To my son Michael Sam and my daughter Andrea Rachel for being the major source of inspiration and happiness.

Enrico Ascher, July 2012
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Preface

Henry Haimovici was one of the founding fathers of vascular surgery and it has been a privilege and an honor for me to be allowed to help edit yet another version of his book. Henry died on July 10, 2001 at the age of 93 in New York City following a brilliant clinical and academic career as a vascular surgeon. Henry was a prolific scientific researcher and a well respected surgeon-scientist who contributed in many ways for the maturation of vascular surgery. His pioneer work in the understanding of the pathophysiology and treatment of vascular diseases is impressive. One example is the recognition of renal and metabolic complications of extensive venous thrombosis of the lower extremities leading to gangrene. Henry called it “ischemic venous thrombosis” but the condition became popular under the name of phlegmasia cerula dolens. Dr. Haimovici’s leadership position among vascular surgeons worldwide led him to be one of the founders of the International Society for Cardiovascular Surgery as well as a founding co-editor of the Journal of Cardiovascular Surgery. He became president of the prestigious North American Chapter of the ISCVS (1959–1960) and in 1986 he was elected a corresponding member of the French National Academy of Medicine, an honor bestowed upon so few of the great academicians. Henry Haimovici, a mentor and friend, continues to live among us through his many important contributions to vascular surgery.

Since the last edition of Haimovici’s Vascular Surgery in 2004, endovascular surgery and management of venous diseases continued to play an increasingly important role in the daily activities of vascular surgeons. Accordingly, I was elated when both Drs. Frank J. Veith and Peter Gloviczki accepted to be the principal Co-Editors of the current edition. These legendary surgeons have added significantly to the book and I want to thank them for all their contributions. Equally, I need to recognize and thank all the Co-Editors who did an excellent job reviewing the various chapters and for writing their own chapters. Without this superb group of highly talented surgeons the 6th edition would not have come to fruition.

This edition follows the same principles originally outlined by Henry Haimovici, that is, a combination of fundamental surgical principles with well established vascular and endovascular techniques. Of the 100 chapters in this edition, 31 are totally new chapters and most others have been updated. We left most of Haimovici’s chapters unchanged since they are technical in nature and very well described. I believe the readers of this book will find these and all other chapters to be of great value.

I want to thank Dr. Anil P. Hingorani for his contributions to the book and for allowing me the time to complete this and many other projects. Anne Ober, my assistant of 16 years has been very helpful in following-up with the various authors and keeping us on schedule. Lastly, I want to thank Wiley-Blackwell for all their support and guidance during the creation of this edition.

Enrico Ascher, MD
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2012
Preface to the Fifth Edition

It has been nearly three decades since the late Dr Henry Haimovici (1907–2001) first presented to us his landmark publication Vascular Surgery: Principles and Techniques. Even then he observed that, in this historically brief period of time, we had already experienced momentous developments in the magnitude and scope of our specialty. I believe that, unlike any other period of time and unlike any other surgical specialty, we have also maintained the ability to focus and redirect our craft in tandem with, if not in advance of, the changing needs of our patients and the technological advancements available to us. As a great pioneer of vascular surgery, Dr Haimovici was a principal instrument of our success throughout the infancy and maturation of vascular surgery. He was ever committed to its future beyond measure. Henry was also my mentor and a great friend. I am forever indebted to him for the privilege of assuming editorship of this grand textbook.

We are also saddened by the loss of yet another great leader in vascular surgery: D. Eugene Strandness, Jr., MD (1928–2002). Dr Strandness fielded numerous contributions throughout the formative years of noninvasive vascular testing and ultimately established what has now become our most effective asset in the diagnosis of vascular disease—the vascular laboratory. His early work focused on physiologic tests, but he was also responsible for the development and application of direct ultrasonic methods for vascular diagnosis. Working with engineers at the University of Washington, he combined a B-mode imaging system and a Doppler flow detector to create the first duplex scanner. These explorers of science were prolific in their contributions to our specialty through their research, publications, and societal leaderships. It is in their footsteps that the current and successive generations of vascular leaders must walk—and they have left great shoes for them to fill.

