ASE 临床实践指南 超声心动图指导下的介入治疗

ASE RECOMMENDATIONS FOR CLINICAL PRACTICE

Echocardiography-Guided Interventions

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关键词: 超声心动图, 心脏超声, 经食道超声心动图, 心内超声心动图,3维超声心动图, 先天性心脏病, 心包穿刺术, 穿隔导管术, 心肌活检, 经皮经静脉球囊瓣膜成形术, 房间隔缺损,卵圆孔未闭, 肥厚型心肌病, 酒精室间隔消融术, 心脏电生理, 左心耳封闭术

I. 摘要

相对于其他先进的影像技术（磁共振，CTA），超声心动图的主要优势在于它的可移动性和实时性。超声心动图操作可以在床边，导管室，心血管监护病房，急诊室进行，任何地方只要能容得下一个小推车就可以进行操作。这一特殊的优势，使其能在各种手术，包括介

入手术的术前，术中，和术后即刻进行检查。本篇报告的目的旨在为超声心动图对介入手术的指导作一综述。我们为介入术前患者的选择提供依据，术中进行监测，术后评估介入疗效。

本文涉及了超声心动图最常应用的一些手术：穿隔导管术，心包穿刺术，心肌活检，经皮经静脉球囊瓣膜成形术，房间隔缺损及卵圆孔未闭的导管封堵术，肥厚型心肌病酒精室间隔消融术，心脏电生理。结论部分涉及了目前还在研究阶段，但将很快进入实践领域的介入手术：复杂二尖瓣修补术，左心耳封闭术，三维超声引导，经皮主动脉瓣置换术。

应用超声心动图选择和指导心室再同步化手术的内容已发表在ASE的单独文献上，在此不作赘述。

即使是业已成熟的手术，在术中应用影像学技术指导，也将改善其有效性和安全性。

表1介入手术：使用超声心动图指导

介入手术	TTE	TEE	ICE
穿隔导管术	+	++	++（径向或者相控心内超声）

PMBV (经皮经静脉二尖瓣球囊成形术)	++	+++	++
房间隔缺损，室间隔缺损及卵圆孔未闭的导管封堵术	+	++	++（相控心内超声）
肥厚型梗阻性心肌病酒精室间隔消融术	++	++	−
经皮二尖瓣修补术	+	+++	+
经皮左室辅助装置植入术	−	++	++
经皮人工主动脉瓣置入术	−	+	+
球囊或刀头房间隔造口术	++	++	++
左心耳封闭器的放置	−	++	++
心肌血管内活检	++	++	++（相控心内超声）
先天性心脏病治疗（Fontan手术，缩窄修复）	+	+	+
主动脉腔内植入术	−	−	+（径向或者相控心

	内超 声）

-，文献中未见报道或获益； +，有使用报道，存在获益，但还需进一步研究；++，使用有益处；+++，作用与获益有明确报道

II. 介绍

传统的经皮心血管介入手术通过血管造影，放射透视来指导，而当涉及心肌，心包，心瓣膜时，这一作用就有限了。

本报告的目的在于（1）划定超声心动图在各类介入手术和电生理手术中的指导作用，（2）讨论这些手术中的超声心动图相关问题，（3）利用现有数据，比较经胸，经食道，心内超声心动图在术中使用的不同之处。对于心内超声心动图我们会适当强调，因为该项检查是最新的超声心动图手段，读者可能不清楚它的潜在应用价值。表1提供各种超声心动图手段在不同手术中应用的文献总结。本报告目的不在于提供如何进行手术操作的详细方法，手术操作细则详见参考文献。本文希望阐明超声心动图对手术操作和手术结果的重要影响。每一节的最后，我们都会给出黑体字的总结和建议。

随着心脏病经皮介入手术的不断发展，术中超声心动图导引技术也在迅速跟进。本文加入了一节关于未来发展方向的内容，作为目前资料的补充。类似的，其他影像学方法，如磁共振成像，多种技术联合成像（例如，3维CT重建联合实时超声心动图）在复杂手术中的应用，都将不断发展完善。

III. 成像概述

A. 经胸超声心动图（TTE）

TTE 图像清晰，操作便捷，广泛应用于各种非冠脉介入手术及电生理手术。现有的超声系统，包括手持和便携式超声系统，都可为各种介入手术提供清晰的2维和多普勒超声图像， 例如，超声引导下的心包穿刺，肥厚型心肌病室间隔酒精消融术，经皮二尖瓣球囊成形术（PBMV）， 以及心肌活检。组织多普勒技术的发展，TTE在优化双心室起搏中尤为重要。

B. 经食道超声心动图（TEE）

TEE替代TTE广泛应用于复杂手术指导。TEE相对于TTE图像分辨率更好，可作为多种手术的监护，例如，间隔缺损的经皮导管封堵，PBMW，穿隔导管术等等。与TTE相比，它对术中解剖结构，生理评估，导管位置和接触的检测,并发症的排查,如血栓,心包积液等的效果更优异。

C.心内超声心动图（ICE）

ICE是较新的一项心脏超声应用，对介入手术的监测和指导有很大的潜在价值。实验研究和临床研究业已证明ICE的用途，它可用来监测左右心室的功能，判定解剖结构，指导间隔穿刺和治疗，以及心脏占位的心肌活检。[1-13] ICE提供的图像可以与TEE相媲美甚至优于TEE。在房颤的射频消融和房间隔缺损封堵术中，已证实使用ICE有更多获益，许多中心已将其列为该类手术的影像学标准。[14-25] 在导管室，术中ICE优于TEE的方面在于，它不需要全麻，不需要额外超声心动图医生支

持。与TEE相比，使用ICE可以提高患者舒适度，缩短手术时间及放射暴露时间，所需费用也与TEE相当。[15-17,25,28,29] ICE还可应用于指导穿隔导管术，左心耳封堵器的放置，左室辅助装置经皮套管植入，PBMV等手术。对于TEE有绝对禁忌症的患者（如食道癌切除术后），或者TEE无法显示解剖结构（如气道遮挡导致的TEE盲区使升主动脉无法清晰显示），心内影像学诊断可以替代TEE检查。表2列举了ICE的风险。

表2　ICE的潜在风险

血管
ℓ　导管穿刺处有创伤
ℓ　出血
ℓ　血肿
ℓ　腹膜后出血
ℓ　静脉穿孔
心脏穿孔
ℓ　心包积液
ℓ　心包填塞
心律失常
ℓ　房性早搏
房颤
ℓ　室性早搏室速
ℓ　心脏传导阻滞
血栓栓塞

ℓ 静脉

ℓ 动脉

皮神经麻痹

IV.超声心动图在穿隔导管术中的应用

穿隔导管术用于需要进入左房的介入手术，如PBMV，主动脉瓣球囊成形术，房颤及其他左心来源心律失常的射频消融，卵圆孔未闭穿隔封堵术，左室辅助装置套管的置入，球囊或刀头房间隔造口术，复杂的血流动力学检查（如，主动脉机械瓣或重度主动脉瓣狭窄，无法过瓣的评估）。最近有研究应用于左心耳封堵器放置以及经皮二尖瓣修补术，以往透视影像指导不能直接显示一些解剖结构。

观察性研究显示，TTE或TEE由于能直观的提供穿隔导管与卵圆孔的位置关系因而可能有助于该类手术。虽然TTE/TEE对于成功的穿隔导管术并非不可或缺，但是超声心动图的确提供了优于传统透视的指导作用。[7,30,41-50] 解剖结构的变异，卵圆孔的寻找以及周边结构的确认，即使对于穿隔经验非常丰富的心脏介入医师，也是一个挑战。借助超声影像，能提高安全性，降低穿到卵圆窝邻近组织的风险，减少误伤主动脉的风险。同样，超声影像可缩短术中穿隔所用的时间及透视时间。对于怀孕的PBMV患者，超声心动图指导，可以减少患者放射暴露时间及穿隔时间。[43] 超声影像还可以帮助穿隔经验缺乏的手术者，进行学习。

TTE指导穿隔手术的早期研究表明，TTE能明确卵圆孔周围的主动脉，

房间隔结构，在房间隔穿刺前良好定位。[49] TTE加生理盐水超声造影有助于确认穿刺针穿刺前在右房的位置，穿刺后在左房的位置。当TTE无法提供满意的影像指导穿隔导管术时，可以用TEE和ICE确定准确的间隔穿刺位置。这在二尖瓣反流的介入治疗中尤为重要，因为如果穿刺点过于靠近二尖瓣环平面，手术操作和定位就会更加困难。由于ICE不需要镇静和全麻，许多中心将其作为穿隔手术影像学检查的标准配置。[7,30,42,43,45,48,50,51] 穿隔手术中，穿刺前在ICE的导引下确定房间隔及穿隔鞘的位置（图1）。穿隔手术中，可能发生主动脉，肺动脉，心房壁的穿孔。当穿刺针穿过间隔时，注射少量微气泡或造影剂，可以用来证实左房的路径（图2）。最后，在ICE的导引下在在房内置入导引导丝，建立稳定的左房通路（图3）。

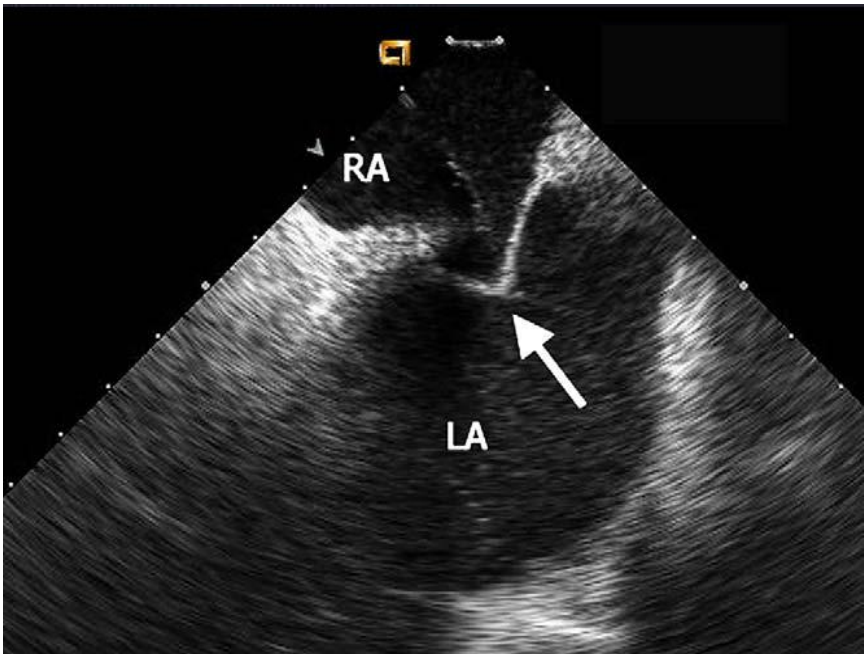

图1 ICE.右房 Phased-array ICE， 穿隔手术前，证实卵圆窝的隆起朝向左房。右房内可见导管长度。

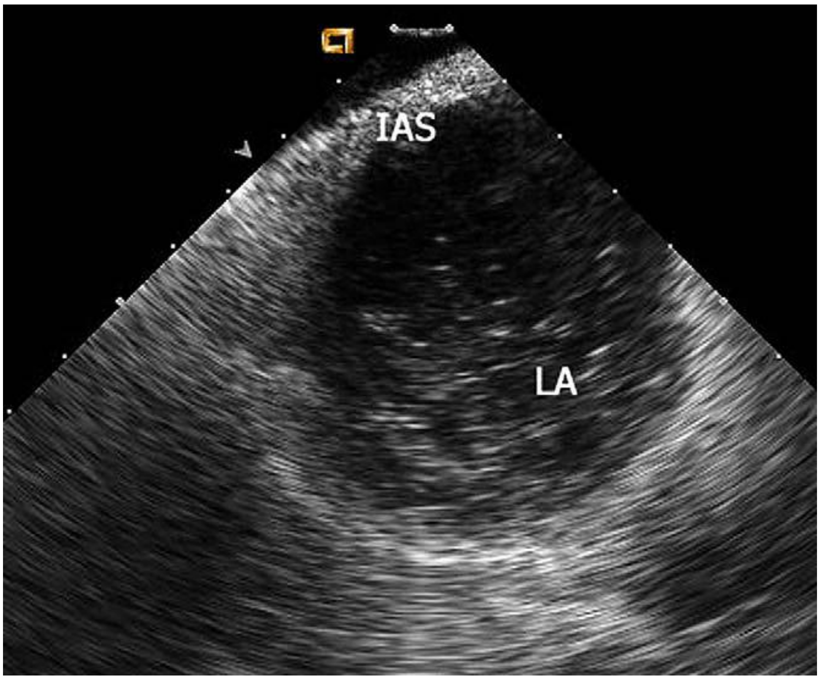

图 2 ICE. 注射少量生理盐水微气泡确认进入左房（LA）。心内超声导管正放在房间隔。

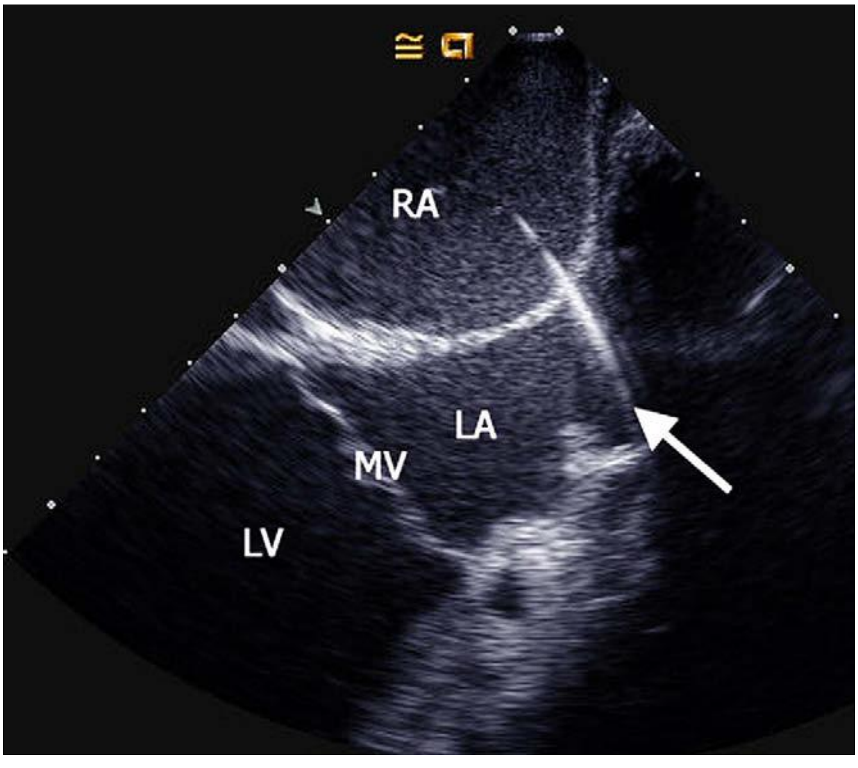

图 3 ICE. 右房左房内可见导引导丝长度，已进入肺静脉（箭头所指），远场可见二尖瓣和左室。

超声心动图可以提高穿隔手术的安全性。虽然没有规定所有手术必须采用，但是目前已经得到推荐。ICE的优点在于穿隔手术操作中不需要超声心动图技师的支持。

V. 超声心动图指导下的心包穿刺

，透视指导和心电图针监测曾用提高心包穿刺的安全性[51, 53]，但是仍有并发症发生的报道，并发症包括肝脏损伤，心肌，冠状动脉，以及肺的损伤。[54]

A. 超声心动图指导下的心包穿刺的安全性和有效性

Mayo Clinic的一项系列研究发现，在超声心动图引导下进行心包穿刺引流心包积液用于治疗心包填塞，其成功率为97%。[55] 1.2%的患者出现重大并发症（包括：心腔损伤，肋间血管损伤，需要胸腔置管的气胸，持续性室性心动过速（VT）、菌血症和死亡），3.2%的患者有轻微并发症（包括：短暂性心腔的进入，短暂性心律失常，小气胸、血管迷走反应）[55] 在多个亚组中，包括儿科患者；[56] 继发于介入治疗心肌穿孔，血流动力学极不稳定的患者；[57] 术后患者；[58]以及恶性肿瘤患者[59]和结缔组织病患者。[60]超声心动图指导下心包穿刺均显示出其安全性和有效性，

B. 超声心动图指导心包穿刺的技巧

以下指南仅针对超声心动图指导心包穿刺的一些关键部分，其他详细的操作内容见参考文献。二维超声及多普勒检查确定深度，分布和积液对血流动力学的影响，从而决定心包穿刺点和穿刺轨迹。理想的心包穿刺点是积液最多，最靠近体表，穿刺轨迹为直线，能避开重要脏器。因为超声无法穿透气体，所以肺可以有效的避开。为提高安全性，应使用穿刺鞘针，进入液体区域后，回撤穿刺针。左胸壁是常用的穿刺部位，[55] 剑突下穿刺路径较长，经过肝包膜的前方，直接朝向右心。为了确定导管是否在心包腔内，可以注射生理盐水微气泡。这一方法也可用于抽吸出血性液体时或导管位置有疑问的情况。心包腔内出现造影剂即可明确导管位置（图4）。如果导管不在心包腔内，就必须重置或尝试别的穿刺通路。当引流量减少（一般24小时<25 mL），随访超声心动图没有明显的残余积液时，留置导管可予以撤除。

