Third Edition

Atlas of Ultrasound-Guided Regional Anesthesia

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1600 John F. Kennedy Blvd.
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THIRD EDITION

ISBN: 978-0-323-50951-0

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Library of Congress Cataloging-in-Publication Data

Names: Gray, Andrew T., author.
Title: Atlas of ultrasound-guided regional anesthesia / Andrew T. Gray.
Description: Third edition. | Philadelphia, PA : Elsevier, Inc., [2019] | Includes bibliographical references and index.
Identifiers: LCCN 2017056978 | ISBN 9780323509510 (hardcover : alk. paper)
Subjects: | MESH: Anesthesia, Conduction | Ultrasonography, Interventional | Atlases
Classification: LCC RD84 | NLM WO 517 | DDC 617.9/640222–dc23
LC record available at https://lccn.loc.gov/2017056978

Publisher: Dolores Meloni
Senior Content Development Specialist: Anne Snyder
Publishing Services Manager: Catherine Jackson
Project Manager: Kate Mannix
Design Direction: Patrick Ferguson
Illustrations Manager: Lesley Frazier

Printed in China

Last digit is the print number: 9 8 7 6 5 4 3 2 1

To my family of writers: Mary, Sarah, Alex, and Anna.

Preface

The third edition of *Atlas of Ultrasound-Guided Regional Anesthesia* marks a change in format. There are now many new chapters by contributing authors that vastly improve and expand the section of topics from what would be possible with a single-author text. A wide variety of newly described techniques are presented in this edition, and chapters from the previous editions underwent extensive editing and updating. The new chapters are mostly dedicated to blocks in the trunk and head and neck regions. The emphasis on safety continues, with a detailed contributed chapter that reviews large studies of rare events. Also included is a chapter on limited resources that discusses techniques and alternatives in different clinical settings.

We have tried to present clear and concise summaries of suggested techniques so that readers will have the confidence and background they need to begin using the interventional procedures. Wide fields of view, long axis views, three-dimensional imaging, and step-by-step instruction are all used to improve the educational format and illustrate anatomic structures that lie near or outside the conventional two-dimensional field of imaging. Where appropriate, chapters have additional sonograms that illustrate variations of normal anatomy that one may encounter in clinical practice. New videos show the dynamics of interventional acute pain medicine in stunning detail. All the chapters highlight recent advances and techniques in the rapidly changing field of ultrasound-guided regional anesthesia.

Very special thanks to Allegra Greher (artwork), Tin-na Kan (sciatic nerve blocks), David Mai (catheters), Ed Mathews (information technology), Stefan Simon (intercostal nerve blocks), Robin Stackhouse and Susan Yoo (figures and media production), and Ranier Litz and Tim Maecken (organizing the USRA Symposia at which much of this educational material was presented and discussed). We are grateful to the anesthesiologists, CRNAs, anesthesia technicians, and perioperative nurses at Kaiser Permanente hospitals in Oakland, Richmond, and San Francisco, California for their help with the catheter sonograms and video clips.