We are proud to have returning Section Editors Larry Hollier (Aortic and Peripheral Aneurysms), Eugene Strandness (Imaging Techniques), and Jonathan B. Towne (Acute Arterial Occlusions of the Lower Extremities). We are also fortunate to have joining us K. Craig Kent (Basic Cardiovascular Problems), John J. Ricotta (Cerebrovascular Insufficiency), Keith D. Calligaro (Visceral Vessels), Gregory L. Moneta (Specific Upper Extremity Occlusions), and William H. Pearce (Venous and Lymphatic Surgery) as Section Editors.

This 5th edition of Haimovici’s Vascular Surgery remains true to its heritage of the comprehensive inspection of the practice of vascular surgery. Innovations in operative technique and reflections on noninvasive diagnostic imaging have been examined and each topic has been updated and expanded. This textbook has now included the most current topics regarding endovascular therapy. Extensive changes have been made to this edition—fully 75 chapters have been revised and 25 new chapters have been added.

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Chicago, IL, USA
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AAA</td>
<td>abdominal aortic aneurysm</td>
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<tr>
<td>AAAP-40</td>
<td>aortic aneurysm-associated protein 40</td>
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<td>AASV</td>
<td>anterior accessory saphenous vein</td>
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<td>ABF</td>
<td>aortofemoral bypass</td>
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<td>ABI</td>
<td>ankle-brachial index</td>
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<td>ABPI</td>
<td>ankle brachial pressure index</td>
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<td>ACE</td>
<td>angiotensin-converting enzyme</td>
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<td>ACP</td>
<td>antegrade cerebral perfusion</td>
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<td>ACS</td>
<td>acute coronary syndromes</td>
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<td>ACT</td>
<td>activated clotting time</td>
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<td>ADP</td>
<td>adenosine diphosphate</td>
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<td>AER</td>
<td>abduction external rotation</td>
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<td>AIOD</td>
<td>aortoiliac occlusive disease</td>
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<td>ALI</td>
<td>acute limb ischemia</td>
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<td>AMI</td>
<td>acute mesenteric ischemia</td>
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<td>AMP</td>
<td>adenosine monophosphate</td>
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<td>AMS</td>
<td>absorbable metal stent</td>
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<td>ANA</td>
<td>antinuclear antibody</td>
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<td>AP</td>
<td>ambulatory phlebectomy</td>
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<td>APC</td>
<td>activated protein C</td>
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<td>APG</td>
<td>air plethysmography</td>
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<td>ApoA</td>
<td>apoprotein A</td>
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<td>ApoB</td>
<td>apoprotein B</td>
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<td>aPTT</td>
<td>activated partial thromboplastin time</td>
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<td>ARB</td>
<td>angiotensin-receptor blocking agent</td>
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<td>anterior scalen muscle</td>
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<td>ASO</td>
<td>arteriosclerosis obliterans</td>
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<td>antithrombin III</td>
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<td>adenosine triphosphate</td>
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<td>AVA</td>
<td>arteriovenous anastomosis</td>
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<td>arteriovenous fistula</td>
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<td>AVG</td>
<td>arteriovenous grafts</td>
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<td>AVM</td>
<td>arteriovenous malformation</td>
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<td>AVSS</td>
<td>Aberdeen varicose vein severity score</td>
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<td>BAI</td>
<td>blunt aortic injury</td>
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<td>BAM</td>
<td>balloon-assisted maturation</td>
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<td>Budd–Chiari syndrome</td>
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<td>BCVI</td>
<td>blunt cerebrovascular injury</td>
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<td>bFGF</td>
<td>basic fibroblast growth factor</td>
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<td>BIPAP</td>
<td>bi-level positive airway pressure</td>
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<td>BMAC</td>
<td>bone marrow aspirate concentrate</td>
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<td>BMS</td>
<td>bare-metal stent</td>
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<td>BP</td>
<td>blood pressure</td>
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<td>BPA</td>
<td>blood-pool contrast agents</td>
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<td>BRTO</td>
<td>balloon-occluded retrograde transvenous obliteration</td>
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<td>CA</td>
<td>carotid artery, contrast angiography</td>
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<td>CAA</td>
<td>carotid artery atherosclerosis, celiac artery aneurysm</td>
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<td>CABG</td>
<td>coronary artery bypass graft</td>
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<td>celiac artery compression syndrome</td>
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<td>CAD</td>
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<td>CAMP</td>
<td>cyclic adenosine monophosphate</td>
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<td>CAS</td>
<td>carotid artery stenting</td>
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<td>CBA</td>
<td>cutting-balloon angioplasty</td>
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<td>CBP</td>
<td>cardiopulmonary bypass</td>