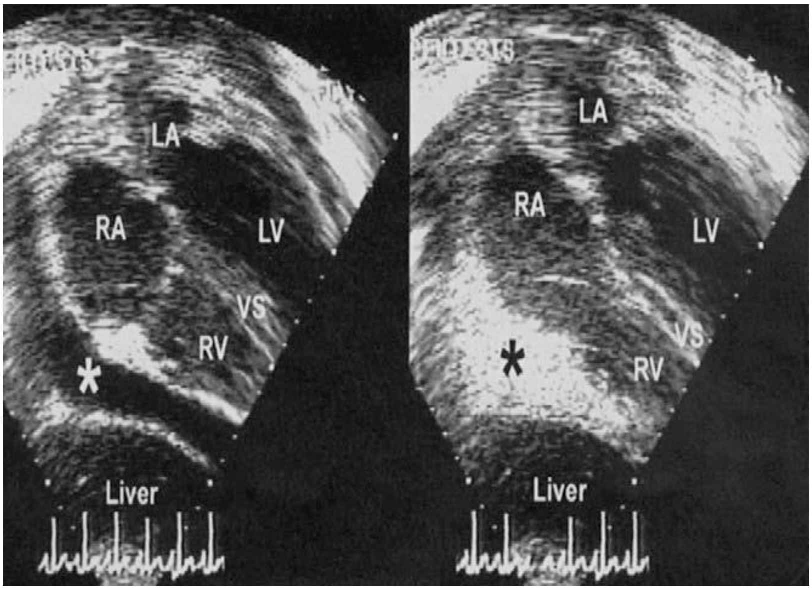

图 4 TTE. 心包穿刺时，注入生理盐水微气泡以明确穿刺针的位置，生理盐水造影剂注入后，心包腔显影（星号所指）LA，左房；LV，左

室；RV，右室；RA，右房；VS，室间隔。

C. 注意事项及禁忌症

超声心动图指导下心包穿刺的禁忌症很少，而且需要在个案基础上进行评估。理论上说，心包穿刺的禁忌症有心脏破裂或主动脉夹层，因为减压可能引起破裂或夹层的扩大。[61]

超声心动图指导下的心包穿刺和心包引流，可以在有操作条件（具有经验丰富的操作者）的中心，安全有效的开展。使用超声心动图指导手术可以避免透视的放射线，并可以在导管室，床旁或者超声室内进行操作。与外科手术相比，这项操作增加了安全性，显著降低了费用，因此超声心动图指导下的心包穿刺是理想的选择。

VI. 使用超声心动图指导心肌活检

心肌活检通常在右室进行，用于心肌疾病的诊断，包括浸润性心肌病，心脏移植的排斥检测。虽然心肌活检一般仅使用透视指导，但是有的中心采用二维TTE辅助或替代透视。[62-66] 与此类似，也有报道在患者中选择性地采用TEE或ICE指导右心及主动脉肿块的活检。[10,67-69]

超声心动图的指导可能为心肌活检提供更多的活检部位。除室间隔外，右室心尖部和游离壁也可以进行活检。并且这一措施可以减少活检中由于在同一部位取材（室间隔中部）而出现纤维样本。这一操作还可以减少穿孔的发生及三尖瓣的损伤。[66] 超声心动图指导心肌活检的优

势还在于能减少放射暴露以及操作方便。

TTE指导右室活检的理想切面包括，心尖四腔心和剑突下四腔心（图5，6）。探头尽量靠近内侧（锁骨中线），以使右室在活检过程中尽可能良好显示。TEE的理想切面为食道中段四腔心，及经胃短轴和长轴切面。

ICE既可以从右房也可以从右室对右心活检进行指导。但是应注意导管的顶端不一定总是能看见。

超声心动图指导心肌活检的其他局限性包括：在导管室仰卧位患者TTE操作困难，有胸部引流管或绷带的患者，肥胖患者，慢性肺病患者，很难获得清晰的图像。TEE和ICE可以克服这些影像局限性，但是需要超声心动图技师的支持、镇静（TEE），往往有额外的花费以及血管并发症的风险（ICE）。

超声心动图，特别是TTE，已成为心内或血管内活检的辅助影像工具。虽然TEE和ICE的图像优于TTE，但是需要权衡其增加的风险和费用，故仅推荐用于严格筛选的患者。

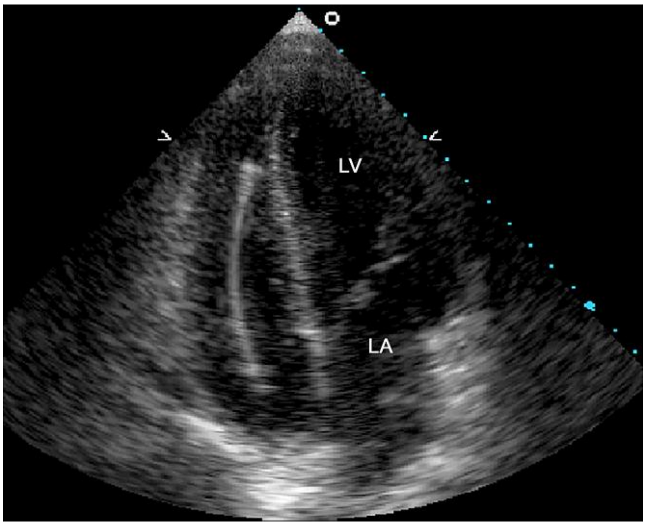

图 5 TTE. 心尖四腔心切面显示，位于右室内的活检钳沿着室间隔走

行。LA，左房；LV，左室。

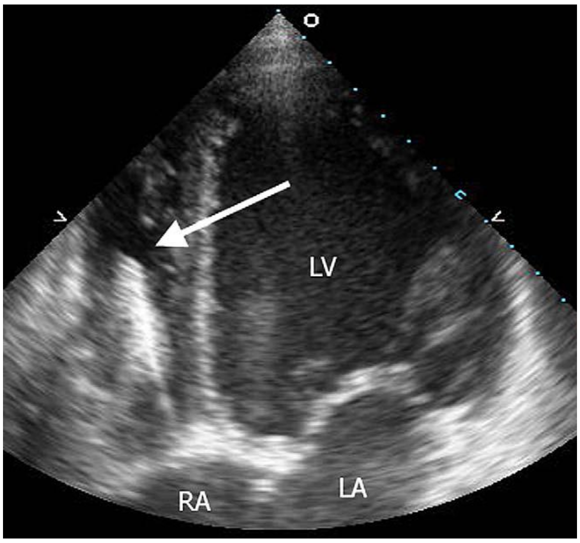

图6TTE. 心尖四腔心切面显示，活检钳（箭头所指）位置不良，在右室内呈游离状态。超声心动图可用于确认非理想的活检位置并重新定位活检钳。但是，注意导管的顶端不一定总是能看到。LA，左房；LV，左室；RA，右房。

VII. 超声心动图指导经皮经静脉二尖瓣球囊成形术

A. 影像学总体考虑

PBMV在很多中心都是仅用透视指导的，但是即使是经验丰富的术者，有时也会被放射学的解剖标志误导，Kronzon等[49]推荐在PBMV手术导管穿隔时，使用二维TTE（心尖四腔心切面和胸骨旁短轴观）作为透视的有效辅助。Pandian等[70] 还建议用剑突下切面辅助PBMV手术。TTE的缺点包括中断手术流程，可能影响无菌操作，以及部分患者图像不满意。

TEE也可用于指导PBMV[71-75] (S. A. Goldstein, 个人观点)，无论是术前还是术中都是成熟的技术。TEE可用于患者的选择[76,77]，术中各方面

的指导[71-75] (S. A. Goldstein, 个人观点)，它多用于指导穿隔导管术，从这一点来说一般优于TTE。TEE在排除左房或左心耳血栓方面也优于TTE，在球囊扩张前及扩张时可确定导丝和球囊的位置（图7）。TEE可以用来测量二尖瓣跨瓣压，二尖瓣面积，评估每一次球囊扩张后即刻二尖瓣反流的程度。最后，TEE还可以用于发现PBMV的并发症，例如重度的二尖瓣反流，心包积液或心包填塞，血栓脱落和残余房间隔缺损。另外，有的作者认为现场使用TEE可以缩短透视时间和手术时间，改善效果[71-75] (S. A. Goldstein, 个人观点图 7 TEE. 食道中部四腔心切面显示：瓣膜成形球囊（箭头所指）已充盈并跨过二尖瓣。LA，左房；RA，右房。

ICE是PBMV实时指导的另一个选择。[32,48,78] 它能良好的显示卵圆窝，指导间隔穿刺。[48] 新一代的相控心内超声导管，有脉冲多普勒，连续多普勒，彩色血流多普勒，及组织多普勒成像。这样，和TEE与TTE一样，ICE也能完成瓣膜成形术后即刻的效果评估，包括二尖瓣跨瓣压，二尖瓣面积，是否有二尖瓣反流或反流加重，发现并发症，如心脏穿孔，心包填塞，二尖瓣撕裂。和TEE一样，ICE不会干扰心导管手术，可用于二尖瓣成形术的每一个环节。[32,78] ICE与TTE和TEE相比的价值所在尚未明确。费用问题需要考虑，因为一个相控心内超声导管大约需要$2500到$3000，每个导管最多只能用三次。ICE对左侧结构的显示可能优于或劣于TTE和TEE，这要取决于导管位于哪个腔室。心内超声导管在右房时，左心耳不能良好显示，无法判定是否有血栓存在。从左房或肺动脉采图可以克服这个局限性。另一方面，ICE与TEE和TTE相

比，空间分辨率更高，能显示腱索、乳头肌等二尖瓣瓣架结构。[78] 图像要传输到监视器，能让术者方便看到，一般设在透视监视器旁边。

B. 即刻评估疗效

术中实时超声心动图适合评估PBMV的即刻疗效。[7] 通过评估二尖瓣叶的最大分离度，通过连续多普勒测定二尖瓣平均跨瓣压和二尖瓣口面积，可以判定瓣膜分离术是否充分。TEE 和 ICE 还可以测量肺静脉血流，成功的PBMV可以看到舒张期的减速加快。[79] 最后， 彩色多普勒还可以检出新发的或加重的二尖瓣反流。基于超声心动图的结果和血流动力学的参数，以决定手术是否充分，是否需要进一步扩张。

C. 早期发现并发症

虽然PBMV严重并发症并不常见，但是仍有发。术中实时超声心动图可以准确快速的发现大多数并发症。（例如出现重度二尖瓣反流，心肌穿孔，心包填塞，ASDs）PBMV术后，大约半数的患者会有二尖瓣反流的加重[49,70,80,81](S. A. Goldstein, 个人观点). 大多数是轻度反流，重度二尖瓣反流的发生率是1%到6%。[74] 急性重度二尖瓣反流的原因可能为二尖瓣瓣叶撕裂破损，腱索断裂，或更为少见的乳头肌撕脱。[82] 这些状况超声心动图都能探查到，尤其是TEE或ICE。而且，二尖瓣反流的探查和严重程度的确定，不需要左室造影即可完成。心包填塞在PBMV术中的发生率在0%到9%。[74,83] 房间隔穿刺时，心房游离壁的穿孔是心包积血的最常见原因。超声心动图可以即刻发现这类积液，及时心包穿刺可避免血流动力学的恶化。左室穿孔亦有报道，尤其是使用双球囊技术。实时TEE可以及时发现这一威胁生命的并发症。[83]房间隔

缺损的发生率报道差异较大，取决于使用何种探查手段。使用血氧饱和度探查左向右分流的结果是8%到25%的患者有分流，[73] TTE在PBMV术后探查结果是15%到60%的患者有房内分流，TEE作为更为敏感的技术，探查结果是90%的患者有分流。ICE能良好的显示卵圆窝，其敏感性应该相似。由于缺损往往很小，而这些患者的左房压力高，所以小的左向右分流在TEE或ICE的彩色多普勒上很容易看到。这类小房缺应该归结为患者手术的结果之一而非并发症。

D. 局限性

多个学者指出，PBMV术后即刻，通过多普勒测二尖瓣压力半降时间估测二尖瓣口面积要慎重，因为与心导管测得的血流动力学参数一致性不高。这一差异可能与左房和左室急性顺应性改变以及二尖瓣早期血流峰值阶差下降有关。

E. 对结果的影响

术中使用超声心动图指导可以改善手术成功率和并发症的发生率。[84,85] 实时影像可以更精确的将穿刺针定位于卵圆窝，这样就减少了穿孔的可能性。[75,83,86,87] 而且，影像不仅可以减少并发症的风险，一旦发生并发症亦可及时发现，正确补救。另外，用超声心动图指导可以减少手术及透视时间。[83] (S. A. Goldstein, 个人观点). Park 等[83] 对比了PBMV手术中，只用透视指导（n = 64）和用现场食道内超声心动图指导（n = 70）的患者，发现后者的手术时间明显缩短（99±48 vs 64±22 分钟; P < .0001）。平均透视时间TEE组也较短（30±17 vs 19±15 分钟），但是没有统计学差异（P =0.25）。超声心动图的指

导可以更好的评估球囊扩张的次数，优化球囊导管的位置，从而可以减低二尖瓣反流加重的风险。在PBMV手术指导中，超声心动图作为透视的补充或替代，其安全性和有效性还将进一步研究。

超声心动图可以为经皮球囊瓣膜成形术治疗二尖瓣狭窄，提供有益帮助，推荐用于患者的选择和疗效评估。与透视相比，术中实时超声心动图指导能更好的监测手术效果和并发症。TEE也可用于指导手术操作。术前已经做过TEE的患者，推荐使用TTE作为手术指导，监测并发症，评估手术结果。ICE可用于手术指导，所提供的影像与TEE相当。

VIII. 超声心动图指导房间隔缺损（ASD）及卵圆孔未闭（PFO）封堵术

A. 介绍

房间隔缺损和卵圆孔未闭的经皮导管封堵术已经成为越来越有吸引力的治疗手段，以替代外科修补手术。 这些手术被广泛应用于治疗血流动力学上明显的左向右分流情况，以防止反复发生的反常性血栓栓塞以及平卧呼吸直立（platypnea-orthodeoxia）综合征。用于指导ASDs和PFO的经皮导管封堵术的方法有很多，但每种方法都有它所特有的优缺点。这些方法包括最早的透视指引和超声心动图指引，如TTE、TEE和最近兴起的ICE。[15, 17, 20, 25, 27, 29, 88-90]

B. 超声心动图方法

TTE、TEE和ICE均可用于评估和指导PFOs和ASDs的经皮导管封堵。TTE的优势在于可以提供多个切面来评估封堵器和房间隔，但是它的劣势

在于在封堵器植入后，它不能探查清下腔静脉上方的房间隔组织下缘，因为封堵器几乎从各个层面都干扰成像。另外，因为房间隔离探头相对较远（相对TEE和ICE而言），所以在体型较大的病人中彩色成像效果往往欠佳。然而一些中心仍使用TTE监测所有的病人。在成年患者中，TTE通常提供房间隔及其周围结构的图像往往更为受限，因此大多数成人心脏中心通常会应用TEE和ICE指导PTC。

经食道超声引导被广泛地使用于成人患者，因为其优势在于能够提供实时的、非常详细的房间隔、周围结构、导管和封堵器的图像。[15,20,25]然而，TEE需要将患者镇静，这将增加仰卧病人误吸的风险，或者需要全身麻醉，应用气道内插管将降低此类风险。因此要求在介入医师进行封堵手术的同时，需要有一名经验丰富的超声技师操作TEE。同样，如果患者需要全身麻醉时，则还需要有麻醉支持人员在场。

ICE也可提供与TEE相媲美的房间隔及其周围结构的图像，但不需要额外的镇静或全身麻醉。目前可用的心内超声系统提供一次性使用的8F-10F的机械或者相控心内超声导管，需要有单独的8F-11F的静脉径路。更新、更小口径导管的发明使ICE技术可以应用于年龄更小的儿科患者。另外，ICE不仅使成人患者避免了行全身麻醉的需要，而且可能减少额外超声心动图支持的需要，因为术者在进行PTC手术时候可以同时操作导管。然而在一些中心，仍然需要额外的超声心动图专家在术中协助ICE。这样特别有助于缺损较大的患者，因为此类病人发生放置不良或栓塞的风险更大。对于这些病人，封堵器放置过程中持续应用超声心动图进行监测可以避免手术并发症。

与TEE相比较，ICE指导PTC的其他优势在于可以缩短手术和透视时间，提高成像质量，并提供更多的诊断信息，正因为如此，它正在成为评估房间隔和指导PTC手术的标准成像方法。[15,17,20,27,29,88] ICE可以作为主要的成像方法，不需要TTE或TEE的补充。目前，ICE的手术费用与全麻下TEE指导房间隔封堵术的费用相当。[15,17,20,25,27,29,88,89,91]

C.手术的总体考虑

目前有许多不同的封堵器可用于PTC，每一种封堵器的植入方法都是有所不同和独特的。所有封堵器的封堵机制均包括填补缺损、随后的血栓形成以及沿着房间隔的新生内皮化。

术前房间隔评估包括评估整个房间隔及其周围结构。卵圆孔未闭的定义是通过卵圆孔的任何解剖学上的左、右心房共通，扩展的卵圆孔未闭的定义是，彩色多普勒成像发现休息时或间歇性左向右血流（图8）。PFO的右向左分流一般是在静息和做一些激惹性的动作如Valsalva动作时，通过注入微气泡生理盐水证实。房间隔膨出瘤常被定义为基底为15毫米的房间隔组织向左侧或右侧共膨出11-15毫米。

超声心动图能够确定ASD的类型（原发孔型、继发孔型、静脉窦型或冠脉静脉窦型），ASD的最大直径，以及多发性缺损的缺损数量。目前只有继发孔型房间隔缺损适合行PTC手术，而且如果房间隔缺损呈筛状，以目前可供使用的封堵器也不能施以PTC手术。直径在40mm以内的缺损可以通过PTC手术成功封堵，包括多发性房缺或合并有房间隔膨出瘤的病例。合并有肺静脉、上下腔静脉、冠状窦和房室瓣异常的房间隔缺损需要除外。评估缺损周围房间隔组织边缘的尺寸对于判

断患者能否成功施行PTC手术至关重要，而且周围边缘为5毫米通常认为是足够的。尽管有少量报道为边缘不足的患者进行PTC手术并取得成功的案例，[90]但是为保证PTC手术的成功，上下边缘尤为重要。在年龄较小的患者中，评估间隔的总长度是重要的附带考虑因素，因为它可能限制了原本可以成功植入的封堵器的尺寸。[92]

超声心动图推荐用于指导PFO和ASDs的PTC手术。所有超声心动图方法都可以使用，但ICE的使用需要足够的专业知识。选择理想的超声心动图方法进行手术指导需要考虑多种因素，包括患者人群、特殊的解剖结构和当地的专业知识水平。

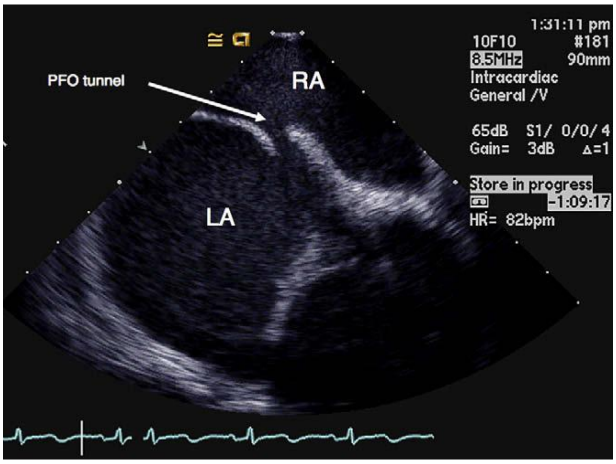

图 8 ICE. 相控 ICE 自右房 (RA), 显示房间隔膨出，形成巨大的PFO通向左房 (LA).