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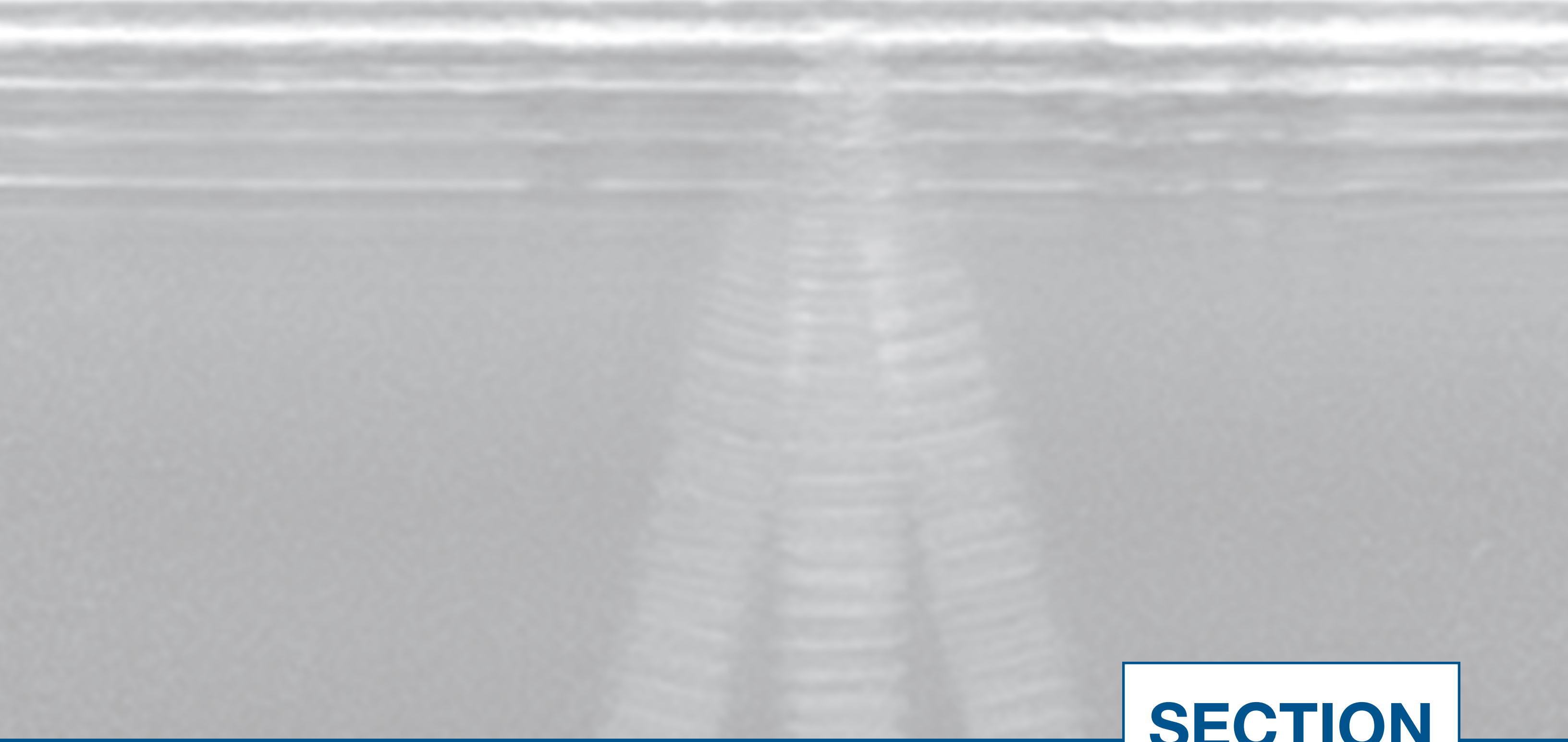
Video Contents



SECTION 1

Introduction to Ultrasound Imaging

CHAPTER 1

Ultrasound

See Video 1.1 on ExpertConsult.com.

Ultrasound waves are high-frequency sound waves generated in specific frequency ranges and sent through tissues.[1] How sound waves penetrate a tissue depends on the range of the frequency produced. Lower frequencies penetrate deeper than high frequencies do. The frequencies for clinical imaging (1 to 70 MHz) are well above the upper limit of normal human hearing (15 to 20 KHz). Wave motion transports energy and momentum from one point in space to another without transport of matter. In mechanical waves (e.g., water waves, waves on a string, and sound waves), energy and momentum are transported by means of disturbance in the medium because the medium has elastic properties. Any wave in which the disturbance is parallel to the direction of propagation is referred to as a longitudinal wave. Sound waves are longitudinal waves of compression and rarefaction of a medium such as air or soft tissue. *Compression* refers to high-pressure zones, and *rarefaction* refers to low-pressure zones (these zones alternate in position).