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<td>CCA</td>
<td>common carotid artery</td>
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<td>CCS</td>
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<td>carotid endarterectomy</td>
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<td>common femoral artery</td>
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<td>color flow duplex imaging</td>
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<td>cGFR</td>
<td>calculated glomerular filtration rate</td>
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<td>cGMP</td>
<td>cyclic guanine monophosphate</td>
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<td>CGRP</td>
<td>calcitonin gene-related peptide</td>
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<td>congestive heart failure</td>
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<td>CIN</td>
<td>contrast-induced nephropathy</td>
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<tr>
<td>CLI</td>
<td>critical limb ischemia</td>
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<tr>
<td>CMI</td>
<td>chronic mesenteric ischemia</td>
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<tr>
<td>COPD</td>
<td>chronic obstructive pulmonary disease</td>
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<td>CPAP</td>
<td>continuous positive airway pressure</td>
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<td>CPB</td>
<td>cardiopulmonary bypass</td>
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<td>CRI</td>
<td>chronic renal insufficiency</td>
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<td>CRP</td>
<td>C-reactive protein</td>
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<td>CRPS</td>
<td>complex regional pain syndrome</td>
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<tr>
<td>CSF</td>
<td>cerebrospinal fluid</td>
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<tr>
<td>CT</td>
<td>computed tomography</td>
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<td>CTA</td>
<td>computed tomographic angiography</td>
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<td>CTO</td>
<td>chronic total occlusion</td>
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<td>CV</td>
<td>contrast venography</td>
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<td>CVD</td>
<td>cardiovascular disease, chronic venous disease</td>
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<tr>
<td>CVI</td>
<td>chronic venous insufficiency</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>DA</td>
<td>duplex arteriography</td>
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<tr>
<td>DAG</td>
<td>diacylglycerol</td>
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<tr>
<td>dAVF</td>
<td>distal arteriovenous fistula</td>
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<td>DES</td>
<td>drug-eluting stent</td>
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<td>DHCA</td>
<td>deep hypothermic circulatory arrest</td>
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<tr>
<td>DLT</td>
<td>deep decongestive lymphatic therapy</td>
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<tr>
<td>DR</td>
<td>diameter reduction</td>
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<td>DSA</td>
<td>digital subtraction angiography</td>
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<td>DSE</td>
<td>dobutamine stress echocardiography</td>
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<td>DR5S</td>
<td>distal splenorenal shunt</td>
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<tr>
<td>DTPA</td>
<td>diethylenetriamine pentaacetic acid</td>
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<td>DUS</td>
<td>duplex ultrasound</td>
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<tr>
<td>DVP</td>
<td>distal vein patch</td>
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<td>DVT</td>
<td>deep vein thrombosis</td>
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<td>DWI</td>
<td>diffusion-weighted imaging</td>
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<tr>
<td>DW-MR</td>
<td>diffusion-weighted magnetic resonance</td>
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<tr>
<td>EAST</td>
<td>elevated arm stress test</td>
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<td>EC</td>
<td>endothelial cell</td>
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<td>ECA</td>
<td>external carotid artery</td>
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<td>ECG</td>
<td>electrocardiogram</td>
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<td>ECM</td>
<td>extracellular matrix</td>
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<td>EDRF</td>
<td>endothelial-dependent relaxing factor</td>
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<td>EDS</td>
<td>Ehlers–Danlos syndrome</td>
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<td>EDV</td>
<td>end-diastolic velocity</td>
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<td>EEG</td>
<td>electroencephalogram</td>
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<td>EEL</td>
<td>external elastic lamina</td>
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<td>EGF</td>
<td>epidermal growth factor</td>
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<td>EHIT</td>
<td>endovenous heat-induced thrombosis</td>
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<td>EIA</td>
<td>external iliac artery</td>
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<td>ELG</td>
<td>endoluminal graft</td>
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<td>ELISA</td>
<td>enzyme-linked immunosorbent assay</td>
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<td>eNOS</td>
<td>endothelial nitric oxide synthase</td>
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<tr>
<td>EPC</td>
<td>endothelial progenitor cell</td>
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<td>EPD</td>
<td>embolic protection devices</td>
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<td>EPSF</td>
<td>early postsurgical fitting</td>
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<td>ePTFE</td>
<td>expanded polytetrafluoroethylene</td>
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<td>ER-DP</td>
<td>extended-release dipyridamole</td>
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<td>E-selectin</td>
<td>endothelial-cell selectin</td>
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<td>ESR</td>