IX. 超声心动图指导肥厚型梗阻性心肌病的室间隔酒精消融

A. 简介

外科心肌切除术治疗有严重症状的肥厚梗阻性心肌病（HOCM）患者已有超过40年的历史。但是目前只有少数有经验的心脏中心可以进行此类手术并且其并发症和死亡率尚可接受。[93，94]房室顺序起搏是一个可

代替外科心肌切除术的方法，但在最初的成功后，随机对照试验发现，因为流出道压力梯度降低不足和缺乏持续的症状改善，使得治疗作用低于预期。[95]替代外科手术外的另一个选择是最近发明的酒精室间隔消融术。[96]这项技术是将酒精注入到左冠状动脉前降支的目标间隔穿支血管，以人为造成室间隔近端的心肌梗死。

1995年由Sigwrt第一次报道这个技术，[96]该技术通过使室间隔局部的心肌梗死，从而达到非外科方法使室间隔变薄的治疗目的。自从Sigwart引入这个技术之后，有许多其他的医疗团体应用并改良了该技术并取得较好的结果。[97-101]该技术最为重要的革新，或许是通过心肌声学造影去分辨个体前降支动脉的间隔穿支血管分布。事实上，使用心肌声学造影对该手术的成功至关重要。[102]

TTE是较为传统的方法，它在术中利用超声心动图监测经冠脉消融肥厚梗阻的室间隔心肌。有些导管室喜欢使用TEE，因为它可以提供比TTE更精确的左心室的主动脉下的解剖结构图像。[103]ICE是该手术过程中的第三种可供使用的图像选择。

B. 指导方法

因为室间隔散布着多条间隔穿支，这些间隔穿支存在着明显的个体差异，并在室间隔局部区域存在着重叠，所以准确地描述每个间隔穿支的血管分布区域对于决定哪根或哪些间隔支需要进行酒精注入至关重要。[104,105] 为了确认术者所确定的目标间隔穿支是正确的选择，术中应该使用心肌声学造影。在确定正确的球囊位置和球囊堵塞后的血流动力学效果以后，在TTE或TEE的连续监控下，将1-2ml经稀释的

超声造影剂和1-2ml生理盐水贯序地通过扩张的球囊导管注入靶血管中。超声造影剂需用生理盐水稀释以达到心肌最佳的显影化并减低其衰减的目的。稀释具体比例因所使用的造影剂的不同而不同。搅拌后的放射造影剂可作为超声造影剂的替代（图9）。

最为理想的室间隔基底段目标区域应当包括经彩色多普勒-评估的最大血流加速度的区域和该区域的SAM现象室间隔接触部位，而没有造影剂显影的任何其他心脏结构（图9-11）。在心肌声学造影确定了目标间隔穿支所灌注的区域为需要消融的室间隔基底段区域后，无水酒精就可以注入该目标间隔穿支了。

如果应用TTE，则需观察心尖四腔心切面和长轴三腔切面。这些切面的视图可能需要胸骨旁长轴和短轴切面的视图来补充。如果应用TEE，则需观察心尖四腔切面（在0°）和纵观切面（通常在120°-130°）。这些切面的视图可能需要经胃短轴切面的视图来补充，以帮助确定没有乳头肌被误灌注酒精的情况发生。经胃深部切面的图像类似于经胸心尖四腔心切面的图像，它可用于通过TEE测量心腔内压力梯度。

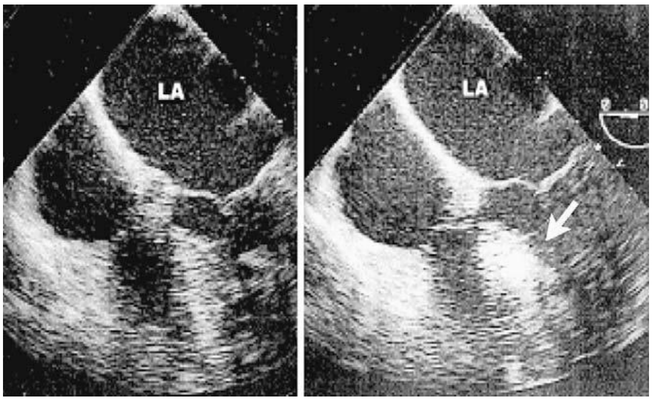

图 9 TEE. 食道中段四腔观，造影剂注入前（左）后（右）对照。（箭

头所指为造影剂）此例使用放射造影剂，可用于显示该患者所选间隔穿支的供血范围，这是超声造影剂的一种替代。

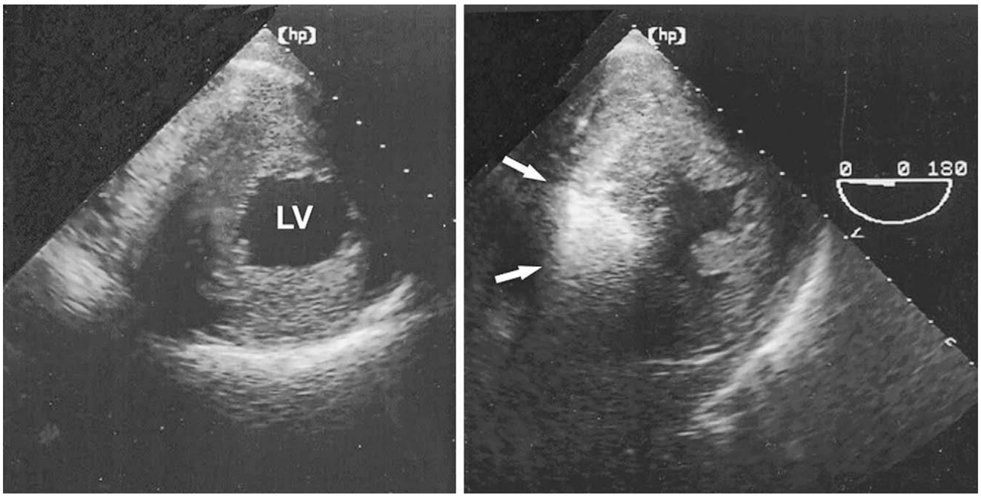

图10 TEE. 胃部短轴观，超声造影剂注入前（左）后（右）对照。（箭头所指为造影剂）显示了所选的间隔穿支的供血范围。超声造影剂不仅可以用来显示靶间隔穿支的供血区域，还可以排除不希望涉及的供血区域，如乳头肌、室间隔远端（心尖段）、右室。这一胃部短轴观尤其适合确认乳头肌。LV，左心室。

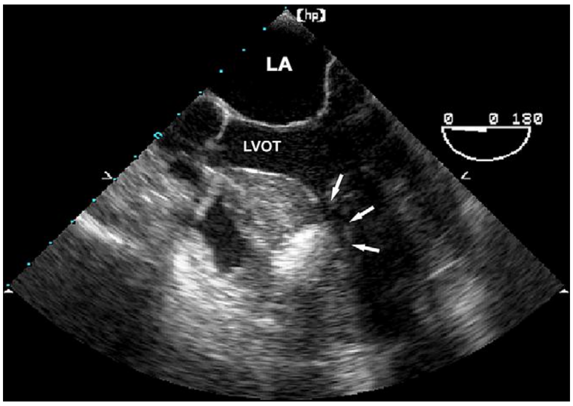

图11 TEE. 食道中段四腔观，造影剂（箭头所指）注入后，可见所选间隔穿支所的供血区域过于靠近心尖部，而非与二尖瓣相接触的部分。LA，左房； LVOT左室流出道

C. 即刻结果的评估

术中超声心动图有助于在导管室内评估手术结果。[103,105,106] 经注射无水酒精而发生梗死的室间隔基底段区域，通常有很强的回声密度，另外，这个室间隔区域的心肌厚度增加和收缩力均降低。[103] 二尖瓣前叶收缩期前移的现象应消失或改善，通常MR的程度也会减轻。另外，心腔内压力梯度也应降低或消失。此数据很容易由TTE测得，也常可以通过TEE的经胃深部切面和食道中段长轴切面测得。

D. 效果资料

几项研究表明超声心动图监测有助于在该手术。[103,105,107] 超声心动图监测经皮室间隔心肌消融术，减少了术中酒精的使用量和间隔支的堵塞数量。[102]实时超声心动图还可以减少重复的介入以封堵多个间隔支，因此而避免不必要的室间隔瘢痕组织扩大以及相关左室收缩和舒张功能潜在受损的负面结果。

术中心肌声学造影的另一个重要益处在于，明确显影远离室间隔靶向区域的心肌，以避免将无水酒精滴注到非目标区域，如乳头肌、左室游离壁和右心室。（图11）

最近美国心脏病学会和欧洲心脏病学会关于HOCM的共识声称"心肌声学造影指导对于选取合适的间隔支是非常重要的。"[108,109] 然而，仍缺乏对该问题的随机多中心研究。

推荐在HOCM患者室间隔消融过程中，应用超声心动图选择合适的间隔穿支注射无水酒精。TTE和TEE均可使用。它们可以提供实时的手术结果评估并可监控并发症。

X.心腔内超声心动图和心脏电生理学

A. 解剖结构依赖性心律失常

在心脏电生理导管室，以导管为基础的ICE已经广泛应用于指导消融术。在很大程度上，之所以早期应用ICE，关键在于特定的心律失常取决于相关的解剖结构。例如，对于从心房到心室组织穿过二尖瓣或三尖瓣环的房室旁路，需要选择性的能量输出于特殊的解剖区域，以达到成功消融室上性心动过速的目的。另外，典型房扑的病理生理机制，阐明了三尖瓣峡部是组成房扑折返环最重要的解剖基础。[110,111] 基于此，此类心律失常的命名被修正为“峡部依赖性、逆钟向心房扑动”。由此可见，明确特殊解剖结构对于非药物治疗这些心律失常至关重要。

B. 超声相控阵成像

在早期的研究中就有通过经食道探头应用超声相控阵技术的报道，它用于室速消融术[112]和旁道介导的心动过速治疗中的成像。[113-115] 这一技术的微型化结合心内导管的应用，可以允许更深的组织穿透以及从右心腔内显示左右两侧心脏结构的标准二维视图和多普勒成像。[116] 超声相控阵技术的长轴切面图像尤其适用于电生理导管室。基于前向成像的特点， 心腔内超声常用于指导导管进入特定的心腔，穿过心脏瓣膜进入心室；它也用于从一个成像视角或者轻微旋转导管，指引穿间隔导管进入左心结构。心内超声优于经食道超声，因为它不需要长时间的食道插管，从而避免了病人的不适和误吸的风险。另外，它只要有一个介入医生操作即可，不需要其他人员采集图像和分析结果。

C．超声指引解剖结构的消融

心内超声用于指导消融导管，定位于特殊心脏结构的附近，以便消融与之相关的心律失常，见图12。心腔内超声图像的价值在于它可以显示导管头端与靶组织之间建立清晰的位置关系，这是消融是否成功的至关重要的因素。在多数情况下，消融能量输出产生的损伤可见于导管尖端附近的心肌组织。这一观察具有理论上的重要性，正如线性消融所需要的，识别每个消融损伤可以有助于后续临近的能量输出这是。来自于几个中心的线性消融研究也记录了这一应用。[21，117-119] 然而，观察进展性的病变其变化与成像的频帧、消融位点到传感器的距离、导管头部与组织接触的紧密程度、输出能量的高低、消融组织的厚度等相关。因此，心室消融比心房消融形成的病变更容易被发现。[120-122] 进而，没有必要进行持续能量输出消融心房组织直至心房损伤可，因为可见的心房损伤不是消融成功的标准并且可能过度灼伤心肌。简而言之，B型成像显示损伤作为消融成功的终点不够敏感。其他强化损伤识别的方法正在研究中。[123]

多种研究测试心腔内超声在一系列心律失常如房性心动过速[124]、房室结折返性心动过速[125]、窦性心动过速[126]、室性心律失常[127]、房扑[110,121,128,129] 和房颤[18,21,22,24,130]中的作用。三尖瓣峡部消融根除房扑的成功率高达95%-98%，仅通过识别该类心律失常起源的解剖位点就可以达到该疗效。[110,111] 近期研究同样显示了心肌梗死后的左室瘢痕成像在消融心梗后室速中的作用。稳定型室速通常起源于心梗边缘区。在这种情况下，心内超声可以指导消融并创建一个消融损伤路径。该路径

从瘢痕中心，穿过心梗边缘区，到达邻近的具有电惰性的心脏结构如二尖瓣环。该消融损伤中断室速环路，该环路迅速穿过心梗周围的剩余心肌，例如下壁心梗相关的二尖瓣瓣环下峡部阀。[133]直接成像亦有助于沿心梗边缘区进行线性消融治疗频率快而且不稳定的室速。[131]这类左心室成像最好从三尖瓣环下邻近右室流出道定位，从这个位置可以获得左心室的长轴和短轴图像。[116]

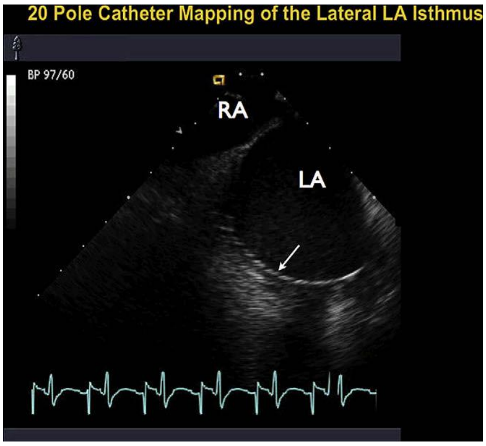

图 12 ICE. 相控ICE 由右房（RA）显示的左房（LA）长轴切面。可见一20-电极导管定位于二尖瓣后叶瓣环处时（箭头所指）导管-组织的接触状况。

D. 房颤的消融

ICE最常用于指导房颤消融。这个方法用于确定肺静脉的数量和位置，明确是否存在有左上下肺静脉形成的左肺静脉窦。ICE还可以明确右肺静脉的分支模式，指引介入导管放置，检查导管尖端和组织的接触，评估潜在的肺静脉生理机能，帮助定位球形导管进行介入消融，并监控组织过热所产生的观微泡，现象。此外，早期的研究显示超声所建立的静脉心房连接模型比静脉造影术所显示的更为精确。[134,135] 由于Marshall静脉和左肺静脉的位置关系，确定其位置对于房颤消融有意

义，可以通过 ‘‘Q-尖’’嵴成像在左心耳和肺静脉之间观察。[136] 超声波束不仅可以识别潜在的肺静脉和其他相关的结构，而且可以快速地将指引导管如环形的Lasso导管置于肺静脉的开口处。这是非常重要的，因为这些导管有向静脉内漂移的趋势，常常使术者产生导管已经真的在静脉开口处的错觉。[137] 消融位置过深会增加肺静脉缩窄的风险并降低房颤消融的疗效。[138] 几项研究显示在心腔内超声指导下，[18,22,130,139,140] 对肺静脉口或肺静脉口外侧进行消融可以提高房颤消融的疗效。

E. 监控消融相关的并发症

微气泡形成常被心腔内超声成像观察到。[21,141,142] 对于评估的消融心脏组织过程中产生的热量而言，这个现象的出现比导管头端的温度监控器更为准确。[142,143] 然而，尽管已建议将这一发现作为一个指导消融的终点，最近研究表明，微泡的出现往往反映了有过多组织热量产生，其实际温度比导管尖端温度监测器记录的温度要高很多。[139,141] 这种无意引起的组织过热，可能导致心肌组织结痂、焦糊或者火山口样坏死形成，心腔内血栓形成，甚至肺静脉缩窄。因此，超声探测到微泡可以用于提示中断能量输出。

同理，心腔内超声也可用于监测消融治疗中潜在的并发症。除了对组织过热的不良结果的观察，最近一些研究表明超声具有检测介入导管上血栓形成的作用，血栓会导致中风或外周血栓事件发生。[144,145] 介入操作中，持续监测心包有助于在心包填塞相关的生理表现出现之前，及早发现心包积液（图13）。从心内超声成像观察，也有利于留

置导管治疗心包积液。

多普勒成像也同样可以在监测过程中发挥作用。脉冲多普勒成像，在消融过程中利用相控阵成像技术，揭示了血流速度增加常合并有肺静脉狭窄。流速增量超过1.6米/秒的水平可作为预测后续狭窄的因素。反之，如果静脉血流速较低，≤1.0米/秒，则不大会进展为严重的狭窄。然而值得注意的是，这些心腔内多普勒流量很大程度上受到房颤或儿茶酚胺的影响。[148]