As the sound passes through tissues, it is absorbed, reflected, or allowed to pass through, depending on the echodensity of the tissue. Substances with high water content (e.g., blood, cerebrospinal fluid) conduct sound very well and reflect very poorly and thus are termed *echolucent*. Because they reflect very little of the sound, they appear as dark areas (hypoechoic). Substances low in water content or high in materials that are poor sound conductors (e.g., air, bone) reflect almost all the sound and appear very bright (hyperechoic). Substances with sound conduction properties between these extremes appear darker to lighter, depending on the amount of wave energy they reflect.

Audible sounds spread out in all directions, whereas ultrasound beams are well collimated. The frequency of sound does not change with propagation unless the wave strikes a moving object, in which case the changes are small. The product of the frequency and wavelength of sound waves is the wave speed. Because the speed of sound in soft tissue is nearly constant, higher-frequency sound waves have shorter wavelengths. Two adjacent structures cannot be identified as separate entities on an ultrasound scan if they are less than one wavelength apart. Therefore sound wave frequency is one of the main determinants of spatial resolution of ultrasound scans.

Reference

1. Aldrich JE. Basic physics of ultrasound imaging. *Crit Care Med*. 2007;35:S131–S137.

CHAPTER 2

Speed of Sound

See Video 1.1 on ExpertConsult.com.

The speed of sound is determined by properties of the medium in which it propagates. The sound velocity equals $\sqrt{(B/rho)}$, where *B* equals the bulk modulus and *rho* equals density. The bulk modulus is proportional to stiffness. Thus stiffness (change in shape) and wave speed are related. Density (weight per unit volume) and wave speed are inversely related. The speed of sound in a given medium is essentially independent of frequency.

Because the velocity of sound in soft tissue is 1540 m/s, 13 microseconds elapse for each centimeter of tissue the sound wave must travel (the back-and-forth time of flight). Speed-of-sound artifacts relate to both time-of-flight considerations and refraction that occurs at the interface of tissues with different speeds of sound.[1-3]

References

1. Scanlan KA. Sonographic artifacts and their origins. *AJR Am J Roentgenol*. 1991;156:1267–1272.
2. Fornage BD. Sonographically guided core-needle biopsy of breast masses: the "bayonet artifact". *AJR Am J Roentgenol*. 1995;164:1022–1023.
3. Gray AT, Schafhalter-Zoppoth I. "Bayonet artifact" during ultrasound-guided transarterial axillary block. *Anesthesiology*. 2005;102:1291–1292.

