无创血管实验室检测指南
美国超声心动图学会和血管医学和生物学学会的报告

Guidelines for Noninvasive Vascular Laboratory Testing: A Report from the American Society of Echocardiography and the Society of Vascular Medicine and Biology

中文翻译：钟　优 北京医院国家老年医学中心

中文校对：戴旭明　纽约长老会医疗集团皇后区医院

执行概要

随着经皮血管介入病例的快速增长，心血管专家对用超声进行无创血管检查有了越来越大的兴趣。为了对血管实验室检测的提供最佳的实践建议，由美国超声心动图学会（ASE）和血管医学和生物学学会的一个写作小组撰写了该报告。该文件总结了血管超声的基本原则－包括彩色多普勒，频谱多普勒及波形分析系统，能量多普勒，以及超声造影剂的应用;描述了应用超声成像检查颈动脉，肾动脉，腹主动脉，和外周动脉的适应症和结果分析及解释。有一个专门的章节总结了无创技术应用于下肢动脉的生理性血管检测－包括测量节段性血压和脉冲容积描记法。应用运动试验评定外周动脉疾病，对下肢动脉经皮血管重建术的超声评价，以及医源性假性动脉瘤（PSA）的诊断和治疗也进行了讨论。这份报告还包括了另一个重要的话题就是是对血管实验室的资质认证。最后，有关各种血管检测的具体操作和步骤的额外的技术细节都包含在附录中。

背景

在已经从业的和正在接受培训的心脏科医生中,对血管超声技术培训的需求越来越大。例如，最近的心血管病学专科医生培训条例，COCATS-2，就推荐全职或兼职地在无创性血管实验室接受 2 个月的血管超声 1 级培训［1］。本文将对无创血管检测颈动脉，肾动脉，腹主动脉性，和周围动脉的一般性原则，适应症，结果解释做一综述。对于血管超声检查的技术细节详见附录。本工作组的另一篇文章，“无创血管超声在评估心血管危险评估中的临床应用”，将回顾颈动脉（内－中膜厚度）和肱动脉（血流介导血管扩张）的测量与其在心血管危险分层中的应用。

仪器仪表：一般性建议

血管检测包括双相超声成像和生理学评价。血管超声检查需要机器配有 5 到 12 MHz 线阵探头（用于颈部和四肢）和 2.25 - 3.5 MHz 的曲线线性或相控阵换能器（针对腹部）。除了适当的传感器外，还需要一个血管软件包。双相成像是指同时获取和记录灰阶和多普勒信息的超声扫描程序。包括二维结构和动态，多普勒频谱分析，及彩色血流速度标记。颈动脉，肾动脉，腹主动脉及外周动脉，均可采用这种设备检测。生理学检测包括脉冲容积记录和节段性压力测量，需使用大小适当的下肢袖带和体积描记记录仪。

双相成像：适用于所有血管检测的基本原则

超声束垂直于检查对象的表面，以获得最强的灰度成像回声和动脉壁的最佳图像。垂直角度通常是容易获得的，因为动脉一般是与换能器的表面平行。（图1）

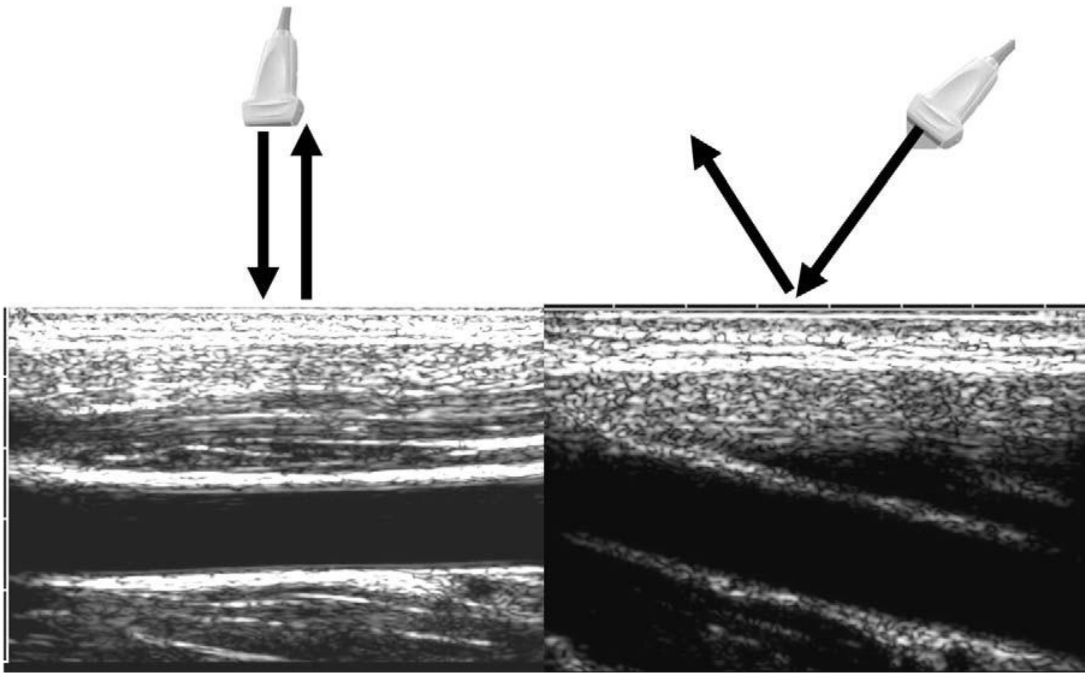


图1，进行二维呈像时超声束应垂直于感兴趣的血管以获得最清晰的图像。左，超声束垂直于血管壁（箭头）可获得的颈动脉二维图像，可显示动脉壁三层结构。右，超声束非垂直角度（箭头）血管壁结构不清晰。

对于双相成像的多普勒部分，多普勒超声束与血管壁之间的角度应保持在60度。这一多普勒角是以运动速度进行分类的疾病的一个重要的考虑因素。角度在 60 度以上会导致显著高估速度所以应该尽量避免。与血管壁的相关角度不适当可能

会低估真实的峰值速度（图 2）。

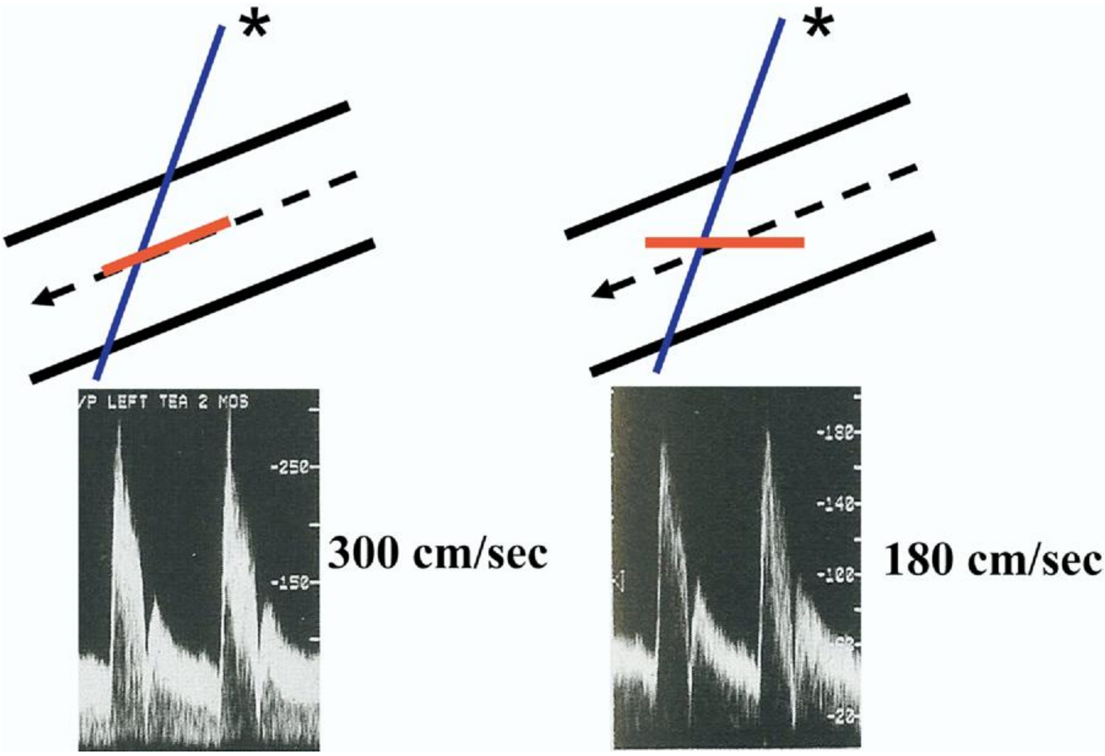


图 2，多普勒声波采样线与血管轴的夹角小于 60 度角时可较精确的测得多普勒速度。应使用角度校正来保持这个夹角不超过 60 度。多普勒光标应平行于动脉血流中心的血管轴。左，多普勒波束与血管壁成 60 度角，取样容积校正光标平行于血管轴（在血管中心绘制的假想线）。右，多普勒夹角不准确。光标与血管轴不平行。从同一颈内动脉获得的脉冲波多普勒图像显示，在多普勒夹角不准确的情况下，低估了收缩期峰值速度（右）。

彩色多普勒

脉冲波重复频率的测量范围可以决定的彩色的饱和度，通过适当的调整测量范围，可使正常的层流呈现为一个颜色均匀的区域。血管狭窄导致高速的射流和彩色血流模式的突然变化。在管腔变窄的部位的彩色显示为混叠或去饱和度（白色）。混叠是由于血流运动的速度超过尼奎斯特极限，结果显示出与血流方向反向的彩色（溢出）。狭窄后的区域以马赛克图案表明湍流（图 3）。

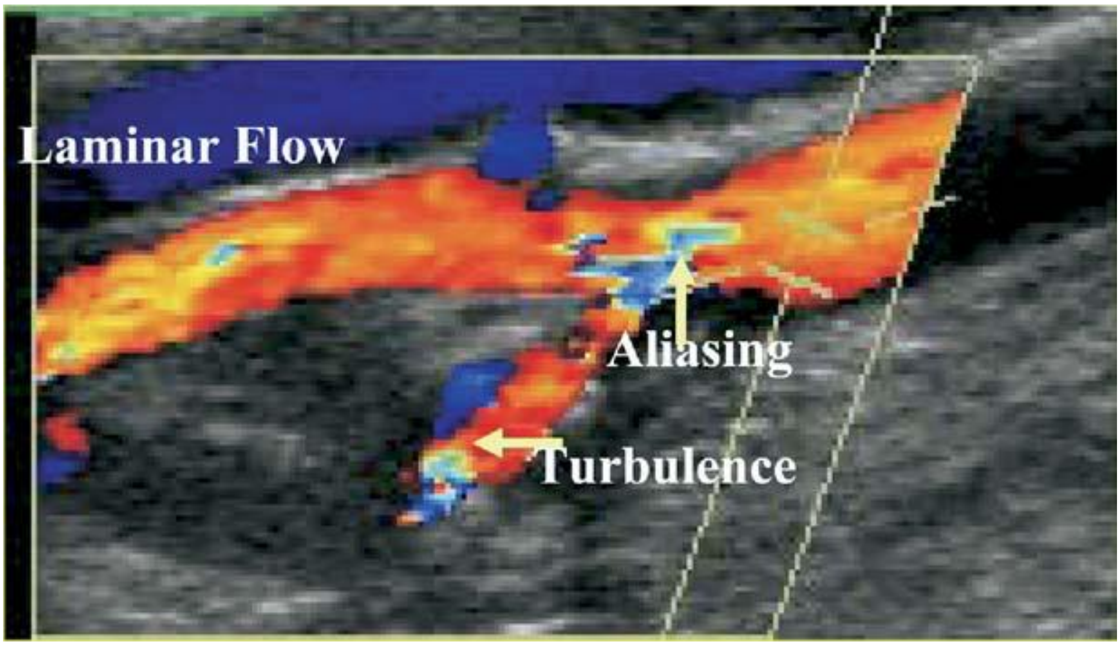
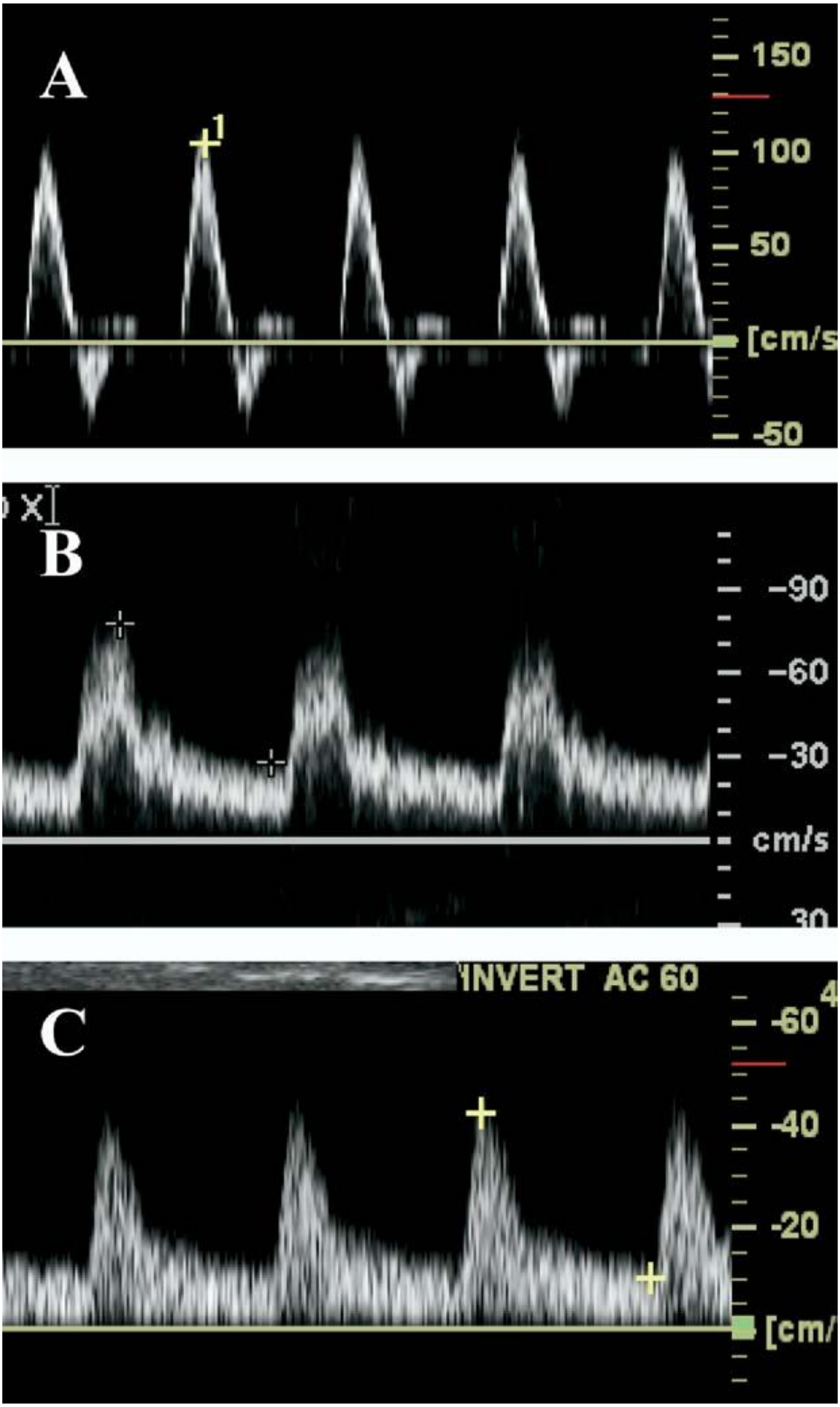


图 3 颈动脉分叉处的彩色多普勒图像
颈外动脉的血流显示为颜色均匀分布的层流，血管中心的血流颜色最浅。
颈内动脉（ICA）起源处出现色彩混叠，表现为在 ICA 起源处彩色回声缺失的斑块处，血流中心的颜色突然从红色变为蓝色， ICA 其余部分的彩色镶嵌与狭窄后湍流的表现一致。

调整灰阶设置，使这些异常血流部位的腔内斑块或血栓的可视化得以优化。当用于检测一个显著的狭窄时，彩色血流提供了更多的信息。混叠的持续的和播散的彩色表明血流扰动的情况。相对于正常动脉中出现的交替的颜色，只见于前进方向上的色彩的延迟是一个连续血流的信号［4］。色彩的延迟对应于严重狭窄的单相多普勒频谱波形。周围软组织中出现彩色播散也表明血流扰动。这种颜色的伪影是由于高速射流在周围的软组织中引起的振动。彩色血流异常表明有狭窄的可能，然后用脉冲波速度进一步确定的血流的速度。

频谱多普勒波形分析

正常的脉冲波多普勒波形清晰的有狭窄的频谱包络线，表明血细胞在整个心动周期正在以相似的速度移动（图 4）。



A
150
100
50
[cm/s
-50
B
-90
-60
-30
cm/s
30
INVERT AC 60
C
-60
-40
-20
[cm/

图 4 频谱多普勒波形。
A，正常的层流，整个心动周期的血流速度在一个很窄的范围之内。
十字光标放置在清晰的频谱窗口上方（或包络线上方）。
B，双相多普勒波形，伴有反向舒张血流缺失和频谱包络线轻度增宽（频谱增宽）。
C，频谱窗口填充的湍流（频谱增宽）和峰值收缩期速度降低。