ICE推荐使用于房颤的射频消融。可用于指导导管穿刺房间隔，以及手术的其他方面，如监测并发症，在消融术前和消融术后评估肺静脉血流。

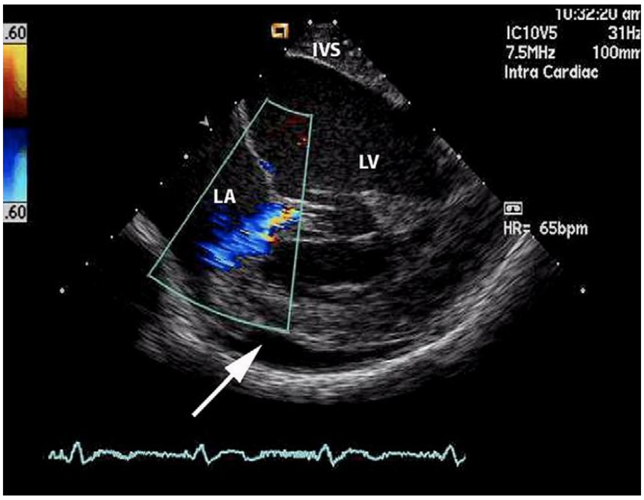

图13 ICE. 相控ICE 右室观. 通过室间隔 (IVS) 可见左室(LV) 和左房(LA) ，在消融术中证实有心包积液出现 (箭头所指)。彩色多普勒提示二尖瓣反流。

XI. 未来的方向

A. 超声心动图应用于复杂二尖瓣手术（研制中的装置）

新一代的经皮二尖瓣修补术系统正逐步取代二尖瓣反流的外科手术治疗，有的是采用Alfieri等[149-151]发明的边对边二尖瓣修补发，通过经皮血管内修补系统操作[152-158]；有的采用经皮二尖瓣瓣环成形术，需将手术装置放置于冠状窦或二尖瓣环。目前有各种手术输送系统。例如，血管内二尖瓣修补系统采用可操的导引导管来精确操纵瓣夹定位于二尖瓣前后叶中部，来减少或消除二尖瓣反流。[155] 这一系统目前正在做人体的I期和II期临床研究。其他经皮二尖瓣边对边修补系统也在开发中。

经皮二尖瓣边对边修补系统的输送有五个步骤需要超声心动图指导：导管穿隔，将瓣夹输送装置垂直对准二尖瓣瓣叶平面及闭合线，将瓣夹的活动臂垂直对准二尖瓣闭合线，合上瓣夹活动臂靠近二尖瓣瓣叶尖端，释放植入装置。目前联合使用TEE及辅助使用TTE对手术进行指导。

其他经皮二尖瓣环成形术的冠脉窦和二尖瓣环装置也在开发中，用以加强二尖瓣的对合改善二尖瓣反流。TEE 或 ICE 可用于指导冠状窦开口的插管定位，监测并发症，并于术前和术后测量二尖瓣反流的程度及二尖瓣跨瓣压差。

B. 超声心动图在左心耳封堵手术中的作用（研制中的装置）

大多数房颤的血栓都发生在左心耳。[159-161]这一观察结果导致了左心耳封闭可预防中风的假说。所以在一些外科手术中，有适应症的患者进行了左心耳预防性结扎术。[162,163] 还有人建议所有心脏手术的患者，

不论有无适应症，都进行左心耳结扎术。[164]

经皮导管术预防房颤患者心源性脑栓塞，是通过放置封堵器将左心耳与左房隔离。最初的动物[31]和人体[165]试验，以及近期的解剖和血流动力学资料[166]，都显示封堵成功可预防中风。经皮左心耳导管封堵装置是第一个应用于人体的封堵装置，最终因发病率和死亡率的增加而停止了该试验。所有已发表的该装置的人体试验，都采用了TEE指导。新型的装置[167] 是镍钛合金装置，在透视和TEE的指导下，经皮通过标准穿隔技术经导管置入左心耳。TEE在左心耳的测量和封堵器大小的选择上都非常重要。

封堵器释放后，要复查TEE确认放置的位置，评估手术并发症。封堵器要检查其稳定性和密闭性。检查房间隔寻找房间隔缺损，术后少量的残余分流是常见的。心包腔要再次扫查有无心包积液。

C. 三维超声心动图

超声心动图的新技术，三维成像，对介入手术有着巨大贡献。例如，三维成像指导心肌活检的活检钳定位(相对于标准透视定位方法)。一项63例同种心脏移植患者右室心肌活检的研究发现，三维成像是可行的，能改善活检钳的定位，并可能改善心肌活检的疗效和安全性。[168]

三维成像比二维成像能更好地研究二尖瓣的解剖结构。（图14）所以，三维成像对于二尖瓣外科修补手术或介入手术的规划有重要意义[169-171]（图15）。患者术中三维TEE研究显示，在判断瓣宽和脱垂节段上，它和外科术中所见的一致性非常好（94% [34 /36 患者]）。

[171]

还有研究发现，对于PBMV手术患者，三维TEE和TTE优于二维超声心动图，它可以更好的选择病人，术后能更准确直观的发现联合部及瓣叶撕裂。[172]，[173] 同样，三维超声心动图也有望用于规划二尖瓣反流患者的二尖瓣修补手术，参见图16。[174]

经皮房间隔缺损(ASD)或卵圆孔未闭(PFO)修补装置的使用日渐增多，三维成像可以为手术准确地提供解剖测量、封堵器定位，以及其与邻近心内结构的关系，故而提高手术成功率，并可能减少并发症。[175] 在41例房缺封堵患者中，40例（98%）采用三维成像测量缺损，发现其对缺损大小的测量比二维TEE更准确（以球囊测量值为金标准）。此外，采用三维成像能更准确的判断封堵器的位置。[176] 实时三维超声心动图也应用于房缺和卵圆孔未闭封堵术，用以准确测量形态和疗效评估。[177] 在4例房缺和卵圆孔未闭封堵术患者(3 ASDs, 1 PFO)中，实时三维超声心动图提供了全面的解剖测量和封堵器评估。[177]

肥厚梗阻性心肌病患者的介入治疗数量越来越多。[101] 实时三维超声心动图已成功应用于10例心肌切除和二尖瓣修补术患者，3D超声心动图的“外科医师视角”可以精确的指导外科医师修订手术方案。

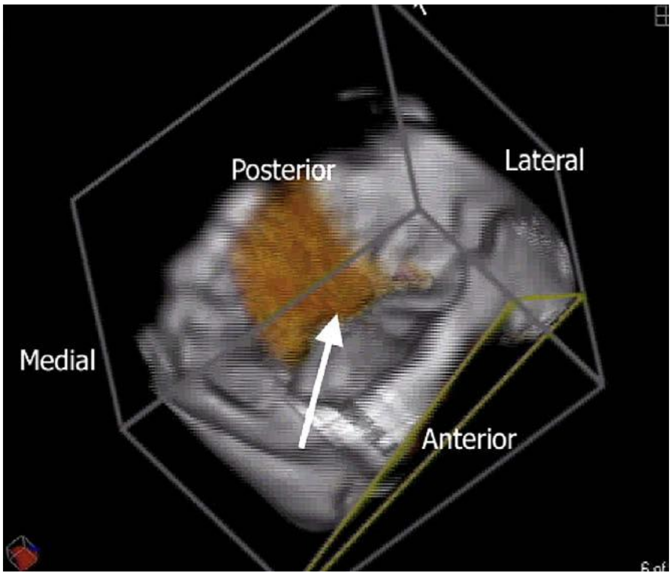

图 14 TEE 三维重建的二尖瓣左房侧图像：可见患者的重度二尖瓣反流来自几乎整个前叶闭合缘(箭头所指彩图中红色进入左房的血流)。解剖方位已给出作参考。

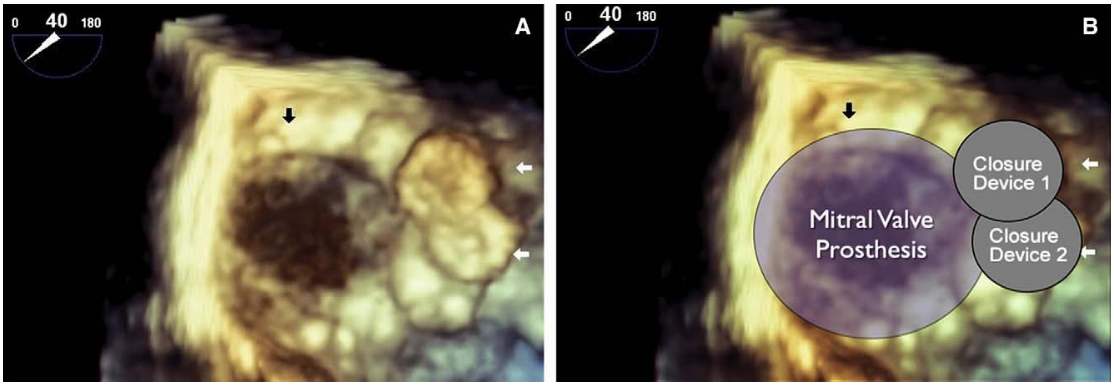

图 15 三维 TEE. (A) 二尖瓣生物瓣（黑色箭头所指）及封闭瓣周反流的两个闭合装置（白色箭头所指）的三维成像 (B) 加用叠加圈解释。左房侧观。确认反流的准确位置常常是困难的，修补瓣周漏时，指导介入闭合装置正确定位也是困难的。本例患者，三维成像在封闭器的定位和瓣周漏的定位上有重要作用。

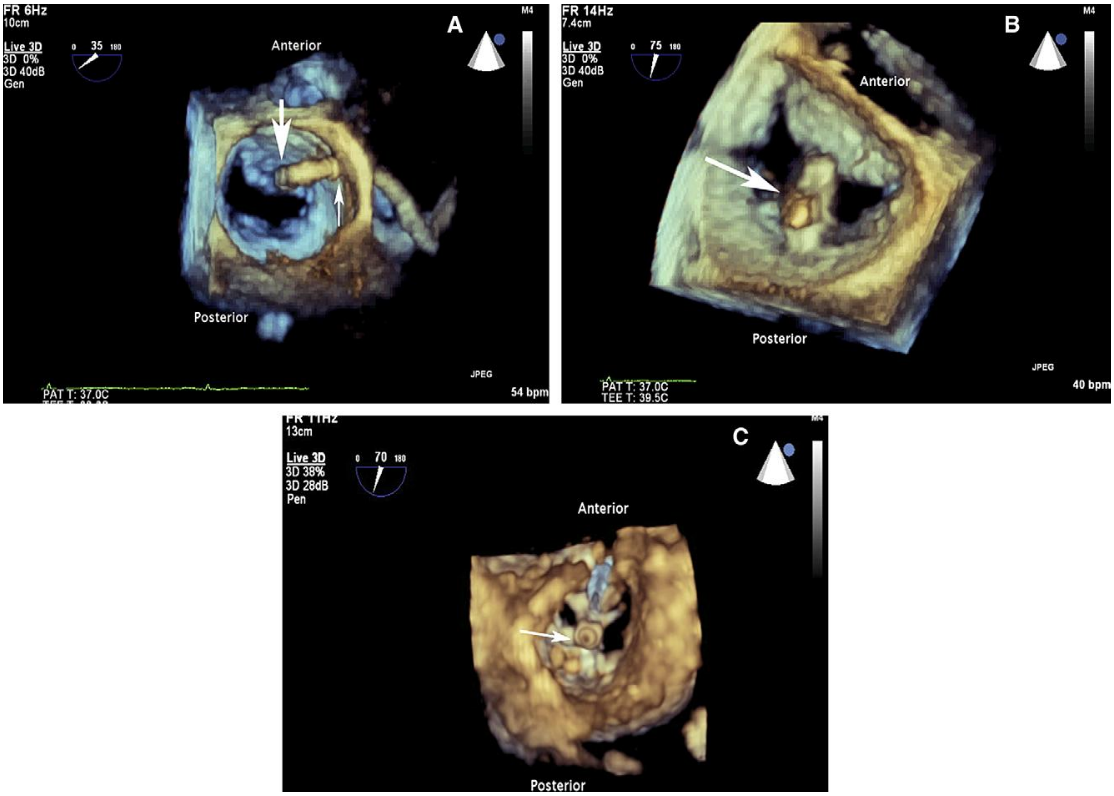

图16 三维TEE. 经皮二尖瓣瓣缘夹修补二尖瓣反流。(A) 左房内，经皮二尖瓣夹对齐二尖瓣。大箭头所指为打开之前的二尖瓣夹，小箭头所指为导引导管前段。(B) 二尖瓣夹钳夹瓣叶前，其“张开臂”（箭头所指）垂直对齐二尖瓣闭合线。 (C) 从左室面看到的二尖瓣钳夹已闭合（箭头所指），呈现双孔二尖瓣修补术后图。

D. 超声心动图在经皮主动脉瓣置换术中的应用

近来，经皮导管内主动脉瓣置换术已开始应用。初期的研究是将两个特殊的生物瓣安装在支架上，卷载于球囊上送入，采用瓣膜成形技术。[179-181] 这些瓣膜可通过经皮逆行主动脉通路植入，也可以通过外科手术从心尖径路植入。[182-184] 超声心动图在患者选择上起到决定性作用，尤其是植入人工瓣尺寸的选择。特别值得一提的是，主动脉瓣瓣环直径是决定人工瓣大小的关键。[182] TTE和TEE在主动脉瓣瓣环直径和形态

测量上有少量差异。术中使用TEE协助确认人工瓣的位置以及评估植入后瓣周反流情况。实时三维TEE也有应用于术中的报道，但是它的作用及优于普通TEE的价值，目前尚未明确。

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Echocardiography-Guided Interventions

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Keywords: Echocardiography, Cardiac ultrasound, Transesophageal echocardiography, Intracardiac echocardiography, 3-dimensional echocardiography, Congenital heart disease, Pericardiocentesis, Transseptal catheterization, Myocardial biopsy, Percutaneous transvenous balloon valvuloplasty, Atrial septal defect, Parent foramen ovale, Hypertrophic cardiomyopathy, Alcohol septal ablation, Cardiac electrophysiology, Left atrial appendage occlusion

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Participation should include individuals from the fields of echocardiography, interventional cardiology, electrophysiology, cardiac sonography, and cardiac surgery, as well as medical residents, fellows, and students.
Learning Objectives:
After reading this article, participants should be able to: (1) Assess the strengths and weaknesses of each echocardiographic modality (transthoracic echocardiography, transesophageal echocardiography, intracardiac echocardiography, 3-dimensional echocardiography) in guiding interventional cardiologic and electrophysiologic procedures. (2) Use echocardiography to guide interventional procedures. (3) Recognize echocardiographers' role in catheterization and electrophysiology laboratories.
Author Disclosures:
Frank E. Silvestry is a consultant for Biosense Webster (Diamond Bar, CA), formerly Siemens Medical Systems (Erlangen, Germany). John D. Carroll is a consultant and lecturer for and a recipient of royalties from Philips Healthcare (Andover, MA), a consultant for Biosense Webster, and a consultant for W. L. Gore & Associates (Newark, DE). Howard C. Herrmann is a consultant for Biosense Webster and AGA Medical (Plymouth, MN) and has received research funding from Edwards Lifesciences (Irvine, CA), Evalve (Menlo Park, CA), and W. L. Gore & Associates. Douglas L. Packer has received research support from Siemens Acuson (Mountain View, CA), is a past advisory board member for Siemens Acuson, and is a current scientific advisory board member for Siemens. Richard E. Kerber, Michael M. Brook, Karen M. Eberman, Steven A. Goldstein, Shunichi Homma, Roxana Mehran, Alfred F. Parisi, Todd Pulerwitz, James Bernard Seward, Teresa S. M. Tsang, and Mark A. Wood have no disclosures to report.
Estimated Time to Complete This Activity: 1 hour

I. ABSTRACT

A major advantage of echocardiography over other advanced imaging modalities (magnetic resonance imaging, computed tomographic angiography) is that echocardiography is mobile and real time. Echocardiograms can be recorded at the bedside, in the cardiac catheterization laboratory, in the cardiovascular intensive care unit, in the emergency room—indeed, any place that can accommodate a wheeled cart. This tremendous advantage allows for the performance of imaging immediately before, during, and after various procedures involving interventions. The purpose of this report is to review the use of echocardiography to guide interventions. We provide information on the selection of patients for interventions, monitoring during the performance of interventions, and assessing the effects of interventions after their completion.

In this document, we address the use of echocardiography in commonly performed procedures: transatrial septal catheterization, pericardiocentesis, myocardial biopsy, percutaneous transvenous balloon valvuloplasty, catheter closure of atrial septal defects (ASDs) and patent foramen ovale (PFO), alcohol septal ablation for hypertrophic cardiomyopathy, and cardiac electrophysiology. A concluding section addresses interventions that are presently investigational but are likely to enter the realm of practice in the very near future: complex mitral valve repairs, left atrial appendage (LAA) occlusion devices, 3-dimensional (3D) echocardiographic guidance, and percutaneous aortic valve replacement.

The use of echocardiography to select and guide cardiac resynchronization therapy has recently been addressed in a separate document published by the American Society of Echocardiography and is not further discussed in this document.

The use of imaging techniques to guide even well-established procedures enhances the efficiency and safety of these procedures.

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0894-7317/$36.00

doi:10.1016/j.echo.2008.12.013

Table 1 Interventional procedures: use of echocardiography for guidance

Interventional Procedure	TTE	TEE	ICE
Transseptal catheterization	+	++	++ (radial or phased array)
PMBV	++	+++	++
Transcatheter closure of ASD, ventricular septal defect, and PFO	+	++	++ (phased array)
Alcohol septal ablation in HOCM	++	++	−
Percutaneous mitral valve repair	+	+++	+
Percutaneous left ventricular assist device placement	−	++	++
Percutaneous stented aortic valve prosthetic placement	−	+	+
Balloon or blade atrial septostomy	++	++	++
Placement of LAA occlusion devices	−	++	++
Myocardial and intravascular biopsy	++	++	++ (phased array)
Congenital heart disease applications (completion of Fontan procedure, coarctation repair)	+	+	+
Placement of aortic endograft	−	−	+ (radial or phased array)

−, No documented role or benefit in the literature; +, anecdotal reports of use and benefit exist, but further study is needed to delineate; ++, advantages favor use when available; +++, clearly documented benefit or role.