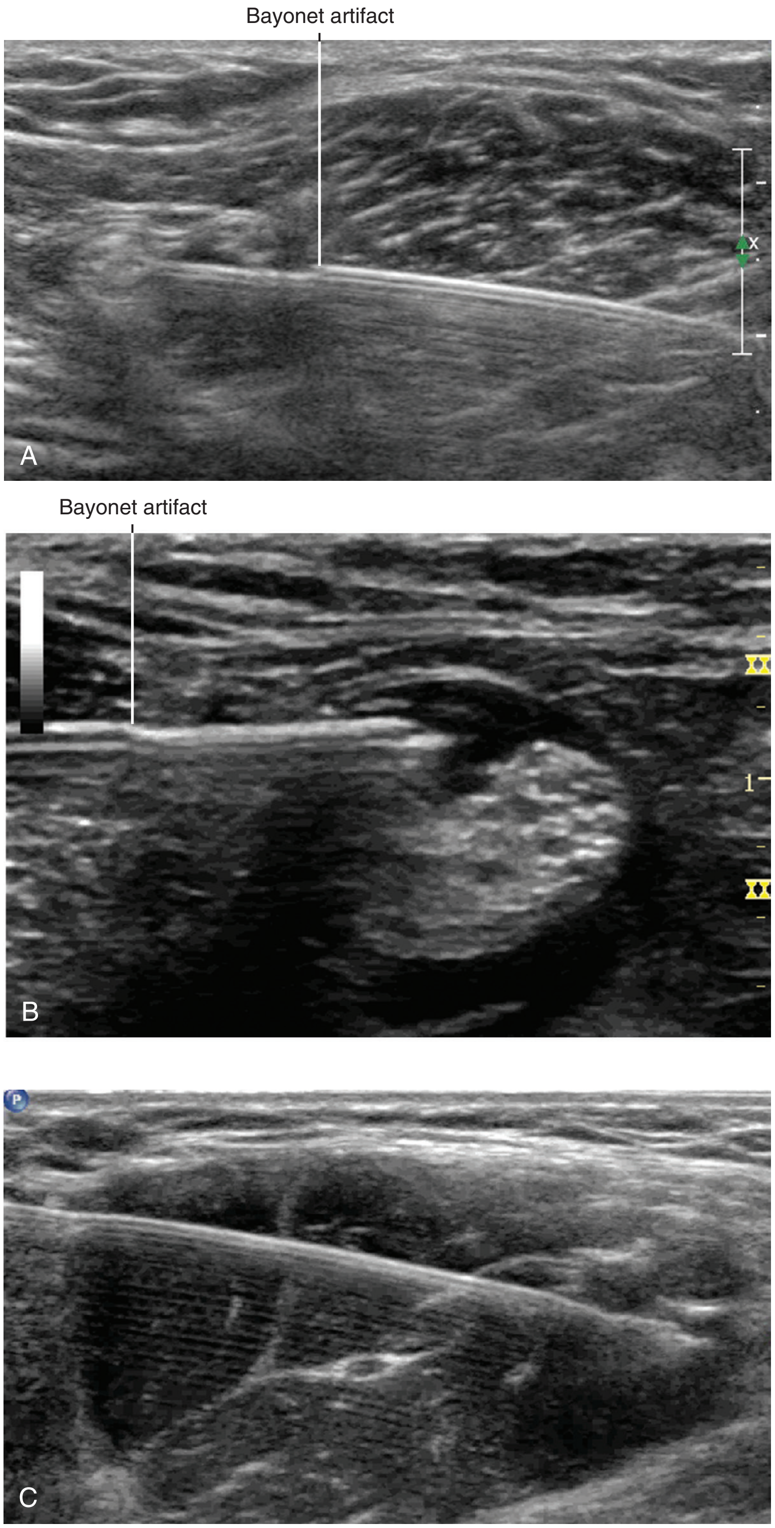


FIGURE 2.1 Bayonet artifacts during popliteal block (A and B). Because the speed of sound is not necessarily homogeneous in soft tissue, the needle can sometimes appear to bend, similar to a bayonet. Actual mechanical bending of the needle typically appears as gentle bowing of the needle (C).

CHAPTER 3

Attenuation

See Video 1.1 on ExpertConsult.com.

Attenuation is a decrease in wave amplitude as it travels through a medium. The attenuation of ultrasound in soft tissue is approximately 0.5 to 0.75 dB/(MHz-cm), indicating that the extent of attenuation depends on the distance traveled and the frequency of insonation. The units of the attenuation coefficient directly show the greater attenuation of high-frequency ultrasound beams. In soft tissue, 80% or more of the total attenuation is caused by absorption of the ultrasound wave, thereby generating heat.

Time gain compensation (TGC) adjusts for attenuation of an ultrasound beam as a function of depth. When TGC is properly adjusted, images of similar reflectors appear the same regardless of depth.

An acoustic shadow is said to exist when a localized object reflects or attenuates sound to impede transmission. Bone is a strong absorber of ultrasound waves. Therefore shadowing occurs deep to bony structures ("bone shadow").

When a nonattenuating fluid (e.g., blood or injected local anesthetic) lies within an attenuating sound field (e.g., soft tissue), enhancement of echoes deep to the fluid occurs. This phenomenon, originally described as posterior acoustic enhancement (also called increased through-transmission), is due to lack of absorption of the sound waves by the fluid.[1] This attenuation artifact is a potential source of problems, especially during regional blocks where nerves are situated close to blood vessels.