而在血管分岔处和管腔狭窄流动变为湍流，引起的多普勒波形频谱增宽。这是由于血细胞的移动速度在很宽的范围内波动，频谱波形的低速区域被填充（图 4）。正常外周动脉波形式是三相（图 4）。第一部分是起源于心室收缩早期的正向血流，形成可以检测到的收缩期峰值流速（PSV）测量结果。在不同的血管段，这个 PSV 通常都是小于 125 厘米/ 秒的。在波形的第二相，有一个舒张早期的逆向血流，它是由于在主动脉瓣关闭前左心室压力降低形成的。第三相是在舒张末期，有少量的正向流动，反映血管壁弹性回缩。当动脉粥样硬化血管僵硬时第三相消失。波形的形状也表现为高阻型（如，正常外周动脉波型），或低阻型（例如，正常颈内动脉波形）（图 4）。舒张期流量是由远端阻力小动脉扩张的程度来决定的。

能量多普勒

能量多普勒是一种可以显示返回的多普勒信号的总强度（振幅）的技术，这不需要区分方向性。能量多普勒的敏感性比彩色血流多普勒增加 3 至 5 倍[6]。因此，能量多普勒可以识别彩色多普勒不能识别的缓慢血流。能量多普勒对探测角度的依赖较小（不需要区分方向），它可以更清楚的描绘管腔轮廓[7]。能量多普勒可以用来区分重度狭窄和完全闭塞、检测侧支血管及识别小血管病变。

动脉狭窄的评价

多普勒流速是评价血管狭窄程度的主要手段。血管狭窄的典型双相超声特征包括速度增快，颜色杂乱，频谱包络线增宽，和狭窄后波形［表 1］。如果狭窄后的波形不能确定，那么这种血流速度增快的原因可能是由不恰当的角度或血管扭曲人为造成的。

表 1 动脉狭窄的双相超声表现

•流速增快：诊断标准包括收缩峰流速、病变远端与近端收缩峰流速比值、舒张末期流速，

支持标准包括彩色多普勒信号

• 管径减小：横向或纵向测量显示管腔直径减小，是支持标准，而非诊断标准

• 频谱展宽或颜色镶嵌：发现湍流是支持标准，非诊断标准；在狭窄病变远端此表现较明显

• 颜色播散或持续：颜色播散说明狭窄血管周围组织震动，是支持标准，而非诊断标准；持续前向血流也是动脉狭窄的支持标准

造影剂在血管成像中的应用

外周血管疾病的超声评价在很大程度上取决于设备的功能和操作者的技能[8]。彩色多普勒技术的加入可以更好地识别外周血管疾病的解剖结构异常，包括位置、长度、有无狭窄或闭塞、侧支血管的形成和血流重建区域。超声造影剂则用于优化处理不理想的图像及在因血管壁钙化影响对管腔的观察和速度测定的地方提高血管疾病的诊断[3]。目前的临床试验已经证明造影剂在颈动脉管腔的勾勒、内中膜厚度的测量、斑块形态的描述及闭塞和重度狭窄的鉴别等方面都有帮助。比如，在存在多个肾主动脉的情况下，肾血管的超声增强造影就有帮助[3-9]。几个大规模的研究发现，在基线超声扫描图像不理想时，使用造影剂可以提高对外周动脉疾病的诊断[10]。对一些传统超声技术难以充分显像的血管，比如髂动脉、内收肌管内的股浅动脉、三分叉血管和足底动脉等，造影剂可以提高成像质量。当存在普通超声成像困难的情况时（如肥胖、水肿、全身钙化的病人中），超声造影剂对于区分血管是否通畅很有帮助[11]。然而，应该强调的是，尽管这个报告详列了造影剂在改善血管超声成像中的有效性，但这些造影剂还没有通过美国食物药品监督管理局的批准用于所有的适应症。因此，这些应用目前还处于试验阶段。

颈动脉超声

无创超声检测颈动脉疾病的目的是用一种安全经济的方式区分正常和病变血管，对一系列病变状态进行分类及评估大脑的侧支循环。一是确定有中风风险和可能需要特殊治疗的患者。二是对已知风险患者的疾病进展和复发进行记录评估。颈动脉超声检查的适应症见表 2。［12-15］

表 2 颈动脉超声检查的适应症

• 颈动脉杂音

• 一过性黑矇

• 偏身卒中

• 短暂性脑缺血发作（表现为局部症状，比如一侧面瘫、言语不清、肢体力弱、视野缺损）

• 跌倒发作或晕厥

• 血管炎累及颅外动脉

• 颈部搏动性肿块

• 颈部外伤

• 不需要再血管化的颈动脉粥样硬化的随访

• 颈动脉支架术后 30 天内超声作为基线，以后定期复查

解读

颈动脉双相超声成像应该至少包括颈总动脉、颈内动脉、颈外动脉和椎动脉。频谱波形的分析基于收缩期峰流速、舒张末期流速和频谱宽度等参数的（图 5）。

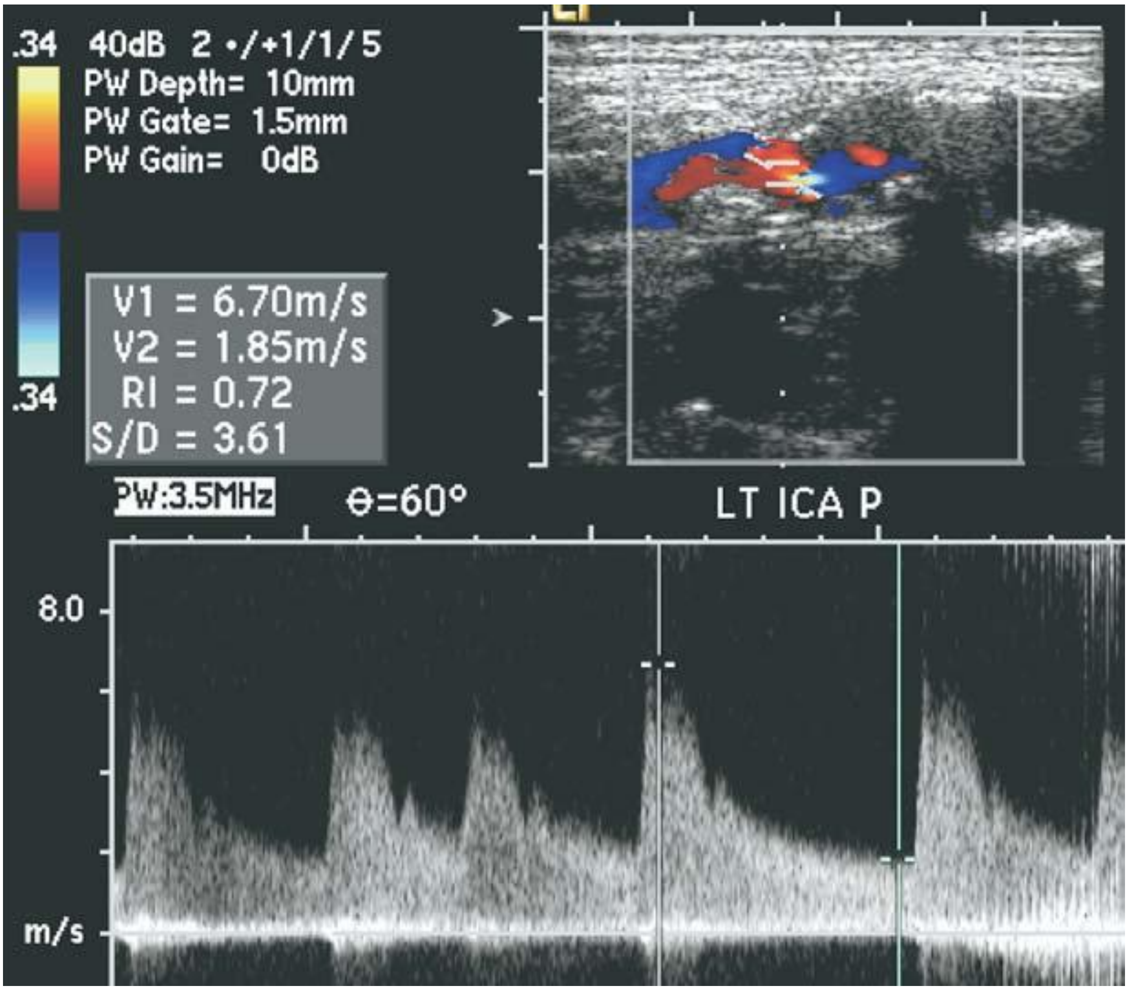


图 5 颈内动脉狭窄的双重证据。双相图像，取样容积光标平行于动脉壁，置于颜色混叠和管腔变窄处。频谱多普勒收缩期峰值速度（670 cm/s）、舒张末期速度

（185 cm/s）和频谱增宽（湍流）。这些发现表明 ICA 严重狭窄（80%-99%）。血管实验室的检测结果必须与金标准（例如，动脉造影）进行对比验证。目前已有多个用于检测颈动脉疾病及其严重程度的流速标准已经被研究发表[16]。表 3 总结了用于诊断颈内动脉狭窄的绝对流速和速度比值标准。

表 3 通过双相超声脉冲信号的频谱波形分析对颈内动脉疾病的分类标准

狭窄程度（%）	**颈内动脉 PSV（cm/s）**	**斑块评估（%）**	**颈内动脉 EDV（cm/s）**	**颈内/颈总 PSV 比值**
正常	＜125	0	＜40	＜2
＜50	＜125	＜50	＜40	＜2
50-69	125-230	＞50	40-100	2-4
＞70	＞230	＞50	＞100	＞4
次全闭塞	变动	＞50	＞0	变动
完全闭塞	0	＞50	0	＜1

PSV：收缩峰流速，EDV：舒张末期流速

与动脉造影相比，诊断颈内动脉病变的特异性为 84%，敏感性为 99%[17]。检测 50%-99%狭窄的准确率为 93%。在内径减少 50%以上的病变血管的分类方面与动脉造影匹配得非常好［18］。颈动脉双相超声成像在拟行颈动脉内膜剥脱术的病人中的经验提示，当双相血管超声显示无症状患者的动脉狭窄 80-99%或有偏身症状的患者同侧动脉狭窄 50-99%时，动脉造影的结果很少改变既定的治疗方案［19，20］。

在诊断颈动脉支架术后再狭窄时，颈动脉双相超声测得的血流的绝对速度不如流速的前后改变有意义。由于血流撞击血管闭塞处后的倒流，在颈内动脉闭塞起始处可以听到一个明显的敲击杂音。近端的小幅波形对狭窄有提示意义。颈总动脉狭窄的诊断标准还没有详细的描述。病变远端的收缩期峰流速为近端的 2 倍提示狭窄超过 50%。在颈总动脉检测中，晚期的小幅波形也提示近端血管的狭窄。解读结果时还要注意椎动脉的血流方面：正向（流向大脑）或者逆向 (流向心脏)。另外，椎动脉波形要描述成正常（低阻力）或异常（双相或高阻力）。颈内动脉和颈外动脉的正确区分在检查结果的解读中也是必不可少的［表 4］。

表 4 颈内动脉和颈外动脉的区别

颈内动脉	**颈外动脉**

较大	较小
多在侧方和后方	多在中间和前方
包含颈动脉球	不包含颈动脉球
在颈部没有分支	在颈部有 8 个分支
低阻频谱波形	高阻频谱波形
叩击试验（-）：无震动	叩击试验（+）：有震动

颈动脉双相超声的局限和误区

那些长而光滑的斑块病变，因为它不会形成加速湍流而对血流动力学有影响，从而可能被超声检查低估。心排量的高或者低均可影响收缩期峰值流速。在心排量明显异常的病人中，颈内动脉和颈总动脉收缩期峰流速比值应该作为诊断颈内动脉狭窄的主要标准。当对侧颈内动脉闭塞时，由于代偿导致同侧动脉收缩期峰流速增加，会使同侧血管狭窄被高估［8］。

肾动脉多普勒超声

肾动脉粥样硬化性狭窄是顽固性高血压的重要原因之一［21］，可导致肾功能的不断恶化。严重的双侧肾动脉硬化性狭窄，或是功能性孤立肾的肾动脉狭窄的病人极易发展至终末期肾病［22］。肾动脉粥样硬化性狭窄的病人当需要透析治疗时，其远期生存率很低［23］。尽管有许多无创的诊断方法可以用来筛查和诊断肾动脉狭窄，但这些方法都无法取代肾动脉造影这一金标准。每一种筛查方法都因其限制性而不能被广泛应用。

适应症，操作和说明

表 5　肾动脉超声检查的适应症

- 既往控制良好的高血压突然恶化
- 青年患者的初诊高血压
- 恶性高血压
- 无法解释的氮质血症
- 高血压合并腹主-髂动脉或腹股沟下动脉粥样硬化
- 服用 ACEI 类药物后出现氮质血症
- 肾萎缩
- 心脏疾病不能解释的反复一过性肺水肿
- 肾动脉再通程度的评估

- 肾动脉内治疗后再狭窄的评估

多普勒超声是评估肾动脉再通是否充分的理想检测方法（**表 5**）[25]，可评价血管内治疗（经皮支架植入血管成形术）后再狭窄的程度[26]。肾脏多普勒超声检查包括测定肾动脉、肾实质和腹主动脉的频谱多普勒流速。通过测量肾髓质水平的肾动脉分支的收缩期峰值流速（PSV）和舒张末期峰值流速可以计算出肾阻力指数（RI），对肾实质的损害程度进行评价（**表 6**）。

表 6　　肾动脉严重狭窄的诊断标准

- 肾动脉与腹主动脉收缩期峰值流速之比大于 3.5
- 肾动脉狭窄湍流处 PSV>200cm/s
- EDV>150cm/s（肾动脉狭窄>80%）
- RI>0.8（用于肾动脉血运重建术后血压、肾功能的预测）
- 病变血管未探及血流提示血管闭塞

另外，需要对肾脏上下径长度进行测定。**图 6** 显示肾动脉狭窄时的典型超声图像。

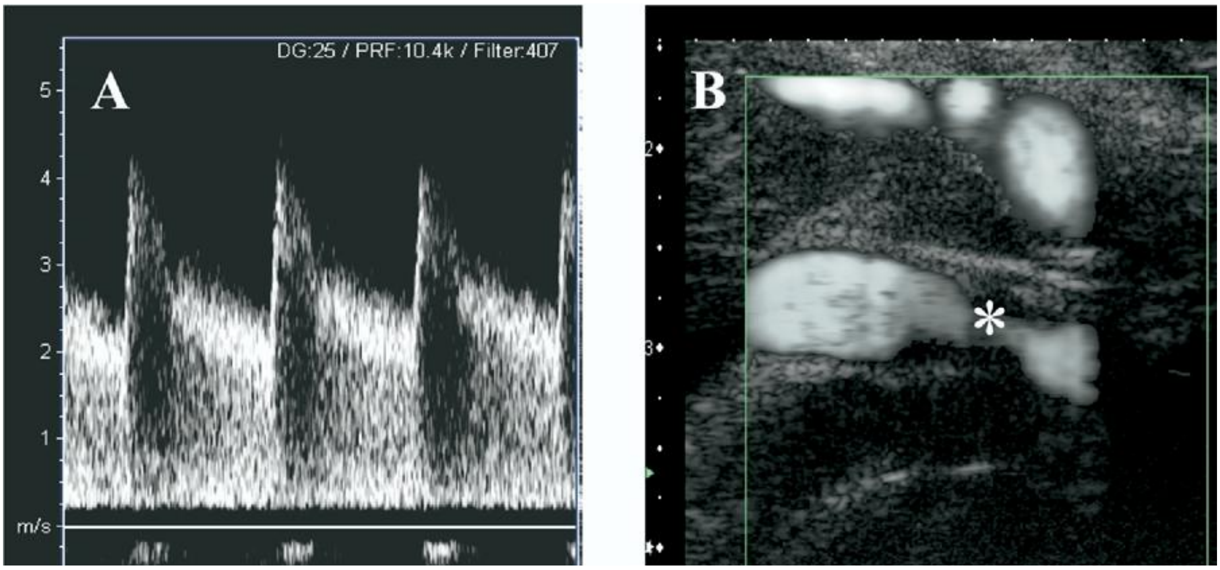


图6 A，肾动脉狭窄。多普勒频谱波形显示出湍流，收缩期峰值和舒张末期速度明显升高。B，功率多普勒显示狭窄部位管腔狭窄（*）

腹主动脉瘤的超声影像检查

适应症

超声影像检查对于腹主动脉瘤的诊断和随访都是极敏感的检测手段。有家族史的人群患有腹主动脉瘤的风险增加 4 倍。另外，机体任何一处的血管如果发现

主动脉瘤，比如腘动脉有动脉瘤，腹主动有动脉瘤的危险性也增加。行腹主动脉超声检查以评估腹主动脉瘤的主要适应症见**表 7**。

表 7　腹主动脉超声检查指证

	腹部疼痛
	体格检查发现动脉搏动弥散/增强
	血流动力学异常提示动脉瘤破裂
	直系亲属有腹主动脉瘤的病史
	其它血管有动脉瘤
	动脉腔内移植物的随访

说明

表 8　腹主动脉瘤和内漏的诊断标准

	动脉瘤：直径＞3.0cm
	内漏：动脉瘤腔内移植物的外周探及血流
	解剖结构：真假腔形成

腹主动脉管腔的正常直径约为 2.0cm（1.4-3.0cm）（**表 8**），轻度的腹主动脉管腔直径的增加仅被描述为动脉增宽，当动脉直径大于 3cm 时才诊断动脉瘤样增宽[28-29]。腹主动脉瘤可呈囊状或梭形，或筒状。腹主动脉瘤大部分是梭形，位于肾动脉水平以下，可能累及一侧或双侧髂动脉。动脉瘤体可形成动脉粥样硬化或附壁血栓。主动脉壁夹层有报道，但不常见。据文献报道，直径 3-5.9cm 的腹主动脉瘤会以每年 0.3-0.4cm 的速度增长[30]，且动脉瘤越大，增长速度越快。外科修补后或进行了血管腔内支架植入的动脉瘤有特定的超声表现。动脉腔内植入物外侧可能会有血栓形成。随着时间的推移，腔内植入物外周的动脉瘤直径会逐渐减小。