<td>erythrocyte sedimentation rate</td>
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<td>ESRD</td>
<td>end-stage renal disease</td>
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<td>ET</td>
<td>endothelin</td>
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<td>EVAR</td>
<td>endovascular aneurysm repair</td>
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<td>EVL</td>
<td>endovenous laser</td>
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<td>EVPAR</td>
<td>endovascular popliteal artery aneurysm repair</td>
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<td>FAP</td>
<td>femoral artery pressure</td>
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<td>FAK</td>
<td>focal adhesion kinase</td>
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<td>FDA</td>
<td>Food and Drug Administration</td>
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<tr>
<td>FEP</td>
<td>fluorinated ethylene propylene</td>
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<td>FEVI</td>
<td>forced expiratory volume in one second</td>
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<td>FGF</td>
<td>fibroblast growth factor</td>
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<td>FOV</td>
<td>field of view</td>
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<td>factor XII</td>
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<td>glucose-6-phosphate dehydrogenase</td>
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<td>general anesthesia</td>
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<td>G-CSF</td>
<td>granulocyte colony-stimulating factor</td>
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<td>GDAA</td>
<td>gastroduodenal aneurysm</td>
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<td>GFR</td>
<td>glomerular filtration rate</td>
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<td>GFV</td>
<td>graft flow velocity</td>
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<td>GRE</td>
<td>gradient echo</td>
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<td>GSM</td>
<td>grayscale medium</td>
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<td>great saphenous vein</td>
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<td>hepatic artery aneurysm</td>
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<td>HB-EGF</td>
<td>heparin-binding epidermal growth factor</td>
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<td>HBOT</td>
<td>hyperbaric oxygen therapy</td>
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<td>hepatocellular carcinoma</td>
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<td>HCFI</td>
<td>hypobaric compression interface</td>
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<td>HDL</td>
<td>high-density lipoprotein</td>
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<td>HGF</td>
<td>hepatocyte growth factor</td>
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<td>HIF</td>
<td>hypoxia-inducible factor</td>
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<td>HIS</td>
<td>hypobaric cushion interface with integrated suspension</td>
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<td>HIT</td>
<td>heparin-induced thrombocytopenia</td>
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<td>HLA</td>
<td>human leukocyte antigen</td>
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<td>HMVEC</td>
<td>human microvascular endothelial cell</td>
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<td>HMWK</td>
<td>high-molecular-weight kininogen</td>
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<td>heme oxygenase</td>
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<td>hypoxia response element</td>
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<td>Hounsfield unit</td>
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<td>HUVEC</td>
<td>human umbilical-vein endothelial cell</td>
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<td>iliac artery aneurysm</td>
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<td>iliac branched device</td>
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<td>internal carotid artery</td>
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<td>ICAM</td>
<td>intercellular cell-adhesion molecule</td>
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<td>IDE</td>
<td>investigational device exemption</td>
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<td>IDL</td>
<td>intermediate-density lipoprotein</td>
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<td>IEL</td>
<td>internal elastic lamina</td>
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<td>IEUS</td>
<td>intraoperative epiaortic ultrasound</td>
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<td>IFN</td>
<td>interferon</td>
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<td>IGF</td>
<td>insulin-related growth factor</td>
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<td>intimal hyperplasia</td>
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<td>internal iliac artery</td>
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<td>interleukin 1</td>
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<td>IMA</td>
<td>inferior mesenteric artery</td>
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<td>iNOS</td>
<td>inducible nitric oxide synthase</td>
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<td>INR</td>
<td>international normalized ratio</td>
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<td>IP3</td>
<td>inositol triphosphate</td>
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<td>IPG</td>
<td>intraoperative pressure gradient</td>
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<td>IPSF</td>
<td>immediate postsurgical fitting</td>
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<td>IPV</td>
<td>incompetent perforator veins</td>
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<td>IVT</td>
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<td>IVUS</td>
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<td>KTS</td>
<td>Klippel–Trénaunay syndrome</td>
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<td>LAO</td>
<td>left anterior oblique</td>
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<tr>
<td>LDL</td>
<td>low-density lipoprotein</td>
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<td>LDL-C</td>
<td>low-density lipoprotein cholesterol</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------------------------------------------</td>