Clinical Pearls

- In general, the highest frequency capable of adequate penetration to the depth of interest should be used for imaging.
- Decibels (dB) are a relative logarithmic measure of sound wave intensity.

Reference

1. Filly RA, Sommer FG, Minton MJ. Characterization of biological fluids by ultrasound and computed tomography. *Radiology*. 1980;134:167–171.

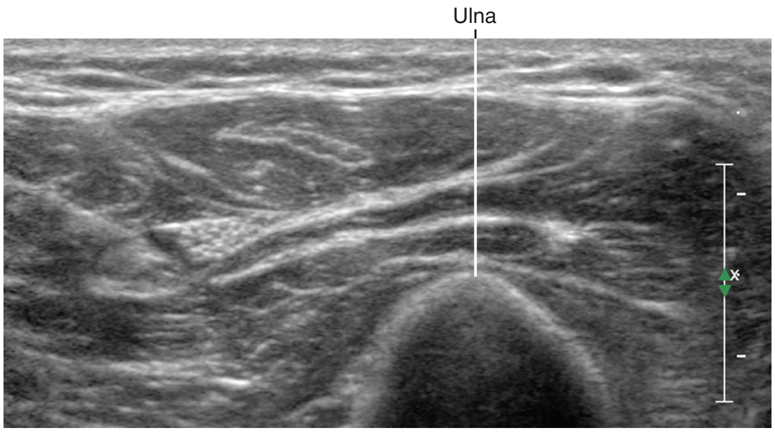


FIGURE 3.1 Acoustic shadowing by bone. In this sonogram from the forearm, the acoustic shadowing by the ulna is evident. The bright cortical line of the surface of the bone is followed by extinction of the sound wave below.

Reflection

CHAPTER 4

See Video 1.1 on ExpertConsult.com.

Ultrasonography measures the amplitude of the return echo as a function of time.[1] Sound waves are reflected at the interface of tissues with different acoustic impedances. The acoustic impedance (kg/[m^2-s]) is the product of the density (kg/m^3) and velocity (m/sec). The extent of reflection is governed by the reflection coefficient: $R = (Z1 - Z2)/(Z1 + Z2)$. If $Z1 = Z2$, there is no reflected wave.[2] Ultrasound characteristics of biologic tissue and interventional materials are summarized in Table 4.1.

Reflections off a smooth surface are called *specular*. If two specular reflectors are close to each other, reverberation within the sound field can result, displayed as parallel, equally spaced lines deep to the reflectors. Csomet-tail artifact, which is a form of reverberation artifact, is caused by multiple internal reflections from a small, highly reflective interface.[3,4]

Clinical Pearls

- The normal pleural line is thin and smooth, which generates a few comet-tail artifacts (between one and three artifacts per intercostal space scan). In the presence of parenchymal lung disease, the pleural line is irregular and thickened, generating many more comet-tail artifacts.[5]
- No comet-tail artifact is observed from the lung when pneumothorax is present.
- Hyperechoic reverberation artifacts are seen with metallic foreign bodies such as block needles.

TABLE 4.1 Ultrasound Characteristics of Biologic Tissue and Interventional Materials

Substance	Velocity (m/s)	Attenuation (dB/[MHz-cm])	Impedance (mrayls × 10^{-6})
Air	330	7.5	0.0001
Water	1480	0.0022	1.5
Soft tissue	1540	0.75	1.7
Blood	1575	0.15	1.6
Bone	4080	15	8
Stainless steel	5790	0.2	47

Data from Ziskin MC. Fundamental physics of ultrasound and its propagation in tissue. *Radiographics*. 1993;13:705–709; Ziskin MC, Thickman DI, Goldenberg NJ, Lapayowker MS, Becker JM. The comet tail artifact. *J Ultrasound Med*. 1982;1:1–7; Gawdzinska K. Investigation into the propagation of acoustic waves in metal. *Metalurgija*. 2005;44:125–128; Smith SW, Booi RC, Light ED, Merdes CL, Wolf PD. Guidance of cardiac pacemaker leads using real time 3D ultrasound: feasibility studies. *Ultrason Imaging*. 2002;24:119–128.