下肢动脉无创性血管生理检测

外周动脉疾病无创检测的目的是确立临床诊断，进一步明确梗阻的类型和程度。在血管实验室，多种不同的流程和手段可以用于外周动脉疾病的无创检测。其中包括脉冲容积描记法测定节段肢体动脉压力、平板运动试验和动脉超声检查。

进行外周动脉疾病无创检测评估的主要适应症见**表 9**。

表 9 无创检测评估指证

	运动相关的肢体疼痛（跛行）
	休息时的肢体疼痛
	手足溃疡/坏疽
	康复潜能的评估
	外周动脉搏动消失
	手指苍白
	冷刺激敏感
	动脉外伤或动脉瘤
	ABI 异常

肢体节段压力测定及解读

生理状态下，收缩期血管内压力由股动脉到胫动脉会略有增加，因此胫动脉比股动脉测定的动脉压力要稍高一些。4-袖带方法是使用较窄的袖带，通过人为制造压力的介入，测量评估腿部不同水平的压力变化。在健康个体中，大腿动脉压力要高于踝部。因此，大腿/肱动脉压力指数≥1.1 提示血流动力学正常，而该指数小于 0.9 则提示外周动脉疾病（**表 10**）。

表 10 异常节段压力的评判标准

病变节段水平	结果
主髂动脉	双侧大腿/肱指数＜0.9
髂动脉	大腿/肱指数＜0.9
股浅动脉	大腿上段和下段袖带压力梯度
股浅动脉远端或腘窝动脉	大腿和小腿袖带压力梯度
膝下动脉	小腿和踝袖带压力梯度
压力梯度 20-30mmHg 为界值，≥30mmHg 为异常	

值得注意的是，当大腿动脉压力比肱动脉压低时，梗阻的部分可能位于袖带近端或下方，即梗阻的部位可能在主动脉、髂动脉、股总动脉或股浅动脉近端。当双侧均有血流动力学异常时，梗阻部位可能位于髂总动脉区段。然而，如果低血流压力是单侧的，那么只有一个同侧髂或股总动脉狭窄的可能，而排除主动脉节段存在异常。节段压力测定需要与同侧临近节段之间的压力比较，与对侧同一水平节段比较以及与两侧肱动脉收缩压的高值进行比较。当同一下肢不同节段间

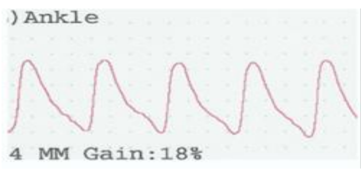
的压力阶差或与对侧同一水平的压力差＞20mmHg 时有重要的提示意义［32］。

脉冲容积描记法及解读

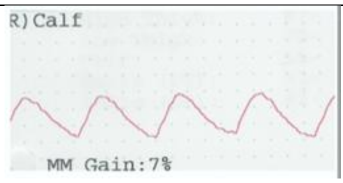
肢体节段描记波形分析系统是一种基于波形和信号幅度的检测方法。针对不同解剖部位和疾病血流动力学严重程度的波形标准范围是诊断的依据。脉冲容积记录通常是由标准体积的空气注入气动袖带，旧机器可以通过校正袖带内的空气量，使得两腿或肢体的不同部位间可以作精确的比较。而一些较新的机器，由于不校准袖带内空气量，因此，在比较不同肢体或不同部位记录的脉冲容积时要特别谨慎。袖带内注入的空气足以阻断静脉循环，但并不阻断动脉循环。

袖带远端的肢体容积变化可以通过压力脉冲来反映。而这个压力脉冲可以通过一个传感器检测到并用压力脉冲波形显示出来。一个正常的脉冲容积记录，类似于动脉波形，包含锐利的收缩峰的陡峭收缩期升支后，紧跟有显著重搏切迹的降支。如果存在血流动力学显著异常的血管狭窄，因狭窄出现能量耗散，这将体现在脉冲容积记录波形轮廓的变化，以此表明近端动脉存在梗阻。脉冲容积记录轮廓的变异程度可以反映疾病的严重程度，如**表11**所示。

表11 脉冲体积描记法：不同程度的血管疾病时脉冲体积记录轮廓

正常 陡峭的上升支 波峰之间的平坦间隔波 可能会有重博切迹	
轻度异常 陡峭的上升支 波峰之间的平坦间隔波消失 无重博切迹	
中度异常 波峰平坦 升支和降支的时间相同	

- 无重博切迹



重度异常

- 波峰平坦
- 升支和降支的时间相同
- 无重博切迹
- 波幅低

节段压力测量和脉冲容积记录的局限性

节段压力测量和容积描记都是间接的检测方法，并以此用来反应血管病变的解剖位置和结构结构。这个检查无法区分充气袖带上游可能的多发性狭窄病变。例如，测得的大腿压力的下降可能是由髂动脉段梗阻，亦或是股总动脉病变，或股浅动脉和股深动脉的复合病变造成的。

外周动脉疾病的运动试验

通过测定运动后下肢动脉血压的降低能反映出外周动脉疾病（表 12 和表 13）。

表 12 下肢动脉负荷试验的适应症

- 有间歇性跛行的病史，静息状态下下肢动脉节段压力和脉搏容积测量正常
- 有间歇性跛行的病史，静息状态下下肢动脉节段压力和脉搏容积测量轻度减低，如踝臂指数为 0.8-0.96

表 13 运动后踝臂指数的意义解释

- 运动结束后 1 分钟时踝臂指数＜0.9 提示有血流动力学意义的外周动脉疾病

下肢动脉运动平板试验的禁忌症包括：静息疼、没有可以静息状态下压迫测量的血管、急性深静脉血栓、静息状态下或极轻微运动后气短、没有控制的心绞痛、肢体或机体残疾不能参与平板运动。在正常情况下，踝动脉压应该和肱动脉一样在运动后升高。

外周动脉超声

外周动脉双相超声检查应需而异，可以局限于某一支动脉，也可以扩展于全身四肢动脉测量（表 14）。测量的目的是明确肢体动脉狭窄的位置和严重程度。这在制定外周动脉闭塞疾病的治疗方案时特别有帮助。

表 14 外周动脉超声的适应症

- 跛行
- 下肢疼痛
- 溃疡
- 下肢动脉介入治疗后

解读报告

外周动脉狭窄通过脉冲波多普勒的表现特征来确定。诊断标准使用动脉近端到远端收缩期峰流速升高和仔细的波形分析（表 15）。

表 15 外周动脉管径减小的分级标准

	管径减小	波形	频谱展宽	远端/近端 PSV 比值
正常	0	三相	无	不变
轻度	1-19%	三相	有	＜2:1
中度	20-49%	双相	有	＜2:1
重度	50-99%	单相	有	＞2:1

在动脉狭窄水平测得的收缩期峰流速是近段的两倍。在严重狭窄时会有频谱增宽和前向血流延迟的表现。在某段血管内没有血流通过则提示有闭塞。如果没有侧支循环，闭塞近端会有高阻波形。如果侧支循环丰富则在近端出现持续前向舒张期血流。狭窄远端动脉会出现典型的狭窄后晚期小波形。

多普勒检查可以准确诊断外周动脉疾病[35,36]。和金标准动脉造影相比，双相超声用于检测下肢动脉近端狭窄有较高的敏感性（82%）和特异性（92%）。应用彩色多普勒和脉冲波多普勒后敏感性和特异性均有提高，分别为 87-88%和 95-99%[36,37]。动脉狭窄处与近端的收缩期峰流速比值比收缩期峰流速绝对值更好的应用于外周动脉狭窄的分级。例如，收缩期峰流速比值 2 和 7 分别相当于动

脉狭窄大于 50%和 90%[38]。下肢动脉收缩期峰流速由正常到异常的波动很大，所以使用比值能更好的反映动脉狭窄情况。

外周动脉血管旁路移植血管超声检查

移植血管监测被证实对维持旁路血管开放非常有用。腹股沟下旁路移植血管 5 年通畅率为 60-85%[39]。超声发现后行手术处理狭窄使 5 年通畅率升至 93%[40,41]。局部压力测量对旁路血管闭塞的预测和外科再干预无明显效果[42]。多普勒检查能在旁路血管闭塞前发现血流减少。标准监测方案推荐术后第 1 年对桥血管复查两次超声，以后每年 1 次（表 16）。

表 16 动脉旁路移植超声检查的适应症

• 介入治疗后第 3 个月和第 6 个月
• 介入治疗 1 年后每年检查 1 次

早期干预能够使长期通畅率提高 15-20%。手术技术操作失误通常会使旁路血管在术后 1 个月内闭塞，几年后的闭塞多是由于内膜增生及动脉粥样硬化的进展引起。

解释

表 17 应用收缩峰流速对静脉桥血管进行分级的标准

• 轻度狭窄＜20%，收缩峰流速＜125cm/s、比值＜1.4
• 中度狭窄 20-50%，收缩峰流速＜180cm/s、比值 1.5-2.4
• 重度狭窄 50-75%，收缩峰流速＞180cm/s、比值 2.5-4
• 极重度狭窄＞75%，收缩峰流速＞300cm/s、比值＞4

收缩期峰流速比值对旁路血管来说和自身动脉一样（表 17）[43,44]。使用远端向近端收缩期峰流速比值须除外移植血管与近端血管直径不匹配的情况。这种情况下，使用远端收缩期峰流速绝对值替代比值[44]。收缩期峰流速比值翻倍表明桥血管狭窄超过 50%，其敏感性为 95%，特异性为 100%［45］。

严重的狭窄需要进行干预。流速减低说明动脉灌注减少、近端狭窄或桥血管过粗。出现晚期小波形则说明灌注不足或近端狭窄。另外，旁路血管收缩期峰流速＜45cm/s 多提示旁路血管会发生闭塞[46]。超声评估旁路血管的基本标准包括：收缩期峰流速＞180cm/s 或比值＞2 提示 50%狭窄，＜45cm/s 多提示桥血管闭塞。

连续检查中的波形或流速改变提示要密切随访或需要干预。

经皮再血管化治疗后的下肢动脉超声

下肢动脉经皮血管成形及支架术后长期通畅率为 50-85%[47-50]。双相超声检测目前应用于检查血管介入治疗后有无再狭窄。早期检测有助于识别需要再干预的病人。一般在介入治疗后，症状再发时，以及每年随访时行双相超声检查。彩色多普勒和脉冲多普勒主要用于介入治疗部位及其邻近部位［51］（图 7）。

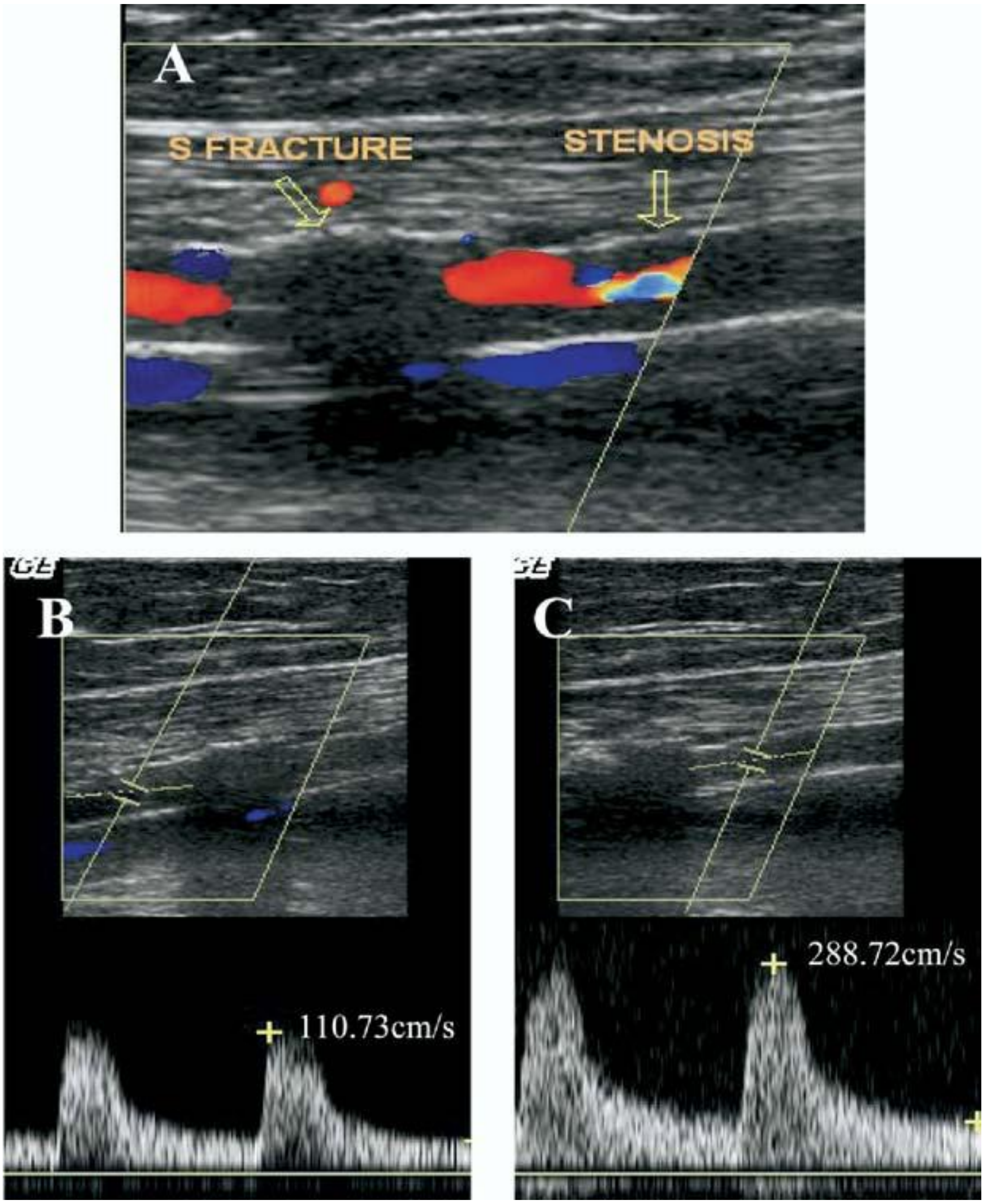


图 7 介入治疗后股浅动脉双相超声检查。A、彩色多普勒血流显示血流为层流，

之后的支架破裂部位及复杂钙化性动脉粥样硬化斑块处彩色信号缺失，支架破裂远端呈混叠信号。B，支架破裂部位近端的频谱多普勒呈湍流。C，支架破裂的狭窄区域远端收缩血流的峰值速度增加提示有 50%到 99%的狭窄。

狭窄的评估标准和前面提到的自身血管的标准一样（表 18），收缩期峰流速比值为 2 提示狭窄＞50%[44]。

表 18 介入治疗后再狭窄的解读标准

- 收缩峰流速＞180cm/s
- 收缩峰流速比值＞2 提示有意义的狭窄
- 波形和流速的改变提示需要减小随访间隔

对医源性假性动脉瘤的诊断和处理

血管介入治疗已经成为心血管疾病的主要治疗手段，导致血管方面并发症的发生率增加。尽管血管介入治疗有很好的疗效，但是血肿、动静脉瘘、感染、动脉粥样硬化性栓塞、腹膜后出血、原位动脉血栓形成、假性动脉瘤等并发症确实增加了。假性动脉瘤是最常见的并发症，并且有扩大、对周围血管压迫、破裂、栓塞和感染等风险。假性动脉瘤是血管内中外 3 层膜均破裂后出血，在血管外由周围软组织包裹形成的血肿。

诊断假性动脉瘤的关键是要对此保持警惕（表 19）。临床上，做过因动脉造影或介入治疗而进行动脉穿刺的病人，如果术后出现穿刺点周围疼痛，都需要考虑有出现假性动脉瘤的风险。查体触及搏动性肿块或穿刺点血管杂音都是有助于诊断假性动脉瘤的体征。但是，也有很多假性动脉瘤并没有这些体征表现。穿刺点广泛皮肤瘀斑也提示存在假性动脉瘤的可能。

