11 An HVAD inflow-cannula Doppler exam is typically not possible due to the characteristic color artifacts **(A)** (**) and spectral Doppler artifacts **(B)**. See also Video 12. When the inflow cannula is excluded from the 2D imaging sector **(C)**, the artifacts diminish, and other aspects of the Doppler exam can be performed. **(D)** Successful continuous-wave Doppler examination of MR in the same patient after slight rotation of the imaging sector away from the inflow cannula. Because the 2D image (view A: *arrow*) suggests that the inflow cannula is directed towards the ventricular septum, normal inflow-cannula flow must be confirmed by other methods, whether TEE or TTE. See also Video 13.

could be helpful, particularly when correlated with symptoms in individual patients, and at the discretion of the interpreter since they may reflect changes in the degree of LV unloading when compared to a prior study's data or at different pump speeds during the same exam. Previous data suggest that the mitral E velocity (cm/s), left atrial volume (mL), pulmonary vascular resistance (Wood units), and pulmonary artery systolic pressure (mmHg) are significantly reduced and that the mitral deceleration time (ms) is significantly prolonged in outpatients whose condition is stable 3 to 6 months after HM-II implantation.[55,56] How these parameters should be integrated into postimplantation clinical management is currently undefined, as is their prognostic value for patient outcomes. For a clinical LVAD echo reporting purposes, a practical approach at this time may be to use the following (or a similar) statement: "Interpretation of the degree of LV diastolic dysfunction (presumed abnormal) is not provided because of continuous flow LVAD support."

KEY POINTS

- It may be assumed that LVAD patients have markedly abnormal baseline diastolic function.
- How LV diastolic parameters measured after LVAD implantation should be integrated into the echocardiography interpretation and clinical management is currently undefined, as is their prognostic value for patient outcomes.

RV Size and Systolic Function. Many of the standard measures of RV size and systolic function,[22] including linear dimensions, RV FAC, TAPSE, and right-sided cardiac output, can feasibly be measured in LVAD patients.[56,63,64] However, recent data suggest that the correlation of TAPSE with overall RV systolic function may be weaker after cardiothoracic surgery and, therefore, this variable may have less clinical utility than the other measures.[65] Current data regarding the expected response of RV systolic function after LVAD implantation are conflicting: one study showed a significant improvement in RV FAC at 3 months,[55] but another study did not show a significant difference in this parameter at either 1 month or 6 months.[56]

Valvular Assessment. *Aortic Valve.*–Evaluating and reporting the degree of AV opening (if any) is important because it is affected by a number of other parameters, including LVAD speed, native LV function, volume status, and peripheral vascular resistance. In addition, whether or not the AV opens may have clinical implications. Whereas recent guidelines recommend that the LVAD speed be set low enough to allow

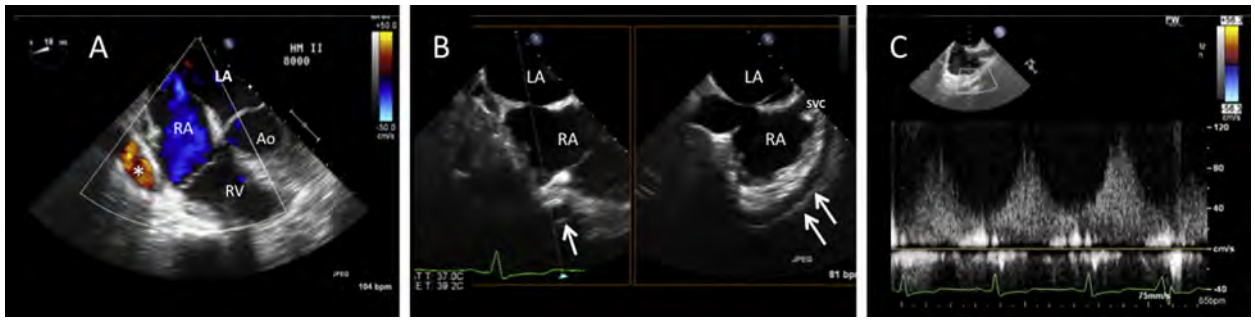


Figure 12 LVAD outflow graft, as assessed by TEE. **(A,B)** In a modified mid-esophageal 4-chamber view **(A)**, the outflow graft (*) is frequently seen in near short-axis orientation. See also Video 14. **(B)** Shows the utility of simultaneous orthogonal-plane imaging, which, in this case, a short axis image of the outflow graft (*single arrow*) is used as a reference image to reveal a long segment of the graft overlying the RA in a standard bicaval view (*double arrows*). See also Video 15. **(C)** Successful pulsed Doppler interrogation of the outflow graft (this is not always possible in practice). See also Video 16.

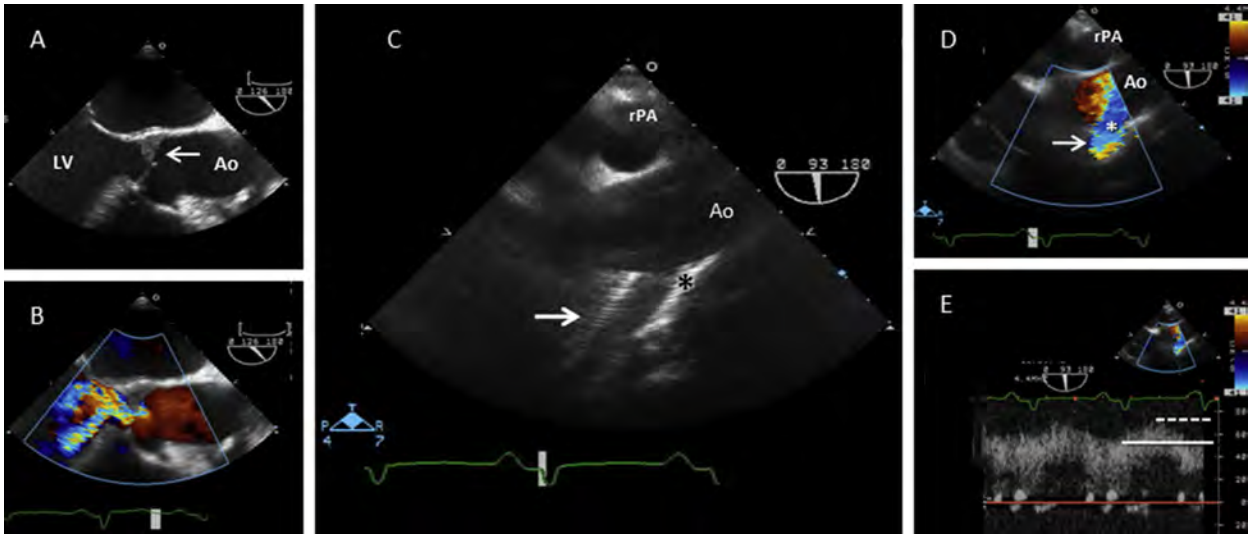


Figure 13 TEE characteristics of severe AR due to aortic cusp fusion associated with longstanding LVAD support. **(A)** Mural thrombus within the AV noncoronary cusp (*arrow*). See also Video 17. **(B)** Severe AR, as detected by color-flow Doppler. See also Video 18. **(C)** Using the right pulmonary artery (rPA) as an acoustic window, an upper esophageal long-axis view of the ascending aorta (Ao) shows the LVAD outflow graft (*arrow*) and its ascending aortic anastomosis site (*). **(D)** Color-flow Doppler evaluation of the outflow- graft–aorta anastomosis. See also Video 19. **(E)** Pulsed Doppler assessment of the outflow anastomosis reveals a laminar signal with high flow characterized by nearly equal systolic (*dotted line*) and diastolic (*solid line*) velocities (*arrow*), consistent with severe AR.

at least intermittent AV opening,[4] such opening may not occur at *any* LVAD speed in patients with extremely poor native LV function. The frequency of AV opening is most accurately assessed by recording multiple (five to six) cardiac cycles at a slow M-mode sweep speed (eg, 25-50 mm/s) (Figure 8D,E); the valve should be characterized as either opening with every cardiac cycle, opening intermittently, or remaining closed.[49,66] Many HF teams also request that the duration of AV opening (ms) be measured from the same M-mode acquisitions. This parameter may vary from beat to beat, so it is best to measure several beats and report an average value. When the AV-opening duration is relatively constant, a faster sweep speed (eg, 75-100 mm/s) may be appropriate (Figure 8A,B). An important potential pitfall of using M-mode to assess the presence and duration of aortic cusp separation is illustrated in Figure 17. The AV semilunar cusp conformation, combined with cardiac translational motion or slightly off-axis imaging, can create the false appearance of aortic cusp separation, even when the cusps are not separating. Careful attention and the additional use of color M-mode may be useful in difficult cases to avoid M-mode "pseudo AV opening" or an exaggerated AV-opening duration. However, an additional interesting observation is that in some cases of "minimal" AV opening, the duration of AV cusp separation and duration of forward systolic flow are not always the same, and color M-mode can help to document this finding (Figure 9G,H). In patients whose AV remains closed, it is important to evaluate for aortic root thrombus, which may be transient or associated with commissural fusion. Continuously closed aortic cusps have been associated with the development of aortic root thrombosis and LVAD-associated AR, as discussed below.[67] Fusion of the aortic cusps, either surgical or secondary to chronic aortic cusp closure, can be recognized on speed-change echocardiograms (discussed below).

New-onset ("de novo") AR occurs in approximately 25% to 33% of patients 12 months after LVAD implantation[68,69] and is a key finding, given its known adverse effects on LVAD performance, morbidity, and mortality.[70-72] Several studies suggest that persistent AV closure is a risk factor for de novo AR after LVAD implantation, even without the presence of aortic root thrombus (Figure 18).[68,73,74] For the reasons noted above in the postimplant TEE section, standard methods for quantifying AR[32] may be challenging to use after

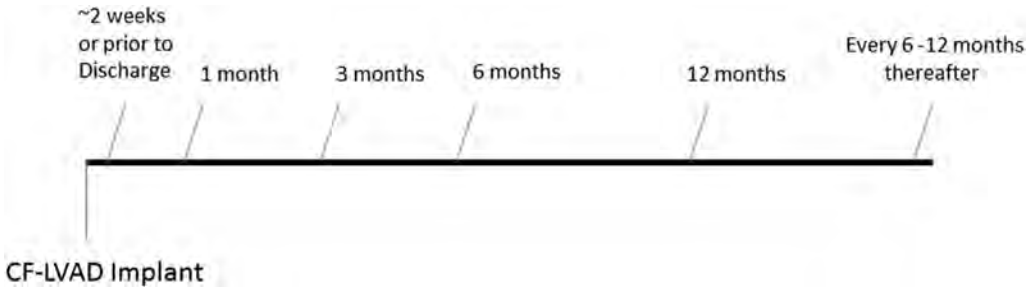


Figure 14 Sample schedule for initial and follow-up surveillance echocardiography of patients with no evidence of device malfunction.

LVAD implantation. In the absence of definitive cutoff criteria to define mild, moderate, and severe AR after LVAD implantation, one should perform an aggregate assessment based on duration (predominantly diastolic vs. continuous), AR jet VC width, jet height relative to the LVOT, comparative LVAD and native circuit flow measures and LV chamber size. Additionally, significant AR noted on LVAD surveillance echocardiography may be further evaluated with device controller data and the cardiac response during LVAD problem-focused echocardiography with speed changes, as described below.

KEY POINTS

- Recording multiple cardiac cycles with color M-mode at a sweep speed of 25-50 mm/s is recommended to accurately assess the frequency and duration of AV opening.
- Persistent AV closure can be associated with aortic root thrombus and de novo AR.
- If aortic root thrombus is suspected, a decrease in the LVAD pump speed should be avoided, as it could result in sudden AV opening (eg, during a planned speed-change exam).
- After LVAD implantation, the presence of AR is not uncommon. Assessment of severity is partly based on careful color Doppler analysis in the parasternal long-axis view.

*Mitral Valve.–*As noted above, LV unloading generally leads to reduced MV annular dilatation, improved leaflet coaptation, and, ultimately, reduced MR severity. Persistence of significant MR after initiation of LVAD support may indicate inadequate LV unloading or inflow cannula malposition and interference with the submitral apparatus. If MR is present, it can be quantified by using standard methods.[32] Incidental post-LVAD MR may also represent LVAD malfunction and should be discussed with the clinical team.

*Tricuspid and Pulmonary Valves.–*Like MR, moderate or greater TR is an important finding on LVAD surveillance echocardiography, as this condition may be associated with insufficient LV unloading (functional TR), excessive LV unloading with a leftward shift of the interventricular septum (eg, a suction event), elevated systolic pulmonary pressures, and/or intrinsic RV systolic dysfunction. Distinguishing between these etiologies by utilizing echocardiographic parameters is discussed in further detail below. Regardless of the etiology, TR after LVAD implantation can generally be assessed with standard methods.[32] Furthermore, the native pulmonary valve typically remains functionally normal after LVAD implantation and can be interrogated by using standard methods when significant stenosis or regurgitation is suspected.[32,33] As noted in the foregoing discussion of perioperative TEE, the presence of significant preexisting or acquired PR may have implications with regards to RV function and/or the ability to perform RVAD implantation if needed.

Interventricular Septal Position. The end-diastolic interventricular septal position, which is dependent on the interventricular pressure gradient, should be routinely *reported as neutral, leftward-shifted, or rightward-shifted*. A leftward shift can be due to elevated RV end-diastolic pressures, reduced LV preload, or LV over-decompression resulting from excessive LVAD speed; differentiation of these etiologies is further discussed below. A rightward shift is generally due to elevated LV end-diastolic pressures resulting from an inadequate LVAD speed setting, pump dysfunction, severe AR, or an increased LV afterload.

Inflow-Cannula and Outflow-Graft Interrogation. *Inflow Cannula.–*Usually, the apically inserted inflow cannula can be adequately imaged in standard or modified 2D parasternal and apical TTE views. The sonographer's objective is to reveal the inflow cannula's location and orientation in relation to the interventricular septum and other LV structures. The inflow cannula can often be visualized with 3D echo techniques, and this approach may be used as a complementary imaging method by examiners experienced in 3D imaging. As noted above in the section on perioperative TEE, color Doppler interrogation of a properly aligned inflow cannula should reveal laminar, unidirectional flow from the ventricle to the inflow cannula, with no evidence of turbulence or regurgitation.[39] Pulsed and CW spectral Doppler interrogation may require "off-axis" modification of a standard parasternal, apical, or short-axis TTE view to achieve true coaxial alignment between the sampling beam and inflow-cannula flow; such interrogation should additionally reveal the flow to have a low peak velocity (<1.5 m/s). Due to native LV contractility, cannula flow generally remains pulsatile to some degree even when the AV does not open.[49,55] Recording both the peak systolic and nadir diastolic velocities over at least three to four cardiac cycles is recommended (Figures 5 and 19).

The inflow cannula should be routinely interrogated with CW spectral Doppler at the baseline pump speed and particularly during the course of speed-change exams (discussed, below) to screen for inflow obstruction. Note that in many cases, a normal inflow-cannula spectral Doppler flow-velocity profile may be contaminated by low-velocity diastolic AR or mitral inflow (Figure 20). Moreover, in the setting of TEE evaluation of the inflow cannula, the CW Doppler signal can be contaminated by MR (Figure 5C) as well. The HVAD inflow-cannula flow velocities typically cannot be evaluated by using either color or spectral Doppler due to a characteristic Doppler artifact (Figure 21) related to the inflow cannula's direct connection to the adjacent impeller housing.

*Outflow Graft.–*In contrast to inflow-cannula imaging, visualizing the outflow graft requires the utilization of atypical echocardiographic windows. The terminal portion of the outflow conduit and its

Table 3 Sonographer checklist/ordering worksheet: LVAD-specific demographic data, image acquisition, and safety considerations particularly relating to "speed-change" echo exams (optimization, problem-solving/ramp studies)

√	Sonographer Checklist / Ordering Worksheet
	Study Type being ordered
	• **Surveillance, initial** (+/− optimization, pre/discharge)
	• **Surveillance, post-discharge** (+/− optimization, number months post: 1, 3, 6, 12, 18, etc.)
	• **Problem-solving at baseline speed only**
	• **Problem-solving at baseline + other speed settings**
	• **Recovery**
	Ordering/responsible physician identified
	Implant date documented
	Symptoms noted (if applicable)
	Device alarms: if present, type of alarm identified
	Other key clinical history/information related to indication noted
	Anticoagulation therapy adequate if low pump speeds tested
	LVAD name noted on worksheet and annotated on screen
	LVAD speeds (baseline and changes) noted on worksheet and annotated on screen
	Blood pressure (cuff or Doppler) noted on worksheet and annotated on screen *(obtained by designated trained individual at time of exam)*
	Designated person to change pump speed available
	Supervision: appropriate staff to perform speed changes; safety endpoint recognition (eg, low flow, suction event, hypo/hypertension)
	Aortic Root Thrombus detection: reason not to proceed (lowering speed could open AV)
	Endpoints for speed-change exams • Protocol completion • Hypotension • Hypertension • New symptoms • Device alarm • Signs of a suction event ○ Decrease in LV size (typically <3 cm) ○ Interventricular septum shifting leftward ○ Flow impeded into inlet cannula ○ Worsening TR due to septal shifting and/or RV enlargement • Signs of low cardiac output • Cannula flow reversal (at low pump speeds)

AR, Aortic regurgitation; *AV,* aortic valve; *LV,* left ventricular; *LVAD,* left ventricular assist device; *TR,* tricuspid regurgitation.

anastomosis to the aorta can generally be visualized from a high left parasternal long-axis view (Figures 22 and 23). The mid-portion of the outflow graft is best visualized from a right parasternal view while the patient is in a right lateral decubitus position. Color Doppler and spectral Doppler interrogations are usually possible from these views; and, as with the inflow cannula, recording both the peak systolic and nadir diastolic velocities over at least three to five cardiac cycles is recommended (Figure 24), depending upon the uniformity of the spectral Doppler signal. Note that the outflow-graft flow-velocity profile will appear either above or below the baseline in the spectral Doppler display, depending upon the sonographer's positioning of the sample volume direction (caudad vs. cephalad) within the graft. There is no standard recommendation for a positive-versus-negative outflow graft display other than to provide the most coaxial alignment and to ensure that the flow direction (caudad vs. cephalad) is apparent. In some patients, the outflow graft may be visualized in subcostal and/or sternal notch views, depending upon the body habitus. At similar flow rates, normal flow velocities within the HM-II outflow graft (16-mm diameter) are somewhat lower than those within the smaller-caliber HVAD outflow graft (10-mm diameter). Otherwise, phasic holosystolic and holodiastolic laminar flow-velocity patterns should be similar between the two devices. The outflow-graft pulsed Doppler velocity-time integral (VTI) combined with the expected or measured outflow-graft area may be used to directly measure LVAD flow (see Figure 22 and the discussion below).

KEY POINTS

- When 2D imaging is inconclusive, 3D echocardiography can help delineate the relationship of the inflow cannula to the interventricular septum and other LV structures.
- In patients with an HM-II LVAD, peak systolic and nadir diastolic inflow-cannula and outflow-graft velocities may be derived from coaxially-aligned spectral Doppler.
- HM-II inflow-cannula peak systolic flow velocities are typically <1.5 m/sec. Higher velocities suggest possible inflow-cannula obstruction.
- HVAD: inflow-cannula velocities cannot be accurately measured due to a characteristic Doppler artifact.

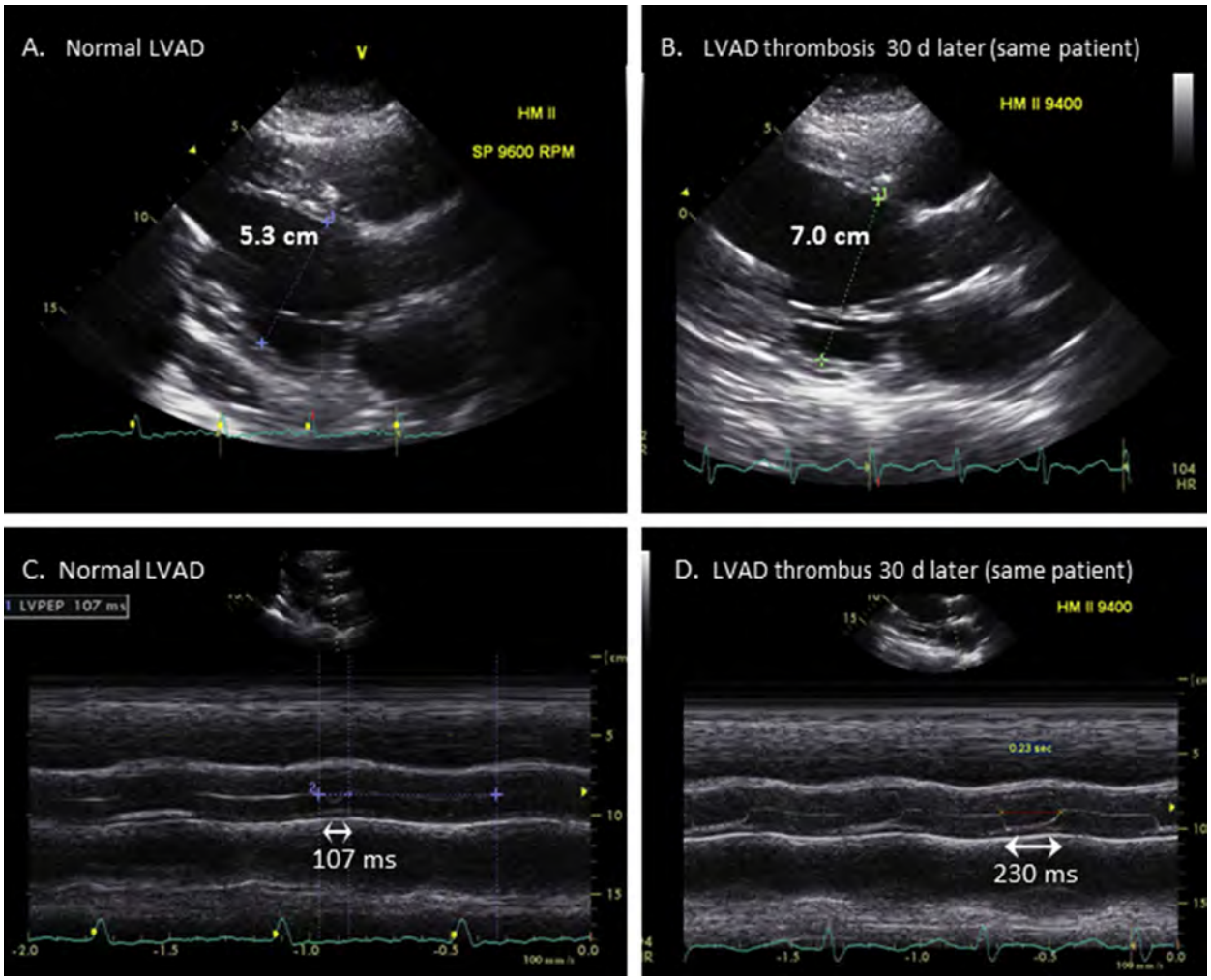


Figure 15 Side-by-side comparison of multiple imaging metrics in the same patient before and after HM-II LVAD impeller thrombosis. **(A)** LVIDd, normal LVAD; **(B)** increased size by LVIDd after LVAD thrombosis; **(C)** AV M-mode, minimal opening (107 ms) during normal LVAD function; **(D)** markedly increased AoV opening duration (230 ms) after internal LVAD thrombosis; **(E,G)** Inflow-cannula color-flow (*arrow*) and pulsed Doppler images, respectively, during normal LVAD function (see also Video 20); **(F,H)** Very low velocity inflow-cannula systolic flow on color-flow (*arrow*) and pulsed Doppler images, respectively, with nearly absent diastolic flow (view H) after development of impeller thrombosis; **(I)** RVOT pulsed Doppler VTI = 15 cm during normal LVAD function; **(J)** RVOT pulsed Doppler VTI = 7.9 cm after LVAD thrombosis. *Inflow*, inflow cannula; *vel*., velocity.