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1. Ziskin MC. Fundamental physics of ultrasound and its propagation in tissue. *Radiographics*. 1993;13:705–709.
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4. Thickman DI, Ziskin MC, Goldenberg NJ, Linder BE. Clinical manifestations of the comet tail artifact. *J Ultrasound Med*. 1983;2:225–230.
5. Reissig A, Kroegel C. Transthoracic sonography of diffuse parenchymal lung disease: the role of comet tail artifacts. *J Ultrasound Med*. 2003;22:173–180.

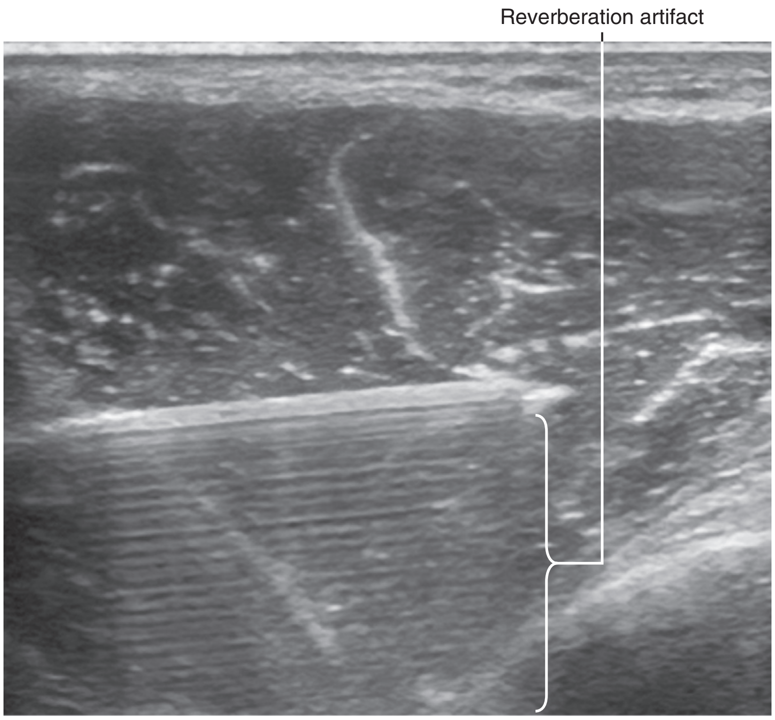

FIGURE 4.1 Reverberation artifact from a block needle placed nearly parallel to the active face of the transducer.

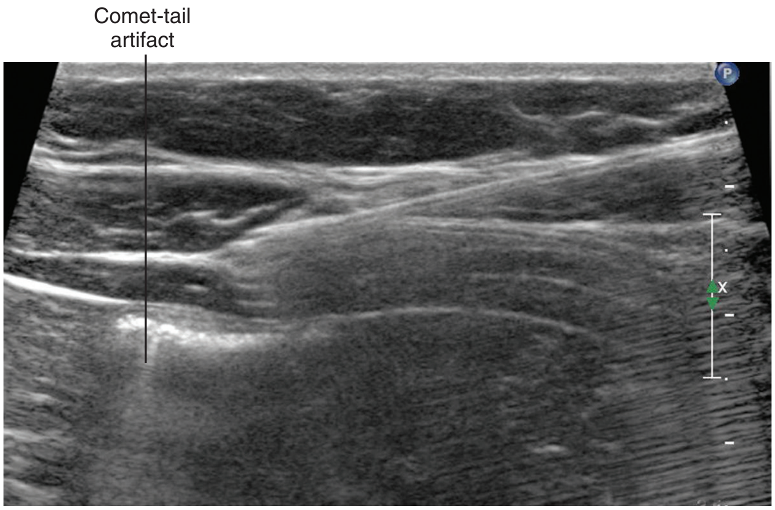

FIGURE 4.2 Comet-tail artifact from the peritoneum during rectus sheath block. The peritoneum and pleura have similar appearances on ultrasound scans.