表 19 假性动脉瘤超声检查的适应症

- 穿刺点搏动性包块
- 穿刺点突发疼痛
- 穿刺点血管杂音

表 20 假性动脉瘤的诊断标准

- 血管壁外囊袋伴血流
- 血液在动脉与囊袋间流通

• 原动脉有双向血流

如果超声检查发现血流由血管流向血管外囊袋，那么假性动脉瘤的诊断就可以确立（表 20）。在囊袋口可以发现双向的血流信号，另外近端血管阻力会低于远端（图 8）。

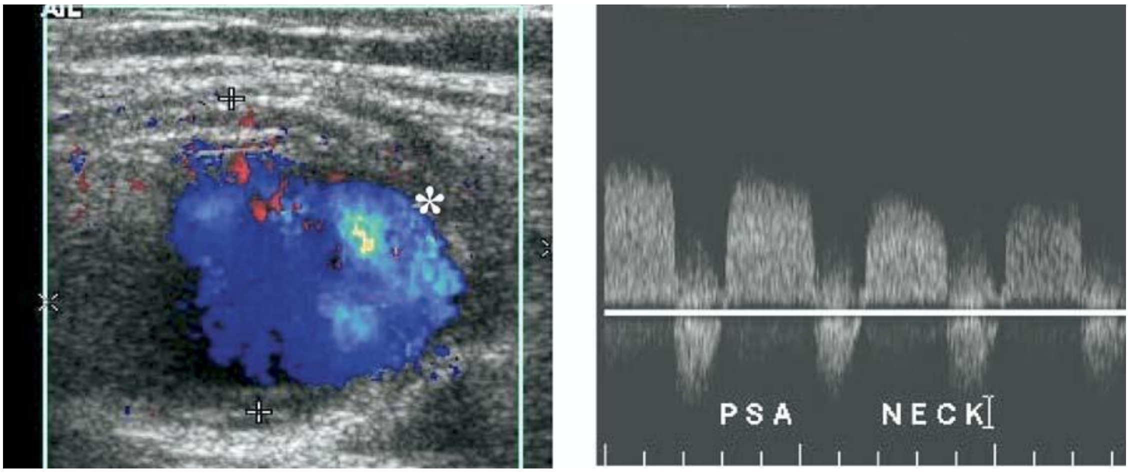


图 8 假动脉瘤（PSA）的双重证据。左图，假动脉瘤囊内彩色多普勒显示血栓（*）沿腔壁形成。腔内有明显的颜色流动。右图，在假动脉瘤的颈部记录到的独特的出入瘤囊的频谱多普勒是诊断假动脉瘤的关键。

治疗选择

虽然假性动脉瘤可能导致严重的并发症，但不是所有假性动脉瘤都需要治疗。假性动脉瘤的治疗包括观察、手术修补、超声引导下压迫或注射凝血酶等。（见附录）

血管实验室认证

实验室认证过程为实验室程序、员工经验和质量保证提供了标准。血管实验室认证国际委员会（ICAVL）是其中一个资质认证机构[19]。美国放射学会也提供实验室认证（www.acr.org）。根据国际委员会的标准，血管实验室是一个在医学主任的指导下进行无创血管检测试验的机构。他们已经发布的标准对场地，设备、辅助支持及员工组成提出了最低标准。下面主要举例说明获得这些认证的条件要求。

检查、解释报告和记录

医学主任和医务人员必须都是有执照的医生，他们才能够对无创血管检查的结果进行解读和出具正式报告。所有检查报告必须标准化，内容包含超声检查医师的

姓名、检查日期、临床适应症、检查操作的描述、结果（包括位置、异常发现的数量、和之前检查结果的对比）及签名。最终报告必须在 2 个工作日内完成，除非有重要的临床信息需要补充完善。关键结果或具有重要临床意义的发现必须在当天向临床医生报告。

医学和技术人员的资质要求

血管超声实验室的医学主任可以通过完成住院医师培训或者非正式渠道继续医学教育，都必须在导师的指导下每个血管检测领域完成 100 个病例的报告解读。这些血管检测领域包括颈动脉双相超声、经颅多普勒、外周动脉生理检查、外周动脉双相超声、静脉双相超声等，还要完成 75 个内脏血管超声病例并对其进行解读[19]。医学主任如果没有通过标准的住院医师培训或非正式的培训，但有 3 年以上在已经建立的血管实验室的工作经历工作经验，就须在有经验的导师的指导下上述每个领域完成 300 个病例（他/她必须参与解读报告这些病例）及 225 份内脏血管超声病例。其他医务人员必须具有行医执照和相关的培训和工作经历才能参与解读报告。从 2006 年开始，美国超声医师注册协会（ARDMS）将为医师提供血管实验室资格认证和注册，称为血管检测解读注册医师证书(RPVI 证书)。

主任技师必须拥有操作和解读实验室检查血管的经验。主任技师必须要有 3 年以上血管实验室检测工作经验及完成 1800 例以上无创血管检测。而且这些病例在各个相关的检查领域合理地分布。从 2003 年 1 月开始，所有主任技师都要求获得血管检测资质认证证书。超声技师则须在每个血管检测领域完成 100 个病例。

血管实验室认证国际委员会（ICAVL）有关于颅外血管、颅内血管、外周动脉及外周静脉等检测的特殊推荐[20-23,25]。针对每个模块的指南推荐涉及仪器设备、适应症、检查操作技术方法等的标准，以及诊断标准和质量保证等。

超声技师的培训

美国超声心动学会建议所有超声技师都要参加并完成由联合健康组织、心血管技术复核委员会及医学超声检查复核委员会认证的培训[26]。超声技师和医师成功通过血管检测考核及血管仪器和技术考试后可以获得美国超声医师注册协会资质认证的注册血管技术人员。参加该考试的要求根据学历水平而不同，具体参见官网（www.ardms.org/applicants/ prechart.html）。资格认证的证书由国际心血管资格认证协会颁发。

报销：医保指导

Medicare A 类医保通常覆盖在医院进行的检查的技术操作费用，而医生解读报告费用则通过 Medicare B 类医保报销。报销以后者为主，尤其是在私人诊所和办公室进行的检查。至于在血管实验室的检查获得医保报销的条件，比如血管实验室是否有特殊的资质认证，员工是否需要注册和通过资质论证等，各个州会有自己的要求。ICAVL 网站上有提供各个州不同要求（www.icavl.org）。Medicare 医保报销的政策是通过付款后抽查审计来确保执行。实验室记录会被审查，以确保符合规定。违反规定报销的人员和单位，必须偿还保险部门已经支付的那些错误的报销款项。

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附录

颈动脉超声技术

第一段颈动脉超声检查，包括颈动脉颅外段的完整的横切面和纵切面的解剖视图、对是否存在异常及疾病位置的评估。从两侧的颈根部开始，先行前外侧切面然后后外侧切面，探查者应把探头慢慢地从锁骨水平滑到下颌水平。右颈总动脉位于甲状腺外侧和颈内静脉内侧。颈内动脉通常位于颈部后外侧，而颈外动脉（ECA）位于内侧稍偏前。大多数患者的颈内静脉很容易压闭，而颈总动脉则不容易被压闭。在大多数患者中，将探头轻微的侧向足侧，右侧颈总动脉的起源和右锁骨下动脉做为头臂干动脉的分支，很容易被探头探查到。左颈总动脉起源在颈根部近端，从这个切面无法确定左侧颈总动脉的起源。顺着颈总动脉扫查至 ICA 和 ECA 的起源，ICA 和 ECA 的分叉通常可在环状软骨水平发现（通常是 C3 或 C4 水平，但从 C1 到 C6 水平均有可能）。ICA 和 ECA 应尽可能顺着颈部探查至最远端。为了评估斑块性质和位置，整个颈总动脉、ICA、ECA 均应该通过二维模式（灰度）扫描，不须彩色。

长轴切面可用于彩色多普勒的评估，行血流速度测量时指导多普勒采样容积的正确的位置。颈总动脉的整个长度均是可以被探查的，频谱多普勒评估在右侧可从其起源的水平，在左边则尽可能从颈根部底部开始。

狭窄可以是局限的而血流流动模式可能在超越狭窄的短距离内恢复正常。因此，采样容积不应放在血流离散的位置，在血管长轴方向可以以彩色多普勒为指导方法循序渐进的扫查颈动脉全程。应该从近端的颈总动脉，中段和远段颈总动脉测得代表性血流速度。

颈总动脉的波形特征通常是比颈外动脉舒张期血流大，但比颈内动脉小。颈内动脉应探查至尽可能远，至少超出了变部位 3 厘米以远。使用频谱多普勒，取样容积应在整个颈内动脉移动并记录速度频谱－从近段、中段、远段颈内动脉的 PSV 和舒张末期血流速度。颈内动脉远端的取样应从分叉远端至少 3 厘米处获得。

颈动脉超声：实用窍门

●ICA 和 ECA 通常区分基于几个标准，但没有一个单一标准本身可以确定的（表 2）。关键是先直接比较从两个血管获得的波形然后再使用阻力特性来鉴定。

●物理性限制，如最近的颈部手术，根治性颈淋巴清扫术、放射、皮肤钉及缝线，或敷料需要额外的超声波凝胶或坚持以方便成像。

●患者由于固定颈椎病、颈椎项圈，或肌肉挛缩不能向后伸展颈部可采取后侧切面方法.

●病人无法平躺，可采取坐或站立的位置成像。采用低频换能器应用于动脉位置深或脖子粗的患者。

●当存在血管扭曲的时候,如果取样容积置于扭曲的外侧,则狭窄可能被高估。

●ICA / CCA 率可能仍然适用用于确定狭窄程度。在心输出量降低或重度主动脉狭窄的时候,绝对速度的标准不宜直接应用。

●以避免错误估计狭窄的程度，重要的是找到狭窄的最大面积处，以及在任何狭窄的近段和远端采集流速。

肾动脉多普勒超声技术

肾动脉超声检查需要血管技师非常敬业的致力于完善的程序，以及先进的超声设备。患者在检查前日午夜开始禁食。检查通常在上午进行。患者可用少量水送服他们的上午的口服药物。如果有大量的肠道气体，则停止检查，给予患者西甲硅油，并重新安排另一个时间。一个低频 2.25 至 3.5 兆赫的脉冲超声换能器是达到足够深的腹部成像所必需的。加彩色显像将增加肾动脉显像的容易程度。检查开始患者仰卧位和 逆向 Trendelenburg 体位（头高角低）。扫查从横隔膜到主动脉分叉的主动脉纵轴图像。注意动脉粥样硬化斑块的存在和瘤样扩张。确定腹腔、上下肠系膜动脉的起源。在肠系膜上动脉水平上呈 60 度角获得动脉血流的中心区的多普勒速度。记录这一速度，用作计算肾动脉/主动脉的速度比。

然后重新定位换能器为横截平面，注意腹腔及肠系膜上动脉起源于主动脉前面。有 75%的患者左肾静脉从前面横跨腹主动脉，因为它将进入下腔静脉。这 2 个超声标志（肠系膜上动脉的起源，左肾静脉在主动脉面）是确定右肾动脉的重要的标志。

右肾动脉从前侧起源，向后走形进入肾门。左肾动脉一般起源于右肾动脉下方，向后走形。多普勒取样线以 60 度的角（或更少），放置在主动脉内，然后移行到右肾动脉开口。如果可能的话，采集右肾动脉起源，近段，中段，远端肾动脉的峰值收缩期速度和峰值舒张末期速度。肾动脉多普勒波形是典型的低阻抗血流，有显着的正向舒张血流。类似的测量在左肾动脉扫查。扫查到整个肾动脉是至关重要的，因此一个局限性狭窄或网络（在纤维肌性发育不良的情况下）是不容忽视的。应注意到两个肾静脉是潜在的或阻塞的。

病人采取左侧卧位，从侧面探查右肾。测量三次肾脏的长度，以厘米记录。

在 0°角记录皮质、髓质和肾门部血流速度，应采用大的取样容积，因为离散的实质血管难以识别。

然后，超声换能器稍前倾，尝试向从主动脉到右肾门整个肾动脉。这剥香蕉皮技术可应用于肾动脉成像及分析。应用剥香蕉皮方法在右侧的局限性由于右侧有下腔静脉覆盖，而这个问题不会发生在左侧。让患者右侧卧位，重复这个过程显示左肾位置和整个左肾动脉。

腹主动脉超声技术

患者在检查前需要禁食。评价一个主动脉－髂动脉段，需要配备低频换能器（2.4 MHz）的超声设备。中频换能器（4-8 MHz）被用于典型股动脉、腘动脉瘤。动脉瘤的检查应侧重于确定动脉瘤的大小、形态、位置（肾动脉下或肾动脉上），和其他动脉段的距离。

超声扫查开始时采取仰卧位置。为了便于准确测量其大小，通常须获得腹主动脉的 3 个切面：横向平面（前后径与横径），矢状面（前后径），与冠状面（纵、横径）。值得注意的是，探头应改变方向以显示切面的最大长度。然后探头旋转 90 度，以获得横向切面。如果肠内气体阻碍观察主动脉，病人可采取卧位，通过侧面获得主动脉的冠状切面。腹腔动脉从主动脉发出并分成肝总动脉和脾动脉。另外，右肾动脉可从主动脉发出下腔静脉下行经。

最可靠的用于测量腹主动脉的角度是前后图像。侧向视图通常是最不准确的视图，因为从血管壁的镜面反射伪影。妨碍充分的检查的原因包括气体和肥胖，尤其是在腹主动脉近端［30］区域。

节段性肢体压力测量技术

节段性肢体压力测量通常与脉搏容积描记法结合检查（脉搏容积记录）。这两个程序都采用的是气动的袖带，袖带的大小应适合肢体节段的直径并进行正确定位。通常的做法，在测量肢体脉搏容积记录之前，用一个合适的传感器评估袖带远端的动脉血流的出现。测量肢体压力之前患者取仰卧位休息至少 10 分钟。有几款仪器的气动袖带是有自动充气能力的。一个配有 4 至 8 兆赫频率的探头的连续波多普勒检测仪是首选的检测血流信号的仪器。气动袖带开始充气并迅速膨胀使压力升高到收缩压以上。袖带然后慢慢放气直到重新检测到血流信号。袖带下恢复流量信号的袖带压力就是收缩压。例如，如果袖带在大腿而传感器是在腘窝，测得的压力反应的是近端股浅、股深动脉和侧支动脉，而不是腘动脉的压力。虽然公布的研究表明，当流量传感器越靠近袖带测压力会更准确，但大多数实验室从方便考量，仍然使用踝关节动脉的多普勒信号来反应整个下肢的测量。

许多实验室使用 4 袖带方法，袖带的位置如下：高大腿位的袖带上缘置放

于大腿内侧最顶部；低大腿位，袖带上缘位于髌骨以上；小腿位的袖带上缘位置位于胫骨结节以下；脚踝位，则在踝关节以上。另一种方法是只使用 3 个袖带用一个相对较宽的袖带在大腿中部。通常，在踝关节水平足部血管压力可以在胫前动脉及足背动脉测定，因此可产生两个数。选择的胫骨信号作为流量指示器，分别测量大腿的高处和低处及小腿水平的压力。踝关节的压力是用来为每个肢体计算踝臂指数的。踝关节的压力除以最高的肱动脉压力就是踝臂指数。

下肢压力评估从踝关节的水平开始，并且沿动脉系统搜索近段的动脉信号。正常踝臂指数的患者不大可能有近端的血管疾病，可能需要行运动试验或反应性充血试验用于筛查轻度的血管狭窄。此外，如果踝臂指数是正常的，而症状在脚指端，应使用适当大小的袖带评估足背末端或脚指动脉阻塞的可能。

脉搏容积描记法技术

容积描记法，来自希腊的“plethysmos，”意思是“增加”是用来描述肢体的体积由于血流流入或者流出肢体时发生的变化。这一检测通常是与节段性肢体压力测量相结合。脉搏容积曲线类似于动脉压力曲线。使用脉搏容积记录幅度的一个优点是，他们是检查血管钙化有效的方法，而不像节段压力测量技术需要依赖钙化动脉的闭塞作为必要的条件。节段性肢体容积描记（脉搏容积记录）是利用气动袖带，袖带的尺寸应适合拟测量的肢体的直径和放置的位置。每一个袖带按顺序充气到预设的标准压力。 65 毫米汞柱的压力可以使袖带表面接触到皮肤，同时提供可重复的容积描记法的轮廓特征。容积描记波形记录各肢体节段的波形。值得注意的是，袖带的位置可能需要调整，以确保较窄范围内的充气量就能达到所选择的袖带压力。每次检查都必须行双侧检查。

运动试验技术

患者禁食 12 小时后进行平板试验。在跑步机上行走之前，告知患者如果出现任何疼痛感觉都应及时提醒操作技师。标准的跑步机测试以 2 英里/小时的速度和 12%上坡进行。如果患者出现胸痛，呼吸急促和头晕使患者不能继续，则立即停止运动试验。否则的话，行走继续 5 分钟或直到病人因为继发性跛行而停止。

在跑步机被停止后，病人立即被带到一张桌子上，仰卧位。从踝关节测量血压。每 30 秒重复一次，从有症状的腿开始,最初的 4 分钟，然后每分钟一次,持续至 10 分钟。如果压力恢复到基线水平，则提前停止压力测量程序。值得注意的是，肱动脉收缩压必须在第一次测量踝关节的压力时立即记录，也需要记录最后一次运动后踝压力时的肱动脉收缩压数值。如果可以的话，应该有第二个技师测量臂压力以免延误踝关节的压力的测量。跑步机的程序记录的数据应包括测

量踝关节的压力，病人能走的时间，压力回到基线水平所需的时间，病人的症状的性质和位置，停止检查的原因所在，如果出现其他跛行或最大休息时间。

外周动脉超声技术

彩色多普勒用来测定被评估动脉段内的层流状态及非层流状态。湍流，颜色扰动，延迟存在的血流（连续的前向血流）和混叠往往出现在疾病的位置。脉冲（频谱）的采样是用来进一步描述的颜色扰动血流的特性和狭窄的程度。PSV是用来量化疾病的主要测量值。峰值流速速度的测量是为了在病变和近端动脉段的水平之间进行比较。外周动脉疾病的准确诊断部分依靠技术上的考虑，如探头的选择和成像参数选择。5 MHz 线阵探头适用于普通成人检测。高频探头（7.5-10兆赫）被推荐用于小或瘦的患者，较低频率的探头（3-4 MHz）应用于块头较大的患者或者深部血管。多普勒频谱分析的需要取样容积较小并且多普勒角度在60 度以内。取样容积沿着检查的动脉的长轴方向逐渐移动的。每一个新的检查位置都应记录彩色和频谱多普勒。