- Peak systolic and nadir diastolic inflow-cannula and outflow-graft velocities should be derived from 3 to 5 cardiac cycles, depending upon the regularity of the spectral Doppler contour.
- Outflow graft velocities of >2 m/s at any level may be abnormal and warrant further consideration for possible obstruction, although benchmark data are lacking.

Native Heart Versus LVAD Flow Assessment. In the absence of significant pulmonary valve regurgitation, the net cardiac output (combined native LV outflow and LVAD conduit flow) is the same as the right-sided cardiac output. The right-sided output is calculated by using the following commonly applied equation: RVOT cardiac output = RVOT pulsed Doppler VTI*[3.14*(RVOT diameter/2)^2 × HRI (Figure 25), where RVOT is the right ventricular outflow tract and HR is the heart rate. When the AV does not open, and there is no significant AR, the RVOT-derived cardiac output is the same as the LVAD cardiac output. When the AV opens significantly and an adequate LVOT VTI can be measured with pulsed Doppler (and in the absence of significant AR), the LVAD cardiac output should equal the RVOT-derived cardiac output minus the LVOT cardiac output. In the presence of significant AR and no AV opening, the LVAD flow can be assumed to be significantly greater than the RVOT-derived cardiac output, owing to a blind loop of LVAD-to-aorta flow as described, above. In cases of greater than mild AR, it may be useful to calculate the LVAD cardiac output directly by measuring flow within the outflow graft with pulsed Doppler and the following equation: LVAD output = outflow-conduit VTI*[3.14*(outflow graft diameter/2)^2 × HRI (Figure 22),[55,75,76] although this approach has not been well validated for the HVAD. When using this formula, increased accuracy may be achieved by measuring the outflow-graft diameter (area) directly at the site of Doppler interrogation rather than using the manufacturer's reported graft diameter (which could cause over-estimation of flow).[55] The aortic regurgitant volume would then equal the LVAD stroke volume, measured directly, minus the RVOT-derived stroke volume, as described above and in Figure 25. These Doppler methods may be useful for validating normal or abnormal LVAD flows reported by the device's controller (see discussion of alarms, below) or to detect problems early, in advance of an alarm report.

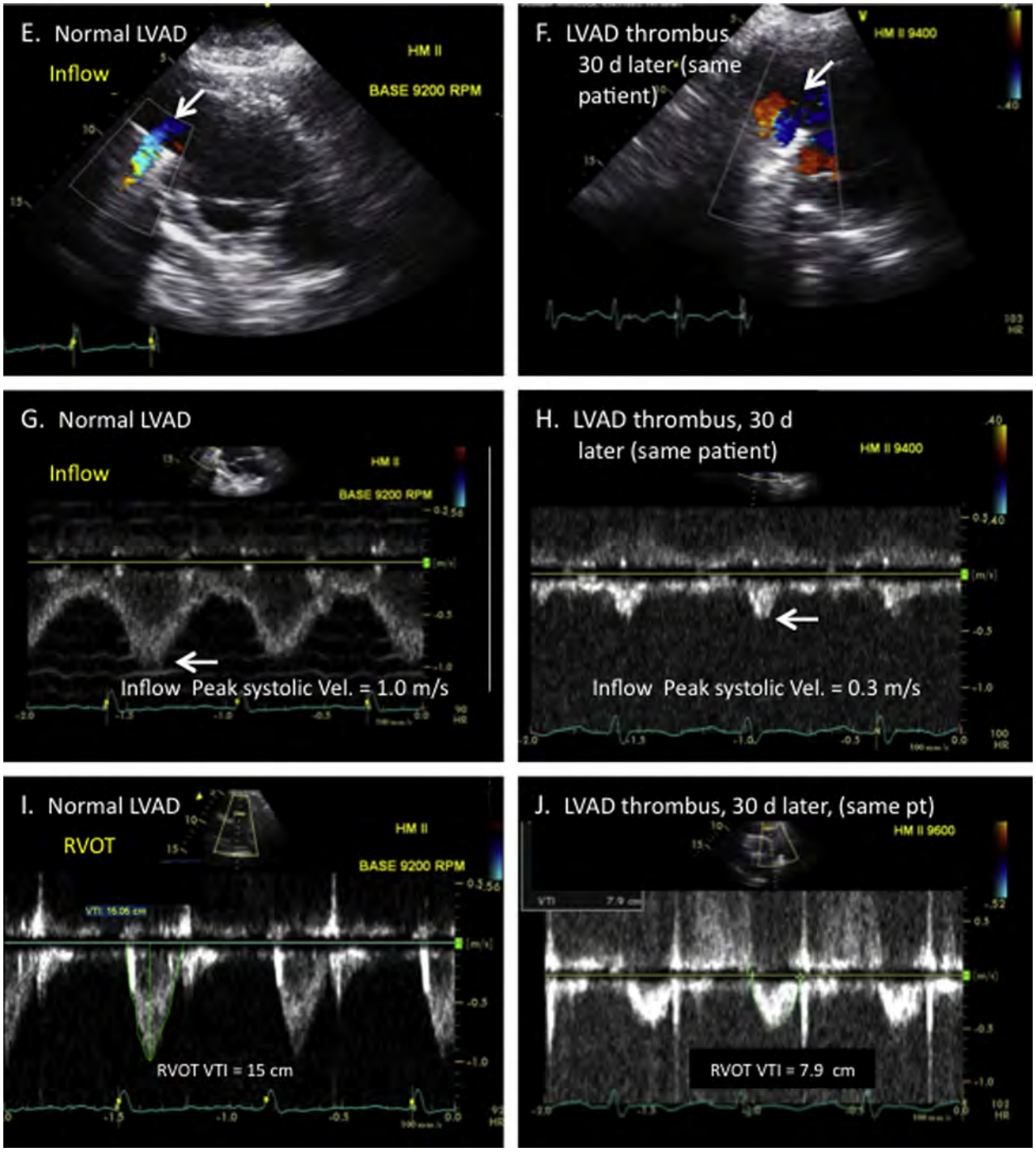


Figure 15 (*continued*).

KEY POINTS

- In the absence of AV opening, significant AR, or significant PR, the RVOT Doppler-derived cardiac output equals the LVAD cardiac output.
- If the AV opens and the LVOT cardiac output can be measured, the result should be subtracted from the RVOT cardiac output when computing the LVAD cardiac output.
- In the presence of significant AR and in the absence of AV opening, it may be best to directly compute the LVAD cardiac output by using pulsed-wave Doppler in the outflow graft. An estimate of regurgitant volume can then be computed by subtracting the RVOT cardiac output.

Echocardiography with Speed Changes and Safety Concerns

"Speed-change testing" occurs in the setting of either an optimization protocol or a problem-focused (ramp) exam, both of which are outlined below. Before initiating a speed-change exam, consideration of the patient's anticoagulant status is recommended.

Speed-change testing is typically performed only if a patient has been receiving therapeutic doses of warfarin or parenteral anticoagulation therapy. Risks of performing speed changes include embolic events associated with sudden AV opening (return to pulsatile flow)

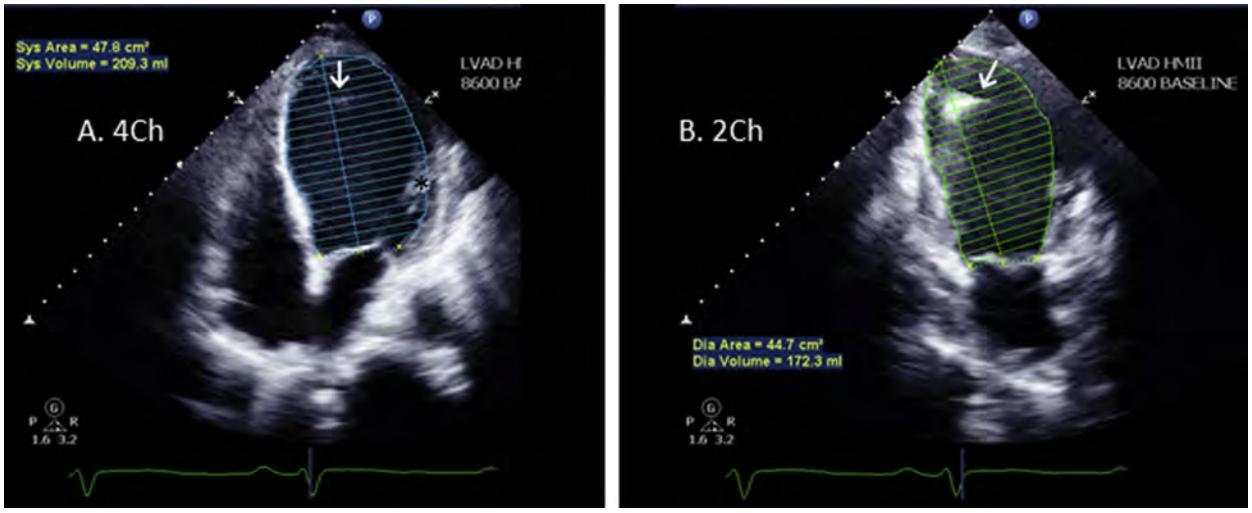


Figure 16 LVEDV, as measured by Simpson's bi-plane method of disks, is preferred for LV size assessment when possible. Simpson's single-plane LVEDV method (using the best/least-foreshortened **(A)** 4-chamber [4Ch] *or* **(B)** 2-chamber [2Ch] view) may suffice for LV size assessment and may be superior to linear measurements (eg, Figure 15). The inflow cannula (*arrow*) and anterolateral papillary muscle (*) are excluded from the endocardial tracing. *Note*: In view B, aneurysmal remodeling of the LV apex (relative to the LV base), which would cause underestimation of LV size by parasternal long-axis-view linear measurements (eg, Figures 15A,B). See also Videos 21 and 22.

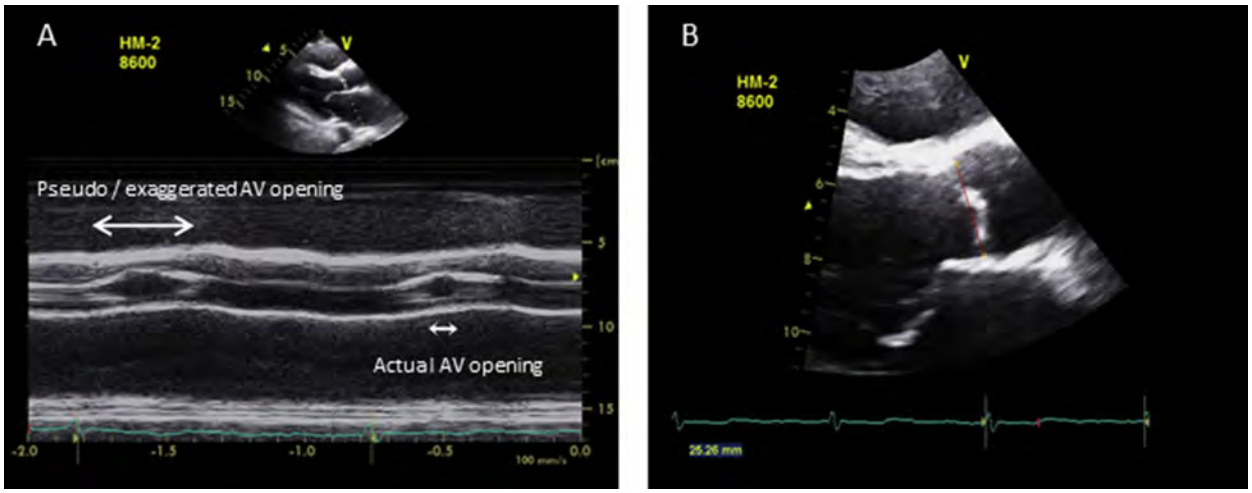


Figure 17 An exaggerated or "false" AV opening duration, as assessed by M-mode, should be suspected when the aortic cusp opening shape is fusiform **(A)**. Although the apparent M-mode AV opening duration in this case appeared to be >200 ms (*arrows*), there was, in fact, little or no AV opening. **(B)** This error was due to several factors, including the semilunar shape of the AV cusps, placement of the interrogating cursor to the left of the cusp closure line (view B: *red line*), and translational motion of the aortic root (see moving image). This pitfall could have negative implications when the examiner relies solely on M-mode for selecting the AV closing speed during an LVAD optimization protocol. M-mode should not be used in isolation. False M-mode AV opening can be identified by correlating M-mode findings with the 2D image; and color M-mode (in the presence of AR) to validate the extent of AV opening. See also Video 23.

in the event of undiagnosed aortic root thrombus or the potential liberation of peripheral or internal pump thrombi, particularly at lower pump speeds. In general, strong consideration should be given to deferring speed-change exams if baseline imaging shows a possible intracardiac or aortic root thrombus. An experienced and knowledgeable member of the MCS team should be immediately available to solve potential problems and recognize key safety endpoints (discussed below) before an optimization or problem-focused echo exam is initiated. In the case of an optimization exam, unless the supervising MCS medical staff member or an experienced echocardiography medical staff member is actively supervising the exam, it is necessary for the ordering HF team to prospectively indicate what speeds should be tested, what echo parameters should be measured at each speed, what defines the "optimal" LVAD speed for that particular patient, and what the LVAD speed should be at the conclusion of the study (eg, the "optimal" speed or the initial baseline LVAD speed setting). A structured ordering template may assist with this process, and a representative template is shown in Table 3, which also outlines reasons to stop a speed-change (ramp) test. These reasons include (1) completion of the test; (2) a suction event (at higher speeds); (3) new symptoms—including, but not limited to—palpitations, dizziness, chest pain, shortness of breath, or headache, which may be related to hypoperfusion or hypotension; (4) hypertension; (5) and cannula flow reversal. Because increasing the pump speed can markedly increase

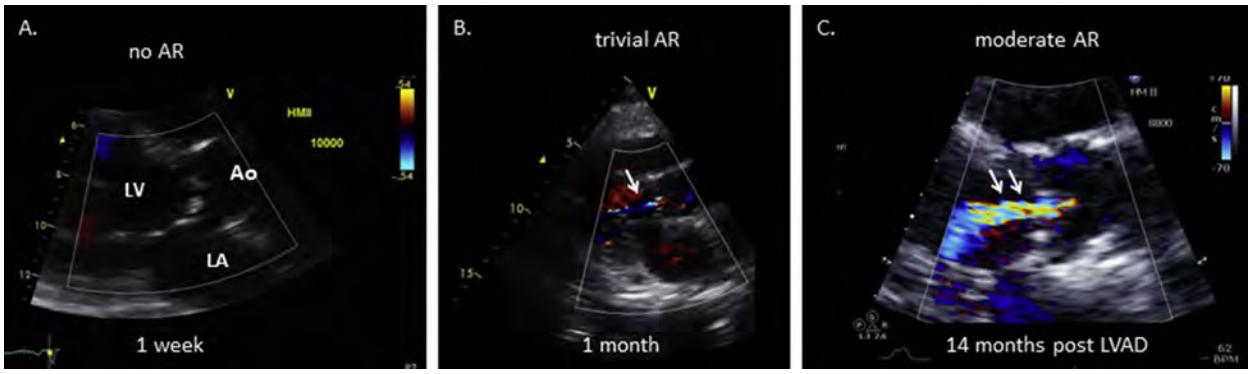


Figure 18 De novo AR after LVAD implantation. This condition progressed from no AR on the baseline surveillance study exam at 1 week **(A)** to trivial AR (*arrow*) at 1 month **(B)**, to at least moderate AR (arrows, VC >3 mm) at 14 months **(C)**. All images are transthoracic parasternal long-axis views with color Doppler. In this patient, the AV never opened at any pump speed during the LVAD support period; aortic root thrombus was not present. See also Videos 24-26.

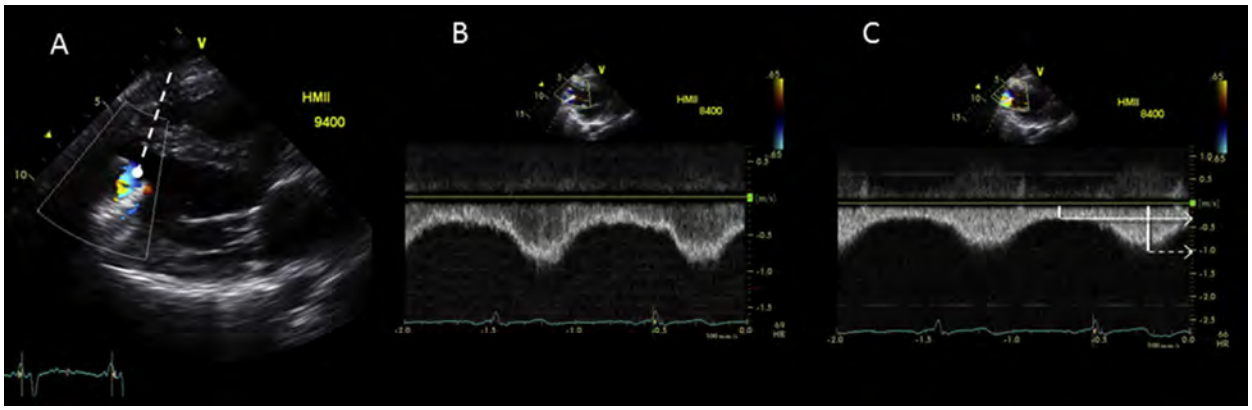


Figure 19 Normal HM-II inflow-cannula flow, which, in this case, required the use of a modified parasternal long-axis view for coaxial alignment of the sampling volume. **(A)** Color-flow Doppler with pulsed Doppler sample volume at the inflow cannula's inflow zone. See also Video 27. The color-flow and pulsed spectral Doppler profiles **(B)** are consistent with laminar flow. **(C)** Peak systolic velocity = 1.0 m/s (*dotted arrow*) and nadir diastolic velocity = .3 m/s (*solid arrow*) as assessed by continuous-wave spectral Doppler. (Normal peak inflow velocities are typically <2 m/s).

the mean arterial BP, the BP should be rechecked at higher pump speed settings.[77] At lower pump speeds, particularly in the presence of elevated mean arterial pressure (hypertension), outflow-graft flow reversal can occur. The inflow-cannula color and spectral Doppler exam should be repeated at each new pump speed in order to establish the following: (1) expected progressive decrease in the peak systolic and nadir diastolic flow-velocity ratio with increasing pump speeds (Figure 24); (2) possible flow reversal (at lower speeds as mentioned or with pump arrest [Figure 26]), (3) inflow-cannula flow obstruction (Figures 27 and 28: suction event) and (4) diminished or absent change in the flow-velocity profile at varying speeds in the case of internal pump thrombosis or other mechanical obstruction or significant AR (Figure 15H). Both pulsed and CW spectral Doppler interrogation of the inflow cannula is useful at the baseline speed and at each new higher pump speed in order to screen for inflow obstruction. However, Doppler evaluation of the outflow graft, although useful at the baseline speed (when possible), may be optional at subsequent pump speeds (eg, during optimization or problem-focused exams, discussed below) unless the baseline values are abnormal or the information might be otherwise relevant for clinical problem solving. The outflow-graft Doppler exam is of greater importance for HVAD patients due to an inability to measure HVAD inflow-cannula velocities with Doppler.

LVAD Optimization Echocardiography

The LVAD optimization echo exam (with speed changes) is generally performed in asymptomatic or minimally symptomatic patients with no device alarms or other clinical indicators of abnormal LVAD or cardiac function. LVAD optimization echocardiography consists of routine comprehensive TTE at the baseline speed setting (Appendix E), followed by stepwise incremental adjustments to the LVAD speed (in rpm), with collection of prespecified echocardiographic parameters (Appendix F) at each new speed, that reflects LVAD and/or native LV function (eg, LVIDd, interventricular septal position, AV-opening frequency/duration, TR and/or MR severity).[49,70,77]

HM-II Speeds. The minimum and maximum speed settings for the HM-II LVAD are 6,000 and 15,000 rpm, respectively. The speed can be changed in 200-rpm increments. Although patient-dependent, the recommended range of typical operating speeds is 8800-10,000 rpm.[78] With the HM-II pump, speed changes for optimizing device function are usually made in small increments of 200-400 rpm.