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<td>LE</td>
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<td>LE DVT</td>
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<td>LIMA</td>
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<tr>
<td>LL</td>
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<td>LMWH</td>
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<td>MET</td>
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<td>matrix metalloproteinase</td>
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<td>mycophenolic acid</td>
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<td>magnetic resonance angiography</td>
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<td>MSC</td>
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<td>NP</td>
<td>natural peptide</td>
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<td>NPMS</td>
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<td>nodular regenerative hyperplasia</td>
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<td>NSF</td>
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<td>NTOS</td>
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<td>PAA</td>
<td>popliteal artery aneurysm</td>
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<td>PAAA</td>
<td>para-anastomotic aortic aneurysm</td>
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<td>PACU</td>
<td>post-anesthesia care unit</td>
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<td>PAD</td>
<td>peripheral arterial disease</td>
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<td>PAF</td>
<td>platelet-activating factor</td>
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<td>PAI-1</td>
<td>plasminogen activator inhibitor 1</td>
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<td>PAI-2</td>
<td>plasminogen activator inhibitor 2</td>
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<td>PAPs</td>
<td>percutaneous ablation of perforators</td>
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<td>PC</td>
<td>primary closure</td>
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<td>PCA</td>
<td>patient-controlled anesthesia</td>
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<tr>
<td>PCD</td>
<td>phlegmasia cerulea dolens</td>
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<tr>
<td>PCI</td>
<td>percutaneous cardiac intervention</td>
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<tr>
<td>Pco2</td>
<td>partial pressure of carbon dioxide</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>SDF</td>
<td>stroma-derived factor</td>
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<td>SEPS</td>
<td>subfascial endoscopic perforator surgery</td>
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<td>SFA</td>
<td>superficial femoral artery</td>
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<tr>
<td>SFJ</td>
<td>saphenofemoral junction</td>
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<tr>
<td>SFJT</td>
<td>saphenofemoral junction</td>
</tr>
<tr>
<td></td>
<td>thrombophlebitis</td>
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<td>SIA</td>
<td>subintimal angioplasty</td>
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<tr>
<td>SIP</td>
<td>sympathetically independent pain</td>
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<tr>
<td>SMA</td>
<td>superior mesenteric artery</td>
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<tr>
<td>SMAA</td>
<td>superior mesenteric artery aneurysm</td>
</tr>
<tr>
<td>SMC</td>
<td>smooth muscle cell</td>
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<td>SMP</td>
<td>sympathetically maintained pain</td>
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<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
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<td>SSEP</td>
<td>somatosensory-evoked potential</td>
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<tr>
<td>SSFP</td>
<td>steady-state free precession</td>
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<tr>
<td>SSV</td>
<td>short saphenous vein</td>
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<tr>
<td>SSVT</td>
<td>suppurative superficial venous thrombophlebitis</td>
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<tr>
<td>SVC</td>
<td>superior vena cava</td>
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<td>SVC-GF</td>
<td>superior vena cava Greenfield filter</td>
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<td>SVR</td>
<td>superficial venous reflux</td>
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<tr>
<td>SVT</td>
<td>superficial venous thrombophlebitis</td>
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<tr>
<td>TAA</td>
<td>thoracic aortic aneurysm</td>
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<tr>
<td>TAAA</td>
<td>thoracoabdominal aortic aneurysm</td>
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<tr>
<td>TAO</td>
<td>thromboangiitis obliterans</td>
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<td>TASC</td>
<td>TransAtlantic Intersociety Consensus</td>
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<tr>
<td>TBPI</td>
<td>toe brachial pressure index</td>
</tr>
<tr>
<td>TCD</td>
<td>transcranial Doppler</td>
</tr>
<tr>
<td>TcPo2</td>
<td>transcutaneous oxygen tension</td>
</tr>
<tr>
<td>TE</td>
<td>echo time</td>
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<tr>
<td>TEA</td>
<td>transaortic endarterectomy</td>
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<td>TEE</td>
<td>transesophageal echocardiography</td>
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<td>TEVAR</td>
<td>thoracic endovascular aneurysm repair</td>
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<tr>
<td>TF</td>
<td>tissue factor</td>
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<tr>
<td>TGF</td>
<td>transforming growth factor</td>
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<tr>
<td>TIA</td>
<td>transient ischemic attack</td>
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<tr>
<td>TIMP</td>
<td>tissue inhibitor of metalloproteinases</td>
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<tr>
<td>TIPS</td>
<td>transjugular intrahepatic portosystemic shunt</td>
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<tr>
<td>TMJ</td>
<td>temporomandibular joint</td>
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PART I
Vascular Imaging Techniques and Physiologic Testing
CHAPTER 1
Arterial and Venous Duplex Scanning