外周动脉桥的超声检查技术

检查前确定桥血管的位置和类型，然后进行超声检查。仰卧位病人的扫描技术类似于原位动脉检查。采用彩色多普勒和脉冲多普勒对移植物的全程进行评价，

区别层流和混叠的区域，或其持久性。用彩色多普勒超声指导脉冲波检查的结果，在下列部位探查 PSV：（1）原位动脉的近端；（2）在近端吻合口；（3）在桥血管段；（4）在远端吻合口；（5）原位动脉的远端。在血流扰动的位置上获得多普勒频谱。这些速度测量可用于诊断狭窄和在随后的检查中寻找变化。

假性动脉瘤的检查技术

假性动脉瘤有两个部分：窦道或颈部是指动脉壁破口由动脉血管壁向外延伸至被周围的肌纤维组织包裹的动脉血部分，以及囊部，指包裹血管外血液的部分。彩色和脉冲多普勒超声被用来评价股动脉和静脉。在标准灰阶超声的基础上加入彩色多普勒使得对假性动脉瘤的诊断达到很高的准确性。[52]，因而成为首选的诊断方法。首先在介入操作的入侵位置确定原位动脉，然后可以看到动脉血管外的血液，通常位于原位动脉的前面。

后位假性动脉瘤最常见的部位在股动脉分为股浅、股深动脉的分叉处。原位动脉和囊之间的连接处被称为颈部，很容易被确定。使用聚焦超声成像技术显

示颈部，应用多普勒技术将狭窄的取样容积其放置于颈部。如果有假性动脉瘤，其多普勒频谱将显示为特征性病理表现,既一个“去-回”（to-and-fro）波形，[53]代表收缩期动脉血从原位动脉进入囊，而舒张期血流从囊流回到原位动脉[54]。

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Guidelines for Noninvasive Vascular Laboratory Testing: A Report from the American Society of Echocardiography and the Society of Vascular Medicine and Biology

Represented by Marie Gerhard-Herman, MD, MMSc, Julius M. Gardin, MD, FASE, Michael Jaff, DO, Emile Mohler, MD, Mary Roman, MD, and Tasneem Z. Naqvi, MD, FASE, RVT

EXECUTIVE SUMMARY

Accompanying the rapid growth of interest in percutaneous vascular interventions, there has been increasing interest among cardiologists in performing noninvasive vascular testing using ultrasound. In an attempt to provide recommendations on the best practices in vascular laboratory testing, this report has been prepared by a writing group from the American Society of Echocardiography (ASE) and the Society of Vascular Medicine and Biology. The document summarizes principles integral to vascular duplex ultrasound–including color Doppler, spectral Doppler waveform analysis, power Doppler, and the use of contrast. Appropriate indications and interpretation of carotid artery, renal artery, abdominal aorta, and peripheral artery ultrasound imaging are described. A dedicated section summarizes noninvasive techniques for physiologic vascular testing of the lower extremity arteries–including measurement of segmental pressures and pulse volume plethysmography. The use of exercise testing in the evaluation of peripheral artery disease, ultrasound evaluation of the lower extremities after percutaneous revascularization, and the diagnosis and management of iatrogenic pseudoaneurysm (PSA) is also discussed. A section on the important topic of vascular laboratory accreditation is included. Finally, additional details regarding proper technique for performance of the various vascular tests and procedures are included in the Appendix.

From Brigham and Women's Hospital, Boston, MA (M.G-H.); St. John Hospital and Medical Center, Detroit, MI (J.M.G.); Massachusetts General Hospital, Boston, MA (M.J.); University of Pennsylvania Health System, Philadelphia, PA (E.M.); Weill Medical College of Cornell University, New York, NY (M.R.); Cedars Sinai Medical Center, Los Angeles, CA (T.Z.N.).

Reprint requests: The American Society of Echocardiography, 1500 Sunday Dr, Suite 102, Raleigh, NC 27607. (919) 864-7754.

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BACKGROUND

There has been increasing demand for vascular ultrasound training among cardiologists in practice and in training. For example, the recent document on training for cardiology fellows, COCATS-2, has recommended 2 months of dedicated or aggregate "instruction in the noninvasive laboratory" for Level 1 training in vascular ultrasound.[1] This article will review general principles, indications, and interpretation of noninvasive vascular testing of the carotid arteries, renal arteries, abdominal aorta, and peripheral arteries. Additional details regarding the techniques of performing vascular ultrasound are provided in the Appendix. Another article by this working group, "Clinical Application of Noninvasive Vascular Ultrasound in Cardiovascular Risk Stratification," will review the application of carotid artery (intimal-medial thickness) and brachial artery (flow-mediated dilatation) measurements for cardiovascular risk stratification.

INSTRUMENTATION: GENERAL CONSIDERATIONS

Vascular testing includes duplex ultrasound and physiologic evaluation. Vascular ultrasound tests require a machine equipped with 5- to 12-MHz linear-array transducers (for the neck and extremities) and 2.25- to 3.5-MHz curved linear- or phased-array transducers (for the abdomen). A vascular software package is required in addition to the appropriate transducers. Duplex scanning refers to an ultrasound scanning procedure recording both gray scale and Doppler information.

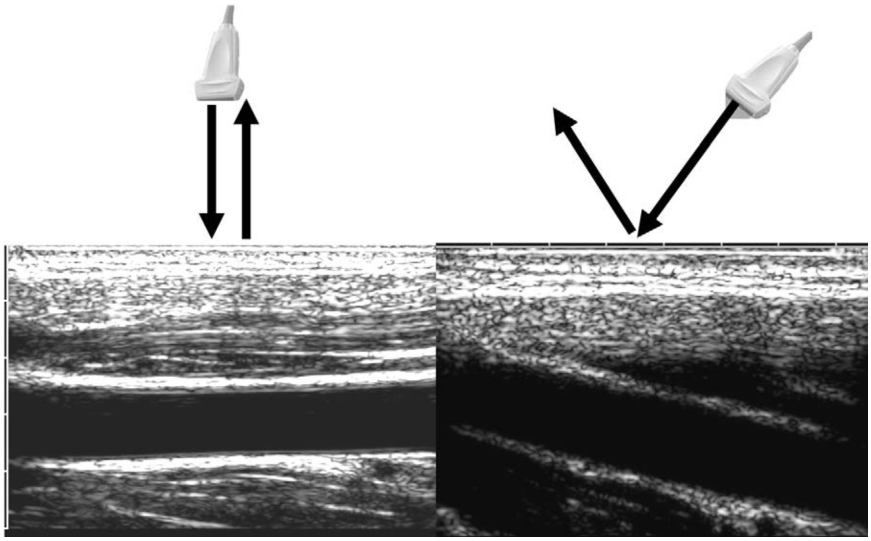


Figure 1 Vessel of interest should be perpendicular to ultrasound beam for B-mode imaging to obtain most distinct echoes. *Left*, Carotid B-mode image obtained with ultrasound beam perpendicular to vessel wall (*arrow*) demonstrates trilaminar structure of arterial wall. *Right*, Wall structure is poorly defined with nonperpendicular angle (*arrow*).

This includes 2-dimensional structure and motion, Doppler spectrum analysis, and color flow velocity mapping. Carotid arteries, renal arteries, abdominal aorta, and peripheral arteries can be appropriately evaluated using this equipment. Physiologic testing includes segmental pulse volume recording and segmental pressure measurements with cuffs appropriately sized for the lower extremities and a plethysmographic recording device.

DUPLEX: PRINCIPLES APPLICABLE TO ALL VASCULAR TESTING

The ultrasound beam is directed perpendicular to the surface of interest to obtain the brightest echo with gray-scale imaging and optimal imaging of the artery wall. The perpendicular angle is often readily obtained, as arteries generally are parallel to the surface of the transducer (Figure 1). For the Doppler component of duplex imaging, an angle of 60 degrees between the Doppler insonation beam and the vessel wall should be maintained. This Doppler angle becomes an important consideration when the velocity data are used to classify disease.[2] Angles above 60 degrees can result in significant overestimation of the velocity and should be avoided. Angles that are not relevant to the vessel wall may misrepresent the true peak velocity[3] (Figure 2).

Color Doppler

The pulse repetition frequency scale determines the degree of color saturation and is adjusted so that normal laminar flow appears as a region of homogeneous color. Stenosis results in the production of a high velocity jet and an abrupt change in the color flow pattern. This is identified as either aliasing or desaturation (whitening) of the color display at the site of luminal narrowing. Aliasing occurs when the flow velocity exceeds the Nyquist limit and results in color display of the reverse flow direction (wrap around). The post-stenotic region demonstrates a mosaic pattern indicating turbulent flow (Figure 3). Gray-scale settings are adjusted to optimize visualization of intraluminal plaque or thrombus at these sites of abnormal flow. Color Doppler provides additional information used to detect a significant stenosis. Color aliasing, persistence, and bruit all indicate flow disturbance. Color persistence is a continuous flow signal that is color of the forward direction only, in contrast to the alternating color in normal arteries.[4] Color persistence corresponds to the monophasic spectral Doppler waveform of severe stenosis. A color bruit in the surrounding soft tissue also indicates flow disturbance. This color artifact is attributed to vibration in the surrounding soft tissue in the presence of a high velocity jet. Abnormalities of color flow indicate possible stenosis that is then characterized using pulsed wave Doppler determination of velocities.

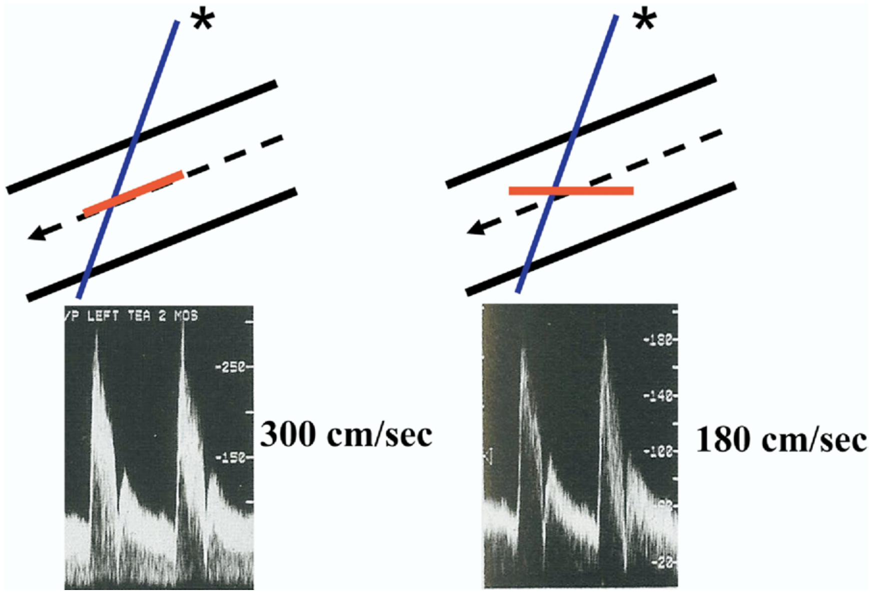


Figure 2 Angle of 60 degrees of Doppler insonation relative to vessel axis provides most accurate Doppler velocities. Angle correction should be used to maintain Doppler angle of 60 degrees or less. Doppler cursor should be parallel to vessel axis in center stream of arterial flow. *Left*, Appropriate alignment of Doppler beam at 60 degrees to vessel wall with sample volume cursor parallel to vessel axis (*imaginary line drawn in center of vessel*). *Right*, Inaccurate Doppler angle. There is misalignment of the cursor not parallel to vessel axis. Pulsed wave Doppler images obtained from same internal carotid artery demonstrates underestimation of peak systolic velocity with inaccurate Doppler angle (*right*).

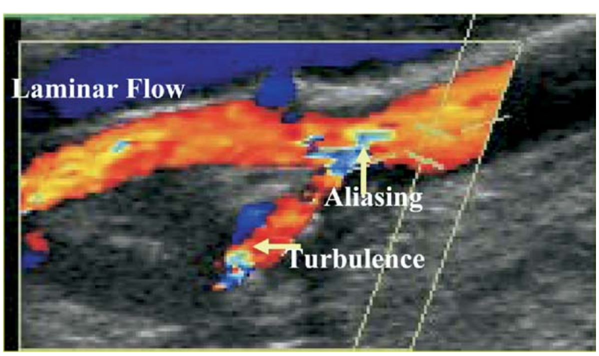


Figure 3 Color Doppler image obtained at carotid bifurcation. Laminar flow in external carotid artery is demonstrated by homogenous color with lightest color toward center of vessel. Aliasing is evident at origin of internal carotid artery (ICA) by abrupt color change from red to blue midstream at origin of ICA where large echolucent plaque is present. Mosaic of color filling remainder of ICA is consistent with poststenotic turbulence.

Spectral Doppler Waveform Analysis

A normal pulsed wave Doppler waveform is a sharply defined tracing with a narrow Doppler spectrum indicating that blood cells are moving at similar speed throughout the cardiac cycle (Figure 4). Flow becomes turbulent at bifurcations and luminal narrowings causing spectral broadening of Doppler waveform, with filling in of the low velocity region in the spectral waveform as the blood cells move at a wide range of velocities (Figure 4). The normal peripheral artery waveform is triphasic (Figure 4). The first component is the consequence of initial forward flow during systole, and results in peak systolic velocity (PSV) measurements that are typically less than 125 cm/s[5] for each arterial segment. There is early diastolic flow reversal in the second phase of the waveform as left ventricular pressure decreases before aortic valve closure. In late diastole, there is a small amount of forward flow that reflects elastic recoil of vessel walls. This diastolic component is absent in stiff atherosclerotic vessels. Waveform shape is also characterized as high resistance (eg, normal peripheral arterial waveform), or low resistance (eg, normal internal carotid artery [ICA] waveform) (Figure 4). The amount of flow during diastole is determined by the degree of dilation in the distal resistance arterioles.

Power Doppler

Power (or energy) Doppler is a technique that displays the total strength (amplitude) of the returning Doppler signal without distinguishing direction.[6] Sensitivity is increased by a factor of 3 to 5

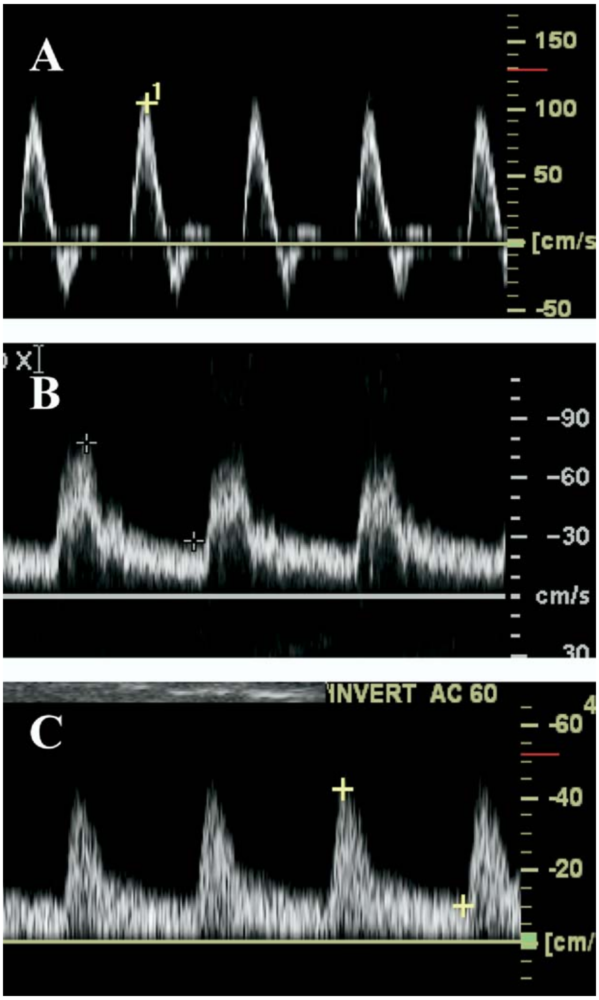


Figure 4 Spectral Doppler waveforms. **A**, Normal laminar flow with narrow range of velocities throughout cardiac cycle. *Cross* is placed above clear spectral window (or envelope). **B**, Biphasic Doppler waveform with loss of reverse diastolic flow and mild widening of spectral envelope (spectral broadening). **C**, Turbulent flow with filling in of spectral window (spectral broadening) and low peak systolic velocities.

times[6] with power Doppler compared with color flow Doppler. Power Doppler can, therefore, identify very slow flow that may not be detected by color flow Doppler. Power Doppler is less angle dependent than is color Doppler and it improves delineation of the lumen.[7] Power Doppler is used to differentiate high-grade stenosis from occlusion, to detect collateral vessels, and to identify small vessel disease.

Assessment of Arterial Stenosis

Doppler velocity is the main tool used to evaluate stenosis severity. Characteristic duplex ultrasound features of stenosis include elevated velocities, color disturbance, spectral broadening, and poststenotic waveforms (Table 1). If no poststenotic turbulence can be identified, inappropriate angle alignment or a tortuous vessel should be suggested as a cause of artifactually high velocities.