HVAD Speeds. The minimum and maximum speed settings for the HVAD are 1,800 and 4,000 rpm, respectively. The speed can be changed in 20-rpm increments. The recommended range of typical

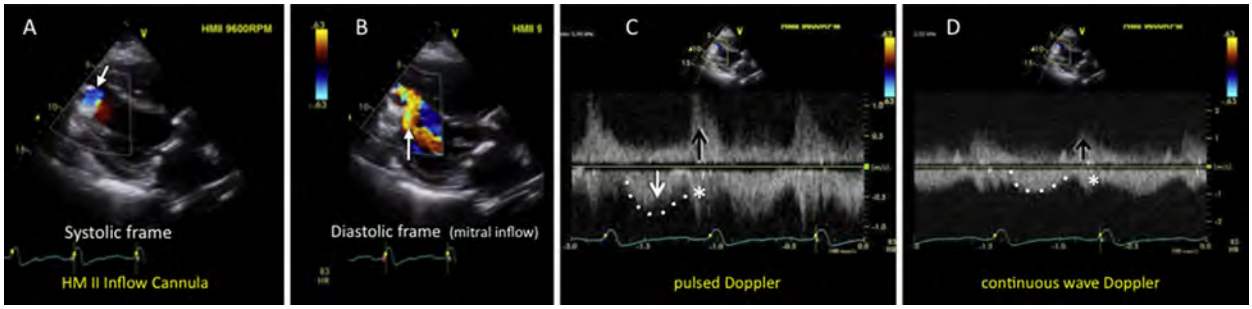


Figure 20 **(A)** HM-II inflow cannula, systolic frame, showing normal color Doppler inflow (*blue, downward arrow*). **(B)** HM-II inflow cannula, diastolic frame, with color Doppler showing prominent diastolic mitral inflow (*orange, upward arrow*) in a patient with a previous mitral annuloplasty repair. See also Video 28. **(C)** Pulsed Doppler examination of the inflow cannula shows normal systolic inflow (*dotted line*). However, prominent bidirectional diastolic velocities are present due to mitral inflow (*arrow*) and interaction between the cannula and the adjacent interventricular septum (*) (see moving image). **(D)** Continuous-wave Doppler shows a similar pattern and rules out obstruction. *Note: Hybrid/contaminated inflow-cannula Doppler signals may also be observed with AR jets. These types of low-velocity, normal-variant, contaminated inflow-cannula spectral Doppler patterns can be explained with color Doppler and should not be confused with higher-velocity signals (typically >2 m/sec), which could signify inflow obstruction. Nonetheless, the pure continuous diastolic inflow, as shown in Figure 19, is not seen, and the diastolic nadir velocity cannot be reported*.

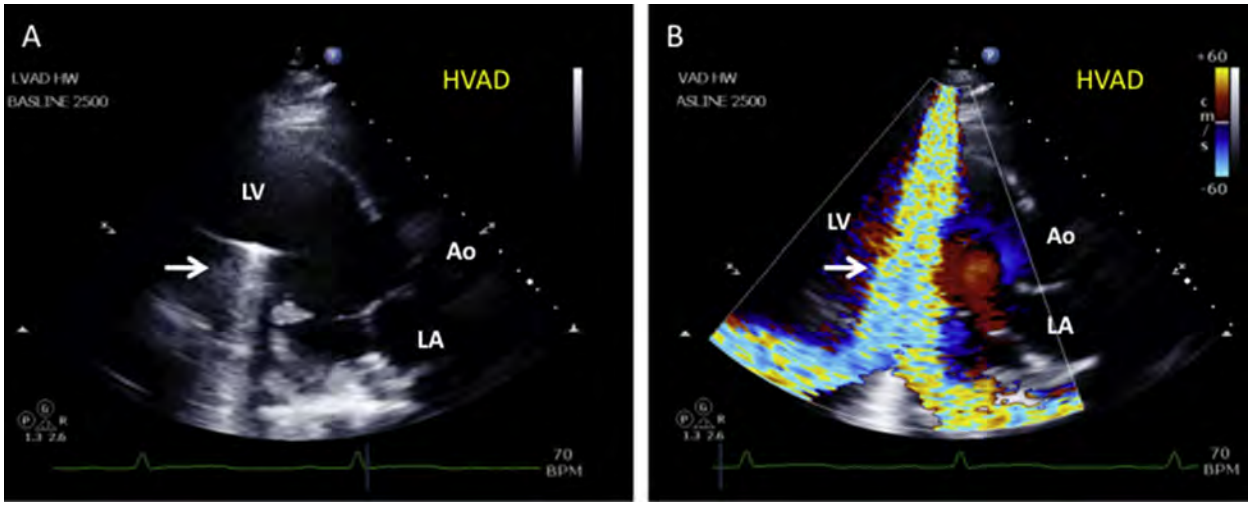


Figure 21 **(A)** HVAD inflow-cannula artifact (*arrow*), 2D parasternal long-axis view, as evaluated by TTE. **(B)** Typical color-flow Doppler artifact (*arrow*) associated with the HVAD inflow cannula. This artifact also prohibits spectral Doppler interrogation of the inflow cannula (as in Figure 11B). Inflow-cannula flow must be surmised by other means (eg, outflow-graft and RVOT flow, AV opening, and LV size changes during pump-speed changes). See also Videos 29 and 30.

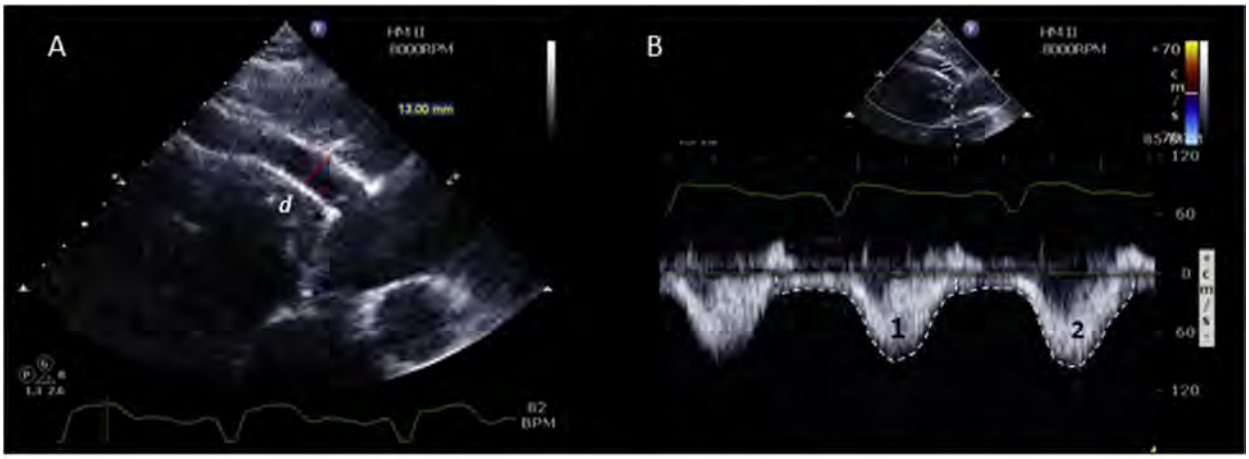
operating speeds is 2,400-3,200 rpm. With this device, speed changes for optimizing device function are usually made in small increments of 20 or 40 rpm.[53]

Some LVAD implantation centers have chosen to include an optimization (speed-change) protocol routinely with all LVAD surveillance echo exams (Figure 14). Others have chosen to include the optimization protocol only with the initial surveillance echo examination (eg, index hospitalization discharge/2 weeks postimplantation) and then only as needed when a routine surveillance echo (without speed changes) reveals a less-than-optimal LVAD speed according to predefined criteria.[63,70] It is important to note that utilization of echocardiography to optimize the LVAD speed is relatively new, and the impact of echocardiography-guided LVAD speed optimization protocols on short- and long-term clinical outcomes is currently unknown. Appendix D shows summary benchmark echocardiography parameters from three cohorts of patients from three different institutions, beginning before LVAD implantation and extending up to 12 months afterward.

Determination of the "Optimal" LVAD Speed. The definition of the optimal LVAD speed varies among implantation centers. However, there is a general consensus among centers that the optimal speed lies between "minimum" and "maximum" speeds, defined as follows:

The ***minimum speed*** is defined by **echocardiography parameters** as the speed below which the LVIDd (cm) is increased relative to baseline; the interventricular septum may be shifted rightward; MR may become more prominent; AV opening may occur or become more frequent or sustained; and estimated RA and systolic pulmonary artery pressures may increase. **Clinically**, the minimum speed is that speed below which the patient develops reduced functional capacity, congestion, and/or worsening end-organ function.

The ***maximum speed*** is defined **echocardiographically** as the speed above which the interventricular septum shifts leftward and/or impedes flow into the inflow cannula; TR may worsen due to the leftward interventricular septal shift with tricuspid valve annular



LVAD output = (outflow graft $d/2)^2$ x ∏ x outflow graft TVI x HR

- For irregular HR or variable stroke volumes, average 3-5 cycles
- Average outflow graft TVI = TVI (throughout *n* cardiac cycles) / *n*
- *Because of continuous flow, the LVAD VTI includes the area under curve for both the systolic and the diastolic periods as shown in B, in which case n = 2. (∏ ~ 3.14)*

This example: n = 2 cycles; TVI_1 = 21.2 cm, TVI_2 = 23.6 cm; HR = 82 bpm; d_{graft} = 1.3 cm
TVI avg = (21.2 + 23.6) / 2 = 44.8 / 2 = 22.4 cm
LVAD Stroke volume = $(1.3\ cm/2)^2$ x ∏ x 22.4 cm = 29.7 ml
LVAD Cardiac output = 29.7 ml x 82 bpm = 2,435 ml / min = 2.4 L/min

Note: Although potentially useful, this type of imaging may be challenging to obtain in routine practice.

Figure 22 Direct Doppler measurement of LVAD flow from the distal outflow graft, as evaluated by TTE **(A)**. See also Video 31. Flow (stroke volume and cardiac output) within the outflow graft (LVAD output) may be derived by measuring the graft's diameter (*arrow*) and the pulsed Doppler VTI at the same location, proximal to the anastomosis site **(B)**.

distortion and/or RV enlargement; the AV may cease opening; and AR (when present) is increased. Some or all of these changes above the maximal speed may constitute a "suction event," with low-flow alarms (see below).

To provide a margin of safety, implantation centers that view maximal LV unloading as paramount in HF management will define the optimal LVAD speed as being just below the maximum speed even when the AV remains closed (typically at least 400 rpm below the maximum speed for the HM-II[78] and at least 40 rpm below the maximum speed for the HVAD). Implantation centers that desire AV opening, when possible, will choose a lower "optimal" LVAD speed, at which AV opening occurs either intermittently or during every cardiac cycle, combined with other echocardiographic data to suggest clinically adequate (if not maximal) LV unloading. A subset of these centers may elect to maximize the AV-opening duration. As noted above, Appendix F provides a typical set of parameters that can be measured at each speed during an LVAD optimization exam, including LVIDd, interventricular septal position, AV-opening frequency/duration, MR severity, and/or TR severity and velocity and cannula flow velocities.

LVAD Problem-Focused Echocardiography

An LVAD problem-focused echocardiography exam should be performed whenever the HF team suspects a problem with LVAD function. The problem-focused exam is generally triggered and guided by one or more of the following indications:

1. An LVAD controller alarm.
2. New or abnormally persistent symptoms.
3. Abnormal serologic findings that suggest intravascular hemolysis or infection.
4. Follow-up testing of abnormalities detected on an echocardiogram at the baseline pump speed.
5. Other abnormal imaging data, monitored results (eg, arrhythmias, hypotension), or other clinical tests that suggest LVAD malfunction.

To maximize the efficiency and utility of a problem-focused echo exam, the HF team should provide the echo lab personnel with the study indication(s). Table 3 presents recommendations for typical exam indications and a list of appropriate LVAD exam protocols.

Regardless of the indication(s), the LVAD problem-focused echo examination begins with all the elements of an LVAD surveillance echo exam (Appendix E), performed at the baseline pump speed setting. This initial portion of the exam does not include any speed changes, and it may generally be performed by a sonographer without MCS staff members present, unless the patient's condition is unstable. Thereafter, the number of different speeds required and the incremental speed changes needed may vary, depending on the suspected problem and the observed response to a speed change in real time. Accordingly, the "speed-change" component of a problem-focused echo exam frequently requires the immediate availability of MCS team members and/or trained echo medical staff for interpreting responses to device speed changes and recognizing safety endpoints for the exam, as discussed above and summarized in Table 3. Incorporating safety endpoint considerations

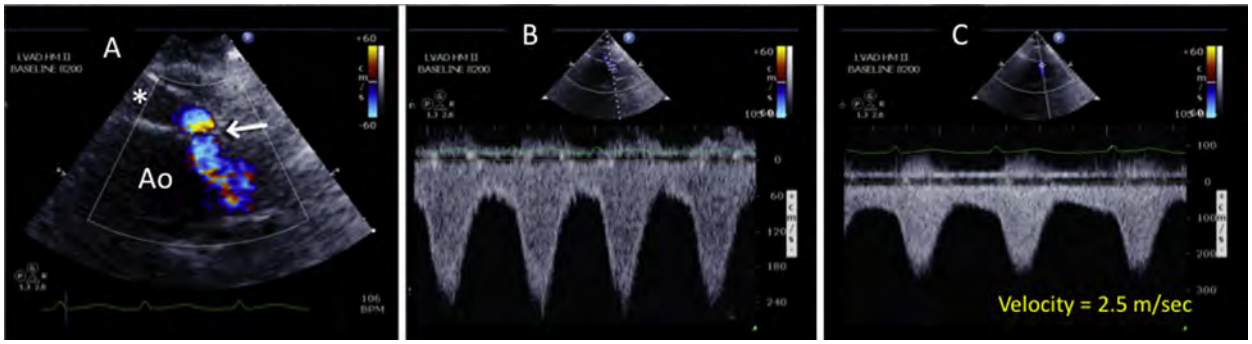


Figure 23 Mild stenosis of the LVAD outflow graft-to-ascending aorta anastomosis site, as assessed by TTE using color and spectral Doppler. **(A)** 2D image: outflow graft (*). The aliased color-Doppler signal reveals the site of anastomotic stenosis (*arrow*). See also Video 32. **(B)** Pulsed-Doppler examination of the anastomotic region shows turbulent flow and an abnormally high peak systolic velocity. **(C)** Continuous-wave Doppler reveals an abnormally high anastomotic velocity of 2.5 m/sec.

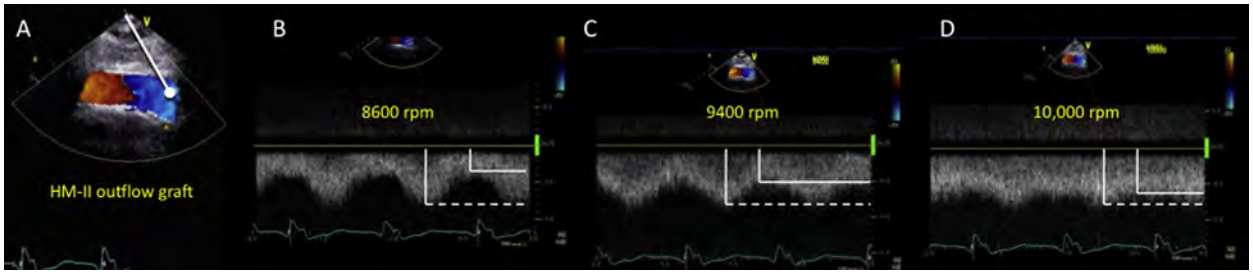


Figure 24 LVAD outflow graft, mid right parasternal window, on TTE. The flow velocity within the outflow graft should appear laminar, with a characteristic diminution of the peak systolic velocity (*dotted line*) and increase in the nadir diastolic velocity (*solid line*) as the pump speed is systematically increased (narrowing of the pulse pressure). *Note*: A similar diminution of the peak systolic velocity and increase in the nadir diastolic velocity occurs as the pump speed is systematically increased in the absence of any provoked inflow obstruction. See also Video 33.

into the conduct of the exam requires considerable knowledge and clinical judgment, and the required staff may or may not be readily available at the bedside to provide the requisite expertise. In some cases, it makes logistical sense for the sonographer to perform the initial comprehensive, baseline "single-speed" phase of the problem-focused exam as a discrete study. Then, after the results are formally interpreted and communicated to the HF team, the speed-change component may be added more strategically, pending availability of the appropriate additional team members. On the other hand, for patients in unstable condition, the situation may need to be managed more expediently, and device speed adjustments may supersede the need for a comprehensive baseline exam. In any case, the HF treatment team, sonographers, and echocardiographers should be familiar with both the clinical indications and characteristic echocardiographic findings for the most frequently encountered normal and abnormal clinical scenarios. Table 2 describes the most common abnormal echocardiography findings that may be encountered, regardless of the indication for the exam (eg, surveillance [no symptoms or alarms] vs. problem-focused). Table 4 outlines the most common LVAD alarm situations and the possible/expected associated echocardiographic findings.

Performing an LVAD Problem-Focused Exam with Speed Changes. The LVAD problem-focused echo exam with "speed changes" (also known as a "ramp study") is used to test for suspected abnormal pump function (eg, pump thrombosis)[77,79,80] to investigate device alarms, and/or to establish the significance of specific cardiac abnormalities (eg, significant AR, worsening MR, RV failure). For ramp studies, one typically uses larger incremental changes in pump speeds than are used for an LVAD optimization protocol associated with a surveillance exam (noted above). "Ramp-up" LVAD problem-focused echo protocols have been designed specifically to test for internal pump thrombosis.[77,79,80] Ramp protocols may be used to assess the clinical significance of other problems, such as suspected RV dysfunction, pericardial effusion, or AR, and for problem solving in the setting of device alarms (outlined below). The following important parameters should be evaluated at each pump speed (see Appendix F): LVIDd; RVOT VTI (for RVOT stroke volume and cardiac output); degree of AV opening; characteristics of the inflow cannula (and the outflow graft when possible), as evaluated by spectral Doppler; degree of AR and MR; MV inflow parameters, as assessed by standard Doppler; interventricular and interatrial septal position; degree of TR; and estimated RV systolic pressure. Reasons to stop a speed-change (ramp) test are outlined in the discussion above and are listed in Appendix G.

KEY POINTS

- Speed-change echocardiography may be added to a surveillance exam (if an optimization protocol is in place) or used in the context of a problem-focused or recovery exam.

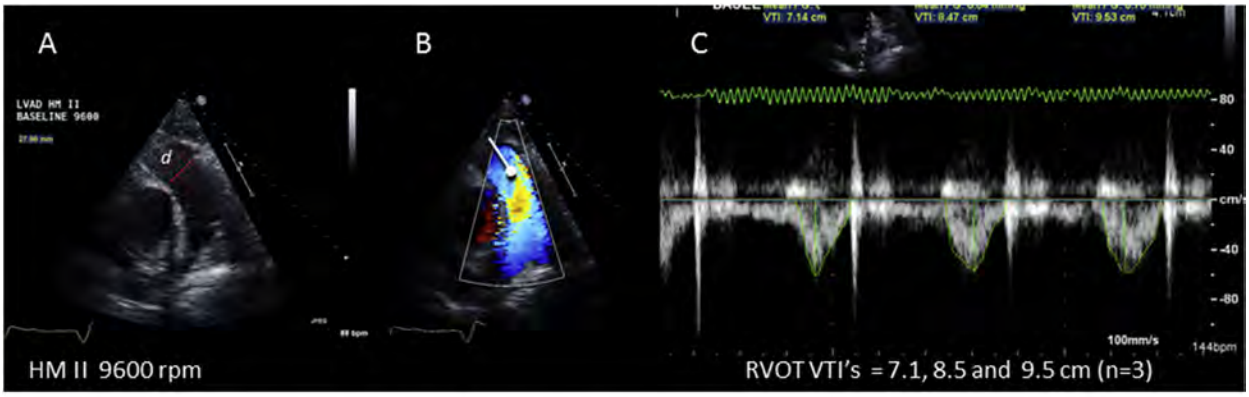


Figure 25 The total cardiac output (combined LVAD flow output and native LVOT flow output [if any]) is the same as the RVOT cardiac output. The RVOT cardiac output is measured by using standard imaging techniques including **(A)** measurement of the RVOT (pulmonary annulus) diameter (*d*). Color-flow **(B)** and spectral Doppler **(C)** studies are performed to rule out significant pulmonary regurgitation and to measure the RVOT VTI. *Note*: In the case shown above, the RVOT VTI is low (7-9 cm) at a relatively high HM-II pump speed of 9600; this was consistent with a low cardiac output, which was due to an obstructed (kinked) outflow graft. It may be useful to average 3 to 5 VTIs, depending on their variability.

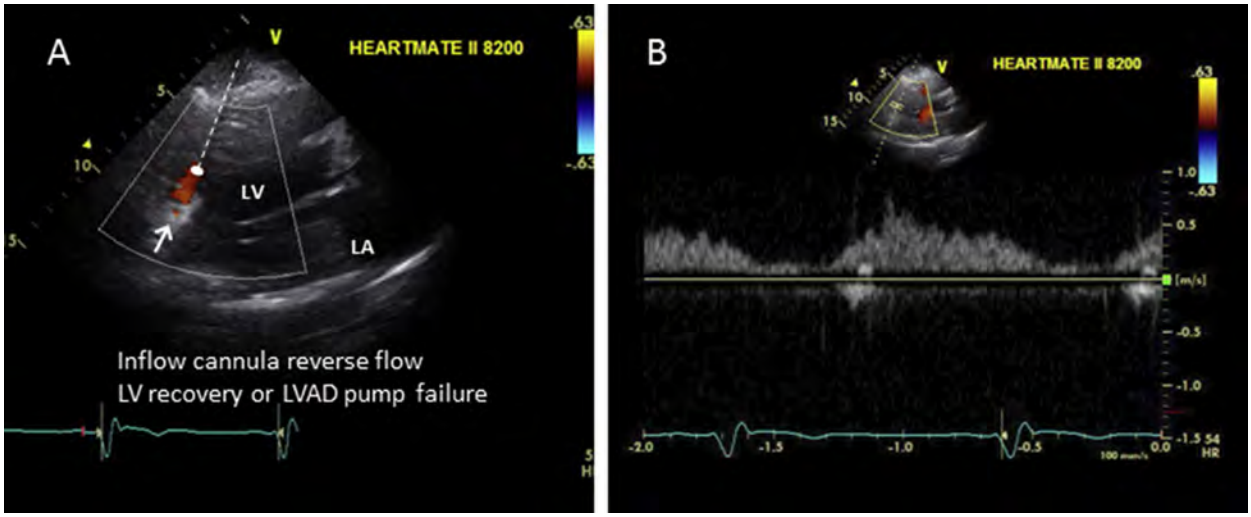


Figure 26 TTE, in the modified parasternal long-axis view, shows HM-II inflow-cannula diastolic flow reversal in a normally functioning LVAD at a relatively low pump speed (8200 rpm) in a patient with significant LV recovery (see moving image). **(A)** Color-flow Doppler image. The inflow cannula is denoted by an *arrow*. See also Video 34. **(B)** Pulsed spectral Doppler image of the inflow cannula shows reduced systolic forward flow but pandiastolic regurgitant flow (aorta to left ventricle) due to improved diastolic recoil. *Note*: A similar Doppler pattern is seen with LVAD pump arrest, although such arrest is associated with symptoms and echocardiographic signs of HF.