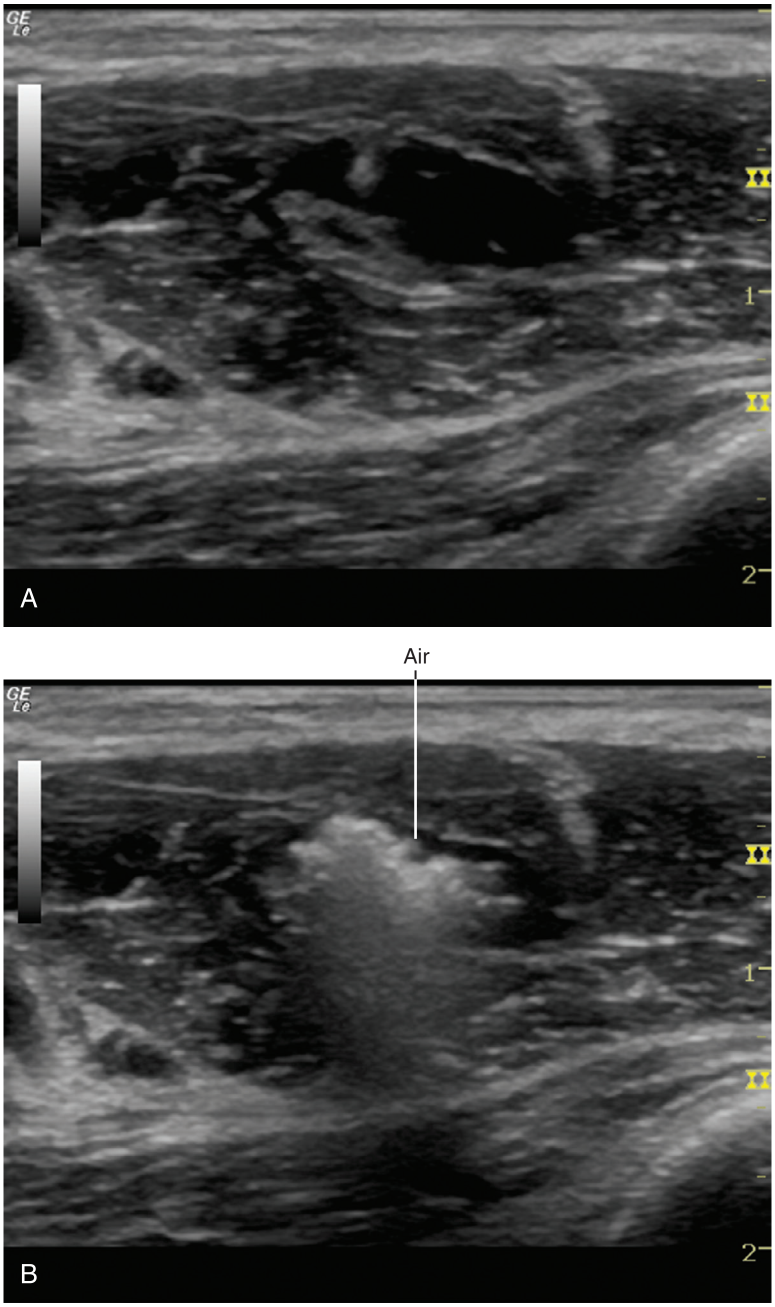

FIGURE 4.3 A strong echo and acoustic shadowing are observed when air is inadvertently injected during musculocutaneous nerve block in the axilla. Sonograms before injection (A) and after injection (B) are shown.