II. INTRODUCTION

Traditionally, percutaneous cardiovascular interventions have predominantly used angiographic and fluoroscopic guidance, which is limited when interventions involve the myocardium, pericardium, and cardiac valves.

The purposes of this report are to (1) delineate the role of echocardiography in guiding a wide variety of interventional and electrophysiological procedures, (2) discuss the critical echocardiographic aspects of these procedures, and (3) delineate the intraprocedural differences between echocardiographic modalities, comparing transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), and intracardiac echocardiography (ICE) wherever appropriate data are available. We have particularly emphasized the use of ICE where appropriate, because it is the newest of the echocardiographic modalities, and readers may be unaware of some potential applications. Table 1 provides a summary of literature data concerning the use of the different echocardiographic modalities for each of the specific procedures. This report is not intended to provide detailed instructions on "how to" perform these procedures; more specific procedural details are available for review in the referenced documents. Instead, we intend to highlight and illustrate the ways in which echocardiography has had an important impact in the procedures being performed and their outcomes. Summary recommendations are listed in boldface type at the end of each section.

As percutaneous therapy for heart disease continues to advance at a rapid pace, it is inevitable that echocardiographic procedural guidance will continue to evolve rapidly as well. We have sought to keep the material in this report current as of this writing, by adding a section on future directions. Similarly, other modalities, such as magnetic resonance imaging and combined multiple imaging modalities (eg, reconstructed 3D computerized tomography with superimposed real-time echocardiography) will continue to evolve and develop roles in guiding these complex procedures as well.

III. GENERAL IMAGING CONSIDERATIONS

A. TTE

TTE is widely available and portable and offers excellent image quality; as such, it has been used widely in guiding percutaneous noncoronary interventional and electrophysiologic procedures. Most currently available ultrasound systems, including handheld and portable ultrasound systems, offer sufficient 2-dimensional (2D) and Doppler capabilities to guide a variety of interventions, such as echocardiography-guided pericardiocentesis, alcohol septal ablation for hypertrophic cardiomyopathy, percutaneous balloon mitral valvuloplasty (PBMV), and myocardial biopsy. The advent of Doppler tissue imaging has made TTE essential in the optimization of biventricular pacemakers.

B. TEE

TEE has been widely used as an alternative to TTE in guiding complex procedures. TEE offers superior image resolution to TTE and can be used to monitor a variety of interventions, such as percutaneous transcatheter closure (PTC) of septal defects, PBMV, transseptal catheterization, and many others. Compared with TTE, it excels at assessing intraprocedural anatomy and physiology, monitoring catheter position and contact, and excluding thrombus, pericardial effusion, and other complications.

C. ICE

A more recent application of cardiac ultrasound, ICE has also demonstrated great potential for monitoring and guiding interventions. Experimental and clinical studies have demonstrated the utility of ICE in monitoring left ventricular and right ventricular function, delineating anatomy, guiding transseptal punctures and therapy, and biopsy of cardiac masses.[1-13]

ICE offers imaging that is comparable with or superior to TEE. ICE has been shown to provide significant benefits when used for radiofrequency ablation of atrial fibrillation (AF) and transcatheter atrial septal closure procedures and has become the imaging standard during these procedures at many centers.[14-28] In the catheterization laboratory during these procedures, an advantage over TEE is that ICE obviates the need for general anesthesia and for additional echocardiography physician support. Compared with guidance using TEE, ICE has been shown to improve patient comfort, shorten both procedure and fluoroscopy times, and offer comparable cost with TEE-guided interventions.[15-17,25,28,29] Additional uses of ICE may include guidance of transseptal catheterization, the placement of LAA occluder devices, the placement of percutaneous left ventricular assist device cannulas, the performance of PBMV, and many others.[5,7,30-33] Diagnostic intracardiac imaging may be considered as an alternative to TEE in selected patients with absolute contraindications to TEE (eg, esophagectomy) or to potentially evaluate anatomic regions

Table 2 Potential risks of ICE

Vascular
• Trauma at catheterization site
• Bleeding
• Hematoma
• Retroperitoneal bleed
• Perforation of venous structures
Cardiac perforation
• Pericardial effusion
• Tamponade
Arrhythmia
• Atrial premature beats
• AF
• Ventricular ectopy and tachycardia
• Heart block
Thromboembolism
• Venous
• Arterial
Cutaneous nerve palsy

that TEE may not be able to visualize well because of shadowing from other structures (eg, ascending aortic evaluation, which is not well seen on TEE because of tracheal shadowing in the "TEE blind spot"). The risks of ICE are listed in Table 2.

IV. ECHOCARDIOGRAPHY IN TRANSSEPTAL CATHETERIZATION

Transseptal catheterization is performed when procedural access to the left atrium is required and is used for PBMV, anterograde aortic balloon valvuloplasty, radiofrequency ablation of AF and other left-sided arrhythmias, transseptal PFO closure, the placement of percutaneous left ventricular assist device cannulas in the left atrium, balloon or blade atrial septostomy, the measurement of complex hemodynamics (such as evaluation of a mechanical aortic valve prosthesis or critical aortic stenosis in which the valve itself cannot be crossed), and, most recently, investigational applications such as the placement of LAA occlusion devices and percutaneous mitral valve repair.[34-40] Traditionally, transseptal catheterization has relied on fluoroscopic guidance, in which anatomic structures are not directly visualized.

Observational studies have suggested that TTE or TEE may be helpful in performing this procedure by allowing direct visualization of the transseptal catheter and its relationship to the fossa ovalis. Although echocardiographic imaging is not invariably required for the successful performance of transseptal catheterization, it offers potential advantages over traditional anatomic and fluoroscopic guidance.[7,30,41-50] Anatomic variability in the position and orientation of the fossa ovalis and its surrounding structures may present specific challenges to even those interventional cardiologists with significant transseptal experience, and imaging offers increased safety, with a lower risk for cannulating other spaces adjacent to the fossa. Inadvertent puncture of the intrapericardial aorta is a serious complication of transseptal catheterization, and echocardiographic imaging reduces this risk. Similarly, imaging may decrease the time required for the transseptal puncture to be performed and minimizes the fluoroscopy time required for the procedure. In patients undergoing PBMV who are pregnant, radiation exposure can be reduced with echocardiographic guidance of the procedure, including the transseptal puncture.[43] Imaging may also assist those operators without significant transseptal experience who are learning the procedure.

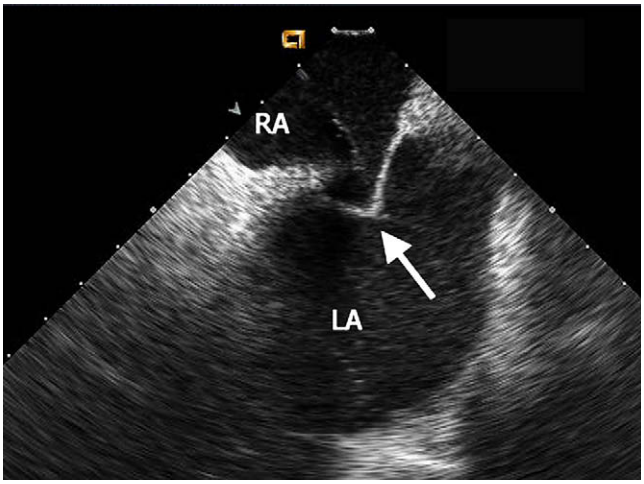

Figure 1 ICE. Phased-array ICE from the right atrium (RA), demonstrating the tenting of the fossa ovalis *(arrow)* toward the left atrium (LA) before transseptal catheterization. The length of the catheter is seen in the RA.

Early studies of TTE-guided transseptal puncture demonstrated that TTE can delineate the aorta and interatrial septum and the characteristic bulging (or tenting) of the fossa ovalis at a satisfactory location that occurs before transseptal puncture.[49] Saline contrast echocardiography with TTE may help confirm needle position in the right atrium before puncture and in the left atrium after puncture. TTE does not always offer sufficient imaging resolution to guide transseptal catheterization, and as such, TEE and more recently ICE have been used when imaging is required. TEE and ICE also provide the ability to choose the exact site of transseptal puncture, which is important in performing advanced mitral valve interventions for mitral regurgitation (MR) because the catheters are more difficult to manipulate and position if the transseptal crossing point is too close to the plane of the mitral valve orifice. Because ICE can be performed without additional sedation or general anesthesia, as well as with minimal additional patient risk and discomfort, it has become the standard at many centers if imaging is required only for the transseptal catheterization aspect of a procedure.[7,30,42,43,45,48,50,51]

With ICE during a transseptal procedure, recognition of tenting of the interatrial septum identifies the location of the transseptal sheath before puncture (Figure 1). The possibility of perforation of the aorta, pulmonary artery, and atrial wall exists during transseptal catheterization. The injection of a small amount of microbubbles or contrast into the left atrium after the needle has crossed the septum is used to confirm left atrial access (Figure 2). Finally, a guidewire is passed into the left atrium under guidance with ICE to establish stable left atrial access (Figure 3).

Echocardiography offers the potential for improved safety in performing transseptal catheterization, and although it is not invariably required in all procedures, its use is recommended. ICE offers the advantage of not requiring echocardiographic support when performing transseptal catheterization.

V. ECHOCARDIOGRAPHY-GUIDED PERICARDIOCENTESIS

Fluoroscopic guidance and electrocardiographic needle monitoring have been used to improve the safety of pericardiocentesis,[52,53] but

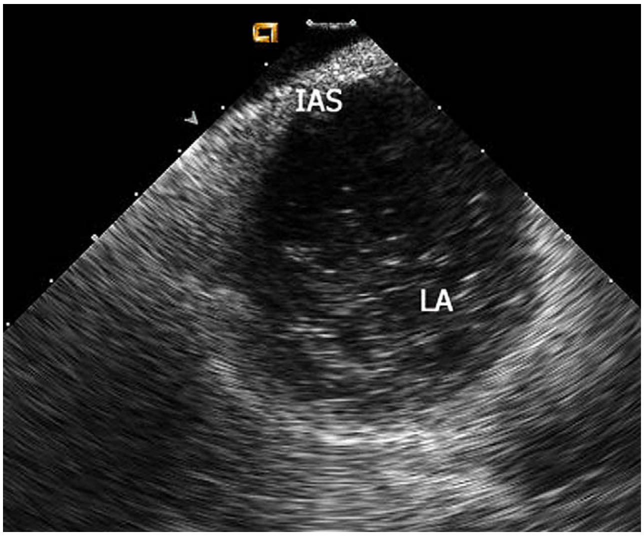

Figure 2 ICE. Injection of a small amount of saline microbubbles confirms access in the left atrium (LA). The intracardiac echocardiographic catheter is resting on the interatrial septum (IAS).

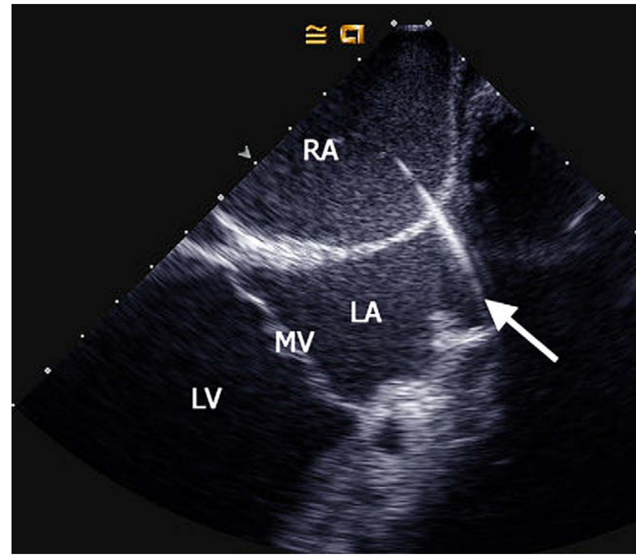

Figure 3 ICE. The length of the guidewire *(arrow)* is seen in the right atrium (RA) and the left atrium (LA) as it enters a left pulmonary vein. The mitral valve (MV) and left ventricle (LV) are seen in the far field.

complications, including damage to the liver, myocardium, coronary arteries, and lungs, have been reported.[54]

A. Safety and Efficacy of Echocardiography-Guided Pericardiocentesis

In a Mayo Clinic series, echocardiography-guided pericardiocentesis was successful in withdrawing pericardial fluid or relieving tamponade in 97% of the procedures.[55] Major complications (including chamber laceration, intercostal vessel injury, pneumothorax requiring a chest tube, sustained ventricular tachycardia (VT), bacteremia, and death) occurred in 1.2% of patients, and minor complications (including transient cardiac chamber entry, transient arrhythmia, minor pneumothorax, and vasovagal reactions) were noted in 3.2%.[55] The safety and efficacy of echocardiography-guided pericardiocentesis had been shown in various subgroups, including pediatric patients,[56] patients who were hemodynamically very unstable after cardiac perforation secondary to invasive percutaneous procedures,[57] postoperative patients,[58] and patients with malignancies[59] or connective tissue diseases.[60]

B. Technique of Echocardiography-Guided Pericardiocentesis

The following is a guide to only the critical aspects of echocardiography-guided pericardiocentesis. Additional procedural details are documented in the references. Two-dimensional and Doppler studies are performed to assess the size, distribution, and hemodynamic impact of the effusion and to identify the ideal entry site and needle trajectory for pericardiocentesis. The ideal site of needle entry is the point at which the largest fluid collection is closest to the body surface and from which a straight needle trajectory avoids vital structures. Because ultrasound does not penetrate air, the lungs are effectively avoided. Safety is ensured by using sheathed needles and withdrawing the steel needle upon entering the fluid space.

The left chest wall is often the location selected for entry.[55] The subcostal route involves a longer path to reach the fluid, passes anterior to the liver capsule, and is directed toward the right chambers of the heart.

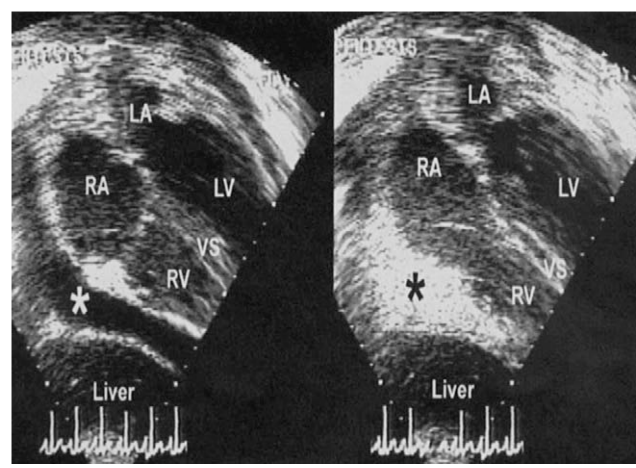

Figure 4 TTE. Agitated saline contrast injection for assessment of position of Teflon-sheathed needle during pericardiocentesis with opacification of the pericardial space *(asterisk)* after saline contrast injection. *LA*, Left atrium; *LV*, left ventricle; *RV*, right ventricle; *RA*, right atrium; *VS*, ventricular septum.

The position of a catheter introduced into the pericardial space can be confirmed by the injection of agitated saline, and this is performed if bloody fluid has been aspirated or if the catheter position is in question. The appearance of contrast in the pericardial sac confirms its position (Figure 4). If the catheter is not in the pericardial space, it should be repositioned, or another needle passage should be attempted.

The indwelling catheter is removed once the drainage has decreased (typically to <25 mL in 24 hours) and follow-up echocardiography reveals no significant residual effusion.

C. Precautions and Contraindications

The contraindications to echocardiography-guided pericardiocentesis are few, and even these should be evaluated on a case-by-case basis.

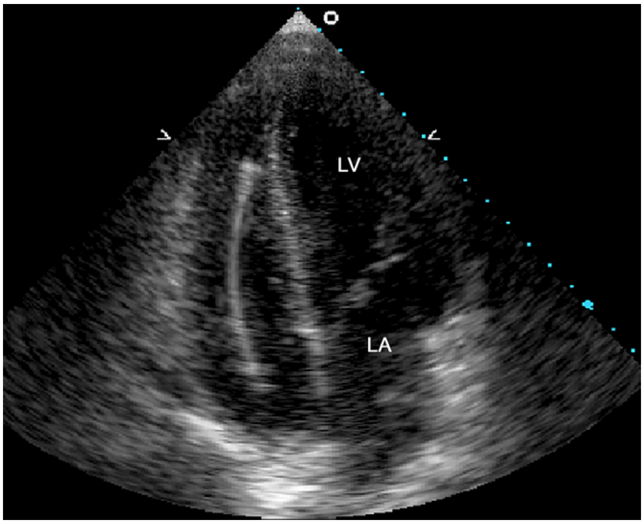

Figure 5 TTE. Apical 4-chamber view demonstrating a bioptome in the right ventricle positioned along the interventricular septum before biopsy. *LA*, Left atrium; *LV*, left ventricle.

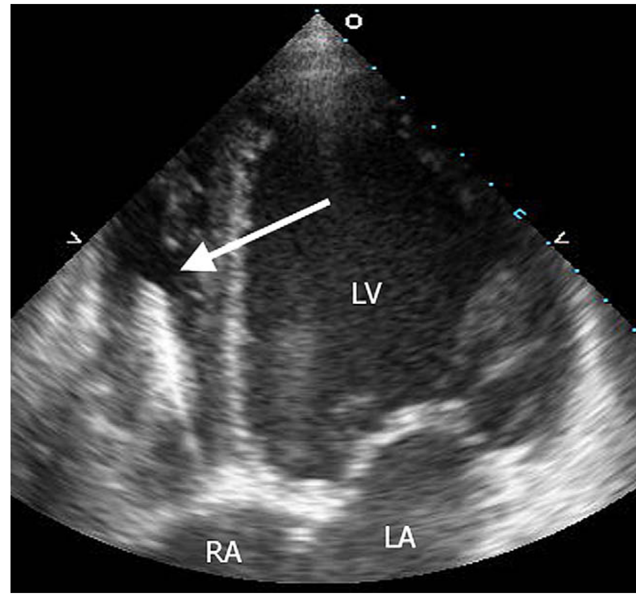

Figure 6 TTE. Apical 4-chamber view demonstrating a bioptome *(arrow)* in the right ventricle in a suboptimal position as it appears free in the right ventricular cavity. Echocardiography facilitates recognition of nonideal biopsy site and repositioning of the bioptome. Note, however, that the tip of a catheter cannot always be visualized with certainty. *LA*, Left atrium; *LV*, left ventricle; *RA*, right atrium.