- Speed-change echocardiography should generally occur under the supervision of an experienced MCS medical staff member.
- A current BP recording (as previously described) should be documented at baseline and repeated, when indicated, after pump-speed changes (particularly when the speed is increased).
- Speed-change echocardiography can precipitate an embolic event and should be performed only after confirming the patient's anticoagulation status and after excluding an intracardiac/aortic root thrombus on baseline imaging.
- An institution's speed-change echocardiography protocols should specify the speeds to be tested, echocardiography parameters to be measured, definition of "optimal" LVAD speed, reasons for early termination, and desired LVAD speed settings after study completion.
- Typically, a comprehensive exam is performed at the baseline speed.
- Subsequent imaging at other pump speeds can be tailored to the indication for the exam.
- Doppler: At a minimum, speed-change echocardiography should include interrogation of the inflow cannula by pulsed-wave and CW Doppler to screen for the development of obstruction at higher pump speeds (which is possible for the HM-II but not possible for the HVAD).
- Color-flow and spectral Doppler at each new speed to assess the degree of AR, MR, TR, and RVOT flow from the parasternal view (and other available

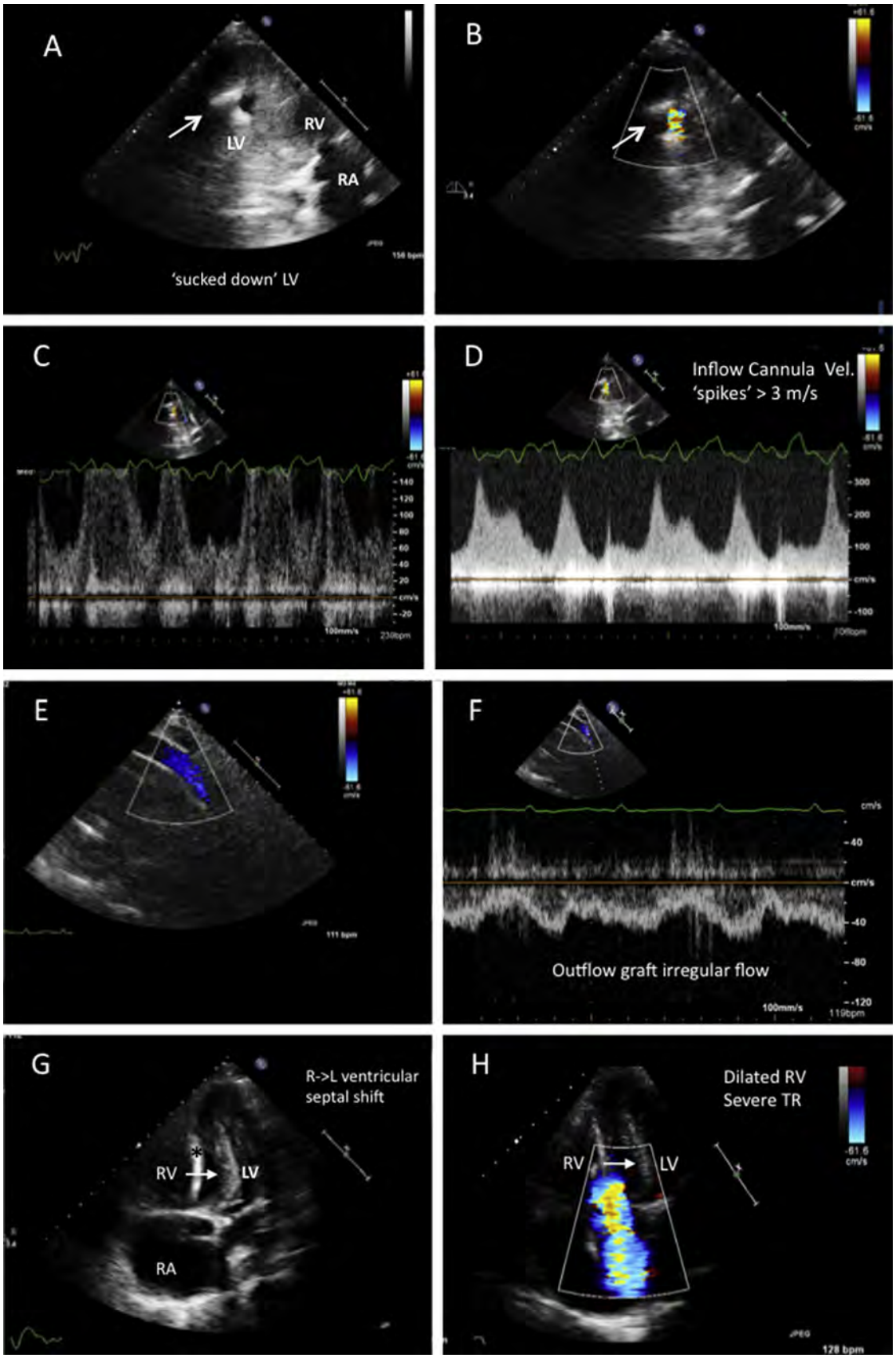


Figure 27 Suction event at a relatively low pump speed (HM-II, 8200 rpm) consistent with severe RV failure. (Because this condition was refractory to medical management, the patient received an RVAD after this exam). **(A)** Modified parasternal RV inflow-tract view. The tiny LV cavity is ''sucked down'' around the inflow cannula (*arrow*), and the ventricular septum is bowed towards the left. See also

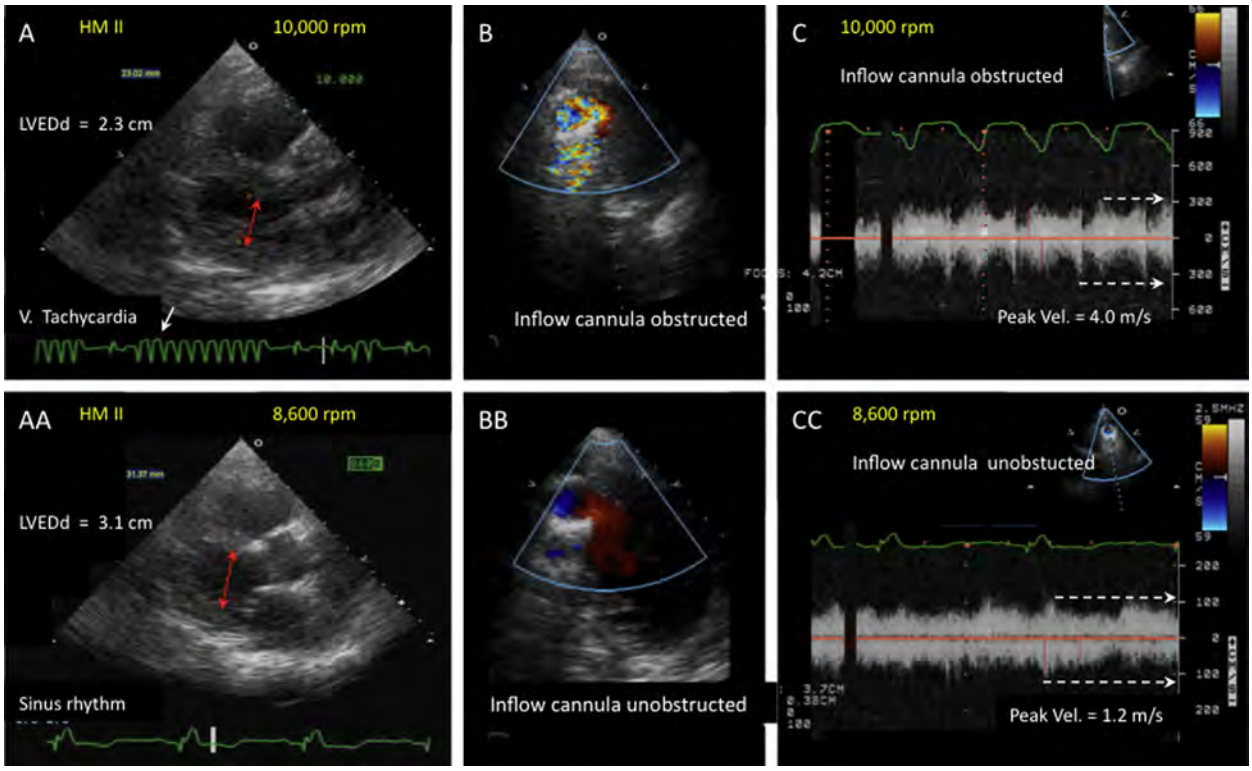


Figure 28 Mechanical ventricular tachycardia due to a suction event at a high pump speed (10,000 rpm), due to new hypovolemia resulting from a gastrointestinal illness. **(A)** Small LV chamber size (LVEDd = 2.3 cm, red arrows), with frequent nonsustained ventricular tachycardia (*white arrows*). See also Video 39. **(B)** Turbulent, aliased inflow-cannula inflow, as assessed by color Doppler. See also Video 40 and 41. **(C)** Complex, "spiky," high inflow-cannula inflow velocities up to 4 m/s on continuous-wave Doppler examination. (**AA)** Reducing the pump speed (to 8600 rpm) immediately increased the LVEDd (to 3.1 cm, *red arrows*) and eliminated the ventricular tachycardia (ie, reduced mechanical contact between the ventricular septum and the inflow cannula). Normal low-velocity inflow-cannula flow is observed on color-flow **(BB)** and continuous-wave Doppler (see also Video 42) (**CC**) at the reduced pump speed. The LV size remained small (3.1 cm) because of the hypovolemia, which later resolved. *Note*: Mechanical ventricular tachycardia may also be associated with excessive inflow-cannula angulation towards the septum or other endocardial surfaces after sternal closure, particularly at increased pump speeds.

windows) can be useful, particularly if the patient is symptomatic or abnormalities are detected on the baseline study.

- Outflow-graft Doppler (possible for both the HM-II and HVAD) should be attempted at the baseline speed and at other speeds if the patient is symptomatic or pump malfunction is suspected.
- At a minimum, imaging of AV opening (M-mode), inflow-cannula position, LV and RV size, and atrial and ventricular septal positions at each new speed may be useful, depending on the reason for the exam.
- Although the definition of the "optimal" LVAD speed varies among implantation centers, minimum and maximum LVAD speeds are invariably defined by echocardiographic parameters.

Echocardiographic Assessment of Abnormal LVAD Alarms

This section outlines the types of abnormal controller alarms, their differential diagnoses, and the extent to which a problem-focused echocardiogram can validate and/or explain the alarm's cause. The LVAD surveillance and problem-focused echo exams outlined above can frequently detect early abnormalities before controller alarms are triggered, providing a means for preemptive management decisions. On the other hand, LVAD controller alarms may be triggered with or without patient symptoms or other abnormal clinical findings. In any case, audible controller alarms will alert patients or caregivers to seek medical attention. Sonographers and echocardiographers should have some familiarity with the different alarm types and the LVAD controller parameters in order to acquire the appropriate echocardiographic information.

Speed denotes the revolutions per minute (rpm) of the impeller. The pump speed is adjusted via the device controller. As noted above, the HM-II LVAD is capable of 6,000-15,000 rpm (typical

Video 35. **(B)** Aliased color-flow Doppler image of the inflow cannula. **(C)** Aliased high-velocity pulsed spectral Doppler image of the inflow cannula. See also Video 36. **(D)** Continuous-wave spectral Doppler examination of the inflow cannula shows irregular flow, with systolic velocity "spikes" of up to 3.5 m/sec during tachycardia (HR = 154 bpm). **(E)** Right parasternal TTE view of the outflow graft shows low-velocity laminar flow, as evaluated by color Doppler. **(F)** Pulsed Doppler of the outflow graft, shows an irregular pattern low-velocity flow, consistent with variable degrees of severe inflow-cannula obstruction. **(G)** Apical 4-chamber view shows severely dilated right-sided chambers, a tiny LV cavity, and right-to-left bowing of the interventricular septum (*arrows*), with associated severe TR on color- flow Doppler **(H)**. See also Videos 37 and 38. The asterisk denotes a pacing lead.

Table 4a LVAD Low-flow alarm differential and echocardiographic findings

VAD Alarm Findings	HM-II*: PI decrease PI event HVAD Suction display‖	HM-II*: PI decrease PI event Low-flow alarm Flow display "−−−" HVAD: Low-flow display Suction display‖	HM-II* PI decrease PI event Low-flow alarm Flow display "−−−" HVAD: Low-flow display Suction display‖	HM-II* PI decrease PI Event Low-flow alarm Flow display"−−−" HVAD Low-flow display Suction display‖	HM-II*: Increase PI#	HM-II*: Decrease PI PI event Low-flow alarm Flow display"−−−;" HVAD: Low-flow display Suction display‖	HM-II*: Decrease PI PI event Low-flow alarm Flow display "−−−" HVAD: Low-flow display Suction display‖
Clinical Diagnosis	LVAD suction event†	Hypovolemia	RV failure	Tamponade	Malignant hypertension	Inflow thrombus or outflow-graft kinking/obstruction	Arrhythmias
Possible Echo Findings‡	LV size: decrease RV size: depends on cause Interatrial septal shift: depends on cause† Interventricular septal shift: depends on cause† AV opening: depends on cause† MV regurgitation: depends on cause† TV regurgitation: depends on cause† RAP estimate§: depends on cause† Other: Inflow cannula abutting endocardium and position "off-axis"# Increased inflow-cannula peak velocity with partial obstruction as cause¶ Ventricular ectopy or dysrhythmia on ECG gating	LV size: decrease RV size: smaller or no change Interatrial septal shift: no change Interventricular septal shift: no change AV opening: may decrease MV regurgitation: possible decrease TV regurgitation: possible decrease RAP estimate§: decrease Other:	LV size: decrease RV size: increase Interatrial septal shift: towards left Interventricular septal shift: towards left AV opening: decrease MV regurgitation: no change TV regurgitation: increase RAP estimate§: increase Other:	LV size: decrease RV size: decrease Interatrial septal shift: no change Interventricular septal shift: no change AV opening: no change MV regurgitation: no change TV regurgitation: may increase RAP estimate§: increase Other: Compressed left and/or right atrium Pericardial effusion	LV size: increase RV size: no change Interatrial septal shift: no change Interventricular septal shift: no change AV opening: decrease MV regurgitation: increase TV regurgitation: no change RAP estimate§: no change Other: Increased outflow-cannula peak systolic velocity Relative increase in estimated left sided ventricular filling and pulmonary pressure	LV size: increase RV size: no change Interatrial septal shift: no change Interventricular septal shift: no change AV opening: increase MV regurgitation: increase TV regurgitation: no change RAP estimate§: increase Other: Elevated peak outflow-cannula velocity >2 m/s with partial obstruction¶ Blunted change in the following parameters with pump-speed augmentation: LVEDd reduction RVOT VTI increase MV DT increase AV opening reduction	LV size: no change RV size: may increase Interatrial septal shift: may shift left with RV failure Interventricular septal shift: typically no change AV opening: may decrease MV regurgitation: may increase TV regurgitation: may increase RAP estimate§: may increase Other: LVAD suction-event findings may be seen

AV, aortic valve; *DT,* deceleration time; *ECG,* electrocardiography; *HM-II*, HeartMate II left ventricular assist device; *HVAD,* HeartWare ventricular assist device; *LV,* left ventricular; *LVAD,* left ventricular assist device; *LVEDd,* left ventricular end-diastolic diameter; *MR,* mitral regurgitation; *MV,* mitral valve; *PI,* pulsatility index; *RAP,* right atrial pressure; *RV,* right ventricular; *RVOT,* right ventricular outflow tract; *TV,* tricuspid valve; *VAD,* ventricular assist device; *VTI*, velocity time integral.

*HeartMate (HM)-II feature. PI = Pulsatility index, which is the left ventricle's pulsatile contribution to the pump; a PI event occurs when there is a 45% + or – change from the previous 15-second running average.

†An LVAD suction event can be seen with hypovolemia, RV failure, and tamponade and may be associated with arrhythmias (atrial and/or ventricular) and/or inflow cannula malposition.

‡Changes *may* be seen and are typically relative to individual benchmark data obtained from previous echo parameters at a similar LVAD pump speed.

§Based on IVC size and response to inspiration and hepatic vein flow (diastolic predominance or systolic flow reversal).

‖HVAD feature for suction event.

¶May observe diminished peak inflow and/or outflow velocity with complete obstruction (very rare).

#Variable power/flow and PI changes can be seen, depending on the severity of hypertension.

Table 4b LVAD high-flow (high-power) alarm differential and echocardiographic findings

VAD Alarm Findings	HM-II* Power >10 watts Flow display "+++" Decreased PI PI event HVAD Alarm display high-watt§	HM-II* Decreased PI (or constant) PI event	HM-II* PI event HVAD Alarm display high-watt§
Clinical Diagnosis	Rotor/bearing thrombosis with pump malfunction†	Sepsis syndrome or medication vasodilation effect	Significant AR
Possible Echo Findings‡	LV size: increase RV size: no change Interatrial septal shift: no change or rightward if elevated LAP Interventricular septal shift: no change AV opening: increase MV regurgitation: increase TV regurgitation: typically no change RAP estimate‖: may increase due to left-sided HF Other: Matched left and right ventricular outflow stroke volume Increase in estimated left-sided ventricular filling and pulmonary pressure Blunted change in the following parameters with pump-speed augmentation: LVEDd reduction RVOT VTI increase MV Deceleration time increase AV opening time reduction Inflow-cannula position "off-axis"¶ Increase in the inflow cannula or outflow cannula systolic-to-diastolic peak velocity ratio	LV size: no change RV size: no change Interatrial septal shift: no change Interventricular septal shift: no change AV opening: increase MV regurgitation: no change or decrease TV regurgitation: no change RAP estimate‖: no change Other:	LV size: increase RV size: no change Interatrial septal shift: no change or rightward if elevated LAP Interventricular septal shift: no change AV opening: typically none MV regurgitation: no change or increase TV regurgitation: typically no change RAP estimate‖: may increase due to left-sided HF Other: Color-Doppler signs of AR throughout cardiac diastole and systole Typically moderate or greater severity characterized by: Vena contracta width ≥0.3 cm or Jet width/LVOT width ≥ 46% Decrease in RVOT stroke volume Increase in systolic pulmonary artery pressure

AR, Aortic regurgitation; *AV,* aortic valve; *HM-II*, HeartMate II left ventricular assist device; *HVAD,* HeartWare ventricular assist device; *LAP,* left atrial pressure; *LV,* left ventricular; *LVAD,* left ventricular assist device; *LVEDd,* left ventricular end-diastolic dimension; *LVOT,* left ventricular outflow tract; *MV,* mitral valve; *PI,* pulsatility index; *RAP,* right atrial pressure; *RV,* right ventricular; *RVF,* right ventricular failure; *RVOT,* right ventricular outflow tract; *TV,* tricuspid valve; *VAD,* ventricular assist device; *VTI*, velocity time integral.

*HeartMate (HM)-II feature: PI = pulsatility index, which is the left ventricle's pulsatile contribution to the pump; a PI event occurs when there is a 45% + or – change from the previous 15-second running average.

†Diagnosis is suspected if associated with significant hemolysis and other signs (see text) and may be confirmed by visual inspection if the pump is exchanged.

‡Changes may be significant relative to normal LVAD benchmarks or individual benchmark data obtained from previous echo parameters at a similar LVAD pump speed.

§HVAD feature: alarm display with potential causes provided.

‖Based on inferior vena cava size and response to inspiration and hepatic vein flow (diastolic predominance or systolic flow reversal).

¶"Off-axis" relative to normal direction of inflow cannula directed towards the mitral valve.

clinical operating range, 8,800-10,000 rpm),[78] and the HVAD is capable of 1,800-4,000 rpm (typical clinical operating range, 2,400-3,200 rpm). The concern with lower pump speed settings is that a relative low-flow state and stagnation of blood may predispose to development of impeller thrombosis. At higher pump speeds, suction events could occur.

Power is a direct measurement of pump motor voltage and current and generally varies directly with speed (eg, higher speeds are associated with higher power). It is measured continuously and displayed on the controller panel as an average over time in watts (a typical value is <10 W). A "***power spike***" refers to an increase in power without an increase in speed and may indicate a mechanical obstruction. For both the HM-II and the HVAD, recurring power spike values that differ from baseline values by ≥2 W are concerning, because they may indicate mechanical obstruction due to impeller thrombosis.

Flow (L/min) is an estimated value that is directly related to the selected speed (rotary pump rotation in rpm) and power. In estimating flow, the HVAD also accounts for blood viscosity derived from the hematocrit. For the HVAD, a hematocrit change of more than ±5% should prompt updating of the system monitor to avoid substantial flow calculation errors, especially at lower LVAD speeds.[9,81]

Pulsatility denotes the difference between the minimum and maximum flows calculated by the device and is analogous to the difference between the trough and peak of an arterial waveform tracing. Pulsatility is directly related to residual native ventricular contractility and is inversely related to afterload. *The* ***pulsatility index (PI)*** is a parameter relevant to the HM-II controller that is tangentially related to pulsatility. The PI, also a derived value, is calculated from the highest-to-lowest power readings over a range, divided by the average power over that range. The PI corresponds to the magnitude of flow through the pump and will increase with increased preload, improved ventricular contractility, and a reduced afterload.

Alarms, in general, can be classified as either ***low-flow*** or ***high-flow/high-power.*** Pump parameter deviations and identified alarms should be placed in a clinical context (see Table 4) and validated with further testing when their etiology is not clearly apparent to the MCS team. The clinical symptoms and signs, along with the type of LVAD alarm findings, will guide the diagnosis and treatment recommendations. Readers are referred to the most recent practice guidelines to review the clinical presentations and treatment recommendations for LVAD-specific problems (ie, pump thrombosis).[4] The HM-II device's low-flow alarms may be associated with, or defined by, one or more of the following signs: the PI is decreased, a PI event is noted (a 45% +/− change from the previous 15-second running PI average), a low-flow alarm is displayed, or flow displayed as "—" is noted as the flow estimate. HVAD low-flow alarms appear as "Low Flow" or "Suction" on the controller alarm display.

KEY POINTS

- Key parameters common to most LVAD consoles are speed, power, and flow. LVAD controller alarms are typically triggered by abnormalities in one or more of these parameters.
- Knowledge of a patient's clinical status, in addition to the alarm type, can help guide echocardiographers during image acquisition (to determine the extent of the exam) and interpretation.
- For clinical problem-solving, it may be useful to divide controller alarms into either "low-flow" or "high-flow," as each of these is associated with a unique set of differential diagnoses (see Table 4a,b).
- "Low-flow" alarms can be caused by "suction events," RV failure, hypovolemia, cardiac tamponade, inflow-cannula/outflow-graft obstruction, malignant hypertension, and/or arrhythmias.
- "High-flow/high-power" alarms can be caused by pump thrombosis, systemic arterial vasodilation, significant AR, and/or recovery of native LV function. Differentiation between possible causes of alarms generally requires evaluation of both clinical and echocardiographic parameters.