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Oregon Health and Science University, Portland, OR, USA

The noninvasive vascular laboratory provides the scientific basis for vascular surgery. It safely provides accurate and quantitative evidence of the presence and physiologic significance of arterial and venous disease. In the modern vascular laboratory ultrasound-based techniques, particularly duplex ultrasound techniques, are most extensively employed.

Ultrasound basics

Duplex ultrasound was introduced in 1974 with application to the carotid artery. “Duplex” indicates the technique combines B-mode imaging and Doppler analysis of blood-flow direction and velocity. It is extensively utilized for evaluation of carotid arteries, intrathoracic arteries and veins, and upper- and lower-extremity arteries and veins. Since its inception, engineering and software advances have been extensive and include: 1) improved gray-scale B-mode imaging, 2) low-frequency scan heads permitting deep penetration of the ultrasound beam from the skin surface, 3) improvements in online computer-based microprocessing, and 4) addition of color-flow imaging.

Color flow is a superimposed real-time colorized image of blood flow onto a standard gray-scale B-mode picture. Echoes from stationary tissues generate B-mode images, whereas those interacting with moving substances (blood) generate a phase shift that is processed separately and color coded to give information on the direction and velocity of blood flow that reflects the magnitude and direction of the Doppler shift. Color flow dramatically reduces the time required to perform duplex examinations by allowing more rapid identification of vessels to be examined. It appears essential for duplex examination of some vessels, such as tibial arteries and veins. Color flow and the ability of modern duplex scanners to detect blood flow velocities <5 cm/s make duplex scanning practical in virtually all areas of the body.

Basics of duplex ultrasound

A vibrating source produces an ultrasonic wave. In duplex ultrasound the vibrating source is the transducer. Ultrasound transducers are contained within scan heads. Scan heads steer and focus the sound beam produced by the transducer. The ultrasound image is derived from the returning echoes and is dependent on precise steering and focusing of the sound beam.