In theory, pericardiocentesis is contraindicated in the setting of myocardial rupture or aortic dissection because of the potential risk for extending the rupture or dissection with decompression.[61]

Echocardiography-guided pericardiocentesis with extended catheter drainage can be performed safely and with efficacy at centers with staff members experienced in this technique. Using echocardiography to guide the procedure avoids the radiation associated with fluoroscopy and allows the procedure to be performed in the catheterization laboratory, at the bedside, or in the echocardiography laboratory. Increased safety and markedly lower cost compared with surgery ensure that echocardiography-directed pericardiocentesis is a procedure of choice.

VI. USE OF ECHOCARDIOGRAPHY TO GUIDE MYOCARDIAL BIOPSY

Endomyocardial biopsies are typically performed in the right ventricle to diagnose a wide variety of myocardial disorders, including infiltrative cardiomyopathy and cardiac transplant rejection. Although endomyocardial biopsy is often performed with fluoroscopic guidance alone, some centers use 2D TTE to complement or replace fluoroscopy.[62-66] Similarly, others have reported using TEE or ICE to guide biopsies of masses in the right heart and aorta in selected patients.[10,67-69]

With echocardiographic guidance, it is possible to provide a wider choice of biopsy sites. In addition to the ventricular septum, both the right ventricular apex and free wall can be biopsied. Moreover, this approach improves the yield of the biopsy by reducing the number of fibrotic samples due to "bites" in the same site (midventricular septum). This approach may also reduce the likelihood of perforation and damage to the tricuspid valve.[66] Other potential advantages of echocardiography-guided endomyocardial biopsy include the reduction of radiation exposure and portability.

Optimal views on TTE for guiding right ventricular biopsies include the apical 4-chamber view and the subxiphoid 4-chamber view (Figures 5 and 6). The transducer may be positioned more medially (midclavicular line) to optimally visualize the right ventricle during biopsy. Optimal views on TEE include the midesophageal 4-chamber view, as well as the transgastric short-axis and long-axis views. ICE from either the right atrium or the right ventricle can be used for the guidance of right ventricular biopsy. Note, however, that the tip of a catheter cannot always be visualized with certainty.

Other limitations to the use of echocardiography for guiding myocardial biopsy include the difficulty in performing TTE in patients in the catheterization laboratory who are in the supine position and the difficulty in imaging patients such as those with chest tubes and bandages, obesity, or chronic lung disease. TEE and ICE overcome these limitations in image quality, although with the need for additional echocardiography physician support and sedation (for TEE), as well as additional cost and attendant vascular risks (for ICE).

Echocardiography, particularly TTE, is useful as an adjunctive imaging modality in patients undergoing intracardiac and intravascular biopsy procedures. Although TEE and ICE may offer improved imaging over TTE, the additional risk and cost must be outweighed by significant procedural benefits, and the modalities are recommended for use only in highly selected patients.

VII. ECHOCARDIOGRAPHIC GUIDANCE OF PERCUTANEOUS TRANSVENOUS BALLOON MITRAL VALVULOPLASTY

A. General Imaging Considerations

PBMV is performed with fluoroscopic guidance alone at many centers, but radiographic anatomic landmarks can mislead even experienced operators. Kronzon et al[49] recommended 2D TTE (in the apical 4-chamber and parasternal short-axis views) as a useful adjunct to fluoroscopy during transseptal cardiac catheterization during

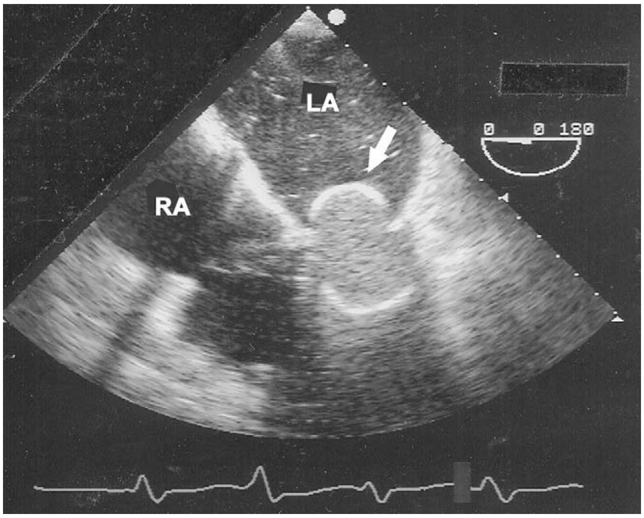

Figure 7 TEE. Midesophageal 4-chamber view demonstrating the valvuloplasty balloon *(arrow)* as it is inflated across the mitral valve. *LA*, Left atrium; *RA*, right atrium.

PBMV. Pandian et al[70] advocated the use of subcostal views to assist PBMV as well. Disadvantages of TTE include that it interrupts the flow of the procedure, potentially interferes with sterile technique, and provides inadequate imaging in some patients.

TEE is an alternative to TTE for guiding PBMV[71-75] (S. A. Goldstein, personal communication). The role of TEE before and during balloon mitral valvuloplasty is well established. TEE can be used for patient selection[76,77] and for all aspects of online procedural guidance[71-75] (S. A. Goldstein, personal communication). It is used to guide the transseptal catheterization and is generally superior to TTE in this regard. TEE is also superior to TTE when it is used to exclude left atrial and LAA thrombus, and it facilitates wire and balloon position before and during inflation (Figure 7). TEE is used to measure transmitral gradients and mitral valve area and to assess the degree of MR immediately after each balloon inflation. Finally, TEE can be used to look for complications of PBMV, such as severe MR, pericardial effusion or tamponade, dislodgement of thrombus, and residual ASD. Moreover, some authors have suggested that the use of online TEE can both reduce fluoroscopic and procedure time and improve results[71-75] (S. A. Goldstein, personal communication).

ICE provides another alternative for online guidance of PBMV.[32,48,78] It provides an excellent view of the fossa ovalis and can be used to guide the transseptal puncture.[48] Newer phased-array intracardiac echocardiographic catheters provide pulsed-wave, continuous-wave, color flow Doppler, and Doppler tissue imaging. Thus, like TEE and TTE, ICE can facilitate the immediate assessment of the results of the valvuloplasty, including the transmitral gradient, the mitral valve area, the presence or worsening of MR, and the detection of complications, such as cardiac perforation, tamponade, or a torn mitral valve. Like TEE, ICE does not interfere with the catheterization process and can be used for each of the sequential tasks needed to perform mitral valvuloplasty.[32,78] The relative value of ICE compared with TTE and TEE has yet to be determined. Cost is a significant consideration, because a phased-array intracardiac echocardiographic catheter costs approximately $2,500 to $3,000, for a catheter that may only be used up to 3 times. Visualization of left-sided structures on ICE may be inferior or superior to that provided by TEE or TTE, depending on the chamber from which the catheter is providing images. In particular, the LAA may not be well visualized when intracardiac echocardiographic images originate only from the right atrium, and the presence or absence of an intracardiac thrombus cannot be confirmed. Imaging from the left atrium or pulmonary artery may overcome this limitation. On the other hand, ICE visualizes the mitral valve structures, especially the subvalvular structures of chordae tendineae and papillary muscles, with superior spatial resolution compared with TEE or TTE.[78] Images should be transmitted to a monitor that is easily viewed by the catheterization operator, usually adjacent to the fluoroscopic monitor.

B. Immediate Assessment of Results

Online echocardiography during the procedure is ideally suited for the immediate assessment of the results of PBMV.[7] The adequacy of valvulotomy can be determined by evaluating the maximal mitral leaflet separation and by continuous-wave Doppler determination of the mean mitral gradient and mitral valve area. With TEE and ICE in addition, the pulmonary venous flow profile can be assessed, with a more rapid diastolic deceleration expected after successful PBMV.[79] Finally, new or worsening MR is sought by color Doppler. Decisions about the adequacy of the procedure versus the need for further dilation should be made on the basis of both echocardiographic and hemodynamic data.

C. Early Detection of Complications

Although uncommon, serious complications do occur with PBMV. The majority of these (eg, the development of severe MR, cardiac perforation and tamponade, ASDs) can be identified accurately and quickly by online echocardiography during the procedure. An increase in the degree of MR occurs in approximately half of patients after PBMV[49,70,80,81] (S. A. Goldstein, personal communication). In most, this increase is mild, but the reported incidence of the development of severe MR is 1% to 6%.[74] Acute, severe MR may be caused by tear or rupture of the mitral leaflets, by ruptured chordae tendineae, or rarely by avulsion of a papillary muscle.[82] Each of these can be detected readily by echocardiography, particularly by TEE or ICE. Moreover, the presence and severity of MR can be determined without the need for ventriculography.

The incidence of cardiac tamponade during PBMV has been reported to be between 0% and 9%.[74,83] Perforation of the atrial free wall at the time of transseptal puncture is the most common cause of bleeding into the pericardial space. Echocardiographic detection of such fluid is immediate and permits rapid pericardiocentesis before major hemodynamic compromise occurs. Perforation of the left ventricle, especially with the double-balloon technique, has also been reported. Online TEE can lead to rapid detection and treatment of this potentially life threatening complication.[83]

The reported incidence of ASD resulting from PBMV is highly variable depending on the technique used for its detection. A left-to-right shunt at the atrial level is detected by oximetry in only 8% to 25% of patients.[73] TTE can detect an atrial shunt after PBMV in 15% to 60% of patients. TEE, a more sensitive technique, has been reported to detect shunts in as many as 90% of patients. ICE, with its excellent visualization of the fossa ovalis, should offer comparable sensitivity. Because the defects are usually small and because left atrial pressure in these patients is high, the small left-to-right shunting jets are easily detected by transesophageal echocardiographic or intracardiac echocardiographic color Doppler imaging. The creation of a small ASD should be considered an expected consequence rather than a true complication in the majority of patients.

D. Limitations

Several investigators have pointed out that immediately after PBMV, Doppler evaluation of mitral valve area by the pressure half-time method should be interpreted with caution because of a reduced correlation with hemodynamic measurements obtained by cardiac catheterization. This discrepancy may be related in part to acute alterations in left atrial and left ventricular compliance and a reduced initial peak mitral valve gradient.

E. Effect on Outcomes

The use of echocardiographic guidance during the procedure may improve the procedural success and complication rates.[84,85] Online imaging can provide more precise targeting of the transseptal needle toward the fossa ovalis region of the atrial septum, thereby minimizing the likelihood of perforation.[75,83,86,87] In addition, imaging not only has the potential to reduce the risk for procedural complications but may also allow immediate identification of these complications should they occur, permitting more prompt correction. Moreover, echocardiographic guidance may reduce procedural and fluoroscopic time[83] (S. A. Goldstein, personal communication). Park et al[83] evaluated fluoroscopic guidance only (n = 64) and patients who underwent PBMV with online transesophageal echocardiographic guidance (n = 70). The procedural time was significantly shorter in the latter group (99 ± 48 vs 64 ± 22 minutes; $P < .0001$). The average fluoroscopic time was also shorter in the TEE-guided group (30 ± 17 vs 19 ± 15 minutes), but this was not statistically significant ($P =$ .25). Echocardiographic guidance may also reduce the risk for worsening MR as a result of the better assessment of the number of balloon inflations required and better positioning of the balloon catheter. Further studies are required to validate the incremental safety and efficacy of echocardiographic guidance to supplement or replace fluoroscopic guidance of PBMV.

Echocardiography provides significant benefit in percutaneous balloon valvuloplasty for mitral stenosis and is recommended for the assessment of patient selection and to assess the adequacy of results. Online intraprocedural echocardiography offers significant advantages compared with fluoroscopic guidance, in monitoring procedural efficacy and monitoring for complications. TEE can also be used to guide the procedure. TTE is recommended for procedural guidance, monitoring for complications, and to assess the adequacy of results, when preprocedural TEE has already been performed. ICE can be used for procedural guidance and provides imaging that is comparable with TEE.

VIII. ECHOCARDIOGRAPHIC GUIDANCE OF ATRIAL SEPTAL DEFECT AND PATENT FORAMEN OVALE CLOSURE

A. Introduction

Percutaneous transcatheter closure of ASDs and PFO is an increasingly attractive alternative to surgical repair. These procedures are widely performed for hemodynamically significant left-to-right shunting, to prevent recurrent paradoxical embolism, and for the platypnea-orthodeoxia syndrome. A variety of different approaches are used to guide PTC of ASDs and PFO, each with unique advantages and disadvantages. These include primary fluoroscopic guidance and echocardiographic guidance with TTE, TEE, and, most recently, ICE.[15,17,20,25,27,29,88-90]

B. Echocardiographic Modalities

TTE, TEE, and ICE are used to evaluate and guide the percutaneous closure of PFOs and ASDs. TTE has the advantage of offering multiple planes to evaluate the device and atrial septum, but it has limited ability to interrogate the lower rim of atrial septal tissue above the inferior vena cava after device placement, because the device interferes with imaging in virtually all planes. In addition, because the septum is relatively far from the transducer (relative to TEE or ICE), color imaging is suboptimal in larger patients. Some centers, however, use TTE for monitoring in all patients. In adult patients, TTE typically provides more limited imaging of the interatrial septum and surrounding structures, and as such, most adult centers typically use TEE or ICE to guide PTC.

Transesophageal echocardiographic guidance has been described extensively in adult patients and offers the advantages of providing real-time, highly detailed imaging of the interatrial septum, surrounding structures, catheters, and closure device.[15,20,25] TEE requires either conscious sedation, with attendant aspiration risk in a supine patient, or general anesthesia, with an endotracheal tube to minimize this risk. This approach also requires a dedicated echocardiographer to perform the TEE while the catheterization operator performs the closure procedure, as well as anesthesia support personnel if general anesthesia is used.

ICE provides imaging of the interatrial septum and surrounding structures that is comparable with TEE but does not require additional sedation or general anesthesia to perform. Currently available intracardiac echocardiographic systems provide a single-use 8Fr to 10Fr mechanical or phased-array intracardiac ultrasound–equipped catheter and require additional 8Fr to 11Fr venous access. The development of newer, smaller caliber catheters has allowed the use of ICE in smaller pediatric patients. In addition to obviating the need for general anesthesia in adults, ICE offers the potential to reduce the need for additional echocardiographic support, because the operator performing the percutaneous closure can also manipulate the catheter. At some centers, however, additional echocardiography expertise is used to assist in ICE during these procedures. This is particularly helpful in patients with large defects, for whom the risk for misplacement or embolization is greater. In these patients, continuous evaluation with echocardiography during device placement can prevent complications of the procedure.

Additional advantages of ICE in the guidance of PTC compared with TEE include shorter procedure and fluoroscopy times, improved imaging, and the addition of supplementary incremental diagnostic information, and as such, it is emerging as the standard imaging modality for evaluation of the interatrial septum and for guiding PTC.[15,17,20,27,29,88] ICE can be used as the primary imaging modality, without supplemental TTE or TEE. Recently, ICE has been shown to offer comparable cost with TEE-guided PTC when general anesthesia is used for those undergoing TEE-guided closure.[15,17,20,25,27,29,88,89,91]

C. General Procedural Considerations

A number of different devices are currently in use for PTC, and the method of implantation is variable and unique to each device. The mechanism of closure of all devices ultimately involves stenting the defect, with subsequent thrombus formation and neoendothelialization along the interatrial septum.

Preprocedural assessment of the interatrial septum includes evaluation of the entire interatrial septum and surrounding structures. A PFO is defined as any anatomic communication through the foramen ovale, and a stretched PFO is defined when resting or intermittent left-to-right

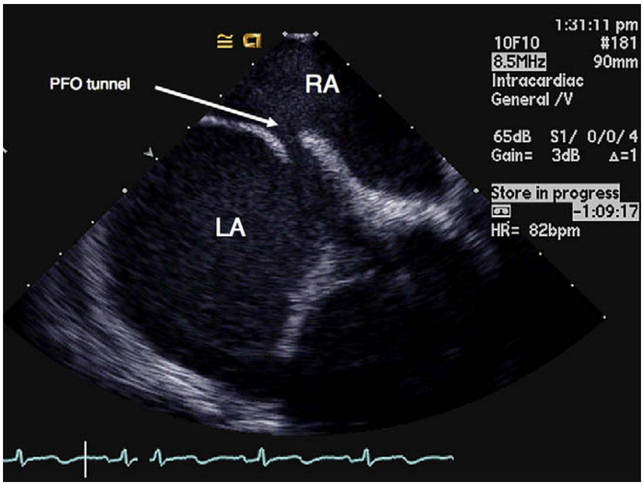

Figure 8 ICE. Phased-array ICE from the right atrium (RA), demonstrating the bulging of septum primum, which opens a large PFO *(arrow)* into the left atrium (LA).

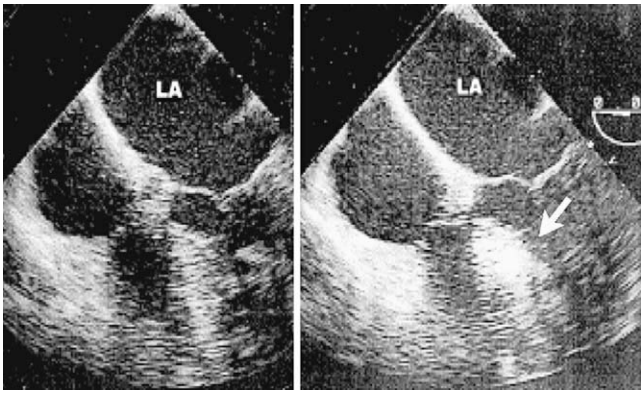

Figure 9 TEE. Midesophageal 4-chamber view before *(left)* and after *(right)* the injection of contrast *(small arrow)*. A radiographic contrast agent is used in this illustration and may be used in patients to demonstrate the perfusion territory supplied by the chosen septal perforator; this is an alternative to the use of an ultrasound contrast agent.

flow on color Doppler imaging is seen (Figure 8). Right-to-left shunting through a PFO is typically demonstrated by the injection of agitated saline microbubbles at rest and with provocative maneuvers such as the Valsalva maneuver. An atrial septal aneurysm is typically defined as 11 to 15 mm of total movement of a 15-mm base of atrial septal tissue.