Low-Flow Alarms. The differential diagnosis of low-flow alarms focuses on patient-related factors, including LVAD suction events, RV failure, hypovolemia, cardiac tamponade, apical inflow-cannula or outflow-cannula kinking or obstruction, malignant hypertension, and atrial and ventricular arrhythmias.

Suction Events.–As previously noted, LVAD suction events relate to contact of the inflow cannula and the LV endocardium, which results in reduced inflow-cannula flow and can be associated with a change in clinical status (eg, presyncope and/or palpitations from ventricular arrhythmias) and/or LVAD function. Any condition that produces LV under-filling places a patient at risk for LVAD suction events. These events can result from hypovolemia (Figure 28), RV failure (Figure 27), cardiac tamponade (Figure 29), and/or pump speed settings that are too high for the prevailing hemodynamic conditions. During suction events, the LVAD "sucks down" the LV chamber to an abnormally small size, leading to a right-to-left ventricular septal shift. Patients with a malpositioned inflow cannula may be predisposed to the development of intermittent inflow-cannula obstruction and/or ventricular arrhythmias from mechanical contact with adjacent (usually septal) endocardium (Figure 28). Monitoring for possible suction events is an important component of a ramp or speed-change protocol, as discussed above. The treatment recommendation is typically twofold: (1) decrease the pump speed and (2) identify and treat the underlying cause of the event.

RV Dysfunction.–There is a spectrum of RV dysfunction severity that can be defined clinically or by echocardiography. Right ventricular dysfunction may or may not be associated with suction events. With acceptable LVAD and RV function, the interventricular septum typically is neutrally positioned at a pump speed that can provide an adequate cardiac output by virtue of an adequate available preload from the right ventricle. In patients with advanced RV dysfunction or failure (based on a severely elevated RV end-diastolic pressure and a very low RV cardiac output) investigation of a low-flow alarm may reveal that the interventricular septum is significantly and continuously bowed towards the left ventricle. New or worsening RV dysfunction can be evaluated echocardiographically by assessing changes from the baseline exam with regard to RV size and function, inferior vena cava size and collapsibility, Doppler measures of pulmonary pressures, and color and spectral Doppler interrogation of TR severity (Figure 27).

Tamponade.–Clinically, pericardial or thoracic cavity tamponade may mimic RV failure and result in a low-flow alarm. Because the LVAD is generally the primary determinant of mitral inflow and significantly influences outflow, there may not be an exaggerated flow paradox across any valves despite increased intrapericardial pressure in cases of tamponade. Therefore, clinical suspicion of tamponade should be high if pericardial effusion or a suspected hematoma is visualized (Figure 29) in conjunction with low-flow alarms and small LV and/or RV chambers. In any of these scenarios, the RVOT cardiac output will be decreased and will fail to vary as expected with pump speed changes.

Inflow-Cannula Obstruction.–Other causes of low-flow alarms include partial or intermittent mechanical obstruction of the inflow cannula secondary to thrombosis, large vegetations, or endocardial contact (eg, suction events). On echocardiography, findings will be similar to those of primary pump dysfunction with regard to LV size, septal shift, and AV opening. However, color and spectral Doppler-derived inflow-cannula velocities may be abnormally increased, frequently with non-uniform inflow velocity patterns (Figures 27 and 28), the severity of which may vary with the degree of residual LVAD flow. The inflow-cannula spectral Doppler velocities may be elevated as blood accelerates proximal to the obstruction, whereas outflow-graft velocities may be relatively decreased and/or appear to have peak velocity variations. Two-dimensional and 3D TTE (and especially TEE) may show thrombi and vegetations obstructing cannulas or cardiac structures (eg, areas

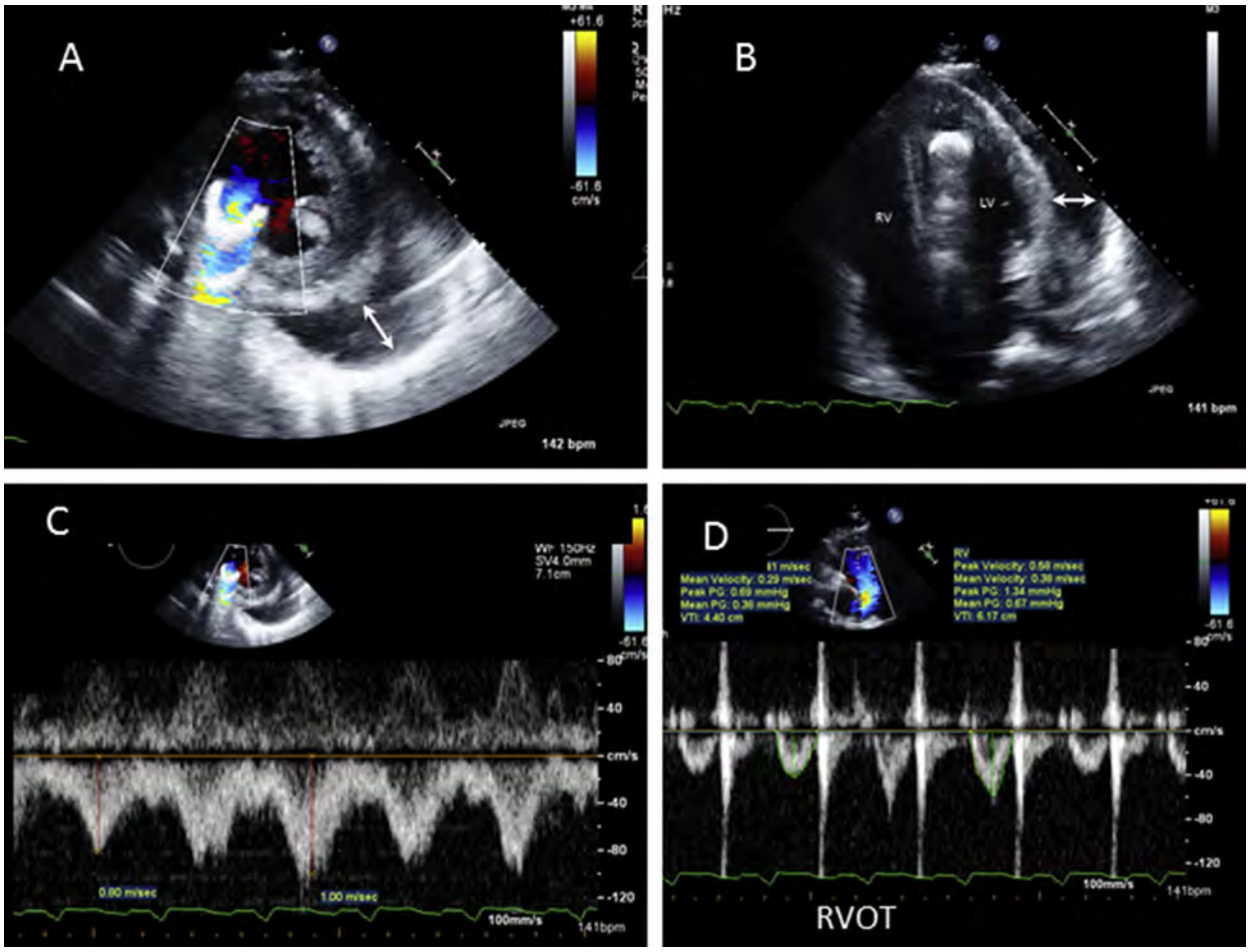


Figure 29 Tamponade after LVAD implantation was suspected because of low LVAD flow unresponsive to speed changes. A large, loculated pericardial effusion is seen posterolateral and lateral to the left ventricle (*arrows*). **(A)** parasternal short-axis view. See also Video 43. **(B)** The apical 4-chamber view ruled out signs of RV failure. See also Video 44. **(C)** Spectral Doppler examination of the inflow cannula ruled out inflow obstruction. **(D)** Pulsed Doppler evaluation of the RVOT shows very low VTIs (4-6 cm) at a high pump speed of 9000 rpm (HM-II). Although suggested in views C and D, respirophasic flow changes in flow velocities are frequently absent in LVAD recipients.

of hypertrabeculation being drawn into the inflow cannula). Inflow-cannula obstruction in the setting of a suction event is "dynamic" and can be demonstrated on a ramp study by a small LV cavity size and increased inflow-cannula velocities that normalize after reductions in pump speeds.

Mechanical Obstruction of the Outflow Graft.–Mechanical obstruction of the outflow graft (eg, resulting from kinking, malposition, external compression, or thrombosis) will function similarly to an increased afterload in opposing LVAD flow (Figures 23 and 30). Findings are similar to those of inflow-cannula obstruction, except that Doppler interrogation of the outflow graft may reveal increased or decreased velocities, depending upon the site and degree of obstruction relative to the velocity sampling site. Inflow-cannula Doppler interrogation may show normal or decreased velocities (depending upon the degree of the distal obstruction); the outflow-graft velocities may be increased if sampled in the region of an obstruction but may be normal or attenuated if sampled significantly proximal or distal to the obstruction. A ramp study may be extremely helpful by revealing attenuation of the expected intracardiac flow changes (eg, RVOT and LVOT VTIs, or conduit systolic-to-diastolic flow-velocity ratios), LV chamber size, and the degree of AV opening at varying pump speeds.

High-Flow/High-Power (or High-Watt) Alarms. The differential diagnosis for high-power alarms focusing on patient characteristics includes impeller thrombosis, systemic arterial vasodilatation (sepsis syndrome versus a medication effect), or significant continuous AR.

Pump dysfunction can be caused by malfunction of a mechanical component, but it is more commonly caused by partial thrombosis of the impeller in CF-LVADs. Any condition that impedes the impeller rotation results in increased LVAD power consumption. In the setting of partial impeller thrombosis that results in high power consumption, the displayed high flow is a calculated and results in a false estimate of high flow. Typically the actual flow is equivalent to baseline flow or is actually decreased. Clinical features associated with pump thrombosis include hemolysis, which is characterized by hemoglobinuria along with elevated lactate dehydrogenase, total bilirubin, and serum free hemoglobin levels.[82,83] On echocardiography, primary pump dysfunction secondary to thrombosis may manifest as signs of reduced LV unloading in comparison with the previous surveillance exam. Echocardiographic signs of reduced pump performance

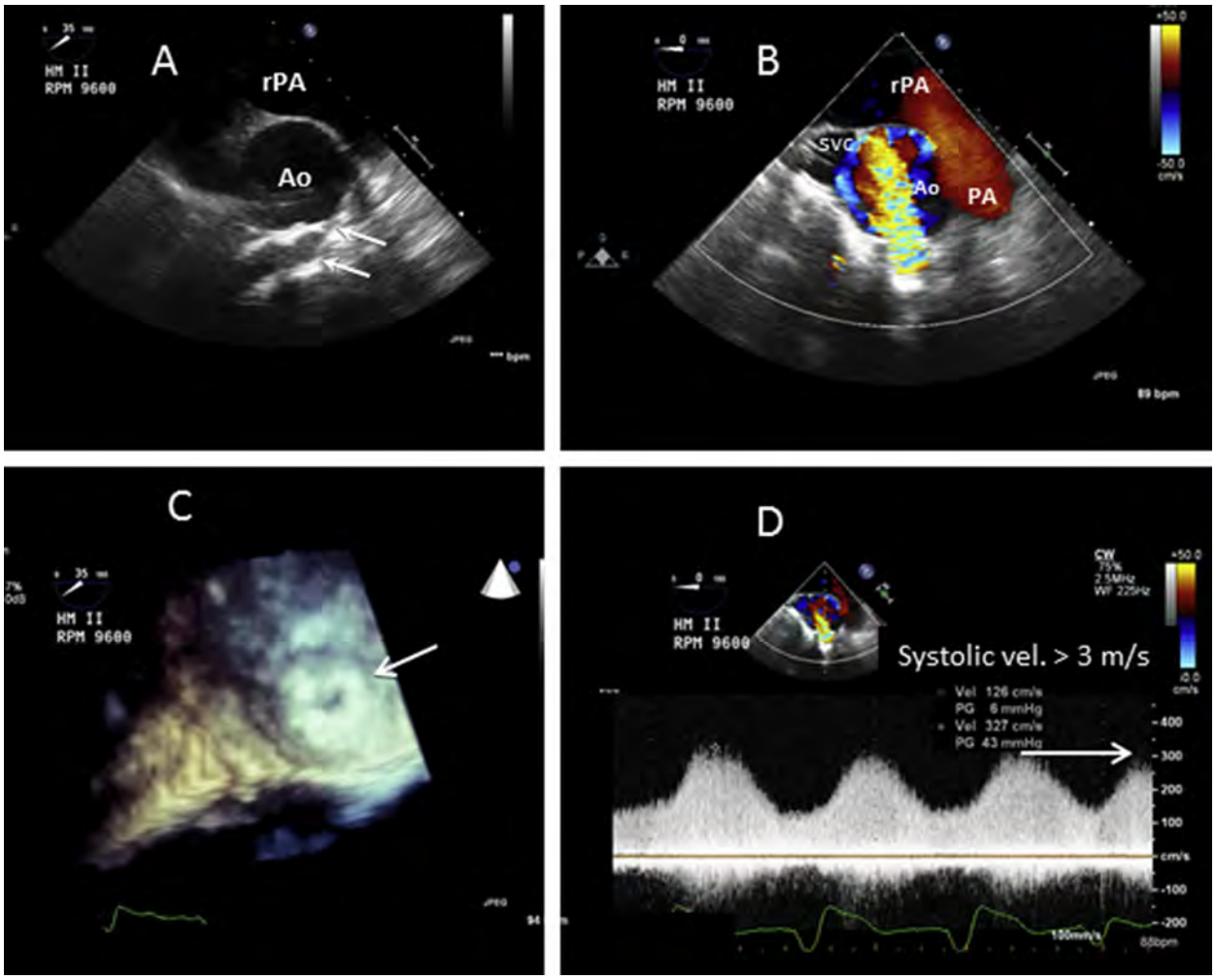


Figure 30 Progressive outflow-graft anastomotic obstruction identified more than 1 year after initiation of LVAD support. Increasing pump speeds were necessary for adequate LVAD flow, which was paradoxically associated with an increased, instead of a decreased, LV diameter at higher pump speeds without evidence of systemic hypertension. Pump alarms had not yet been activated. TEE, upper esophageal ascending aorta short-axis view: **(A)** irregular contour of the distal outflow graft ("kink" and oblique approach) with a small orifice size (*arrows*). See also Video 45. **(B)** Color-Doppler flow is turbulent/aliased (compared with the normal appearance [Figs. 6A, 13C, and 13D]). See also Video 46. **(C)** En face 3D view of the anastomosis (*arrow*) shows a small buttonhole orifice and suggests neointimal hyperplasia (compare with the normal appearance [Fig. 6D]). **(D)** Continuous-wave Doppler image with a peak systolic velocity of >3 m/s. Note that the outflow-graft anastomosis could not be visualized on TTE.

(reduced LV unloading) include an increased LVIDd, a septal shift towards the right ventricle and (depending on residual ventricular function), increased AV opening in comparison with previous findings, as defined in Table 4. In patients with serologic evidence of possible intravascular hemolysis and/or proven internal pump thrombosis, diastolic inflow-cannula and outflow-graft velocities, as measured by Doppler, are typically decreased in association with increased inflow-cannula or outflow-graft peak systolic–to–diastolic flow-velocity ratios in comparison with those seen during the patient's baseline (surveillance) exam.[80] Confirmatory evidence of coexisting pump dysfunction is provided by a subsequent speed-change or "ramp-study" phase of the LVAD problem-focused exam. Obstruction resulting from any cause (eg, internal impeller thrombosis, outflow-graft kinking, etc.) attenuates the expected changes in 2D and inflow-cannula or outflow-graft velocity at varying pump speeds. For example, when the pump speed is increased, the expected decrease in LVIDd, reduction in AV-opening frequency or AV-opening duration, prolongation in MV deceleration time, and increase in RVOT stroke volume will not occur.[77,79,80]

Significant AR may also be associated with a high estimated LVAD flow but with normal power. When added to normal mitral inflow, the aortic regurgitant volume can lead to an increased LV preload, which may result in increased native LVOT output and AV opening, with intermittent AR on color Doppler (Figures 9H,9J). Alternatively, the AR may be continuous if the contractile force is not sufficient to interrupt the regurgitant flow during systole (Figure 9C). With worsening AR, the LVIDd will progressively increase in comparison with that observed on previous surveillance exams, and there may be ventricular septal bowing towards the right ventricle. Doppler flow across the inflow cannula and outflow graft will be normal or increased due to the aorta–left ventricle–LVAD blind loop. However, the net forward cardiac output downstream from the LVAD-to-aorta anastomosis, as reflected by the RVOT VTI-derived cardiac output, will be reduced,[70,73] even though flow is markedly increased within the

Figure 31 The Berlin Heart EXCOR VAD has variable pump sizes ranging from 10 to 60 mL. Image reproduced with the permission of Berlin Heart.

LVAD circuit proximal to the outflow graft-to-aorta anastomosis (Figure 13). Mitral regurgitation may also increase due to increased LV volume and filling pressure (Table 4).

Ventricular Recovery and/or Decreased LV Afterload. The combination of increased LVAD flow and *increased power* may also be due to *ventricular recovery* or *an abnormally decreased LV afterload*. Echocardiography can distinguish between these two conditions, *particularly when the data are compared with previous surveillance findings.* Increased LV filling (associated with LV recovery) or a decreased afterload (associated with arteriolar vasodilatation resulting from sepsis or other causes and associated with decreased LV filling) will generally be reflected by *increased flow and increased power*. Ventricular recovery is characterized by serial improvements in LV systolic function (eg, an increased LVEF and a reduced LV size, accompanied by an increased AV-opening duration and improved RVOT and native LVOT cardiac outputs) at baseline and lower pump speeds. Improvement in other manifestations of HF, such as functional MR, pulmonary hypertension, and TR, would be expected. Ventricular recovery can also be associated with decreased LVAD flow due to the fact that a greater portion of the cardiac output is being pumped through the AV by the improved left ventricle. The LV chamber size and MR severity may also decrease in the setting of abnormally reduced peripheral vascular resistance (decreased LV afterload) resulting from sepsis or other causes (eg, pharmacologic agents) without LV recovery. In this circumstance, Doppler interrogation of the LVAD inflow cannula and outflow graft may show increased systolic velocities with apparent improvement in the LVEF. However, the ventricular septum may continuously bow into the left ventricle, whereas LV recovery is associated with a normal ventricular septal orientation. The RVOT VTI-derived cardiac output will be increased in comparison to previous surveillance-exam findings.

LVAD Recovery Echo Exam

A small percentage of patients recover sufficient native LV function to allow LVAD explantation. An LVAD recovery or "weaning" protocol can play a pivotal role in the complex decision-making process regarding suitability for LVAD removal. The LVAD recovery echo exam is not frequently performed outside of MCS centers. However, it may be performed more often in the context of an organized research protocol that may include site-specific variations. As with some other aspects of LVAD management, there are few outcomes data and little consensus surrounding this potentially important phase of patient care. Although a detailed standard LVAD recovery echo protocol cannot be recommended at this time, Appendix H and the following discussion of basic concepts may be useful for establishing a framework.

The LVAD recovery protocol can be considered when LVAD surveillance echocardiography suggests significant recovery of native LV function.[70] The initial phase of the LVAD recovery protocol should be the same as for any comprehensive LVAD echo exam performed at the baseline speed setting. Very low LVAD pump speeds are associated with retrograde device flow (Figure 26). After the echo exam at the baseline pump setting, gradual speed reductions are used to identify a pump speed at which there is no forward or reverse pump flow (net neutral flow). During most weaning protocols, spectral Doppler interrogation of the LVAD inflow cannula and of the outflow graft is used to determine the speed at which there is net neutral pump flow. Because of blood flow stasis within the entire LVAD system during this phase of the exam, the LVAD recovery protocol typically includes confirmation of adequate systemic anticoagulation before the exam is started. To test the patient's native LV functional reserve, an exercise test (such as a 6-minute walking test or other cardiopulmonary test) should be considered at one or more time intervals at the net neutral low pump speed.[84,85] At the conclusion of the exercise test, LV function parameters, including the LVEF, should again be assessed. Early termination of the test with restoration of the baseline LVAD speed is warranted if the patient becomes symptomatic. See Appendix H for a sample protocol.