USE OF CONTRAST IN VASCULAR IMAGING

Ultrasonographic assessment of peripheral vascular disease is largely dependent on the functioning of the equipment and the skill of the operator.[8] The addition of duplex color Doppler techniques has allowed for improved identification of the anatomy of peripheral vascular disorders, including the location, length, and presence of stenosis or occlusion; development of collateral vessels; and areas of reconstitution. Ultrasound contrast agents also appear useful in enhancing suboptimal images and improving arterial diagnosis in areas where calcification in the vessel wall obscures the view of the lumen and the ability to determine velocity.[3] Contrast agents have been shown investigationally to better outline the lumen of the carotid arteries and facilitate measurement of intimal-medial thickness, and to help in outlining plaque morphology, and in differentiating between occlusion and high-grade stenosis. Contrast enhancement of the renal vasculature has been reported to be useful in cases where multiple main renal arteries are present.[3,9] Several large-scale studies have found improvement in peripheral artery diagnosis using contrast after suboptimal baseline ultrasound scans.[10] Contrast appears to have use in improving images of vessels difficult to adequately capture using traditional ultrasound techniques, such as the iliac arteries, the superficial artery in the adductor canal, the trifurcation vessels, and the plantar arteries. Contrast enhancement may also be useful in differentiating between patent and nonpatent vessels in patients with conditions that interfere with ultrasound scanning (ie, obesity, edema, dense calcification).[11] Nonetheless, it should be emphasized that despite these reports documenting the efficacy of contrast agents in enhancing vascular ultrasound imaging, they have not received US Food and Drug Administration approval for all these indications and, hence, this application should still be, at present, considered experimental.

CAROTID ARTERY ULTRASOUND

The goal of noninvasive ultrasound testing for carotid disease is to distinguish normal from diseased vessels, to classify a wide range of disease states, to assess the cerebral collateral circulation,

Table 1 Duplex evidence of arterial stenosis

- Elevated velocities: diagnostic criteria use peak systolic velocity (eg, >125 cm/s), ratios of distal to proximal sequential peak systolic velocities (eg, 2:1), and elevated end-diastolic velocity, supportive criteria include aliasing of color Doppler signal
- Diameter reduction: transverse or longitudinal measurements indicating reduction in luminal diameter are supportive, not diagnostic
- Spectral broadening or color mosaic pattern: the presence of turbulent flow is supportive, not diagnostic; it is most prominent just distal to significant stenosis
- Color bruit, color persistence: color bruit, providing evidence of vibration in the tissue surrounding arterial narrowing, is supportive, not diagnostic; continuous forward flow, or persistence, is supportive evidence of arterial stenosis

Table 2 Indications for carotid artery ultrasound

- Cervical bruits
- Amaurosis fugax
- Hemispheric stroke
- Focal cerebral or ocular transient ischemic attacks (which demonstrate localizing symptoms, such as weakness of one side of the face, slurred speech, weakness of a limb, retinal or hemispheric visual field deficits)
- Drop attacks or syncope (rare indications primarily seen in vertebrovascular insufficiency or bilateral carotid artery disease)
- Vasculitis involving extracranial arteries
- Pulsatile mass in the neck
- Trauma to neck
- Follow-up of carotid artery atherosclerosis not requiring revascularization
- Follow-up surveillance after carotid revascularization, a baseline ultrasound is recommended within 30 days after carotid stenting

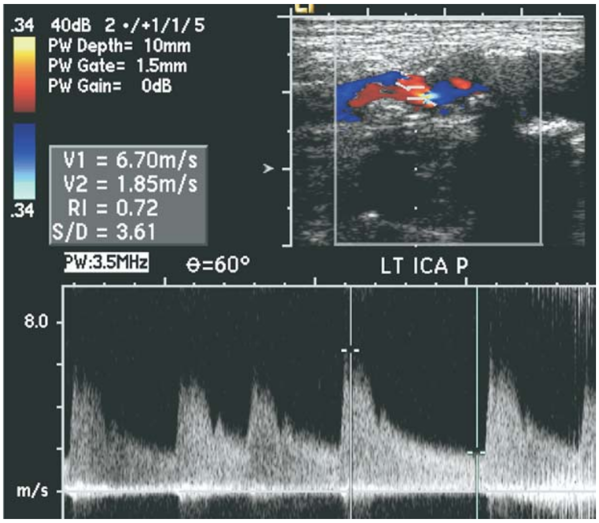


Figure 5 Duplex evidence of internal carotid artery (ICA) stenosis. Duplex image, sample volume cursor parallel to artery wall, at site of color aliasing and luminal narrowing. Spectral Doppler, high peak systolic velocity (670 cm/s), high end-diastolic velocity (185 cm/s), and spectral broadening (turbulence). These findings indicate severe (80%-99%) ICA stenosis.

and to do so in a safe and cost-effective manner. The primary aim is to identify patients who are at risk for stroke and who may require specific treatment. A secondary aim is to document progressive or recurrent disease in patients already known to be at risk. Appropriate indications for carotid artery testing are listed in Table 2.[12-15]

Interpretation

Duplex imaging should include, at a minimum, common carotid artery (CCA), ICA, external carotid artery, and vertebral artery. The interpretation of the spectral waveforms is based on parameters such as PSV, end-diastolic velocity, and the extent of spectral broadening (Figure 5). Individual vascular laboratories must validate their own results against a suitable gold standard (eg, arteriography). Several velocity criteria used to detect presence and severity of carotid artery disease have been published.[16] Table 3 summarizes useful absolute velocities and velocity ratios to diagnose significant ICA stenosis.[16] When all categories of carotid disease are considered, criteria distinguishing between normal and diseased ICA have a specificity of 84% and a sensitivity of 99% when compared with angiography.[17] The accuracy for detecting 50% to 99% diameter stenosis is 93%. The agreement with angiography is excellent for classification of lesions that result in greater than 50% diameter reduction.[18] Experience with duplex scanning in patients undergoing carotid endarterectomy indicates that the results of arteriography rarely altered the clinical treatment plan when a technically adequate duplex scan showed an 80% to 99% stenosis in an asymptomatic patient, or ipsilateral 50% to 99% stenosis in a patient with hemispheric neurologic symptoms.[19,20]

Absolute velocity criteria by duplex ultrasound may be less reliable than change in velocity criteria over time to diagnose recurrent stenosis after carotid artery stenting. A thumping sound may be encountered at the origin of the occluded ICA as a result of flow striking the occlusion followed by flow reversal. Stenosis proximal to the imaged segment is suggested by parvus et tardus waveforms. Diagnosis criteria for stenosis in the CCA are less extensively described. A doubling of PSV from proximal to distal sample indicates greater than 50% stenosis. A parvus et tardus waveform in

Table 3 Criteria for classification of internal carotid artery disease by duplex scanning with spectral waveform analysis of pulsed Doppler signals

Degree of stenosis, %	ICA/PSV, cm/s	Plaque estimate, %	ICA EDV, cm/s	ICA CCA PSV ratio
Normal	<125	0	<40	<2
<50	<125	<50	<40	<2
50-69	125-230	>50	40-100	2-4
>70	>230	>50	>100	>4
Subtotal occlusion	Variable	>50 Narrow lumen	>0	Variable
Total occlusion	0	>50	0	<1

CCA, Common carotid artery; *EDV*, end-diastolic velocity; *ICA*, internal carotid artery; *PSV*, peak systolic velocity.

Table 4 Differentiation of internal and external carotid arteries

Internal carotid artery	External carotid artery
• Usually larger	• Usually smaller
• Usually lateral and posterior	• Usually medial and anterior
• Usually incorporates carotid bulb	• Usually does not incorporate bulb
• No branches in the neck	• Eight branches in the neck
• Low resistance spectral waveform	• High resistance spectral waveform at rest
• Usually no oscillations in Doppler on temporal tap test	• Visible and audible oscillations on Doppler signal waveform on temporal tap test

the CCA again suggests there is stenosis proximal to the imaged region. Interpretation should comment on the direction of vertebral artery flow, forward (toward the brain) or reverse (away from the brain). In addition, the vertebral artery waveform should be described as normal (low resistance) or abnormal (biphasic or high resistance). Correct determination of ICA versus external carotid artery is essential for interpretation of study results (Table 4).

Limitations and Pitfalls of Carotid Duplex Ultrasound

Disease may be underestimated in the presence of long smooth plaque that does not have the accelerated turbulent flow patterns associated with hemodynamically significant lesions. High and low cardiac output can affect PSV. In the setting of markedly abnormal cardiac output, the ICA/CCA PSV ratio should be the primary diagnostic criteria for ICA stenosis. Contralateral ICA occlusion may result in overestimation of stenosis in the ipsilateral carotid artery,[8] due to compensatory increase in peak systolic velocity.

RENAL ARTERY DUPLEX ULTRASOUND

Atherosclerotic renal artery stenosis has become increasingly recognized as a contributing factor to resistant hypertension,[21] and may promote deterioration in renal function. Patients with severe bilateral renal artery stenosis, or stenosis to a solitary functioning kidney, are at risk for the development of end-stage renal disease.[22] Long-term survival of patients with atherosclerotic renal artery stenosis requiring dialysis support is dismal.[23] Although a number of noninvasive methods of diagnosis in renal artery stenosis have been proposed, none have obviated the role of the gold standard, renal arteriography. Each screening test has significant limitations that prevent widespread acceptance.

Indications, Performance, and Interpretation

Duplex ultrasonography is the ideal method of determining the adequacy of renal artery revascularization (Table 5).[25] Duplex ultrasonography is helpful in detecting important areas of restenosis after endovascular therapy (percutaneous angioplasty with stent deployment).[26] The renal duplex examination includes spectral Doppler velocities from the renal arteries, renal parenchyma, and abdominal aorta. PSV and peak end-diastolic velocities obtained in branches of the renal artery at the level of the medulla are used to calculate the renal resistive index, a value reflecting the health of the renal parenchyma itself (Table 6). In addition, the examination should define the pole-to-pole length of each kidney. Figure 6 illustrates duplex findings of renal artery stenosis.

ULTRASOUND IMAGING FOR ABDOMINAL AORTIC ANEURYSM

Indications

Ultrasound imaging is highly sensitive for assessing and following up abdominal aneurysms.[27,28] A family history of an abdominal aneurysm has been reported to increase the risk of developing this condition 4-fold. In addition, if an aneurysm is found in one vascular territory, such as the popliteal artery, there is an increased risk of an aneurysm in the aorta. Major indications for assessment of abdominal aortic aneurysm with ultrasound imaging are included in Table 7.

Table 5 Indications for renal duplex ultrasound[24]

- Sudden exacerbation of previously well-controlled hypertension
- New onset hypertension at a young age
- Malignant hypertension
- Unexplained azotemia
- Hypertension and aortoiliac or infrainguinal atherosclerosis
- Azotemia after administration of an angiotensin-converting enzyme inhibitor
- An atrophic kidney
- Recurrent flash pulmonary edema without cardiac explanation
- Evaluation of adequacy of renal artery revascularization
- Detection of restenosis after endovascular therapy

Table 6 Diagnostic criteria for significant renal artery stenosis

Renal artery to aorta peak systolic velocity ratio is >3.5
PSV > 200 cm/s with evidence of poststenotic turbulence
EDV > 150 cm/s (>80% renal artery stenosis)
RI > 0.8 (used to predict response of blood pressure, renal function, to renal revascularization)
An occluded renal artery demonstrates no flow in the affected vessel

EDV, End-diastolic velocity; *PSV*, peak systolic velocity; *RI*, resistive index (1 − [EDV/maximum systolic velocity] × 100).

Interpretation

A normal diameter of the abdominal aorta is approximately 2.0 cm (range: 1.4-3.0 cm) in most individuals (Table 8). A mildly dilated abdominal aorta is described as ectatic, whereas it is reported as aneurysmal when the diameter is greater than 3.0 cm.[28,29] Abdominal aortic aneurysms are described as saccular (ie, having a baglike structure protruding asymmetrically from the aorta); fusiform (ie, spindle-shaped and tapering from the middle toward each end); or cylindric. The majority of abdominal aortic aneurysms are fusiform in shape, located below the renal arteries, and they may involve one or both of the iliac arteries. Atherosclerotic changes and/or mural thrombus can line the aneurysmal sac. Dissection has been reported with abdominal aortic aneurysm, but is not common. The typical growth rate reported in the literature of abdominal aortic aneurysms measuring 3 to 5.9 cm is approximately 0.3 to 0.4 cm per year.[30] However, larger aneurysms may progress more quickly than others. Aneurysms repaired by endografts and endovascular stents have unique ultrasound characteristics. Thrombus develops in the aneurysm outside of the endograft. Over time, the maximal diameter of the aneurysm sac surrounding an endograft is expected to decrease.

NONINVASIVE PHYSIOLOGIC VASCULAR TESTING OF THE LOWER EXTREMITY ARTERIES

The goals of noninvasive testing for peripheral arterial disease are to confirm a clinical diagnosis and further define the level and extent of obstruction. A variety of algorithms are used to noninvasively diagnose peripheral arterial disease in the vascular laboratory. Some of these include segmental limb pressures with pulse volume plethysmography, exercise treadmill testing, and arterial ultrasonography.

The major indications for assessment of peripheral arterial disease with noninvasive testing are summarized in Table 9.

Segmental Limb Pressure Interpretation

Systolic intravascular pressures increase slightly from the femoral to the tibial level so that intra-arterial measurement of pressures would typically demonstrate a higher pressure in the tibial artery than in the femoral artery. When the 4-cuff method is used with relatively narrow cuffs, a pressure artifact is introduced into the measurement, accounting for the gradual increase in measured pressure in ascending levels of the leg. In healthy individuals, the high thigh pressure typically exceeds the ankle pressure.[31] Thus, a thigh/brachial index of 1.1 or greater is indicative of normal hemodynamics and an index of less than 0.9 is an indicator of peripheral arterial disease (Table 10). Of note, when the high thigh pressure is low compared with the brachial artery pressure, the level of obstruction may be proximal to the cuff or beneath the cuff. Thus, the site of obstruction could be in the aorta, iliac artery, common femoral artery, or proximal superficial femoral artery. When the inflow hemodynamics are abnormal bilaterally, the site of obstruction may be the aortoiliac region. However, if the low pressures are unilateral, then only an ipsilateral iliac or common femoral stenosis is inferred and an abnormality of the aortic segment should not be included in the interpretation. Segmental limb pressures are compared with adjacent ipsilateral segments, contralateral-paired segment, and greater of the two brachial systolic pressures. A reduction of 20 mm Hg or greater in pressures is considered significant if such a gradient is present either between segments along the same leg or when compared with the same level of the opposite leg.[32]

Pulse Volume Plethysmography Interpretation

Segmental limb plethysmographic waveform analysis is based on evaluation of waveform shape and signal amplitude. Standardized criteria relating waveform changes to anatomic site and hemodynamic

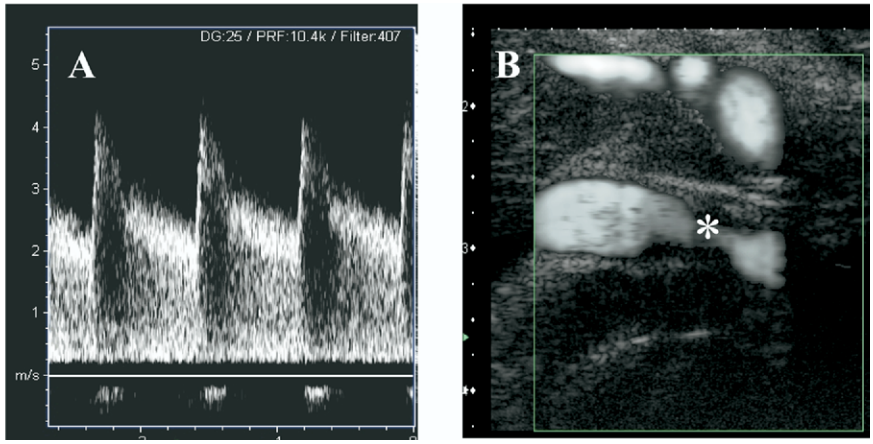


Figure 6 A, Renal artery stenosis. Doppler spectral waveform demonstrates turbulence with marked elevation in peak systolic and end-diastolic velocities. **B**, Power Doppler indicating luminal narrowing (*) at site of stenosis

Table 7 Indications for abdominal aorta ultrasound

- Abdominal pain
- Pulsatile and enlarged aorta on physical examination
- Hemodynamic compromise suggestive of a ruptured aneurysm
- An immediate family member with a history of abdominal aortic aneurysm
- An aneurysm found in another vascular territory
- Follow-up of aortic endograft

Table 8 Diagnostic criteria for abdominal aortic aneurysm and endoleak

- Aneurysm: diameter > 3.0 cm
- Endoleak: flow outside of the aortic endograft, and within the aneurysm sac
- Dissection: true and false lumen present

severity of disease are used in diagnostic interpretation. Pulse volume recordings are typically performed by injecting a standard volume of air into pneumatic cuffs. Older machines adjusted for the amount of air in the cuff so that a precise comparison could be made between legs or at various levels along the extremities. Some newer machines, however, do not calibrate the amount of air in the cuff; thus, caution is advised in interpreting the amplitude of the pulse volume recording in comparison with the other extremity or at various levels. The volume of air injected into the cuff is enough to occlude the venous circulation but does not occlude the arterial circulation.

Volume changes in the limb segment below the cuff are translated into a pulsatile pressure, which is detected by a transducer and then displayed by a pressure pulse contour. A normal pulse volume recording, similar to the arterial waveform, is composed of a systolic upstroke with a sharp systolic peak followed by a downstroke that contains a prominent dicrotic notch. If a hemodynamically significant stenosis is present, dissipation of energy occurs because of arterial narrowing; this is reflected in a change in the pulse volume recording contour, indicating a proximal arterial obstruction. The amount of variation in the pulse volume recording contour is reflective of disease severity, as shown in Table 11.