Echocardiography offers the ability to define ASD type (ostium secundum, ostium primum, sinus venosus, or coronary sinus), maximum ASD diameter, and defect number if multiple defects are present. Presently, only ostium secundum ASDs are amenable to PTC, and an interatrial septum that contains multiple small fenestrations may not be suited to PTC with currently available devices. Defects up to 40 mm in diameter have been closed successfully via PTC, as have multiple ASDs and those associated with atrial septal aneurysms. Associated abnormalities of the pulmonary veins, inferior vena cava, superior vena cava, coronary sinus, and atrioventricular valves should be excluded. Consideration of the size of the atrial septal rim of tissue surrounding the defect is important in evaluating patients for successful PTC, and a surrounding rim of 5 mm is generally considered adequate. The inferior and superior rims may be particularly important for successful PTC, although small series have reported success in patients with deficient rims.[90] In smaller patients, assessment of total septal length is an important additional consideration, because this may limit the size of the device that can be placed successfully.[92]

Echocardiography is recommended to guide PTC of PFO and ASDs. All modalities of echocardiography can be used, but ICE should be considered when suitable expertise is available. Numerous factors must be considered when choosing the ideal echocardiographic modality for procedure guidance, including the patient population, specific anatomy, and local expertise.

IX. ECHOCARDIOGRAPHIC GUIDANCE OF ALCOHOL SEPTAL ABLATION FOR HYPERTROPHIC OBSTRUCTIVE CARDIOMYOPATHY

A. Introduction and Indications

Surgical myectomy for severely symptomatic patients with hypertrophic obstructive cardiomyopathy (HOCM) has been performed for >40 years but is performed at only a relatively small number of experienced centers with acceptable morbidity and mortality.[93,94] Atrial-ventricular sequential pacing is an alternative to surgical myectomy, but after initial enthusiasm, randomized controlled trials reported less favorable results, with incomplete gradient reduction and a lack of sustained symptomatic improvement.[95] A second alternative to surgery is the more recently developed alcohol septal ablation technique.[96] This technique involves the introduction of alcohol into a target septal perforator branch of the left anterior descending coronary artery for the purpose of producing a myocardial infarction within the proximal ventricular septum.

This procedure, which results in a localized septal infarction, was referred to as nonsurgical septal reduction therapy by Sigwart,[96] who first described the procedure in 1995. Since the introduction of this procedure by Sigwart, a number of other groups have applied and modified this technique with good results.[97-101] Perhaps the most important modification has been the use of myocardial contrast echocardiography to delineate the vascular distribution of the individual septal perforator branches of the left anterior descending artery. In fact, the use of contrast echocardiography is paramount to the success of this procedure.[102]

TTE is the conventional approach for intraprocedural echocardiographic monitoring of transcoronary ablation of septal hypertrophy for HOCM. Some laboratories prefer TEE because it provides more precise imaging of the subaortic anatomy of the left ventricle than TTE.[103] ICE is a third imaging alternative for use during this procedure.

B. Methods for Guidance

Because the septum is perfused through a number of septal perforators, with significant individual variation and overlap in distribution, exact delineation of the vascular territory of each perforator artery is important to determine the vessel or vessels that should receive the alcohol injection.[104,105] To determine that the presumed target septal perforator was correctly selected, intraprocedural myocardial contrast echocardiography should be performed. After verification of the correct balloon position and the hemodynamic effect of balloon occlusion, 1 to 2 mL of diluted echocardiographic contrast agent followed by a 1-mL to 2-mL saline flush is injected through the

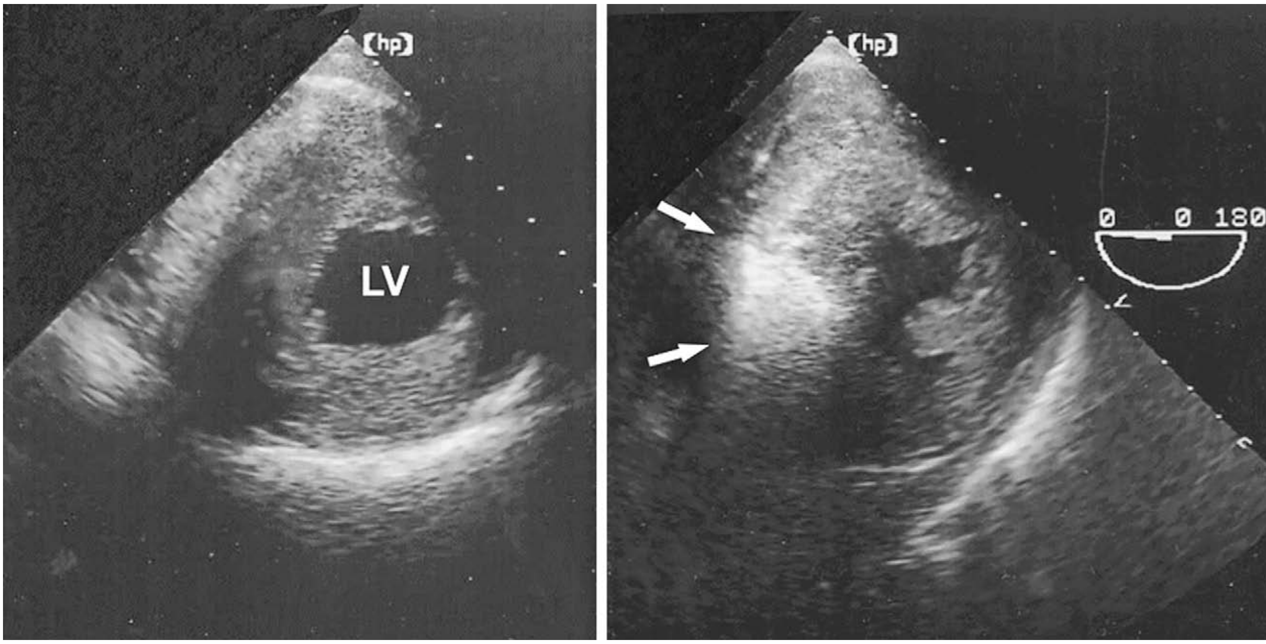

Figure 10 TEE. Transgastric short-axis view before *(left)* and after *(right)* the injection of ultrasound contrast *(arrows)* demonstrating the site of perfusion of the selected septal perforator. Ultrasound contrast is used not only to define the desired perfusion area of the target septal perforator but also to exclude perfusion of unwanted areas, such as the papillary muscles, the distal (apical) portion of the ventricular septum, and the right ventricle. This transgastric short-axis view is particularly useful to delineate the papillary muscles. *LV*, Left ventricle.

inflated balloon catheter under continuous TTE or TEE. The echocardiographic contrast agent should be diluted with normal saline to optimize myocardial opacification and to minimize attenuation. Details of the dilution vary with the contrast agent used. Agitated radiographic contrast can be used instead of an ultrasound contrast agent (Figure 9).

The optimal target territory of the basal septum should include the color Doppler–estimated area of maximal flow acceleration and the area of systolic anterior motion–septal contact without contrast opacification of any other cardiac structures (Figures 9-11). After myocardial contrast echocardiography confirms that the presumed target septal perforator perfuses the desired region of the basal septum, alcohol can be administered.

If TTE is used, apical 4-chamber and 3-chamber (long-axis) views should be used. These views may be supplemented with parasternal long-axis and short-axis views. If TEE is used, the apical 4-chamber view (at 0°) and the longitudinal view (usually 120°-130°) should be used. These views may be supplemented by the transgastric short-axis view to help ensure that no erroneous perfusion of the papillary muscles occurs. The deep transgastric view, which resembles an apical 4-chamber transthoracic view, is useful for measuring the intracavitary gradient with TEE.

C. Immediate Assessment of Results

Intraprocedural echocardiography is also useful for evaluating the results of the procedure in the catheterization laboratory.[103,105,106] The region of the basal septum, which is infarcted by the infused alcohol, is typically intensely echo dense. In addition, this region of the septum should have reduced thickening and contractility.[103] There should also be resolution or improvement of the degree of systolic anterior motion of the anterior mitral leaflet and usually reduction in the degree of MR. In addition, there should be elimination or reduction of the intracavitary gradient. This is readily measured by TTE and can often be measured by TEE with a deep transgastric view or midesophageal long-axis view.

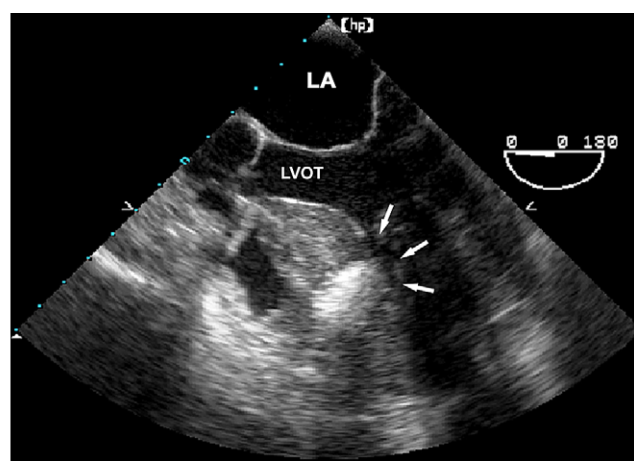

Figure 11 TEE. Midesophageal 4-chamber view after the injection of contrast *(arrows)*, demonstrating that the site of perfusion of the selected septal perforator is too apical and therefore not related to the point of septal contact of the mitral valve. *LA*, Left atrium; *LVOT*, left ventricular outflow tract.

D. Outcome Data

Several studies have suggested a favorable impact of echocardiographic monitoring during this procedure.[102,105,107] Echocardiographic monitoring of percutaneous transluminal septal myocardial ablation has resulted in the reduction of the amount of injected alcohol and the number of occluded septal branches.[102] Online echocardiography may also reduce the need for repeat interventions with occlusions of several septal branches, thus avoiding unnecessary enlargement of the septal scar with all of the associated potential negative consequences for left ventricular systolic and diastolic function.

Another important advantage of myocardial contrast echocardiography during the procedure is that opacification of myocardium distant from the intended target septal area can prevent erroneous instillation of alcohol into unwanted territory, such as the papillary muscle, left ventricular free wall, or right ventricle (Figure 11).

A recent American College of Cardiology and European Society of Cardiology consensus document on HOCM stated that "myocardial contrast echocardiography guidance…is important in selecting the appropriate septal perforator branch."[108,109] Nevertheless, a randomized multicenter study with respect to this issue does not exist.

Echocardiography is recommended in selecting the appropriate septal perforator during alcohol injection during septal ablation for HOCM. Both TTE and TEE can be used. They provide an assessment of immediate procedural results and allow monitoring for complications.

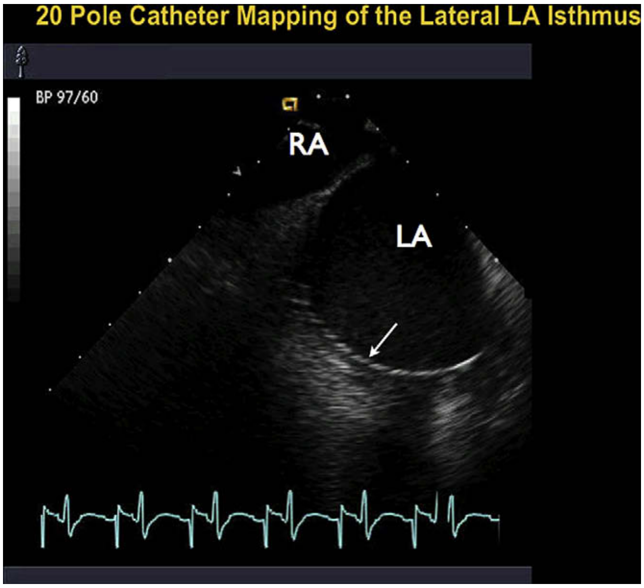

Figure 12 ICE. Phased-array ICE of long-axis view of the left atrium (LA) from the right atrium (RA). Shown is the catheter-tissue contact of a 20-electrode catheter positioned along the posterior mitral annulus *(arrow)*.

X. INTRACARDIAC ECHOCARDIOGRAPHY AND CARDIAC ELECTROPHYSIOLOGY

A. Anatomy-Dependent Arrhythmias

Catheter-based ICE has been applied extensively in cardiac electrophysiology laboratories to guide ablative procedures. To a large degree, this early adoption has occurred because of the critical dependence of specific cardiac arrhythmias on underlying anatomy. For example, accessory atrioventricular pathways bridge from atrial to ventricular tissue across the mitral or tricuspid annulus, requiring selective energy delivery at a specific anatomic location to successfully eliminate related supraventricular tachycardias. In addition, clarification of the pathophysiology of typical atrial flutter demonstrated that the cavotricuspid isthmus was a critically important component of the underlying reentrant circuit.[110,111] Because of this, the nomenclature of this arrhythmia was changed to "isthmus-dependent, counterclockwise atrial flutter." It follows that the ability to visualize specific anatomic structures should be of substantial importance in the nonpharmacologic treatment of these arrhythmias.

B. Phased-Array Imaging

The application of phased-array technology with a transesophageal probe was shown in early studies to be useful for imaging during VT ablation[112] and the treatment of accessory pathway–mediated tachycardias.[113-115] The miniaturization of this technology and application via intracardiac catheters allowed deeper penetration and standard 2D visualization and Doppler imaging of both right-sided and left-sided structures from within the right heart.[116] Long-axis imaging with phased-array technology has been particularly suited for the electrophysiology laboratory environment. Within the context provided by forward imaging, intracardiac ultrasound frequently has been used to guide the insertion of catheters into specific cardiac chambers, across the cardiac valves into the ventricles, and to guide transseptal catheterization into left-heart structures, from a single imaging viewpoint or with minimal catheter rotation. Intracardiac ultrasound has been preferable to transesophageal imaging because it does not require prolonged esophageal intubation, accompanying patient discomfort, or the risk for aspiration. It is also routinely performed by a single interventionist, without the need for other personnel for further image acquisition and interpretation.

C. Ultrasound-Guided Anatomic Ablation

Intracardiac ultrasound has been applied to guide the positioning of ablation catheters near specific cardiac structures for ablation of the related arrhythmia, as seen in Figure 12. The value of such intracardiac echocardiographic imaging extends to establishing a clear-cut relationship between the catheter tip and underlying tissue, a critically important determinant of ablation success. In many cases, the lesion produced in the delivery of ablation energy can be visualized in tissue adjacent to the catheter tip. This observation is of theoretical importance, because the identification of each individual lesion could facilitate the juxtaposition of subsequent energy deliveries, as required in linear ablation. This utility has also been documented in linear ablation studies from several centers.[21,117-119] However, the visualization of an evolving lesion is a function of the imaging frequency, the distance of the ablation site from the transducer, the catheter tip–tissue contact, the delivered energy, and the thickness of the underlying tissue. Therefore, the lesions formed by the ablation of ventricular myocardium are more readily seen than with atrial ablation.[120-122] Furthermore, continued energy delivery in the ablation of atrial tissue to the point of lesion visualization is not necessary for a successful outcome and may be excessive. In short, lesion visualization with B-mode imaging is insufficiently sensitive for establishing an end point for ablation. Other means of enhancing lesion detection are currently being studied.[123]

Avariety of studies have tested the utility of intracardiac ultrasound in the setting of atrial tachycardias,[124] atrioventricular nodal reentrant tachycardia,[125] sinus tachycardia,[126] ventricular arrhythmias,[127] atrial flutter,[110,121,128,129] and AF.[18,21,22,24,130] Ablation of the cavotricuspid isthmus has been found to be 95% to 98% successful in eliminating atrial flutter simply through the identification of the anatomic site of origin of that arrhythmia.[110,111] Recent studies[131,132] have also shown

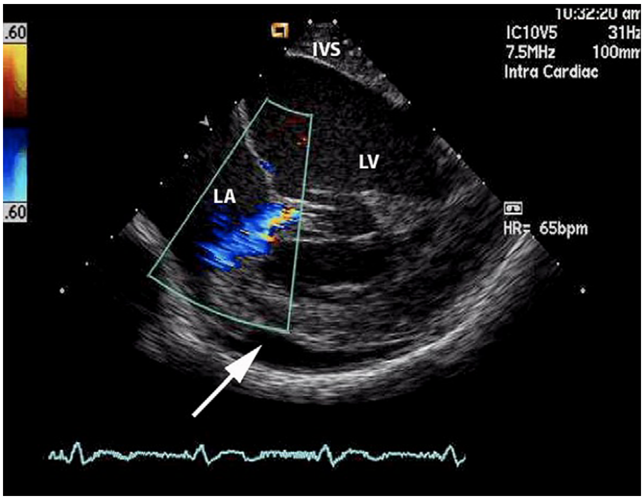

Figure 13 ICE. Phased-array ICE from the right ventricle. Imaging through the interventricular septum (IVS) to display the left ventricle (LV) and left atrium (LA) demonstrates an emerging pericardial effusion *(arrow)* during an ablation procedure. MR is also shown by color Doppler mapping.

the utility of imaging the left ventricular scar that results from myocardial infarction in ablation of postinfarct VT. Typically, stable VT arises within the border zone of an infarct. In such cases, intracardiac ultrasound can be used to guide ablation and create lesion bridges from the center of the scar, across the infarct border zone, on to a neighboring electrically inert cardiac structure such as the mitral annulus. Such lesions interrupt the VT circuit that passes through the spared tissue immediately around the infarct, such as the submitral valve isthmus in the setting of inferior wall infarction.[133] Linear ablation along the border of an infarction, such as is required for ablation of fast, unstable VT, has also been facilitated by direct imaging.[131] Such left ventricular imaging is best conducted from below the tricuspid valve from a venue near the right ventricular outflow tract. From this position, both long-axis and short-axis images of the left ventricle can be created.[116]

D. Ablation of AF

ICE has been used most consistently for the guidance of ablation of AF. This approach establishes the number and position of pulmonary veins and determines whether a left pulmonary vein antrum, formed by the confluence of the left superior and inferior pulmonary veins, is present. ICE also clarifies the branching patterns of the right pulmonary vein, guides the positioning of interventional catheters, verifies catheter tip–tissue contact, assesses underlying pulmonary vein physiology, helps in the positioning of balloon-type catheters for ablative interventions, and monitors for excessive tissue heating as manifested by the occurrence of microbubbles. Furthermore, ultrasound establishment of the venoatrial junction has recently been shown in preliminary studies to be more accurate than is possible with contrast venography.[134,135] Given its position in relationship to the left pulmonary veins, the location of the vein of Marshall, relevant in AF ablation, can also be identified from imaging of the "Q-tip" ridge, seen between the LAA and those pulmonary veins.[136]

Not only does the ultrasound beam allow identification of the underlying pulmonary vein and other relevant structures, it also enables positioning of guidance catheters, such as the circular Lasso catheter, to a position immediately at the orifice of the pulmonary vein. This is particularly critical because these catheters have a tendency to drift into the vein, providing a false sense of the true orifice of the vessel.[137] Ablation too far into a vein increases the risk for pulmonary vein stenosis and decreases the efficacy of AF ablation.[138] Several studies[18,22,130,139,140] have shown the utility of intracardiac ultrasound to guide ablation at or outside the pulmonary vein orifice, which results in increased efficacy for AF ablation.