LVADs for Pediatric and Adolescent Patients

Pediatric and adolescent patients with advanced HF have fewer MCS options than adults and until recently were treated primarily with ECMO. At this time, there are no approved intracorporeal VADs for small children. Two extracorporeal VADs, the Thoratec PediMag and the Berlin Heart EXCOR (see below), are FDA-approved for temporary and extended MCS, respectively. Currently, reports are very limited concerning the use of echocardiography for evaluating pediatric VADs, partly because so few of these patients are encountered at any one center.[86] It may be assumed that many of the same concepts of LVAD echocardiographic imaging apply to pediatric and adult patients. Furthermore, larger pediatric and adolescent patients may be candidates for MCS devices approved for use in adults. Specific details

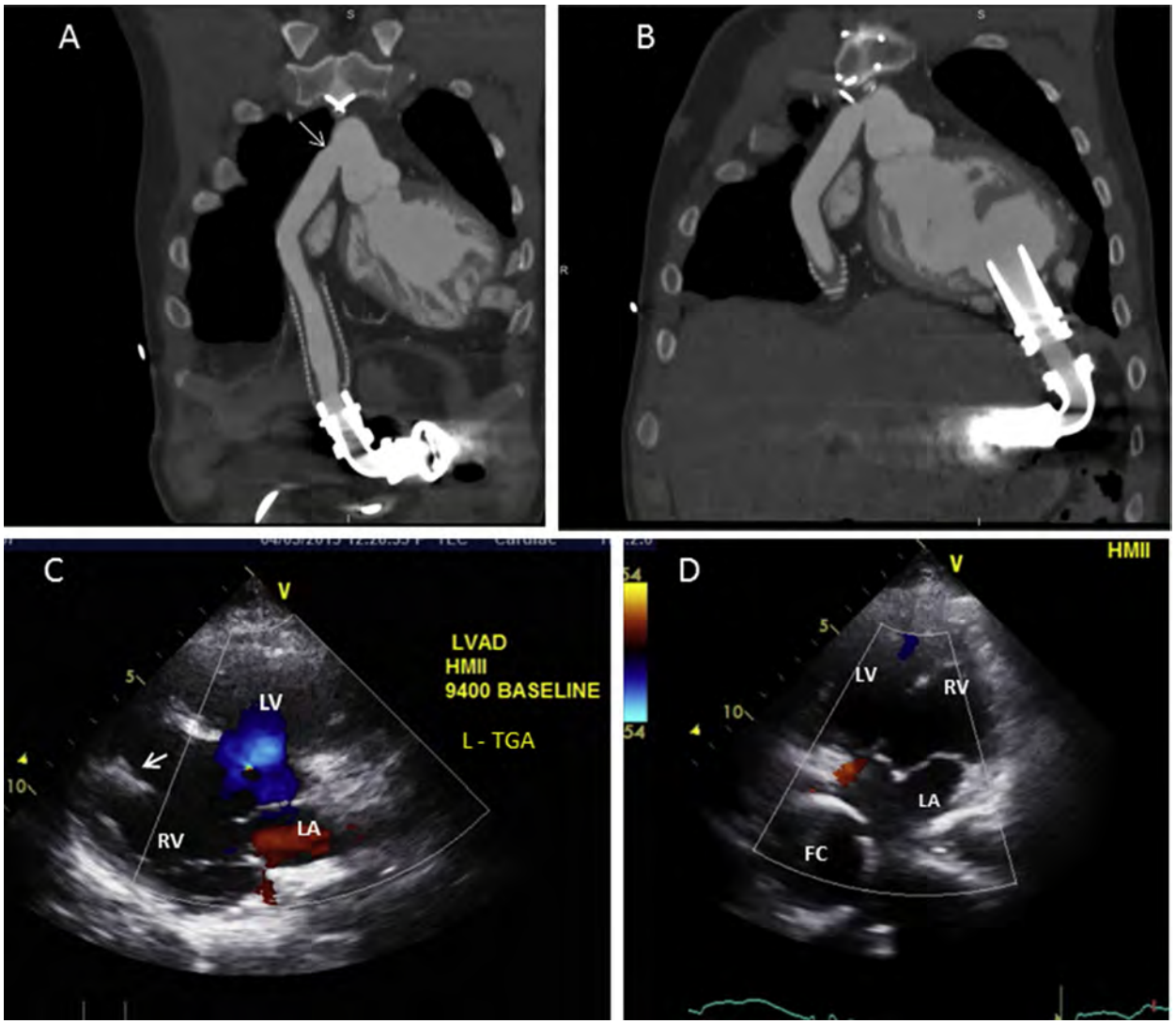


Figure 32 Complementary X-ray CT **(A, B)** and echocardiogram **(C, D)** from a 25-year-old man with single ventricle physiology: L-transposition of the great arteries (L-TGA), complete atrioventricular septal defect (AV canal defect) and subpulmonic stenosis, and a nonfenestrated Fontan conduit (placed at age 5 years). Although he initially received an HM-II LVAD for destination therapy, he eventually underwent cardiac transplantation after 2 years of VAD support (BTT conversion). **(A)** Coronal-plane CT shows a normal outflow graft, including the aortic anastomosis (*arrow*). **(B)** Near-sagittal-plane CT reveals an unobstructed inflow cannula. **(C)** Parasternal long-axis view of a nonrestrictive VSD (*blue color flow*) and inflow cannula (*arrow*) within the morphologic RV. See also Video 47. **(D)** Apical 4-chamber view showing the Fontan conduit (FC). See also Video 48.

concerning VAD suitability based on patient size are beyond the scope of this document. It should be noted that there are no benchmark normal LVAD inflow-cannula or outflow-graft flow velocities for smaller patients. In addition, smaller LV chamber sizes may result in an increased propensity for inflow-cannula obstruction and, in some cases, the need for surgical modification of the MV apparatus.

Short-Term VAD Support for Pediatric Patients. A miniaturized version of the CentriMag VAD (see Figure A-6), the **Thoratec PediMag** extracorporeal centrifugal CF blood pump (previously known as the Levitronix PediMag), is approved for short-term (acute bridge-to-recovery or bridge-to-decision) use as an LVAD, an RVAD, or a BiVAD in small children [FDA 510(k), October 2009]. The pump is driven by a bearingless, magnetically levitated impeller and can deliver flows of up to 1.5 L/min. Its echocardiographic features are expected to be similar to those of the other CF-LVADs previously discussed in this document.

Long-Term VAD Support for Pediatric Patients. The **Berlin Heart EXCOR Pediatric VAD** (Berlin Heart, Inc., The Woodlands, TX) is currently the only VAD approved for BTT therapy in infants and small children. Since this device received FDA approval in 2011, its use has grown significantly.[87] The EXCOR is an extracorporeal pneumatically driven pulsatile VAD that differs significantly from similarly designed adult devices in that it offers a wide range of graduated cannula and pump chamber sizes (10 to 60 mL) to accommodate the pediatric and adolescent population (Figure 31). In a prospective US multicenter cohort outcomes study of 204 pediatric patients, the 1-year survival rate was 75%: 64% of the patients underwent transplantation, 6% recovered and underwent device

removal, and 5% continued to undergo device support at 1 year.[87] These results represented a dramatic improvement over previously reported results of conventional management. The echocardiographic features of pulsatile pumps are characterized by inflow and outflow that is not timed with the cardiac cycle (intermittent LV assistance). In "automatic mode" (maximum support) a sensor detects passive chamber filling, which triggers ejection of blood. The device may be set to lower "fixed-rate" settings for lower levels of support. For a discussion of echocardiographic features that differ from those of CF-LVADs, please refer to Estep and coauthors.[49]

KEY POINT

- In many respects, LVAD echocardiography in pediatric and adolescent patients is similar to LVAD echocardiography in adults, but there are important methodological differences; and age-, size-, and device-specific benchmark values have not yet been established.

Other Areas of Research

Current research in echocardiography includes the potential application of many parameters of myocardial function that have not been included in the recommended protocols. Many of the traditional variables used to assess systolic and diastolic function before MCS device implantation are exquisitely preload and afterload dependent, and the ability to extrapolate their usefulness in patients with continuous mechanical LV unloading is limited at this time. Of note, patients with recurrent HF after LVAD implantation may have an increased prevalence of a lower mitral deceleration index (deceleration time/mitral E) and of rightward interatrial-septal deviation suggestive of partial LV unloading. Recently a proposed diagnostic algorithm integrating simple and standard echocardiographic parameters (ie, mitral E/A ratio, RA pressure, systolic pulmonary artery pressure, left atrial volume index, and E/e′) reliably distinguished between invasively measured normal and elevated LV filling pressures on baseline levels of LVAD support as evidence of partial LV unloading.[88] There are, however, no data to suggest that tailoring the pump speed setting to echo-derived diastolic parameters (eg, lowering the mitral inflow E velocity or prolonging the deceleration time by adjusting the pump speed) is associated with symptomatic improvement.

Newer echocardiographically derived mechanical metrics of myocardial function include myocardial displacement, velocity, deformation (strain), strain rate, twist, and dyssynchrony.[19] Mechanical indices may be assessed in longitudinal, circumferential, and radial vectors or as static information using M-mode speckle tracking echocardiography (STE), spectral Doppler, integrated backscatter, or contrast agents. Increasing use of MCS devices provides a fertile ground for further research to test the clinical utility of traditional and emerging functional metrics that may be useful for predicting a patient's clinical trajectory. Because data regarding the clinical use of advanced mechanical metrics are limited or nonexistent at this time, we suggest that the recommended basic protocols provided for routine LVAD management be used as a framework to which more advanced data collection procedures can be added in a methodical site-specific fashion.

KEY POINT

- Increasing clinical use of LVADs provides a fertile ground for testing the clinical utility of traditional and emerging functional metrics in predicting and managing a patient's clinical trajectory.

Indications for Other Imaging Methods After LVAD Implantation

One limitation of echocardiography is its inability to view the entire outflow graft. On the other hand, CCT) allows direct, complete visualization of the LVAD, including the inflow-cannula position and the entire course of the outflow graft (Figure 32). This is a robust technique for assessing CF-LVAD complications such as RV compression secondary to pericardial clot, cannula kinking and/or malposition, and thrombus.[70,89,90] Using intraoperative findings as the gold standard, Raman and associates[90] demonstrated that the sensitivity and specificity of CCT in detecting cannula thrombosis or inflow-cannula malposition were 85% and 100%, respectively. A limitation of CCT relates to radiation exposure and the risk of nephrotoxicity resulting from an iodinated contrast agent. However, for LVAD patients with a serum creatinine level of <1.5 mg/dL and a glomerular filtration rate of >60 mL/min/1.73 m^2, CCT appears to be safe.[91] In the presence of nondiagnostic TTE and TEE, indications for CCT in a CF-LVAD patient include (1) clinical concern about inflow-cannula malposition (ie, unexplained frequent LVAD suction events, recurring ventricular dysrhythmias independent of LVAD console parameter deviations, or residual HF due to partial LV unloading), (2) suspected pump thrombosis (involving the inflow and/or outflow graft) with clinical evidence of hemolysis, (3) suspected LVAD malfunction due to outflow-graft kinking, and (4) exclusion of an intracardiac and/or aortic root clot in patients with an unexplained transient ischemic attack or stroke. Echocardiography remains the first-line test to screen for myocardial recovery; however, if poor acoustic windows preclude accurate assessment of ventricular size and function, one may use either multiple-gated acquisition equilibrium radionuclide angiography or electrocardiographically gated CCT as a second-line alternative.[4,70]

KEY POINT

- Echocardiography may be inconclusive for LVAD complications, including inflow-cannula malposition, pump thrombosis, outflow-graft kinking or obstruction, intra- or extracardiac thrombus, or cardiac compression (low flow) secondary to a pericardial or extrapericardial thoracic hematoma or effusion. In such cases, CCT can provide important complementary information for a more definitive diagnosis.

SUMMARY/DISCUSSION

Echocardiography is important in the management of LVAD patients. Guidance about when and how to perform echocardiography in these patients has previously been lacking. Because the field of MCS is relatively new, many of the recommendations made herein are partly based on consensus expert opinion from several large LVAD centers. In the literature, there is growing support for specific echocardiography parameters that may constitute contraindications or precautions before LVAD surgery. During and after LVAD implantation, one may use perioperative TEE and TTE/TEE, respectively, when needed, to confirm normal versus abnormal device function and to determine whether or not the native heart is responding to LVAD support as expected. For organizing these recommendations, we have used a *phase of care* approach, which includes (1) preoperative assessment, (2) perioperative TEE, (3) postoperative surveillance echocardiography, (4) postoperative problem-focused echocardiography, and (5) recovery protocols.

Patient Populations

The majority of patients who receive LVADs are adults with end-stage dilated cardiomyopathies, and many of our recommendations apply to this group. The role of echocardiography in the management of other, smaller populations is less established. These smaller (but potentially growing) populations include patients with infiltrative cardiomyopathies, pediatric and adolescent patients with dilated cardiomyopathies, and pediatric or adult patients with complex congenital heart disease (Figure 32). Because these smaller, less-studied groups may benefit from LVAD support, they are briefly discussed separately when they are thought to overlap with adult dilated cardiomyopathy patients with regard to patient selection, device type, and functional assessment after implantation. However, these special populations may require considerable individualized consideration with respect to patient and device selection and follow-up evaluation. Currently, published data about these populations are limited, and detailed recommendations are not included in this document. A separate pediatric LVAD discussion is included towards the end of the document.

Frequency and Extent of Echocardiography

The number of LVAD patients living in the outpatient, ambulatory environment has grown considerably over the past several years, and further growth is expected due to increasing patient survival and expansion of implant centers. A primary goal of these recommendations is to provide a framework for managing a busy ambulatory MCS center in an efficient manner. Figure 14 presents a reasonable strategy for organizing routine surveillance echocardiography examinations for patients who are doing well after LVAD implantation. Routine surveillance echocardiography is useful for confirming normal LVAD function and assessing the native cardiac response to LVAD support over time. These exams are analogous to appropriate echocardiograms performed in HF patients without LVADs to evaluate their response to guideline-based medical therapy. Many patients tolerate and even thrive on long-term LVAD support. However, routine follow-up surveillance echo exams are recommended to screen for the development of known LVAD complications that may begin in an occult fashion (before symptoms or device alarms), including (but not limited to) de novo or worsening AR, inappropriate speed settings due to either improvement or deterioration of native heart function, internal pump thrombosis, other conduit obstruction, aortic root thrombus, aortic cusp fusion, and ongoing/smoldering HF in inactive patients. Theoretically, early detection of LVAD complications or early intervention in smoldering persistent HF should improve patient outcomes and reduce hospital readmissions for overt HF or for problems that have activated device alarms. From an abundance of caution, some centers may perform too-frequent and/or too-detailed echocardiographic examinations. In such cases, these guidelines may be useful for establishing the optimal frequency of echocardiography examination, based on individual patient circumstances. These recommendations also may help establish a reasonable timetable for routine follow-up examination of patients who are doing well or who may be able to have an LVAD echo exam in a laboratory closer to their home. When a patient does develop overt signs or symptoms of HF or LVAD malfunction, the guidelines provide a framework for performing problem-focused echocardiography examinations.

Laboratory Resources and Extent of Examination

A frequent concern is whether or not "speed changes" should be incorporated into the LVAD echocardiography exam, as this could be an extremely labor- and time-intensive approach. Additionally, the distinct echocardiography data elements obtained at each pump speed are not well defined. In general, either a surveillance or a problem-focused exam at the LVAD's baseline pump speed should be equivalent to a comprehensive HF echocardiogram (not a limited study). Additional LVAD-specific imaging during the baseline exam simply includes (when possible) 2D and Doppler interrogation of the inflow cannula, outflow graft, and aortic anastomosis (using TEE if indicated). Thereafter, a "limited" exam at each pump speed is recommended. The extent of imaging required at each pump speed depends on the suspected problem and should be targeted. In stable, asymptomatic patients with normal LVAD function at baseline, subsequent pump speed data acquisition can proceed quite expediently and may even be optional for surveillance exams, depending on the center's internal standards. A framework for minimal speed-change parameters is provided in the appendix section and can be adapted for each patient, depending on the situation at hand. Pump speed changes may be performed periodically in asymptomatic patients, as this can be a means of establishing a patient's own benchmark data, which can be useful for comparison if suspected abnormalities are apparent on subsequent exams. Speed-change/ramp studies can be useful, if not critical, for a problem-focused exam (eg, screening for pump malfunction in the setting of hemolysis and suspected impeller thrombosis) and for the assessment of LV recovery. Special knowledge of contraindications for certain speed adjustments and of safety endpoints for speed changes is required by personnel performing, supervising, and interpreting the studies, and the necessary information is outlined in the text and listed in the tables and appendices.

Patient flow within busy LVAD clinics may be streamlined by advance scheduling of routine surveillance examinations so that the appropriate time, the necessary exam room space, and adequately trained sonographers are available, either within the facility's dedicated echocardiography laboratory or within a dedicated satellite echocardiography laboratory in the HF/MCS center. When abnormalities are suspected, the type and extent of the examination can be more readily determined if the knowledgeable sonographer and echocardiographer are provided with a detailed indication for examination, as listed in the sample worksheet. In some cases, a limited confirmatory exam may be performed at the baseline pump speed, and a more detailed examination may be more appropriate after hospitalization. A new facet of examining LVAD patients is the need for arterial Doppler-derived BP measurement in many cases before starting the echocardiography exam and for ensuring safety and accurate interpretation when higher pump speed changes are included in the exam. In general, a primary goal of this document is to provide a framework for incorporating echocardiography more efficiently into both the routine follow-up care and the acute care of LVAD patients. In the absence of validation and outcomes studies, considerable room for adaptation of these recommendations is possible according to institutional internal standards and individual patient circumstances. However, the provision of adequately trained personnel, appropriate equipment, and quality-improvement measures is necessary for the implementation of echocardiography in these often complex cases, in which images are sometimes difficult to acquire and interpret.

Referring/Community Hospitals

Although LVAD expertise is required within device implantation and follow-up facilities, an increasing number of ambulatory LVAD patients can be expected to present at less experienced facilities because of either symptoms or device alarm reports. Therefore, an additional goal of this document is to provide an easily understood and available

key reference for non-expert echocardiographers. Ideally, such individuals will be able to quickly grasp key points, develop problem-solving skills, observe safety precautions, and effectively communicate with referral centers when examining unexpected LVAD patients. Potentially, local laboratories may develop the recommended level of sophistication for performing surveillance examinations that can be communicated to the tertiary implant center.

Other Devices

This document primarily addresses two FDA-approved, long-term, surgically implanted CF-LVADs (the HM-II and HVAD). However, echocardiographers may increasingly encounter temporary LVADs, which are briefly discussed in Appendix A in order to contextualize their use under the heading of MCS.

The Right Ventricle and Biventricular/RVAD Support

Right ventricular support is sometimes required, and outcomes may be improved when RVAD support is provided at the time of initial LVAD implantation. Development of echocardiographic predictors for RV failure after LVAD implantation has been the focus of relatively intensive clinical investigation, as discussed in some detail within this document. Unfortunately, recommendations for a single echocardiography parameter or set of parameters that can reliably predict the need for biventricular support cannot be made at this time. Instead, laboratories are encouraged to evaluate RV function as extensively as they can and to use an aggregate assessment of clinical and echocardiography parameters of RV dysfunction both pre- and postoperatively for clinical decision-making. A detailed discussion of the types of RVAD support that can be observed (when needed) and the use of echocardiography for assisting in the management of biventricular support is beyond the scope of this document, although a brief discussion is included in Appendix A. An important role for echocardiography in patients with the *clinical* appearance of RV failure after LVAD implantation (low LVAD flow) is to exclude other causes, such as occult pericardial or thoracic tamponade.

In conclusion, the Writing Committee and its special contributors hope that this initial document will provide a framework for better incorporating echocardiography into the care of LVAD patients. There are other MCS devices under development that may be included in future versions of this report. We hope that this document will also provide a stimulus for related validation and outcomes studies in this emerging field.

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SUPPLEMENTARY DATA

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.echo.2015.05.008.

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APPENDIX A

Other FDA-Approved Pumps that may be Encountered by Sonographers and Echocardiographers, Including Percutaneous, Extracorporeal, and Right Ventricular Assist Devices

Percutaneous LVADs for Temporary Support

A percutaneous LVAD (PVAD) can be expediently deployed in the cath lab with the aid of fluoroscopic guidance, either urgently to treat cardiogenic shock or preemptively to provide back-up support during certain high-risk percutaneous coronary interventions.[92] Currently, two types of FDA-approved PVADs are available: the *Impella System* (Abiomed, Inc., Danvers, MA) and the *TandemHeart System* (CardiacAssist, Inc., Pittsburgh, PA).

Impella. The Impella 2.5 [FDA 510(k), 2008] and the slightly larger (up to 4 L/min) Impella CP (Cardiac Power) [FDA 510(k), 2012] are implanted via a traditional femoral arterial approach. The larger Impella 5.0 [FDA 510(k), 2009] delivers flows of up to 5 L/min and requires surgical placement via a left axillary artery graft. The role of echocardiography and the echocardiographic appearance is the same for all three device sizes. The distal portion of the Impella system consists of a microaxial CF pump housed within a cannula that draws blood into an LV inflow port and expels the blood through an aortic root outlet port (intracardiac blood flow circuit) (Figure A1).

Echocardiography Before Deployment.–Significant AR is a relative contraindication, and ventricular thrombus and severe AS or MS are contraindications for use of the Impella. Echocardiography may be used to screen for these conditions and otherwise to confirm the extent and etiology of HF.

Echocardiography After Deployment.–Device console alarms or hemodynamic instability may prompt an urgent or "stat" echo exam to determine the source of the problem. Patient movement (eg, bed transfer, resuscitation, etc.) can cause catheter migration. The Impella is ideally imaged in its entirety in LVOT long-axis views by TTE or TEE. The visible inflow port should be positioned 3.5 to 4.0 cm from the aortic annulus. The pump's characteristic color-flow artifact should lie distal to the annulus. The cannula has a 45-degree angle to better track the normal LVOT course. However, this design can also predispose to entanglement of the distal pigtail portion of the device within the submitral apparatus (Figure A2). This complication may result in worse MR, inability to properly advance the device within the left ventricle and/or "low flow" alarms if the adjacent MV leaflets obstruct the inflow zone. As with other LVADs, the AV may be closed or only partially open after device deployment, and net forward flow can be determined by calculating the RVOT stroke volume and cardiac output with Doppler methods. Additional instructive information regarding echocardiography of the Impella systems is available online.[93]

TandemHeart. The TandemHeart PVAD [FDA 510(k), 2006] is inserted via a femoral vein and requires an atrial transseptal puncture to access the left atrium. The extracorporeal centrifugal pump receives left atrial blood and delivers it to the femoral artery (via an extracardiac blood flow circuit), providing up to 4 or 5 L/min of flow depending on the size of the transseptal inflow cannula (Figure A3).

Echocardiography Before Deployment.–Left atrial thrombus is a potential contraindication for TandemHeart deployment. This device may be useful for cardiogenic shock—including severe postinfarction VSD, severe MR, or severe AS—or in patients for whom the more easily deployed Impella device is contraindicated (eg, by severe AR or LV thrombus). Echocardiography may be used to screen for these conditions and to otherwise confirm the severity and etiology of HF before device deployment.

Echocardiography After Deployment.–The only visible device component is the transseptal cannula, which may be seen throughout its course from the left atrium, interatrial septum, right atrium, and inferior vena cava, using standard echo views. Color Doppler evaluation can confirm the presence of CF. In addition to verifying the cannula position, the post-deployment echo exam is useful for assessing the native heart's response to circulatory support and the ability to withdraw temporary LVAD support. The net forward flow can be calculated from the RVOT stroke volume by Doppler methods. The transseptal cannula often enters the left atrial appendage. Because the cannula has 14 side holes, normal flow will occur even if the catheter tip abuts the wall of the left atrium or left atrial appendage (Figure A3C). Because the left ventricle may be completely bypassed, the sonographer should be alert for possible LV thrombus formation (Figure A4) and for aortic root thrombus when the AV remains closed.