Transducers convert electrical into vibrational energy to produce the ultrasound wave. Transducers can also convert vibrational energy of returning echoes into electrical signals for analysis by the duplex machine’s software. The frequency of the vibration is determined by the design of the transducer and determines the wavelength of the sound wave. Frequency and wavelength are related, \( \lambda = \frac{c}{f} \), where \( \lambda \) is the wavelength, \( c \) is the speed of sound in tissue, and \( f \) is the frequency.

Speed of sound in soft tissues averages 1540 m/s. There is little variation in the soft tissues insonated in clinical use of duplex ultrasound. Wavelength is the principle determinant of how well an ultrasound beam penetrates tissue, and wavelength depends on the frequency of the transducer. The transducer frequency is determined by the design of the transducer and is thus controlled by the manufacturer. For examination of the carotid artery, transducer frequencies of 5 to 7.5 MHz provide optimal tissue penetration for clinical purposes.

As noted above, duplex refers to the combination of Doppler and B-mode ("B" stands for "brightness") ultrasound in the same device. Both require analysis of reflected echoes of the original sound beam created by the ultrasound transducer. B-mode analyzes the strength...
(intensity) and origin of the reflected echo. Doppler analyzes shifts in frequency of the original sound wave produced by the transducer.

**B-mode ultrasound**

As a sound wave passes through tissue and moves away from the transducer its strength depends upon how much the beam is scattered, attenuated, and reflected. Strength of reflected echoes depend, in part, upon differences in acoustic impedance between media. When there are major differences in acoustic impedance a large proportion of the sound beam is reflected back to the transducer. Small differences in acoustic impedances result in little reflection and the beam continues to propagate through the tissue.

In B-mode ultrasound, the brightness of the individual pixels comprising the ultrasound image is proportional to the strength of the returning echo. This is the ultrasound gray scale, and the resulting image is termed a gray-scale image. Very bright pixels in the gray-scale image indicate large differences in acoustic impedance between media. Less dramatic differences are represented by proportionally less-bright pixels. Thus gallstones, with dramatic differences in acoustic properties from soft tissue, produce strong echoes and proportionally very bright pixels on the ultrasound image, whereas blood, which differs little from soft tissue in acoustic characteristics, often cannot be distinguished from soft tissue with B-mode imaging.

The strength of the reflected echo is also dependent upon the strength of the sound beam at the point where it is reflected. Gray-scale images represent the absolute strength of the reflected echo arriving back at the transducer, not the percentage of the beam reflected. Therefore, if the sound beam is very weak at the point of reflection even areas of dramatic acoustic differences will not result in a bright pixel in the B-mode image.

The strength of the ultrasound beam at a specific point also depends on how much the beam has been attenuated passing through tissue. Attenuation depends upon both the tissue traversed and the frequency of the wave. Wave frequency depends upon the frequency of the transducer generating the wave (see discussion above and Equation 1). Higher-frequency sound waves are attenuated more rapidly than lower-frequency sound waves. Higher-frequency transducers therefore provide relatively weak echoes to be reflected from a deep structure. The image generated is comparatively poor compared with a lower-frequency transducer insonating a deeper structure.

Image quality also depends upon linear resolution. Linear resolution is dependent upon the ability to focus the beam. High-frequency sound waves are better focused than sound waves from low-frequency transducers and provide sharper and better quality B-mode images. Image quality is therefore a balance of the strength of the reflected echo and the ability to focus the sound beam. The carotid artery is superficial and higher-frequency transducers can be used to provide clear B-mode images. (Fig. 1.1A and B) Image quality is less when examining deep vessels such as renal or iliac arteries.

**Doppler ultrasound**

Continuous wave Dopplers have transducers that continually emit vibrations into tissue. Therefore, echoes are also continually reflected back to the transducer. Transducers cannot generate and receive echoes simultaneously. A continuous wave Doppler therefore must have separate transmitters and receivers to generate and receive echoes.

Duplex devices utilize pulse Doppler. Pulse Dopplers use a single transducer to generate and receive echoes. With a pulse Doppler it is possible to know when an

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**Figure 1.1** Gray-scale images of (A) mildly and (B) severely diseased bifurcations of the cervical carotid artery.