E. Monitoring for Ablation-Related Complications

Microbubble formation has also been widely observed with intracardiac ultrasound imaging.[21,141,142] This phenomenon may be even more accurate than catheter-tip temperature monitoring for the assessment of heat generation during the ablation of cardiac tissue.[142,143] Nevertheless, although this finding has been proposed as an end point to guide ablation, recent studies have demonstrated that microbubble appearance frequently reflects excess tissue heating to substantially greater temperatures than reflected by catheter-tip temperature monitoring.[139,141] This inadvertent tissue overheating, in turn, may lead to clot, char, or crater formation; intracardiac thrombus; or even pulmonary vein stenosis. Therefore, ultrasound visualization of microbubbles is most useful for prompting discontinuation of energy delivery when microbubbles are seen.

Along this same line, intracardiac ultrasound is useful in monitoring for potential complications of ablative intervention. In addition to the observation of the untoward results of tissue overheating, several studies have recently demonstrated the utility of ultrasound for detecting thrombus formation on the interventional catheter, which could lead to either a stroke or a peripheral thromboembolic event.[144,145] Ongoing surveillance of the pericardium during an interventional case is useful for the early detection of an effusion (Figure 13), before its physiological relevance is manifested by tamponade physiology. Imaging from an intracardiac venue also facilitates the catheter-based treatment of the effusion.

Doppler imaging likewise has contributed in the surveillance process. Pulsed-wave Doppler imaging, available with phased-array imaging over the course of an ablation, reveals an increase in flow velocity with pulmonary vein narrowing. An increment to a level in excess of 1.6 m/s has been found to be predictive of subsequent stenosis.[146] In contrast, veins with lower flow velocities, $\leq$1.0 m/s, are unlikely to progress to any significant degree.[147] It is noteworthy, however, that these intracardiac Doppler flows are highly dependent on the presence of AF or catecholamines.[148]

ICE is recommended for radiofrequency ablation for AF. It is used to guide transseptal catheterization, as well multiple aspects of the procedure, to monitor for complications, and to assess pulmonary vein flow before and after ablation.

XI. FUTURE DIRECTIONS

A. Echocardiography in Complex Mitral Valve Procedures (Investigational Devices)

Newer investigational percutaneous mitral valve repair systems are being developed as an alternative to surgical repair for MR, either using the concepts of the edge-to-edge repair technique developed by Alfieri et al[149-151] but performed with a percutaneous endovascular repair system[152-158] or by the performance of a percutaneous mitral annuloplasty repair with a device placed in the coronary sinus or at the level of the mitral annulus. A variety of delivery approaches for these devices have been proposed. For example, an endovascular mitral repair system uses a steerable guide catheter to precisely manipulate and position a clip that approximates the middle anterior and posterior leaflet scallops of the mitral valve, thus reducing or eliminating MR.[155] This system is currently being investigated in humans in phase I and II trials. Additional percutaneous mitral repair devices that use the concept of edge-to-edge repair are also being developed.

The delivery of the percutaneous edge to edge mitral valve repair system has 5 steps that require echocardiographic guidance: transseptal catheterization, alignment of the clip delivery system perpendicular to the plane of the mitral valve and centered with reference to the line of coaptation, alignment of the clip with the open arms perpendicular to the coaptation line of the mitral valve, closing of the arms and approximation of the tips of the mitral valve, and release of the implant device. A combination of TEE and supplemental TTE has been used to guide the procedure.

Other coronary sinus and mitral annular devices are also being developed to perform percutaneous mitral annuloplasty repair, thereby reducing MR by enhancing mitral coaptation. TEE or ICE can be used to guide cannulation of the coronary sinus ostium, place the device, monitor for procedural complications, and assess the degree of MR and transmitral gradients before and after the procedure.

B. Role of Echocardiography in the Placement of LAA Occluders (Investigational Devices)

The majority of thromboemboli in AF arise in the LAA.[159-161] That observation led to the hypothesis that functional obliteration of the LAA could prevent stroke. For this reason, surgeries for several indications often include prophylactic intraoperative ligation of the LAA,[162,163] and some have recommended LAA ligation in all patients having cardiac surgery, regardless of the indication.[164]

A percutaneous transcatheter approach for the prevention of cardioembolic stroke in patients with AF has been proposed, by the placement of an implantable prosthetic device that seals that the communication between the LAA and the left atrium. Initial testing in animals[31] and humans[165] and, more recently, anatomic and hemodynamic data[166] have suggested successful occlusion and stroke prevention. A percutaneous LAA transcatheter occlusion device was the first device tested in humans; ultimately, the trials of this first device were halted because of increased morbidity and mortality. TEE had been used in all published human trials of this device. A newer device has been described.[167] This nitinol metal device is designed to be placed in the LAA via a percutaneous transcatheter approach by a standard transseptal approach with fluoroscopic and TEE guidance. TEE is important in sizing the ostium of the LAA and selecting an appropriately sized device for implantation.

After device release, TEE is repeated to confirm the proper deployment of the device and to assess for procedural complications. The device is examined for stability and leakage. Atrial septal examination is performed to look for an ASD; a small residual defect is common after the procedure. The pericardium is reevaluated for effusion.

C. 3D Echocardiography

A new application of echocardiography, 3D imaging, offers the potential to contribute significantly to interventional procedures. For example, myocardial biopsy has been performed with 3D imaging as a guide for bioptome position (as opposed to the standard approach with fluoroscopy). In one study of 63 routine right ventricular biopsy procedures in cardiac allograft recipients, 3D imaging was deemed feasible, and improved localization of the bioptome was observed, with the potential to improve cardiac biopsy efficacy and safety.[168]

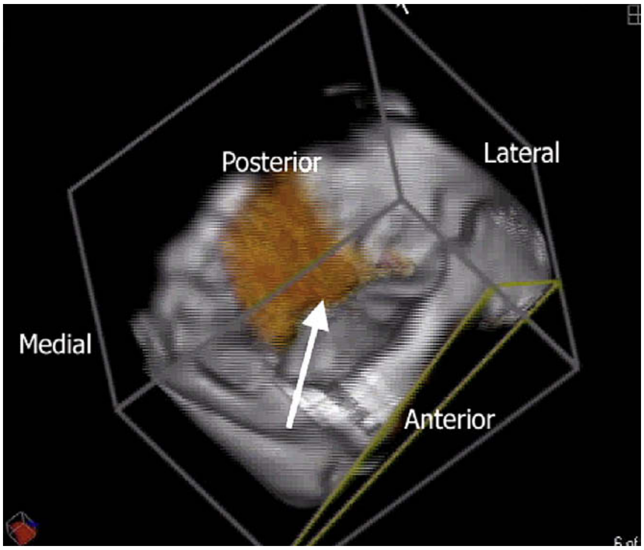

Figure 14 TEE. Reconstructed 3D image of the left atrial surface of the mitral valve in a patient with severe MR originating from nearly the entire mitral coaptation surface (*arrow* indicating red flow into the left atrium on color mapping). Anatomic coordinates are indicated for reference.

Mitral valve anatomy may be better studied with 3D imaging than with 2D imaging (Figure 14), and therefore, 3D imaging can play a significant role in the planning of surgical or percutaneous approaches to mitral valve repair[169-171] (Figure 15). Human studies with intraoperative 3D TEE have shown excellent correlation with surgical findings (94% [34 of 36 patients]) in the correct identification of scallop or segment prolapse.[171]

Others have found incremental value from 3D TEE and TTE over 2D echocardiography for the selection of appropriate patients and the accurate visualization of postprocedural commissural splitting and leaflet tears in patients undergoing PBMV.[172,173] Similarly, it is expected that 3D echocardiography will play a role in the planning of percutaneous mitral repair of MR, such as that shown in Figure 16.[174]

The use of percutaneously delivered devices for ASD or PFO repair is increasing. Three-dimensional imaging allows for accurate anatomic assessment before the procedure and can localize the closure device during the procedure in relation to other cardiac structures, potentially enhancing success and possibly decreasing the complication rate.[175] In 40 of 41 patients (98%) undergoing device ASD closure, 3D images of defects were obtained, and these images more accurately assessed ASD size (using balloon sizing as the "gold standard") than did 2D TEE. Additionally, device position was more accurately assessed with 3D imaging.[176] Real-time 3D echocardiography has also been used for accurate assessment of the morphology and efficacy of transcatheter devices used for ASD and PFO closure.[177] In 4 patients who underwent percutaneous closure of ASDs or PFO (3 ASDs, 1 PFO), real-time 3D echocardiography provided comprehensive anatomic assessment of ASD and PFO closure devices.[177]

Interventional approaches for the treatment of patients with HOCM are also increasing.[101] Real-time 3D echocardiography has also been successfully used to guide the surgical approach to myectomy and mitral valve repair in 10 patients in whom a "surgeon's view" by 3D echocardiography allowed refinement of the planned surgical approach.

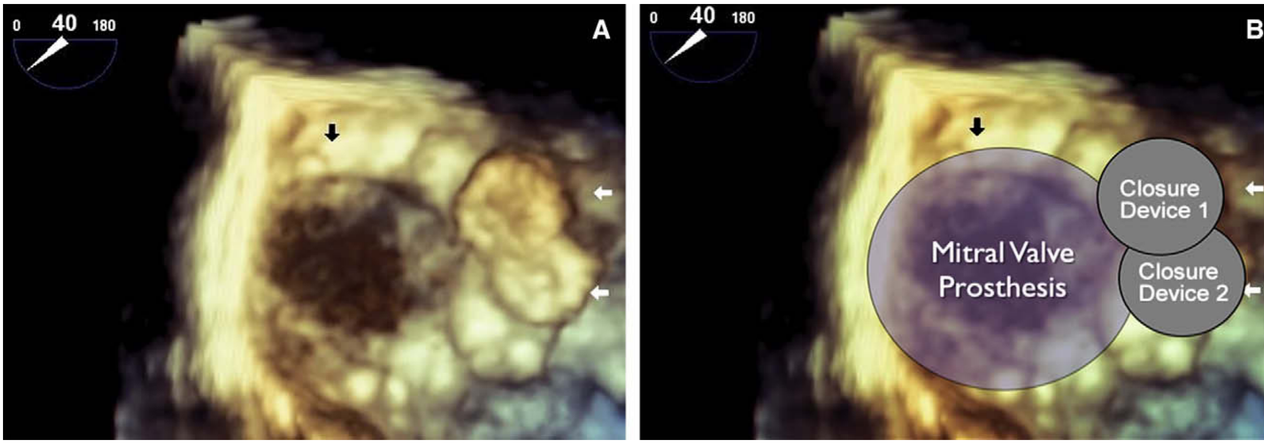

Figure 15 Three-dimensional TEE. **(A)** Three-dimensional image of a mitral bioprosthesis *(black arrow)* and two closure devices *(white arrows)* used to close paravalvular MR. **(B)** Explanatory overlays added. The perspective is from the left atrium. It is often difficult to identify the exact site of regurgitation and also to guide interventional devices to the correct location when repairing paravalvular regurgitation using occluder devices. In this case, real time 3D imaging was critical in positioning the closure devices and defining the location and extent of the paravalvular jet.

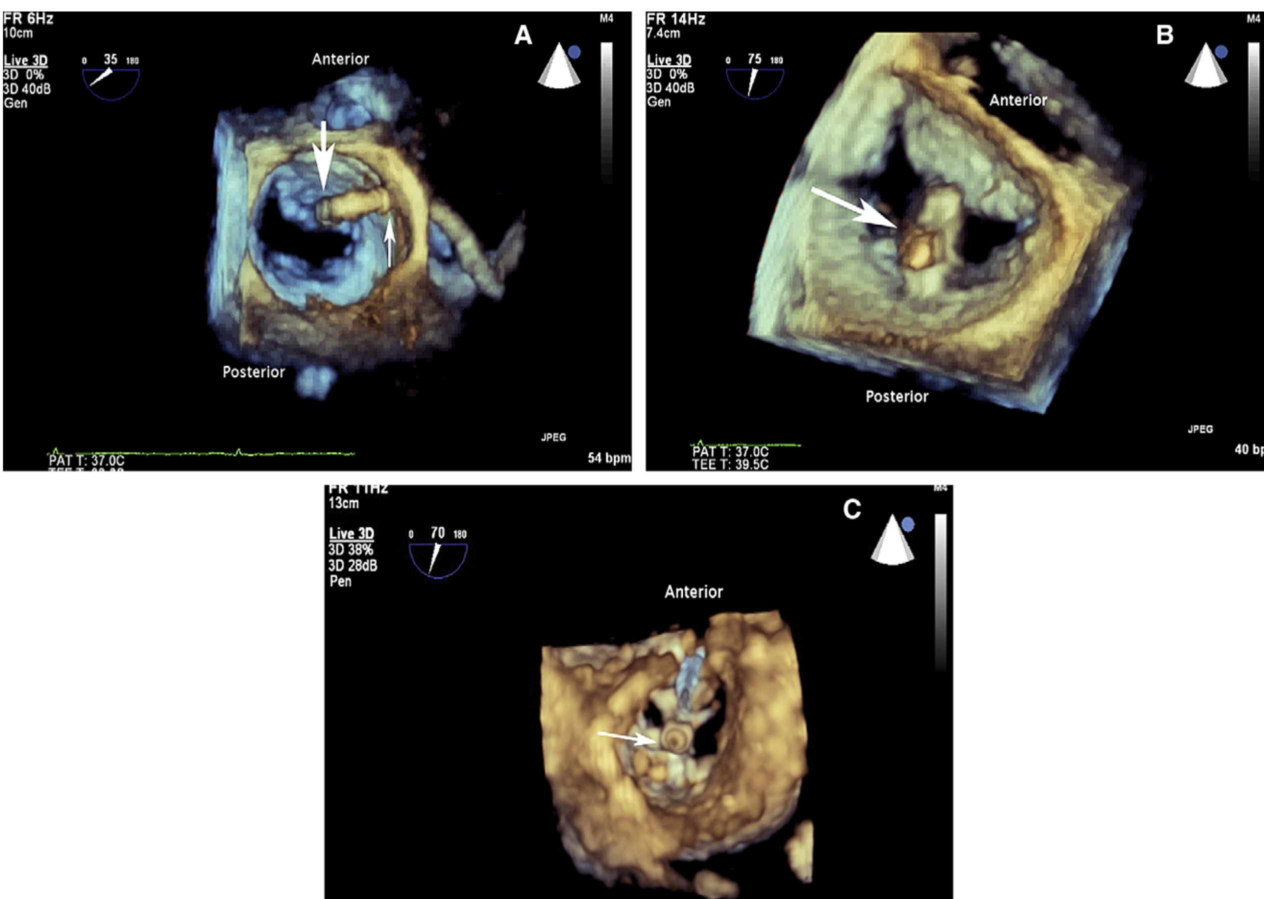

Figure 16 Three-dimensional TEE. Percutaneous edge-to-edge repair of MR using a clip. **(A)** Percutaneous clip being aligned over the mitral valve in the left atrium. The *large arrow* indicates a clip prior to opening, and the smaller arrow indicates a guide catheter tip. **(B)** The open "arms" of the prosthesis *(arrow)* as they are aligned perpendicularly to the line of coaptation prior to grasping of the leaflets. **(C)** Imaging from the left ventricle perspective demonstrates a closed clip *(arrow)* creating a double-orifice mitral valve repair.

D. Echocardiography in Percutaneous Aortic Valve Replacement

Recently, percutaneous transcatheter aortic valve replacement has been described, and initial studies are presently being performed with two distinct biologic valves mounted on stents, which are crimped onto a balloon and delivered using a valvuloplasty technique.[178-181] These valves can be percutaneously placed via a retrograde transaortic approach or via a surgical direct transapical approach.[182-184] Echocardiography plays a critical role in patient selection, particularly in choosing the appropriate size of the prosthesis to be implanted. In particular, the aortic annular diameter is important in determining prosthesis size.[182] Small differences in aortic annular diameter and geometry have been demonstrated between TTE and TEE. During the procedure, TEE has been used to help ensure appropriate positioning of the prosthesis and to assess for paravalvular regurgitation after the valve has been implanted. Real-time 3D TEE has also been described during this procedure, but its role and incremental value compared with standard TEE are not fully known at this time.

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