Surgically Implanted Extracorporeal Ventricular Assist Devices for Temporary Support

Thoratec Paracorporeal Ventricular Assist Device (VAD). The Thoratec Paracorporeal VAD (Thoratec Corporation, Pleasanton, CA) is a first-generation, pneumatically driven, pulsatile displacement pump with FDA 510(c) approval for BTT therapy (1995) and postcardiotomy recovery (1998). As shown in Figure A5, three potential VAD configurations may be used for LVAD or BiVAD support. The inflow cannula may be implanted within the left atrium, and this approach may useful for emergent surgical implantation by surgeons not experienced with the more challenging procedure of off-pump LV cannulation. Although the device was also configured for intracorporeal support, this role has been supplanted by the third-generation CF-LVADs. The echocardiographic features of pulsatile pumps are characterized by inflow and outflow that is not timed with the cardiac cycle (intermittent LV assist). In "automatic mode" (maximum support), a sensor detects passive chamber filling, which triggers ejection of blood. The device may be set to lower "fixed-rate" settings for lower levels of support. For a discussion of echocardiographic features that differ from those of CF-LVADs, please refer to Estep and coauthors.[49]

Thoratec CentriMag (previously Levitronix CentriMag). The CentriMag is approved for short-term LVAD, RVAD, or BiVAD support. The extracorporeal centrifugal CF pump (Figure A6) is driven by a bearingless, magnetically levitated impeller that can provide flows of up to 9.9 L/min. The inflow cannula and outflow graft are placed surgically, usually via a midline sternotomy. The CentriMag is suitable for transporting patients between facilities. Difficulties encountered by sonographers include possible suboptimal imaging windows related to lack of sternal wiring (closure) and to patient intubation. When used for LVAD support, the inflow cannula may be placed in either the right superior pulmonary vein (which may not be visible on echo) or in the left ventricle (which is visible on echo). When the inflow cannula is placed in the right superior pulmonary vein, the left ventricle may be completely "bypassed" if the AV does not open. As noted with the TandemHeart device (above), LV blood stasis (Figure A4) increases the risk of LV thrombus formation, which

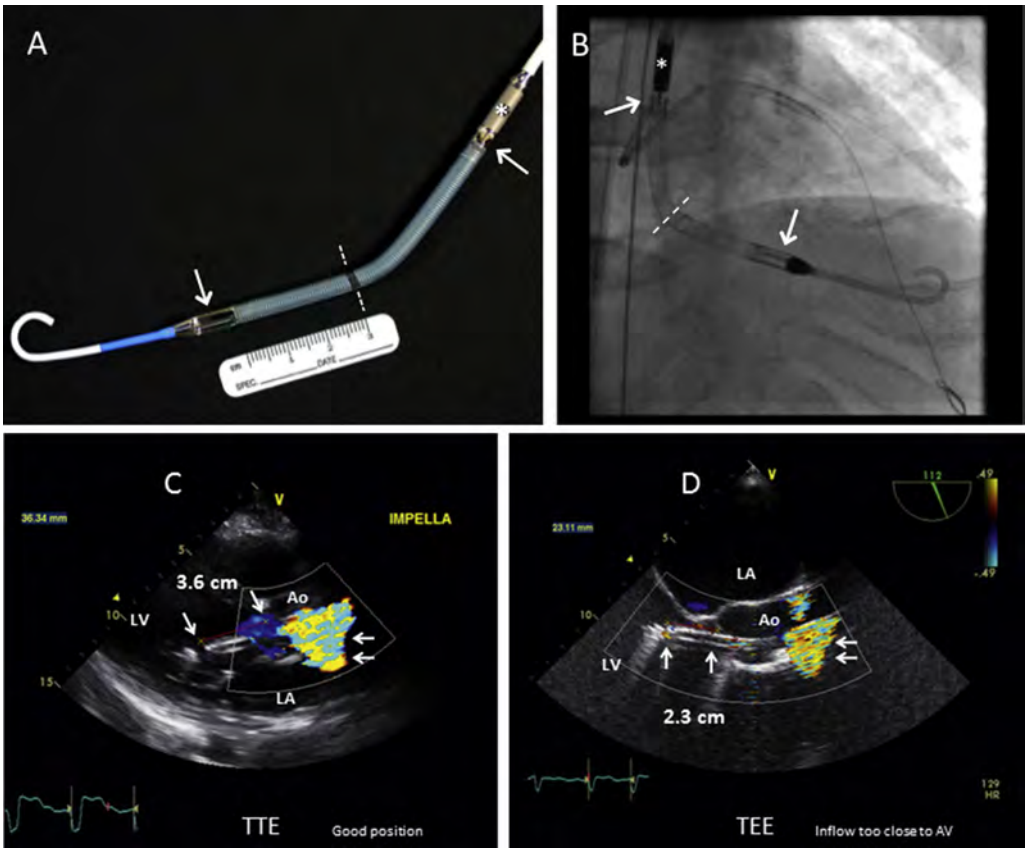

Figure A1 **(A)** Photograph of the Impella CP Percutaneous LVAD, showing the pump impeller housing (*), blood-inflow zone (*downward arrow*) and blood-outflow zone (*upward arrow*) zones, with the distal pigtail catheter component. **(B)** Fluoroscopic X-ray image of the Impella CP device in situ. Blood-inflow zone (*downward arrow*), blood-outflow zone (*upward arrow*), impeller housing (*). The radiopaque marker (*immediately below dotted line*) indicates the desired aortic annulus level, which is 3.5 cm from the middle of the inflow zone. **(C)** TTE parasternal long-axis view. The Impella device crosses the AV. The distance from the blood inflow area (*left single arrow*) to the aortic annulus (*right single arrow*) is approximately 3.6 cm. **(D)** On TEE, the distance from the inflow area (*left single arrow*) to the aortic annulus (*right single arrow*) is 2.3 cm; this is not far enough into the left ventricle to provide a safety margin, although the device is functioning normally). In views C and D, the double arrows indicate a typical pump-impeller aliased color-Doppler artifact. See also Videos 49 and 50.

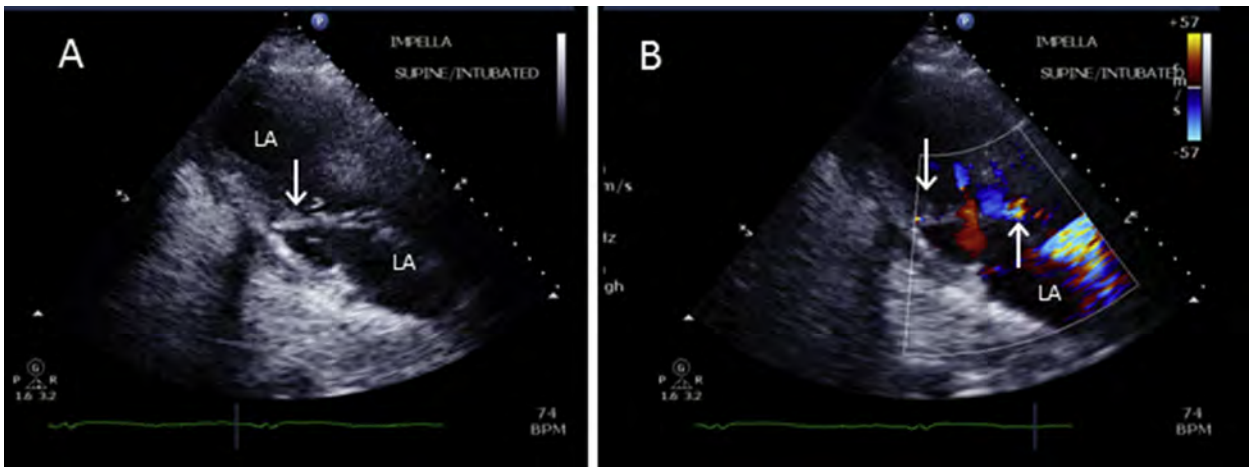

Figure A2 The Impella CP Percutaneous LVAD **(A,B)**, modified TTE parasternal long-axis view, showing the distal pigtail lodged in the submitral apparatus (*downward arrow*) with the inflow zone (cage) adjacent to the MV anterior leaflet and too close to the aortic annulus (*upward arrow*, view B).

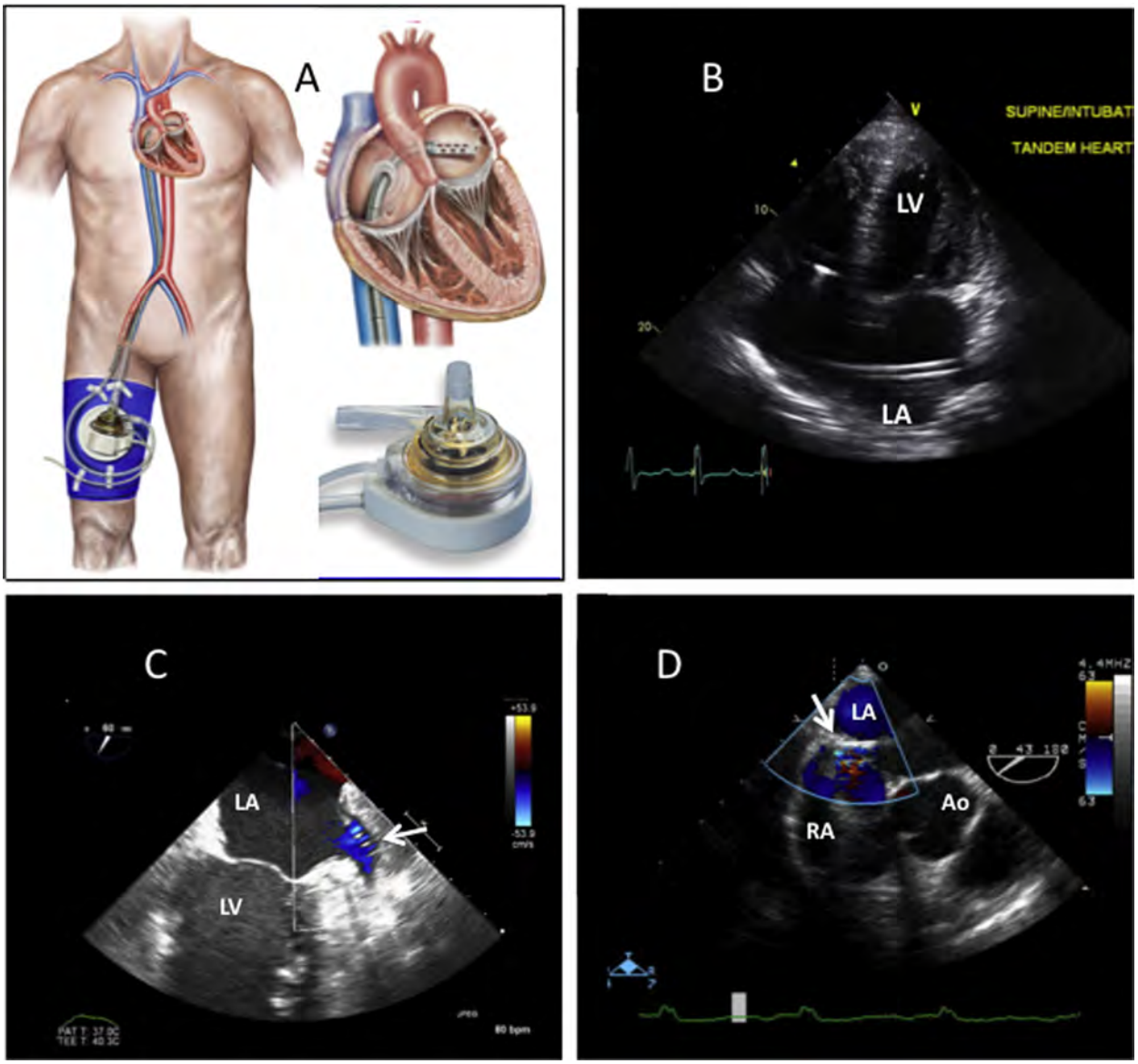

Figure A3 **(A)** Illustration of the TandemHeart PVAD (Images courtesy of CardiacAssist, Inc.). The CF pump is extracorporeal (*outside the body*). **(B)** TTE apical 4-chamber view shows the device's inflow conduit within the left atrium. See also Video 51. **(C)** TEE shows the distal cannula's multiple-port inflow zone within the left atrial appendage (*arrow*). See also Video 52. **(D)** TEE shows the transatrial septal portion of the inflow conduit (*arrow*). See also Video 53.

can be identified echocardiographically. In other respects, the device's imaging characteristics are similar to those of long-term intracorporeal devices, as previously discussed in detail.

Right Ventricular Assist Devices

As previously noted, the primary population addressed in this guideline consists of patients undergoing LVAD support alone. A brief description of RVADs is included, as echocardiographers may encounter patients with RVAD (BiVAD) support. In the acute setting, including the period after LVAD implantation, an RVAD may be needed. Right ventricular failure is difficult to manage long-term. The ability to predict the development of RV failure prospectively after LVAD implantation is limited, and in some cases right-sided failure can develop even if preimplantation RV function was seemingly adequate. When optimization of LVAD function and medical management have failed, the Impella, TandemHeart, HM-II, and HVAD pumps have been used as RVADs (without FDA approval), and the Thoratec PVAD, Berlin Heart EXCOR, CentriMag, and PediMag have been used as RVADs with FDA approval. Other, less frequently used devices may also be available, and new systems are on the horizon. When an RVAD and LVAD are functioning simultaneously, many caveats are involved that are beyond the scope of this document. However, an important point is to observe both the RV and LV size, as both under-filling and over-pumping of either chamber may occur, potentially compromising device inflow or mechanically distorting the adjacent ventricle. Balance between the interventricular septum and interatrial septum is important.

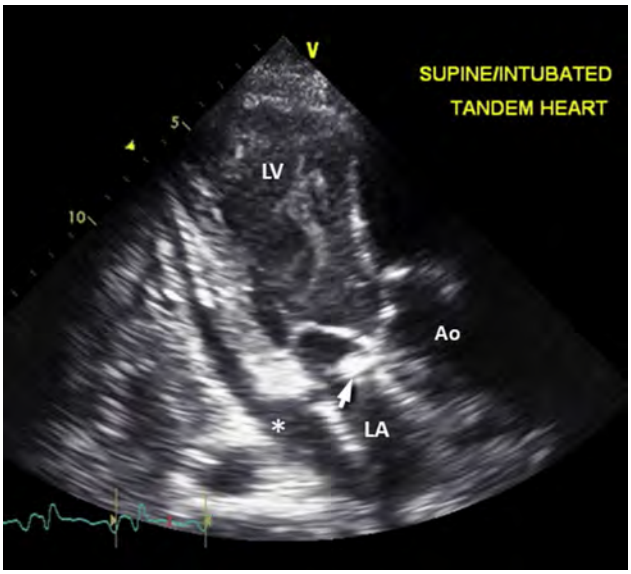

Figure A4 Severe left ventricle (LV) spontaneous echocardiography contrast in a patient with complete LV "bypass" (no aortic valve opening) during TandemHeart support. The risk of LV thrombus is high without systemic anticoagulation therapy. Left Atrium (LA), Aortic Root (Ao), pericardial effusion (*), Tandem Heart inflow cannula (*arrow*). See also Video 54.

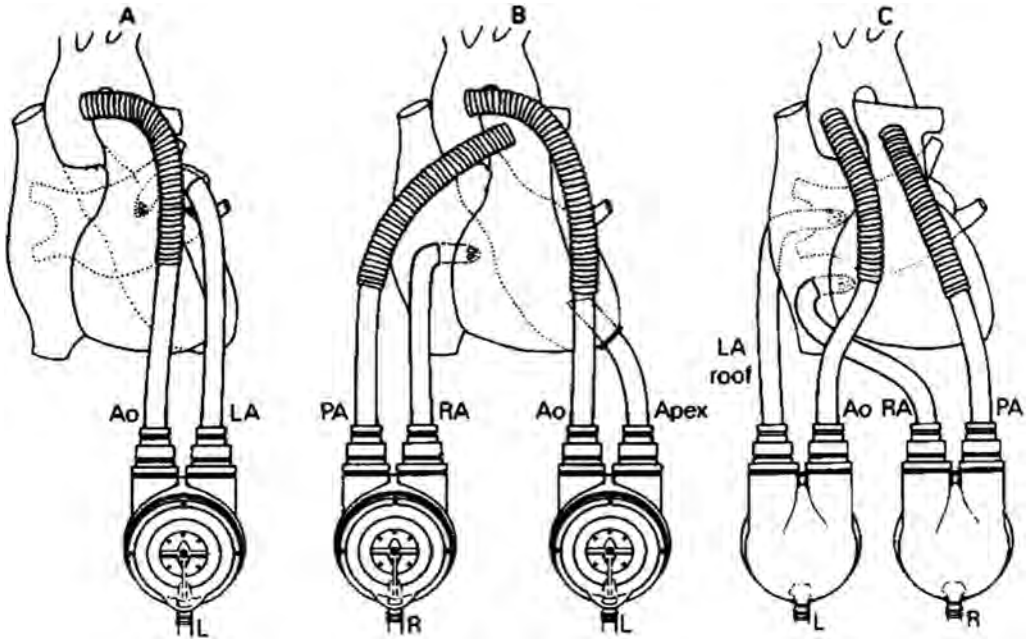

Figure A5 Drawing of the Thoratec Paracorporeal Ventricular Assist Device (VAD) and three cannulation approaches for univentricular left heart support (panel **A**) and biventricular support (panels **B** and **C**). Ao=aorta, LA=left atrial appendage, PA=pulmonary artery, RA=right atrium, Apex=left ventricular apex, IAG=cannula inserted via the interatrial groove and directed towards the LA roof. Note that VADs in Panel **C** are turned over and are on the sides of the chest that are opposite of those in Panel B. (Permission from Farrar DJ et al. N Engl J Med 1988; 318:333-340).

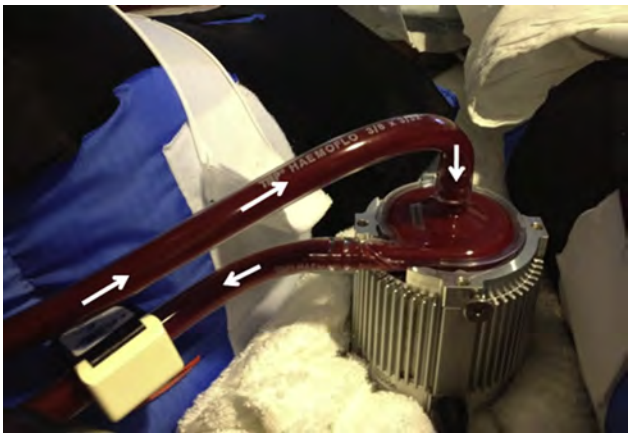

Figure A6 The Thoratec CentriMag extracorporeal centrifugal CF pump. The arrows indicate the blood-flow direction.

Appendix B Recommended Pre–LVAD-Implantation TTE Protocol (with embedded red flags)

Parasternal Long-Axis View
Image acquisition

- LV size
  - **Red-flag findings:** Small LV size, particularly with increased LV trabeculations
- Global and regional LV function
- M-mode evaluation of left ventricle and left atrium/aorta (if lab standard)
- 2D evaluation of AV, MV, TV (TV by RV inflow tract view)
  - **Red-flag finding:** any prosthetic valve
- Color-flow Doppler evaluation of MV and AV
- RV inflow view
- CW Doppler (TR)
- High left parasternal view of ascending aorta
  - **Red-flag findings:** Ascending aortic aneurysm, dissection, or atheroma

Recommended measurements

- LV internal dimension at end-diastole
- LV internal dimension at end-systole
- Posterior wall thickness
- Interventricular septal thickness
- LV ejection fraction
- LVOT diameter
- LA dimension
- Aortic root dimension
- Ascending aorta dimension
- CW Doppler TR velocity for RVSP

Parasternal Short-Axis View
Image acquisition

- 2D short-axis view at AV level and RVOT
- 2D short-axis view of left ventricle at basal, mid, and apical levels
  - **Red-flag findings:** VSD
- Global and regional LV function
- Color-flow Doppler evaluation of PV, AV, and TV
- Spectral Doppler evaluation of RVOT, PV, pulmonary trunk
  - **Red-flag findings:** Moderate or greater PS or PR; PDA, prosthetic valve
- M-mode evaluation (if lab standard)

Recommended measurements

- RVOT velocity
- PV velocity

Apical Four-Chamber View
Image acquisition

- 2D imaging of the four chambers (maximizing LV length)
  - **Red-flag findings:** LV thrombus, LV apical aneurysm, any congenital heart disease
- "Dedicated RV view"
  - **Red-flag findings:** RV dilatation
- Global and regional LV and RV function
  - **Red-flag findings:** RV systolic dysfunction
- **Color-flow Doppler of valvular inflow and regurgitation**
- Color-flow Doppler interrogation of interventricular and interatrial septum
  - **Red-flag findings:** VSD, PFO, or ASD
- Pulsed Doppler of MV
- Pulsed Doppler of pulmonary veins
- Doppler tissue imaging
- LV and RV strain (optional)

(*Continued*)

Appendix B (*Continued*)

- CW Doppler to evaluate valves, native or prosthetic (use multiple views to obtain highest flow velocities)
  - **Red-flag findings:**
  - MV: ≥ moderate MS
  - AV: > mild AR
  - TV: ≥ moderate TR or > mild TS
  - PV: ≥ moderate PS or PR
- Agitated saline contrast at rest and with release of Valsalva maneuver to evaluate intracardiac or intrapulmonary shunting
  - **Red-flag findings:** PFO, significant intrapulmonary shunt

Recommended measurements

- LV systolic function: 2D/3D volumetrics for EF
- LV diastolic function: mitral E/A, DT, medial and lateral MV annulus DTI
- RV function: RV strain, TAPSE, TV DTI
- LA volume index/RA area

Apical Five-Chamber View
Image acquisition

- 2D imaging
- Color-flow Doppler of LVOT
- Pulsed Doppler of LVOT
- CW Doppler of AV if aortic stenosis is present or suspected

Recommended measurements

- LV systolic function: LVOT stroke volume, cardiac output/index

Apical Two-Chamber View
Image acquisition

- 2D imaging
  - **Red-flag findings:** LA appendage thrombus
- Global and regional LV function
- Color-flow Doppler of MV

Recommended measurements

- LA volume

Apical Long-Axis View
Image acquisition

- 2D imaging
- Global and regional LV function
- Color-flow Doppler of MV and AV
- Pulsed Doppler of LVOT
- CW Doppler of AV if aortic stenosis is present or suspected

Recommended measurements

- LV systolic function: LVOT stroke volume, cardiac output/index

Subcostal Views
Four-chamber

- 2D imaging, including assessment of interatrial septum
  - **Red-flag findings:** VSD, PFO, or ASD
- Color-flow Doppler of valvular inflow and for regurgitation
- Color-flow Doppler of interventricular and interatrial septum to assess for shunt

Short-axis

- Complementary to parasternal views
- IVC assessment to estimate RA pressure (IVC size and response to inspiration)
- Doppler of hepatic veins, when appropriate

Suprasternal Notch View

- Long-axis view of aortic arch (short-axis view if indicated)
- Color-flow Doppler of aortic arch and isthmus
  - **Red-flag findings**: aortic pathology (PDA, coarctation)
- Pulsed Doppler in descending aorta in cases of aortic regurgitation

(*Continued*)

Appendix B (*Continued*)

CW Doppler of AV if aortic stenosis is present or suspected
SVC
Other Views
Right parasternal window
Long-axis view to evaluate ascending aorta
CW Doppler of aortic valve if aortic stenosis is present or suspected
Right supraclavicular window
SVC
CW Doppler of aortic valve if aortic stenosis is present or suspected

2D, two-dimensional; *3D*, three-dimensional; *A*, mitral valve late peak diastolic velocity; *ASD*, atrial septal defect; *AV*, aortic valve; *CW*, continuous-wave; *DT*, deceleration time; *DTI*, Doppler tissue imaging; *E*, mitral valve early peak diastolic velocity; *EF*, ejection fraction; *IVC*, inferior vena cava; *LA*, left atrial; *LV*, left ventricular; *LVOT*, left ventricular outflow tract; *MV*, mitral valve; *PDA*, patent ductus arteriosus; *PFO*, patent foramen ovale; *PR*, pulmonary regurgitation; *PS*, pulmonary stenosis; *PV*, pulmonary valve; *RA*, right atrial; *RV*, right ventricular; *RVOT*, right ventricular outflow tract; *RVSP*, right ventricular systolic pressure; *SVC*, superior vena cava; *TAPSE*, tricuspid annular-plane systolic excursion; *TR*, tricuspid regurgitation; *TS*, tricuspid stenosis; *TTE*, transthoracic echocardiography; *TV*, tricuspid valve; *VSD*, ventricular septal defect.