Table 9 Indications for noninvasive physiologic testing

- Exercise-related limb pain (claudication symptoms)
- Limb pain at rest
- Extremity ulcer/gangrene
- Assessment of healing potential
- Absent peripheral pulses
- Digital cyanosis
- Cold sensitivity
- Arterial trauma and aneurysms
- Abnormal ABI

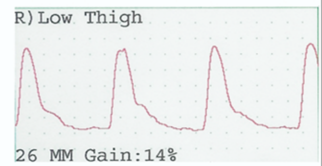
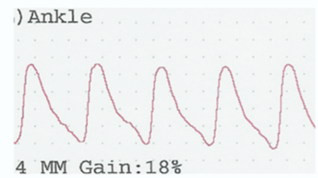
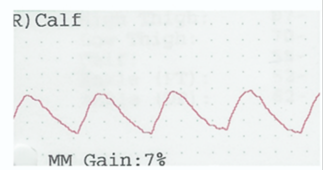
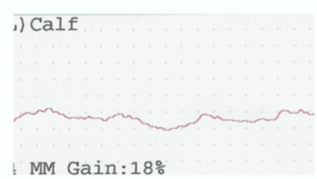
ABI, Ratio of ankle-to-brachial arterial systolic blood pressure.
Follow-up evaluation is warranted for graft surveillance, worsening symptoms of claudication, and assessment of revascularization therapy.

Table 10 Criteria for abnormal segmental pressure study

Level of disease	Findings
Aortoiliac	High thigh/brachial index < 0.9 bilaterally
Iliac	High thigh/brachial index < 0.9
SFA disease	Gradient between high and low thigh cuffs
Distal SFA/popliteal	Gradient between thigh cuff and calf cuff
Infrapopliteal	Gradient between calf and ankle cuffs
Pressure gradient between 20-30 mm Hg is borderline, ≥30 mm Hg is abnormal	

SFA, Superficial femoral artery.

Table 11 Pulse volume plethysmography: Pulse volume recording contour with increasing vascular disease severity

Normal • Sharp upstroke • Scooped or flat interval between peaks • Possible dicrotic notch	
Mildly abnormal • Sharp upstroke • No flat period or scooping between peaks • No dicrotic notch	
Moderately abnormal • Flat peak • Equal upslope and downslope time • No dicrotic notch	
Severely abnormal • Flat peak • Equal upslope and downslope time • No dicrotic notch • Low amplitude	

Limitations of Segmental Pressure Measurement and Pulse Volume Recording

Evaluation of segmental pressures and volume plethysmography are an indirect examination, based on which of the anatomic locations of lesions is inferred. Multiple stenoses located at or above the level of the pneumatic cuff may not be distinguished. For example, a decreased thigh pressure may be caused by obstruction of the aortoiliac segment, or common femoral, or combined superficial femoral artery and profundus femoris artery disease.

EXERCISE TESTING FOR PERIPHERAL ARTERIAL DISEASE

A peripheral arterial lesion may be revealed with measurement of lower extremity pressures after exercise (Tables 12 and 13).

Contraindications to exercise treadmill testing of the lower extremities include: rest pain, noncompressible vessels on a resting study, acute deep venous thrombosis, shortness of breath at rest or with minimal exertion, uncontrolled angina, or a physical disability that limits patient's ability to ambulate on a treadmill. The ankle pressure should increase with exercise as the brachial pressure increases.

PERIPHERAL ARTERIAL ULTRASOUND

The Duplex ultrasound study is tailored to individual requirements and can be limited to a given arterial segment, or extended to evaluate both limbs in their entirety (Table 14). The goal of the examination is to elucidate the location and severity of extremity arterial stenoses. It can be helpful particularly when planning therapy for known peripheral arterial occlusive disease.

Interpretation

Peripheral arterial stenosis is characterized using pulsed wave Doppler evaluation. The diagnostic criteria use step-up in PSV ratios from proximal to

Table 12 Indications for stress testing of the lower extremities[33, 34]

• Normal resting lower extremity arterial segmental limb pressures and pulse volume recordings at rest, in the context of a history of intermittent claudication
• Resting lower extremity segmental limb pressures and pulse volume recording amplitudes mildly abnormal at rest (ie, ABI > 0.80 but < 0.96) in a patient with a history of intermittent claudication

ABI, Ankle-brachial index.

Table 13 Interpretation of postexercise ankle-brachial index

• ABI < 0.90 at 1 minute after exercise indicates hemodynamically significant PAD

ABI, Ankle-brachial index; *PAD*, peripheral arterial disease.

Table 14 Indications for peripheral arterial ultrasound

Claudication
Leg pain
Ulcers
Lower extremity revascularization

distal artery and careful waveform analysis (Table 15). Pulsed Doppler interrogation at the level of a stenosis reveals a PSV double that of the velocity in the proximal segment. There is spectral broadening and forward flow throughout the cardiac cycle in severe stenosis. An occlusion is present when there is no flow within an arterial segment. High-resistance waveforms are present in the artery proximal to the occlusion if there are no collateral vessels. Continuous forward diastolic flow is present in the proximal artery if dilated high capacitance collaterals are present. The artery that reconstitutes distal to a high-grade stenosis will have a characteristic poststenotic parvus et tardus waveform.

Doppler examination can accurately diagnose peripheral arterial disease.[35,36] Compared with the gold standard of arteriography, duplex Doppler evaluation used to detect significant stenoses in patients with proximal lower extremity arterial disease demonstrates a high sensitivity (82%) and specificity (92%). Use of color and pulsed wave Doppler[36,37] increases the sensitivity (87%-88%) and specificity (95%-99%) of stenosis identification. The PSV ratio between the stenosis and the immediately proximal artery segment classifies peripheral arterial stenoses better than absolute PSV measurements. For example, PSV ratios of 2 and 7 correspond to stenoses greater than 50% and greater than 90%, respectively.[38] There is a wide range of PSV measurements obtained in the lower extremities of normal and abnormal cases. There is a greater correlation between PSV ratio and stenosis than between absolute PSV and stenosis.

PERIPHERAL ARTERIAL BYPASS GRAFT ULTRASOUND

Graft surveillance has proven quite useful in efforts to preserve the patency of bypass grafts. Infrainguinal bypass graft 5-year primary patency rate ranges from 60% to 85%.[39] Surgical revision of the stenoses identified with ultrasound increases the 5-year patency rate up to 93%.[40,41] Segmental pressure measurement has not been useful to predict graft failure or the need for revision.[42] Doppler examination is useful to identify flow-reducing lesions before graft failure occurs. Standard surveillance protocols recommend ultrasound evaluation of the graft twice during the first postoperative year, and annually thereafter (Table 16). Early intervention improves long-term patency by 15% to 20%. Technical failure often causes graft failure in the first month. Intimal hyperplasia and progression of atherosclerotic disease cause graft failure over the ensuring years.

Interpretation

PSV ratios are determined for grafts in a manner identical to their use in native arteries (Table 17).[43,44] Exceptions to using distal-to-proximal PSV ratio include cases with a diameter mismatch in the graft or proximal tandem lesions. In these cases a distal PSV can be used instead of the PSV ratio.[44] Doubling of the velocity PSV ratio indicates significant graft stenosis of greater than 50%, with sensitivity of 95% and specificity 100%.[45]

Severe or high-grade lesions warrant intervention. Low velocities indicate poor arterial inflow, proximal stenosis, or large graft diameter. The presence of a parvus et tardus waveform indicates inflow disease or proximal stenosis. In addition,[46] a PSV less than 45 cm/s within a graft indicates that subsequent graft failure is likely to occur. The fundamental criteria of ultrasound evaluation of bypass grafts include: PSV greater than 180 cm/s or PSV ratios greater than 2 indicate up to 50% stenosis; low-flow states (<45 cm/s) indicate increased propensity for graft failure; and changes in waveform shape and velocity measurements on serial examinations warrant close follow-up/possible revision.

Table 15 Diagnostic criteria for peripheral arterial diameter reduction

	Diameter reduction	Waveform	Spectral broadening	PSV distal/PSV proximal
Normal	0	Triphasic	Absent	+++ No change
Mild	1%-19%	Triphasic	Present	< 2:1
Moderate	20%-49%	Biphasic	Present	< 2:1
Severe	50%-99%	Monophasic	Present	> 2:1*

PSV, Peak systolic velocity.
*>4:1 Suggests >75% stenosis, >7:1 suggests > 90% stenosis.

Table 16 Indications for arterial bypass graft ultrasound

- At 3 and 6 mo in the first year after revascularization
- At annual intervals after revascularization after the first year

Table 17 Diagnostic criteria for vein graft lesions using peak systolic velocity

- Minimal stenosis <20% with PSV ratio < 1.4 and < 125 cm/s
- Moderate stenosis of 20% to 50% with PSV ratio 1.5 to 2.4 and a PSV <180 cm/s
- Severe stenosis 50% to 75% with PSV ratio 2.5 to 4 and a PSV >180 cm/s
- High-grade stenosis > 75% with PSV ratio > 4 and PSV > 300 cm/s

PSV, Peak systolic velocity.

LOWER EXTREMITY ARTERY ULTRASOUND AFTER PERCUTANEOUS REVASCULARIZATION

The long-term patency of percutaneous angioplasty and stenting in the lower extremity ranges from 50% to 85%.[47-50] Duplex evaluation is being performed after percutaneous revascularization to detect evidence of stenoses at intervention sites. The concept is that early detection of lesions may assist in identifying individuals who need reintervention. Duplex ultrasound is currently performed after intervention, at recurrence of symptoms, and often annually thereafter. The color and pulsed wave Doppler examination focus on the vessel proximal to the intervention site, at the site, and distal to the site[51] (Figure 7). Stenosis is evaluated in a manner similar to that used in native arteries, discussed previously (Table 18). A PSV ratio of 2 indicates a stenosis greater than 50%.[44]

DIAGNOSIS AND MANAGEMENT OF IATROGENIC PSEUDOANEURYSM USING ULTRASOUND

Increasing interest in endovascular therapy as a primary option for patients with cardiovascular disease has resulted in a greater frequency of vascular complications. Despite the efficacy of these endovascular procedures, complications of vascular access do occur, including hematoma formation, arteriovenous fistulae, infection, atheroemboli, retroperitoneal hemorrhage, native arterial thrombosis, and pseudoaneurysm (PSA). PSA is among the most common iatrogenic vascular complication, and is associated with significant risk of expansion, extrinsic compression on native arteries, rupture, embolization, and infection. A PSA represents a persistent defect throughout all 3 layers of the arterial wall, resulting in extravasation of blood outside of the artery. This extravascular blood is supported by the surrounding soft tissues.

The key to the diagnosis of PSA remains a high index of suspicion (Table 19). Clinically, any patient who undergoes an arterial puncture for arteriography or endovascular intervention and experiences pain at the access site after the procedure should be considered to be at risk for PSA formation. A pulsatile mass on physical examination and/or the presence of an audible bruit on auscultation over the access site are helpful physical findings. However, many PSAs will not have these findings. Extensive ecchymosis at the access site may also be a clue to the potential presence of a PSA.

PSAs are identified when flow into an extravascular sac is detected (Table 20). In addition to the to-and-fro signal in the neck, the proximal native artery of origin may have a lower resistance spectral waveform when compared with the distal artery (Figure 8).

Treatment Options

Although serious complications may occur with PSAs, not all PSAs require treatment. There are several options for treatment of PSAs, including observation, surgical repair, and ultrasound-guided compression or thrombin injection (Appendix).

VASCULAR LABORATORY ACCREDITATION

The laboratory accreditation process provides standards for laboratory procedures, staff experience, and quality assurance. The Intersocietal Commission for the Accreditation of Vascular Laboratories (ICAVL) is one such accrediting agency.[19] The American College of Radiology also provides laboratory certification (www.acr.org). According to ICAVL, "A

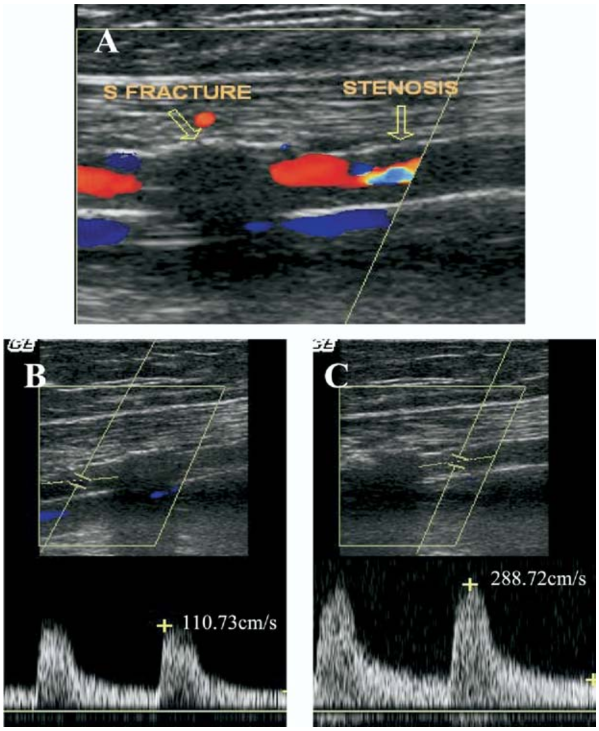


Figure 7 Duplex ultrasound of superficial femoral artery postintervention. **A**, Color Doppler with laminar flow, followed by loss of color signal at site of stent fracture and complex calcific atherosclerotic plaque, with aliasing distal to stent fracture. **B**, Spectral Doppler proximal to site of fracture with turbulent flow. **C**, Peak systolic velocity increases distal to fracture within area of stenosis, suggestive of 50% to 99% stenosis.

vascular laboratory is a unit performing noninvasive vascular diagnostic testing under the overall direction of a Medical Director." Their published standards give minimum criteria for physical facilities, ancillary support, and organization of staff. The following areas are highlighted as examples of the requirements for accreditation by this body.

Examination Interpretation, Reports, and Records

The medical director or a medical staff member–both of whom must be physicians–should interpret and report on all noninvasive vascular examinations. All reporting must be standardized and include the name of the technologist (sonographer) performing the examination, the date of the examination, clinical indications, description of the test performed, results–including localization and quantification of abnormal findings and comparison with available previous studies, and a signature. The final report must be completed within 2 working days of the examination, except when outstanding clinical information is needed for completion. Critical findings must be reported to the referring physician on the same day as found.

Table 18 Interpretation criteria for arterial stenosis after percutaneous revascularization

- PSV >180 cm/s
- PSV ratios >2 indicate significant stenosis
- Changes in waveform shape and velocity measurements on serial examinations warrant close interval follow-up

PSV, Peak systolic velocity.

Table 19 Indications for duplex study for pseudoaneurysm

- Pulsatile mass at arterial access site
- Sudden pain at arterial access site
- Bruit at arterial access site

Table 20 Criteria for diagnosis of pseudoaneurysm sac

- Extravascular arterial sac with flow
- Communication between sac and artery
- Native artery with forward and reverse flow, ie, to and fro

Qualifications of Medical and Technical Personnel

Medical directors of vascular ultrasound laboratories, either through completion of a formal residency or fellowship or less formal (Continuing Medical Education) training program, must have interpreted, under the supervision of an experienced mentor, 100 cases in each of the areas for which they will be interpreting studies: carotid duplex ultrasound, transcranial Doppler, peripheral arterial physiologic tests, peripheral arterial duplex ultrasound, and venous duplex ultrasound, and 75 visceral vascular duplex ultrasound cases to interpret the latter studies.[19] Medical directors with at least 3 years of experience in an established practice, but no formal or informal training per se, must have interpreted 300 cases, under the supervision of an experienced mentor, in each of the following areas (for which they will be interpreting cases): carotid duplex ultrasound, transcranial Doppler, peripheral arterial physiologic tests, peripheral arterial duplex ultrasound, and venous duplex ultrasound, and 225 visceral vascular duplex ultrasound cases.[19] Medical staff must be licensed physicians with similar experience allowing them to participate as interpreters. Beginning in 2006, the American Registry of Diagnostic Medical Sonographers (ARDMS) will be offering certification in vascular laboratory interpretation for physicians, known as the Registered Physician in Vascular Interpretation certification.

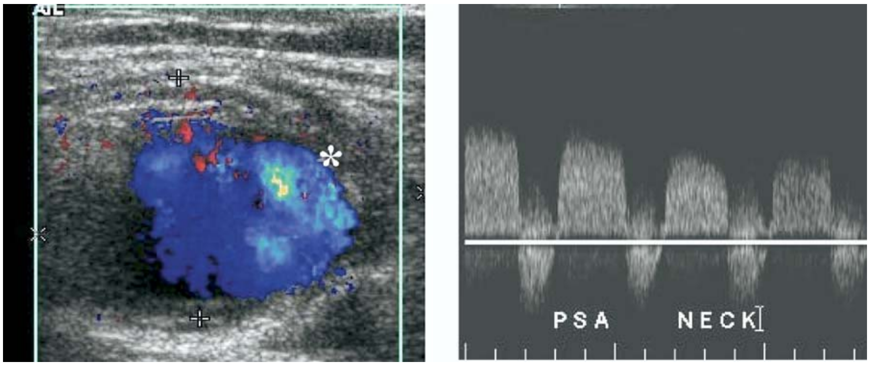


Figure 8 Duplex evidence of pseudoaneurysm (*PSA*). **Left panel,** Color Doppler of PSA sac demonstrating thrombus (*) lining cavity. Color flow is evident within cavity. **Right panel,** Unique to-and-fro spectral Doppler recording in neck of PSA is diagnostic of PSA.

Technical directors must have experience in performing and interpreting vascular laboratory tests. In addition, technical directors should have had 3 years of vascular testing experience, with the performance of at least 1800 noninvasive vascular examinations with appropriate distribution in testing areas being performed by the laboratory. Since January 2003, all technical directors have been required to have an appropriate credential in vascular testing. Technical staff (sonographers) must have performed 100 cases in each applicable area.

Specific recommendations from ICAVL regarding vascular laboratory operations are available for extracranial cerebrovascular, intracranial cerebrovascular, peripheral arterial, peripheral venous testing, and visceral vascular testing.[20-23,25] Each module includes information on standards for instrumentation, indications, techniques and components of examination performance, diagnostic criteria, procedure volumes, and quality assurance.

Training of Sonographers

The ASE has recommended that all sonographers enter and complete training in a program recognized and supported by the ASE, such as those accredited by the Commission on Accreditation of Allied Health Programs, the Joint Review Committee for Cardiovascular Technology, and the Joint Review Committee for Diagnostic Medical Sonography.[26] Sonographers and physicians can become Registered Vascular Technologists, credentialed by the ARDMS, by successfully completing both the Vascular Physical Principles and Instrumentation and Vascular Technology examinations. Prerequisites to taking the ARDMS examinations vary according to education level and are available on the ARDMS Web site (www.ardms.org/applicants/prechart.html). Credentialing as a Registered Vascular Specialist is also offered by Cardiovascular Credentialing International (CCI). For details, see the CCI World Wide Web site (www.cci-online.org). The training qualifications and experience for the sonographers (including the technical director) in a vascular ultrasound laboratory are listed above under "Vascular Laboratory Accreditation."

REIMBURSEMENT: MEDICARE GUIDELINES

For studies performed in the hospital, Medicare Part A usually covers the technical components of the study, whereas the interpretation is billed under Medicare Part B. The majority of reimbursement falls under Medicare Part B, especially for studies performed in private offices and clinics. The requirement that a vascular laboratory be accredited and/or staff registered and certified to receive Medicare reimbursement for vascular studies is determined by each state's medical carrier. ICAVL provides links to requirements for each state on their Web site (www.icavl.org). Medicare payment policies are enforced through postpayment audits. Laboratory records are reviewed to assure compliance, and providers who violate billing regulations must repay the carrier for past erroneous claims.

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APPENDIX
TECHNIQUE OF CAROTID ARTERY ULTRASOUND

The first segment of carotid duplex ultrasound examination involves a complete survey of the extracranial carotid arteries in transverse and longitudinal views, an assessment of the anatomy, and the presence or absence of disease and its location. Beginning at the base of either side of the neck, first from the anterolateral and then the posterolateral view, the operator should move the transducer slowly from the level of the clavicle to the level of the jaw. The right CCA is located lateral to the thyroid gland and medial to the internal jugular vein. The ICA is typically located lateral and posterior in the neck, whereas the external carotid artery (ECA) is medial and slightly more anterior. The internal jugular vein is easily compressible in most patients, whereas the CCA is not. In most patients, the origin of the right CCA and the right subclavian artery are easily accessible to the scan head, with slight caudal angulation of the transducer, as they branch from the brachiocephalic artery. Left CCA as proximal as possible at the base of the neck. The origin of the left CCA cannot be identified from this view. Following the CCA to the origin of the ICA and the ECA, the bifurcation is usually found at the level of the cricoid cartilage (level of C3 or C4, but may vary from C1-C6). ICA and ECA should be followed as far in the neck as possible. For assessment of the plaque character and location, the entire CCA, ICA, and ECA should be scanned in B-mode (gray scale) without color.

The longitudinal view is used to correctly place the Doppler sample volume for velocity measurement and for assessment with color Doppler. The CCA is visualized and its entire length is assessed with spectral Doppler from the level of its origin on the right and as low in the neck as possible on the left. Stenosis can be focal and flow patterns can normalize within a short distance beyond the stenosis. For this reason, the sample volume should not be placed in discrete spots but, rather, methodically advanced throughout the length of the vessel using color Doppler for guidance. Representative velocity measurements should be recorded from the most proximal CCA, the mid-CCA, and the distal CCA. The CCA spectral waveform signature normally has greater diastolic flow than the ECA, but less than the ICA. The ICA should be followed as far distally as possible, at least 3 cm to an area well beyond the disease. Using spectral Doppler, sample volume should be walked throughout the entire ICA, recording velocity samples–PSV and end-diastolic velocity from the proximal, mid, and distal ICA segments. The distal ICA sample should be obtained at least 3 cm distal to the bifurcation.

CAROTID ARTERY ULTRASOUND: PRACTICAL TIPS

- ICA and ECA are usually differentiated based on several criteria, as no one criterion by itself is definitive (Table 2). A direct comparison of the waveforms from the two vessels is critical before using the resistance characteristics for identification.
- Physical limitations such as recent neck surgery, radical neck dissection, prior radiation, skin staples, sutures, or dressings require extra ultrasonic gel or standoff to facilitate imaging.
- Use posterior approach for patients who cannot extend the neck because of fixed cervical spine disease, cervical collar, or muscle contractures.
- For patients unable to lay flat, imaging in the seated or standing position can be performed. A low-frequency transducer should be used in patients with a deep artery or thick neck.
- Stenosis may be overestimated in the presence of tortuosity if the sample volume is placed in the outer curvature.
- ICA/CCA ratio may still apply and should be used for identifying the degree of stenosis. In the presence of decreased cardiac output or severe aortic stenosis absolute velocity criteria will not be directly applicable.
- It is important to obtain sample velocities in the maximum area of stenosis, and just proximal and distal to any narrowing to avoid pitfalls in assessment of stenosis.

TECHNIQUE OF RENAL ARTERY DUPLEX ULTRASOUND

Renal artery duplex ultrasonography requires a vascular technologist who has demonstrated dedication to perfecting the procedure, and state-of-the-art ultrasound equipment. Patients are instructed to fast from midnight before the examination. Each study must be performed in the early morning, and patients are instructed to take their morning medications with small sips of liquid. If significant bowel gas is identified, the study is terminated, the patient given simethicone, and the patient is rescheduled for another morning. A low-frequency 2.25- to 3.5-MHz pulsed Doppler transducer is required for adequate deep abdominal imaging. The addition of color imaging will increase the ease with which the renal arteries are identified. The examination is started with the patient supine and in reverse Trendelenburg's position. The aorta is scanned in the longitudinal view from the diaphragm to the aortic bifurcation. The presence of atherosclerotic plaque and aneurysmal dilation is noted. The origin of the celiac, superior, and inferior mesenteric arteries is defined. A Doppler velocity is obtained at the level of the superior mesenteric artery, in the center stream of arterial flow, at a 60-degree angle. This velocity is recorded, and will be used as the denominator for renal-to-aortic velocity ratio calculations.

The transducer is then reoriented into the transverse plane, and the celiac and superior mesenteric arteries are noted arising from the anterior aspect of the aorta. In 75% of patients, the left renal vein crosses anterior to the abdominal aorta, as it enters the inferior vena cava. These two ultrasound landmarks (origin of the superior mesenteric artery and left renal vein crossing anterior to the aorta) are important for the identification of the right renal artery. The right renal artery arises in an anterior approach, and then courses in posterior fashion as it enters the hilum of the kidney. The left renal artery generally arises inferior to the right, and takes a posterior course. The Doppler cursor, at a 60-degree angle (or less), is placed within the aorta, and then walked into the ostium of the right renal artery. PSV and peak end-diastolic velocities are obtained in the origin, proximal, mid, and, if possible from this orientation, distal renal artery. The renal artery Doppler waveform has a characteristic low-resistant signal, with significant forward diastolic flow. Similar measurements are obtained from the left renal artery. It is critical that the entire renal artery is visualized, so that a focal stenosis or web (in the case of fibromuscular dysplasia) is not overlooked. Both renal veins are noted to be patent or occluded.

The patient is then placed in the left lateral decubitus position, and the right kidney is visualized from the flank. Three discrete measurements of the pole-to-pole length of the kidney are recorded, in centimeters. Doppler velocities in the cortex, medulla, and hilum of the kidney are recorded at a 0-degree angle, with a large sample volume, as discrete parenchymal vessels are difficult to identify. The Doppler transducer is then moved slightly anteriorly, and attempts are made to visualize the entire right renal artery from the aorta to the hilum of the right kidney. This banana-peel technique can be particularly helpful in imaging and analyzing the entire renal artery. A limitation of the banana-peel approach on the right is the presence of the overlying inferior vena cava, a problem that does not occur on the contralateral side. This process is then repeated with the patient in the right lateral decubitus position in an effort to interrogate the left kidney and entire left renal artery.

TECHNIQUE OF ABDOMINAL AORTIC ULTRASOUND

The patient is required to fast before the study. To evaluate an aortoiliac segment, an ultrasound machine with a low-frequency transducer (2.4 MHz) is needed. A midrange transducer (4-8 MHz) is typically used for femoral or popliteal aneurysms. The examination of an aneurysm should be focused on determining the aneurysmal size, shape, location (infrarenal or suprarenal), and distance from other arterial segments.

Ultrasound scanning begins in the supine position. To facilitate accurate measure of its size, 3 sonographic views of the abdominal aorta are usually obtained: transverse plane (A-P diameter and transverse diameters), the sagittal plane (A-P diameter), and coronal plane (longitudinal and transverse diameters). Of note, the transducer should be oriented so that the maximal length of the segment is visualized. The transducer is then rotated 90 degrees to achieve a transverse view. If overlying bowel gas obstructs the aorta from view, patients are placed in the decubitus position and the aorta is visualized by the coronal plane through either flank. The celiac artery may emerge from the aorta and branchi into the common hepatic and splenic arteries. In addition, the right renal artery may be seen emerging from the aorta and traveling under the inferior vena cava.

The most reliable view for measurement of the abdominal aorta is the anterior-posterior image. The lateral view is often the least accurate view because of specular reflection artifact from the vessel wall. Hindrances to an adequate examination include overlying bowel gas and obesity, especially in the region of the proximal neck.[30]

TECHNIQUE OF SEGMENTAL LIMB PRESSURE MEASUREMENT

Segmental limb pressures are typically measured in conjunction with segmental limb plethysmography (pulse volume recordings). Both procedures are performed using pneumatic cuffs that are appropriately sized to the diameter of the limb segment under study and are properly positioned. It is common practice to evaluate the presence of arterial blood flow in the limb distal to the cuff with an appropriate sensor before measuring pulse volume recordings. The patient is initially placed in the supine position for at least 10 minutes before measuring limb pressures. There are several commercially available devices that have pneumatic cuffs with automatic inflation capability. A continuous wave Doppler instrument with a transducer frequency of 4 to 8 MHz is the preferred instrumentation to detect Doppler arterial signals. The pneumatic cuff is initially inflated quickly to a supersystolic value. The cuff is then slowly deflated until a flow signal returns. The cuff pressure at which the flow signal resumes is taken to be the systolic pressure in the arterial segment beneath the cuff. For example, if the cuff is on the high thigh and the sensor is in the popliteal fossa, the measured pressure is reflective of the proximal superficial femoral and profunda femoris arteries, and any collateral arteries, not the popliteal artery. Although published studies indicate that the measured pressure is slightly more accurate when the flow sensor is positioned in close proximity to the cuff, most laboratories for convenience use the Doppler signal from an artery at the ankle for all limb measurements.

Many laboratories use a 4-cuff method where cuffs are positioned as follows: at the high thigh with the upper edge of the cuff positioned at the top most portion of the inner thigh, at the low thigh above the patella, at the calf below the tibial tubercle, and at the ankle above the malleoli. An alternative method involves using only 3 cuffs with a single, relatively wide cuff at the midthigh. Typically, the foot pressure is measured by insonating the posterior tibial and anterior tibial arteries at the ankle level, thus, generating two numbers. Single pressure measurements are made for the calf and the high- and low-thigh levels regardless of the tibial signal selected as the flow indicator. The ankle pressures are used to calculate the ankle-brachial index for each extremity. Each of the ankle pressures is divided by the highest brachial artery pressure.

The lower extremity pressure evaluation begins at the ankle level with a systematic search for arterial signals at ascending levels. Patients who are found to have a normal ankle-brachial index are unlikely to have more proximal disease and an exercise treadmill test or reactive hyperemia test would be necessary to uncover subcritical stenosis. In addition, if the ankle-brachial index is normal and the symptoms are present in the digits of the feet, the toes should be evaluated for the presence of pedal or digital artery obstruction using appropriately sized cuffs.

TECHNIQUE OF PULSE VOLUME PLETHYSMOGRAPHY

Plethysmography, derived from the Greek "plethysmos," meaning "increase," is used to describe the change in the volume of a limb occurring in response to blood flow into and/or out of that limb. This assessment is made in conjunction with the segmental Doppler pressure measurements. The pulse volume curve is analogous to the arterial pressure pulse. An advantage of using pulse volume recording amplitudes is that they are valid when examining calcified vessels, because the test does not rely on occlusion of the calcified artery as is necessary for segmental pressure measurement. Segmental limb plethysmography (pulse volume recordings) is done using pneumatic cuffs, which are appropriately sized to the diameter of the limb segment under study and are properly positioned. Each cuff is sequentially inflated to a predetermined reference pressure. A cuff pressure of 65 mm Hg has been found to achieve surface contact of the cuff to the skin and at the same time impart a reproducible contour characteristic of plethysmography. Plethysmographic waveforms are recorded for each limb segment. Of note, cuff placement may need to be readjusted to ensure that the selected cuff pressure can be achieved within a narrow range of cuff inflation volume. Bilateral testing is considered an integral part of each examination.

TECHNIQUE OF EXERCISE TESTING

Patients fast for 12 hours before the treadmill test. Before walking on the treadmill, patients are instructed to alert the technician regarding development of any pain. The standard treadmill test is performed at a speed of 2 mile/h and a grade of 12%. The exercise treadmill study is stopped immediately if the patient develops chest pain, or if shortness of breath and dizziness impair the patient's ability to continue. The test is continued otherwise for 5 minutes or until the patient stops secondary to claudication.

After the treadmill is stopped, the patient is immediately brought to a table and placed in the supine position. The ankle pressures are obtained initially, starting with the symptomatic leg. The ankle pressures are repeated every 30 seconds for the first 4 minutes and then every minute for up to 10 minutes. The pressure measurement routine is stopped earlier if the pressure returns to baseline. Of note, the brachial systolic pressure should be recorded immediately at the first set of ankle pressures and at the end of the postexercise ankle pressures. If available, a second technologist should take the brachial pressures so as not to delay ankle pressures. Data recorded from the treadmill procedure should include measured ankle pressures, length of time the patient was able to walk, time required for the pressure to return to baseline, nature and location of the patient's symptoms, and reason for discontinuing the test if other claudication or maximum resting time occurs.

TECHNIQUE OF PERIPHERAL ARTERY ULTRASOUND

Color Doppler is used to determine the presence of laminar or nonlaminar flow states throughout the arterial segments being evaluated. Turbulence, color disturbances such as persistence (continuous forward flow), and aliasing are present at sites of disease. Pulsed (spectral) Doppler sampling is used to further characterize the flow and the degree of stenosis at sites of disturbed color flow. PSV is the primary measure used to quantify disease. Peak velocity measurements are compared between the level of the lesion and proximal arterial segments. Accurate diagnosis of peripheral arterial disease relies in part on technical considerations such as transducer choice and selection of imaging parameters. A 5-MHz linear-array transducer is suitable for examination of the average adult. Higher-frequency probes (7.5-10 MHz) are recommended for small or thin patients and lower-frequency probes (3-4 MHz) for a larger patient or evaluation of deep vessels. The Doppler spectral analysis requires that a small sample volume is used and placed center stream, with the Doppler angle at 60 degrees or less. The sample volume is marched progressively through the length of the arterial system being examined. The color and spectral Doppler are recorded at each new site of interrogation.

TECHNIQUE OF PERIPHERAL ARTERIAL BYPASS GRAFT ULTRASOUND

The location and type of graft are identified before performing the ultrasound examination. Scanning techniques in the supine patient are similar to those used in native arterial examinations. Color Doppler evaluation of the entire graft is performed with the pulse repetition frequency adjusted to distinguish between laminar flow and regions of aliasing, or persistence. Pulsed Doppler interrogation is guided by the color Doppler findings. The PSV is determined: (1) in the proximal native artery; (2) at the proximal anastomosis; (3) throughout the graft segment; (4) in the distal anastomosis; (5) and in the distal native vessel. Doppler spectra are obtained more frequently at sites of flow disturbance. These velocity measurements are used to diagnose stenosis and to look for change during subsequent examinations.

TECHNIQUE OF EXAMINATION FOR PSA

PSAs have two components: a sinus tract or neck that extends from the defect in the native arterial wall outside of the artery to the extravascular arterial blood contained by surrounding fibromuscular tissue, and the sac, which is the confined extravascular collection of blood. Color and pulsed wave Doppler evaluation is performed of the femoral arteries and vein. The addition of color to standard gray-scale duplex ultrasonography has made the identification of PSAs highly accurate[52] and, thus, the diagnostic method of choice. The native artery at the access site is identified, and the extravascular collection of arterial blood is seen, most commonly anterior to the native artery. Posterior PSAs occur most commonly at the bifurcation of the common femoral artery into the superficial and deep femoral artery. The connection between the native artery and the sac, known as the neck of the PSA, is readily identified. Once the neck has been identified using focused Doppler imaging with a narrow sample volume, the Doppler cursor is placed in the neck. If a PSA is present, the pattern of the Doppler waveform obtained will be pathognomonic. The Doppler pattern is a classic to-and-fro waveform,[53] representing systolic flow out of the native artery into the sac, and diastolic flow back into the native artery from the sac.[54]

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