Appendix C Perioperative TEE Protocol/Checklist

Two-part exam. For standard views, see previous guidelines Hahn, et al.[42]

1. Preimplantation Perioperative TEE Exam

Goals: confirm previous echocardiography (TTE or TEE) findings; detect unexpected abnormal findings before and after LVAD implantation
Blood pressure: via arterial line; for hypotension, consider vasopressor agent to assess AR severity
LV: size, systolic function, assess for thrombus
LA: size, assess for LA appendage/LA thrombus
RV: size, systolic function, catheters/leads
RA: size, assess for thrombus, catheters/leads
Interatrial septum: detailed 2D, color Doppler, IV saline contrast; ***red flag:*** PFO/ASD
Systemic veins: assess SVC, IVC
Pulmonary veins
Aortic valve: ***red flags:*** > mild AR, prosthetic valve
Mitral valve: ***red flags:*** ≥ moderate mitral stenosis, prosthetic mitral valve
Pulmonary valve: ***red flags:*** > mild PS, ≥ moderate PR, if RVAD planned; prosthetic valve
Pulmonary trunk: ***red flags:*** congenital anomaly (PDA, pulmonary atresia or aneurysm)
Tricuspid valve: TR, systolic PA pressure by TR velocity; **red flags:** ≥ moderate TR, > mild TS, prosthetic valve
Pericardium: screen for effusion; consider constrictive physiology
Aorta: root, ascending, transverse, and descending thoracic aorta; screen for aneurysm, congenital anomaly, dissection, or complex atheroma at each level

2. Postimplantation Perioperative TEE Exam

Goals: monitor for intracardiac air; rule out shunt; confirm device and native heart function
Pump type:
Pump speed:
Blood pressure: via arterial line; for hypotension (MAP of <60 mmHg), consider vasopressor agent before assessing AR severity and other hemodynamic variables
Intracardiac air: left-sided chambers and aortic root during removal from CPB
LV: size, inflow-cannula position and flow velocities, septal position; ***red flags:*** small LV (over-pumping or RV failure), right-to-left septal shift; large LV (obstructed or inadequate pump flows)
Inflow-cannula position: 2D/3D, assess for possible malposition
Inflow-cannula flow: spectral and color Doppler (***red flag:*** abnormal flow pattern/high/low velocities, especially after sternal closure)
LA: Assess LA appendage
RV: size, systolic function; ***red flags:*** signs of RV dysfunction
RA: size, assess for thrombus, catheters/leads
Interatrial septum: repeat IV saline test and color Doppler evaluation of IAS (***red flags:*** PFO/ASD)
Systemic veins: (SVC, IVC)
Pulmonary veins: inspect
Aortic valve: degree of AV opening and degree of AR (***red flags:*** > mild AR)
Mitral valve: exclude inflow-cannula interference with submitral apparatus; assess MR
Pulmonary valve: assess PR, measure RVOT SV if able
Pulmonary trunk: (if applicable, demonstrate RVAD outflow by color Doppler); assess PR
Tricuspid valve: assess TR (***red flags:*** ≥ moderate TR); systolic PA pressure by TR velocity (if not severe TR)
Pericardium: screen for effusion/hematoma
Aorta: exclude iatrogenic dissection
Outflow graft: identify conduit path adjacent to RV/RA with color and spectral Doppler (when able)
Outflow graft-to-aorta anastomosis: assess patency/flow by color and spectral Doppler (when able) ***red flags****:* kinked appearance/turbulent flow/velocity >2 m/sec, particularly after sternal closure

2D, Two-dimensional; *3D,* three-dimensional; *AR,* aortic regurgitation; *ASD,* atrial septal defect; *AV,* aortic valve; *CPB,* cardiopulmonary bypass; *IAS,* interatrial septum; *IV,* intravenous; *IVC,* inferior vena cava; *LA,* left atrium; *LV,* left ventricle; *LVAD,* left ventricular assist device; *LVOT,* left ventricular outflow tract; *MAP,* mean arterial pressure; *MR,* mitral regurgitation; *PA,* pulmonary artery; *PFO,* patent foramen ovale; *PDA*, patent ductus arteriosus; *PR,* pulmonary regurgitation; *PS*, pulmonary stenosis, *RA,* right atrium; *RV,* ventricle; *RVAD,* right ventricular assist device; *RVOT,* right ventricular outflow tract; *SV,* stroke volume; *SVC,* superior vena cava; *TEE,* transesophageal echocardiography; *TR,* tricuspid regurgitation; *TS*, tricuspid stenosis; *TTE,* transthoracic echocardiography.

Appendix D Magnitude and Time Course of Echo LV Parameter Changes Induced by CF-LVAD Unloading

Variable	Pre-LVAD Study 1 (N=21) Study 2 (N=63) Study 3 (N=80)	Post-LVAD 1 mo Study 1 (N=21) — Study 3 (N=68)	Post-LVAD 3 mo — Study 2 (N=63) Study 3 (N=47)	Post-LVAD 6 mo Study 1 (N=10) Study 2 (N=63) Study 3 (N=32)	Post-LVAD 12 mo — — Study 3 (N=20)
LV parameters					
LV diastolic diameter					
Study 1 (mm)	66 ± 11	55 ± 11**	—	52 ± 11*	—
Study 2 (mm)	68 ± 9	—	56 ± 11*	57 ± 12	—
Study 3 (cm/m^2)	3.2 (2.9, 3.6)	2.8 (2.3, 3.2)	2.9 (2.4, 3.4)	2.8 (2.2, 3.4)	2.6 (2.2, 3.0)*
LV systolic diameter					
Study 1 (mm)	58 ± 10	47 ± 12	—	43 ± 13	—
Study 2 (mm)	61 ± 9	—	47 ± 13*	49 ± 13	—
Study 3 (cm/m^2)	3.0 (2.6, 3.3)	2.6 (2.0, 3.1)	2.6 (2.1, 3.1)	2.5 (1.8, 2.9)	2.3 (1.9,2.8)*
LV end-diastolic volume					
Study 1 (mL)	242 ± 108	127 ± 68*	—	113 ± 45*	—
Study 2	—	—	—	—	—
Study 3 (mL/m^2)	113 (94, 141)	77 (54, 109)*	86 (62, 106)*	86 (52, 108)*	69 (45, 93)*
LV end-systolic volume					
Study 1 (mL)	191 ± 93	100 ± 66*	—	82 ± 42*	—
Study 2	—	—	—	—	—
Study 3 (mL/m^2)	3.0 (2.6, 3.3)	2.6 (2.0, 3.1)*	2.6 (2.1, 3.1)	2.5 (1.8,2.9)*	2.3 (1.9,2.8)*
LV ejection fraction (%)					
Study 1	22 ± 5	25 ± 13	—	29 ± 10	—
Study 2	19 ± 7	—	26 ± 12*	27 ± 14	—
Study 3	17 (14, 23)	20 (15, 30)	20 (14, 26)	25 (18, 33)*	22 (15, 31)
LV mass					
Study 1	—	—	—	—	—
Study 2(g)	383 ± 113	—	295.9 ± 188*	314 ± 134	—
Study 3 (g/m^2)	114 (93, 146)	95 (71, 114)**	92 (63, 118)**	111 (74, 134)	77 (50, 104)*
LV diastolic parameters					
LA size					
Study 1 (mm)	*47 ± 7*	37 ± 9**	—	42 ± 13	—
Study 2 (mL/m^2)	*69 ± 30*	—	42 ± 15*	—	—
Study 3 (mL/m^2)	*46 (35, 54)*	28 (22, 36)*	32 (23, 38)*	25 (19, 39)*	28 (18, 38)*
E-wave					
Study 1 (cm/s)	*96 ± 23*	73 ± 27**	—	66 ± 12**	—
Study 2 (cm/s)	*98 ± 35*	—	100 ± 160	80 ± 20	—
Study 3 (cm/s)	*100 (80, 110)*	80 (60, 100)*	80 (70, 100)	80 (70, 110)	100 (60, 120)
E/A ratio					
Study 3	*2.8 (2.1, 4.1)*	2.2 (1.2, 3.6)	1.5 (1.0,2.9)*	1.6 (1.3, 2.2)**	1.7 (1.0, 3.3)
Mitral DT					
Study 1	*124 ± 39*	180 ± 53**	—	164 ± 24	—
Study 2	*132 ± 27*	—	188 + 70*	166 ± 48	—
Study 3	*133 (112, 165)*	175 (137, 220)*	178 (141, 212)*	172 (121, 220)*	170 (157, 225)
Tissue Doppler e′ (cm/s)					
Study 1	—	—	—	—	—
Study 2 (septal e′)	*4 ± 1*	—	4 ± 1	—	—
Study 3 (septal e′)	*4 (3, 6)*	6 (5, 9)*	7(5,9)*	7 (4, 9)*	7 (6, 10)**
(lateral e′)	*8 (5, 11)*	9 (7, 10)	9(6,11)	10 (7, 13)	12 (8, 12)

(*Continued*)

Appendix D (*Continued*)

Variable	Pre-LVAD Study 1 (N=21) Study 2 (N=63) Study 3 (N=80)	Post-LVAD 1 mo Study 1 (N=21) — Study 3 (N=68)	Post-LVAD 3 mo — Study 2 (N=63) Study 3 (N=47)	Post-LVAD 6 mo Study 1 (N=10) Study 2 (N=63) Study 3 (N=32)	Post-LVAD 12 mo — — Study 3 (N=20)
E/ e' (ratio)					
Study 1	—	—	—	—	—
Study 2 (septal e′)	*26 ± 11*	—	20 ± 9**	13 ± 7	—
Study 3 (septal e′)	*23 (16, 30)*	13 (9, 19)*	12 (9, 16)*	12 (9, 19)*	15 (7, 17)**
(lateral e′)	*14 (9, 19)*	9 (16, 13)**	10 (6, 12)	9 (7, 13)	10 (6, 11)

Study 1, Lam et al. JASE 2009[52]; *Study 2*, Topilsky et al. JASE 2011[51]; *Study 3*, Drakos et al. JACC 2013;61:1985-94. Values are mean ± SD for Studies 1 and 2 and median (25th, 75th percentiles) for Study 3; *$P < .01$ versus Pre-LVAD; **$P < .05$ versus Pre-LVAD. Study 2 *P* values only provided comparing Pre-LVAD and Post-LVAD 3-mo measurements. *A,* mitral valve late peak diastolic velocity; *CF,* continuous-flow; *DT,* deceleration time; *E,* mitral valve early peak diastolic velocity; *e′,* mitral annular velocity; *LA,* left atrial; *LV,* left ventricle; *LVAD,* left ventricular assist device.

Appendix E LVAD Surveillance Echo Protocol: Standard Comprehensive TTE (or TEE) with Additional LVAD-Specific Parameters

Blood pressure (if no pulse, Doppler-derived mean arterial pressure)

Pump type and baseline speed

Degree of aortic valve opening/closure
Ventricular and interatrial septal position
LV inflow cannula

- Location
- Note optimal view for visualization
- Flow type
- Flow direction
- Peak systolic and diastolic flow velocities (pulsed Doppler)
- Velocity flow pattern

LV outflow graft

- Location/Note optimal view for visualization
- Flow type
- Flow direction
- Peak systolic and diastolic flow velocities (pulsed Doppler)
- Velocity flow pattern

LVAD output

- Outflow-graft pulsed Doppler VTI
- Cross-sectional area as calculated from the measured cannula diameter or from the known cannula diameter

Total cardiac output

- RVOT pulsed Doppler VTI
- Calculated cross-sectional area from the RVOT diameter

Pericardium: effusion/hematoma
Post-VAD Placement *"Red Flag"* Echo Findings

- Ventricular and/or atrial septal shift from mid-line
- Intracardiac shunt
- Excessive increase in cannula velocities
- Mechanical cannula obstruction
- Cannula suction event
- Worsening aortic or mitral regurgitation
- Cardiac thrombus
- Pericardial hematoma/effusion, with or without tamponade
- RV dysfunction (multiple parameters in aggregate)
  - Enlarged RV cavity size
  - RV systolic dysfunction (quantitative, if possible)
  - Moderate or severe TR
  - Elevated RA pressure

LV, Left ventricular; *LVAD,* left ventricular assist device; *RA,* right atrial; *RV,* right ventricular; *RVOT,* right ventricular outflow tract; *TEE,* transesophageal echocardiography; *TR,* tricuspid regurgitation; *TTE,* transthoracic echocardiography; *VTI,* velocity-time integral.

Refer to Table 2 for guidance regarding the possible implications of abnormal / "red-flag" findings.

Appendix F LVAD Optimization/Ramp Echo Protocol

Perform baseline LVAD surveillance study (annotate BP, pump type, baseline pump speed)
At baseline pump speed, acquire the following:

- LVIDd in the parasternal long-axis view
- RV VTI (to calculate cardiac output) in the parasternal short-axis view
- AV opening by 2D and M-mode in the parasternal long-axis view (color Doppler M-mode if needed)
- 2D imaging in the parasternal long- and short-axis views
- Color Doppler examination of AR and MR in the parasternal long-axis and apical views
- Color Doppler examination of TR in the RV inflow and apical four-chamber view
- Standard mitral valve PW Doppler inflow parameters
- Positioning of the interventricular and interatrial septa

Decrease pump speed to as low as 8000 rpm (for HM-II)

or

Decrease pump speed to as low as 2400 rpm (for HVAD)

- Wait 2 minutes
- Repeat data acquisition

Increase pump speed by 400 rpm (for HM-II)

or

Increase pump speed by 20-40 rpm (for HVAD)

- Wait 2 minutes
- Repeat data acquisition

HM-II:

Continue to increase pump speed in **400-rpm** increments to a pump speed of up to **12,000 rpm** or until endpoint (below), acquiring data at each stage

HVAD:

Continue to increase pump speed in **20-40 rpm** increments to a pump speed of up to **3,200 rpm**, or until endpoint (below), acquiring data at each stage

Endpoints

- Completion of test
- Suction event: decrease in LV size (typically <3 cm), +/- ventricular ectopy, +/- inflow- cannula intermittent obstruction, leftward ventricular septal shift, worsening TR
- Symptoms including, but not limited to, palpitations, dizziness, chest pain, shortness of breath, or headache
- Hypertension (eg, MAP > 100 mm Hg or symptoms)
- Hypotension (eg, MAP < 60 mm Hg or symptoms)

2D, Two-dimensional; *AR,* aortic regurgitation; *AV,* aortic valve; *BP,* blood pressure; *HM-II,* HeartMate II; *HVAD,* HeartWare ventricular assist system; *LV,* left ventricular; *LVAD,* left ventricular assist device; *LVIDd,* left ventricular internal diameter at end-diastole; *MAP,* mean arterial pressure; *MR,* mitral regurgitation; *PLAX,* parasternal long-axis; *PW,* pulsed Doppler; *RV,* right ventricular; *TR,* tricuspid regurgitation; *TV,* tricuspid valve; *VTI,* velocity-time integral.

Note: Inflow-cannula color and spectral Doppler (including CW Doppler) should be evaluated at each pump speed to test for obstruction. Outflow-graft Doppler evaluation is needed at baseline but is optional at speed changes if LVAD function is normal. When abnormal conditions are being evaluated, additional parameters may be assessed when possible, such as outflow-graft velocity profile/stroke volume (eg, for obstruction or to assess AR volume) and outflow-graft–to–aortic anastomosis to assess obstruction or flow reversal.

Appendix G Speed Changes: LVAD Optimization or Problem-Focused (Ramp) Protocol Worksheet

Speed Changes: LVAD Optimization or Problem-Focused (Ramp) Protocol Worksheet

CF-LVAD type: **Implant date:** **[PT INR = _____ PTT = _____]**

Previous echo exam date and significant findings:

- ***Optimization protocol*.** Optimal speed based on MCS center's own standard; sample order sets include the following: (a) Attain at least intermittent AV opening, *or* (b) attain neutral IVS position and/or mild or less MR, *or* (c) attain complete AV closure to maximize LV unloading *or* (d) adjust speed to below the maximum speed associated with complete AV closure and the minimum speed associated with more prominent MR and rightward IVS.
- ***Problem-focused protocol.*** *Indication for exam*: Sample order sets include the following indications:

a. Smoldering left- and/or right-sided heart failure.
b. Screen for pump function in setting of hemolysis and suspected pump thrombosis.
c. Other LVAD-alarm trouble-shooting.

Pump Speed (rpm)	BP	AV Opening (y/n/intermittent)	LVIDd (cm)	RVOT VTI (cm)	Signif AR (y/n)	Signif MR (y/n)	Signif TR (y/n)	TR Velocity (m/s)	MV Peak E Velocity (m/sec), DT (ms)	IVS Direction L/R/Neutral	a. Symptoms (y/n) b. Evidence of Inflow-Cannula Obstruction (y/n)

Reason for termination: (eg, signs of inflow-cannula obstruction, hypotension, hypertension, worsening RV or LV function, etc.)
Final speed setting = ____ rpm
Final BP = _____ mmHg

AR, Aortic regurgitation; *AV,* aortic valve; *BP,* blood pressure; *CF,* continuous-flow; *DT,* deceleration time; *E,* early diastole; *INR,* international normalized ratio; *IVS,* interventricular septum; *LV,* left ventricular; *LVAD,* left ventricular assist device; *LVIDd,* left ventricular internal diameter at end-diastole; *MCS,* mechanical circulatory support; *MR,* mitral regurgitation; *MV,* mitral valve; *PT,* prothrombin time; *PTT,* partial thromboplastin time; *RVOT,* right ventricular outflow tract; *TR,* tricuspid regurgitation; *VTI,* velocity-time integral.
Note: Parameters measured at each speed setting may vary according to an implant center's internal standards. After examination at the baseline pump speed, most of the needed parameters at subsequent pump speeds may be obtained primarily from parasternal views in most cases, as a limited exam.

Appendix H LVAD Recovery Protocol Worksheet

LVAD Recovery Protocol Worksheet

CF-LVAD type: **Implant date:**

Previous echo exam date and significant findings:

PT INR = _____(ensure ≥2.0); PTT = _____(heparin to be used if INR is <2.0 per institutional protocol)

Baseline speed setting = _____rpm;

Low speed testing target achieved:

6000 rpm (HM-II) by increments of 1000 rpm from baseline

1800 rpm (HVAD) by increments of 100 rpm from baseline

Echocardiographic Measurements

Pump Speed (rpm)	BP	Direction of Inflow-Cannula/Outflow-Graft Flow: Forward (f) Neutral (n) Reverse (r)	AV Opening (y/n/intermittent) vs miliseconds (M-mode)	LVEF	LVIDd (cm)	RV systolic function normal? (y/n)	RV size normal (y/n)	RVOT VTI (cm)	Signif AR (y/n)	Signif MR (y/n)	Signif TR (y/n)/TR Velocity (m/s)	MV Peak E Velocity (m/s), DT (ms)	Exercise Test (y/n)	Symptoms (y/n)

Baseline pump speed Low pump speed At intervals per institutional standards	The above echo measurements will be obtained at baseline and low pump speed at different time intervals: i. After 5 min of low speed ii. After 15 min of low speed iii. After 6-min walk*
Hemodynamic measurements (rest ± exercise) per institutional standards	eg, systolic BP, diastolic BP, mean BP, HR, and Swan-Ganz catheter measurements at the following intervals: i. Baseline rpm ii. 0 min of low speed iii. 5 min of low speed iv. 10 min of low speed v. 15 min of low speed vi. After 6-min walk at low speed
Reason for termination (circle)	Shortness of breath, chest pain, blurred vision, dizziness, abdominal pain (perform 12-lead ECG if chest pain is noted)

Final speed setting = ____ rpm
Final BP = _____ mmHg
Final clinical status:

AR, Aortic regurgitation; *AV,* aortic valve; *BP,* blood pressure; *CF,* continuous-flow; *DT,* deceleration time; *E,* early diastole; *ECG,* electrocardiography; *HM-II,* HeartMate left ventricular assist device; *HR,* heart rate; *HVAD,* HeartWare ventricular assist system; *INR,* international normalized ratio; *IVS,* interventricular septum; *LV,* left ventricular; *LVAD,* left ventricular assist device; *LVEF,* left ventricular ejection fraction; *LVIDd,* left ventricular internal diameter at end-diastole; *MCS,* mechanical circulatory support; *MR,* mitral regurgitation; *MS,* mitral stenosis; *MV,* mitral valve; *PT,* prothrombin time; *PTT,* partial thromboplastin time; *RVOT,* right ventricular outflow tract; *TR,* tricuspid regurgitation; *VTI,* velocity-time integral.

Note: Parameters measured at each speed setting and the type and timing of physiologic/exercise testing performed may vary according to an implant center's internal standards. After examination at the baseline pump speed, most of the needed parameters at subsequent pump speeds may be obtained primarily from parasternal views in most cases, as a limited exam. If a quantitative LVEF (preferred) is not obtainable, a qualitative LVEF should be provided.

*Institutional standards regarding spare batteries, second controller availability, and alarm-off mode settings should be followed and confirmed with the LVAD team.