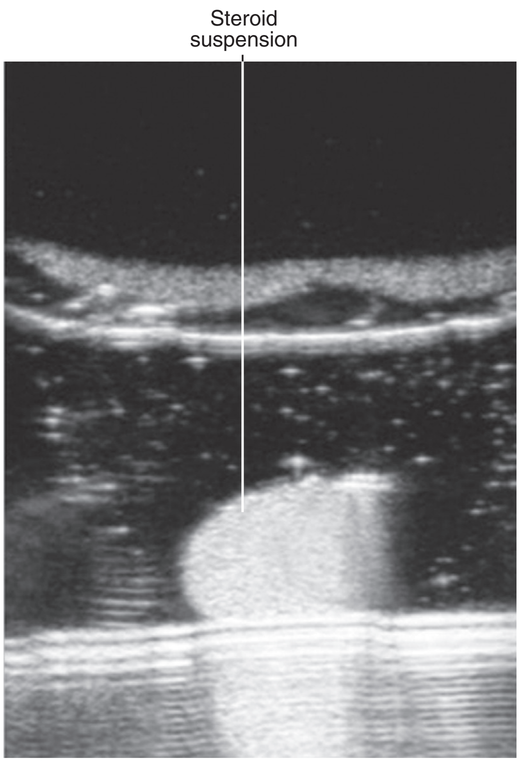

FIGURE 4.4 Acoustic properties of a steroid suspension. Although the local anesthetic injected for most regional blocks is anechoic, the particles of this steroid suspension are sufficiently large to produce a strong echo.

Beam Width (Slice Thickness)

See Video 1.1 on ExpertConsult.com.

Ultrasound systems assume all reflectors lie directly along the main axis of the ultrasound beam (i.e., the acoustic axis or central ray)[1]; however, ultrasound beams have a finite size. The out-of-plane beam width (slice thickness) can be measured with a diffuse scattering plane.[2] The plane is oriented at a 45-degree angle so that the displayed echoes are equal to the out-of-plane echoes. Ultrasound beams can be focused to reduce the out-of-plane beam width and thereby improve image quality.

References

1. Goldstein A, Madrazo BL. Slice-thickness artifacts in gray-scale ultrasound. *J Clin Ultrasound*. 1981;9:365–375.
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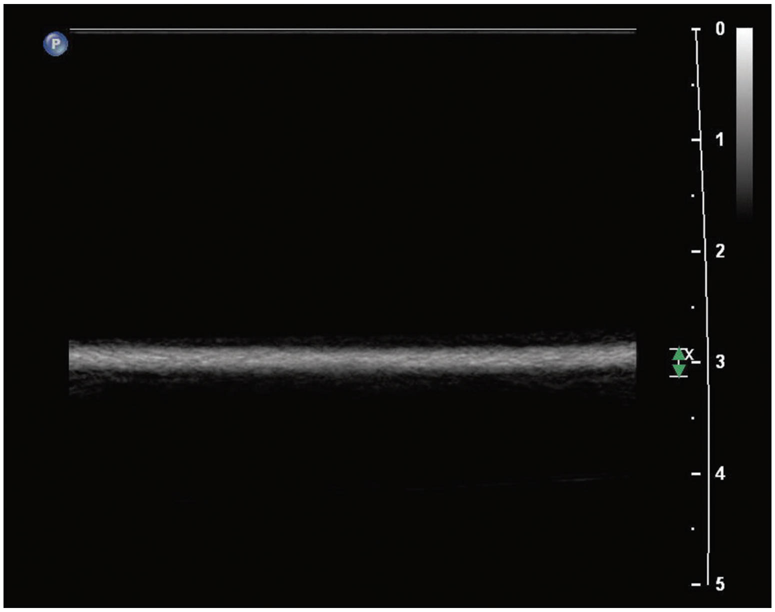

FIGURE 5.1 Out-of-plane slice thickness. Ultrasound scan of a diffuse scattering plane (a sheet of sandpaper).

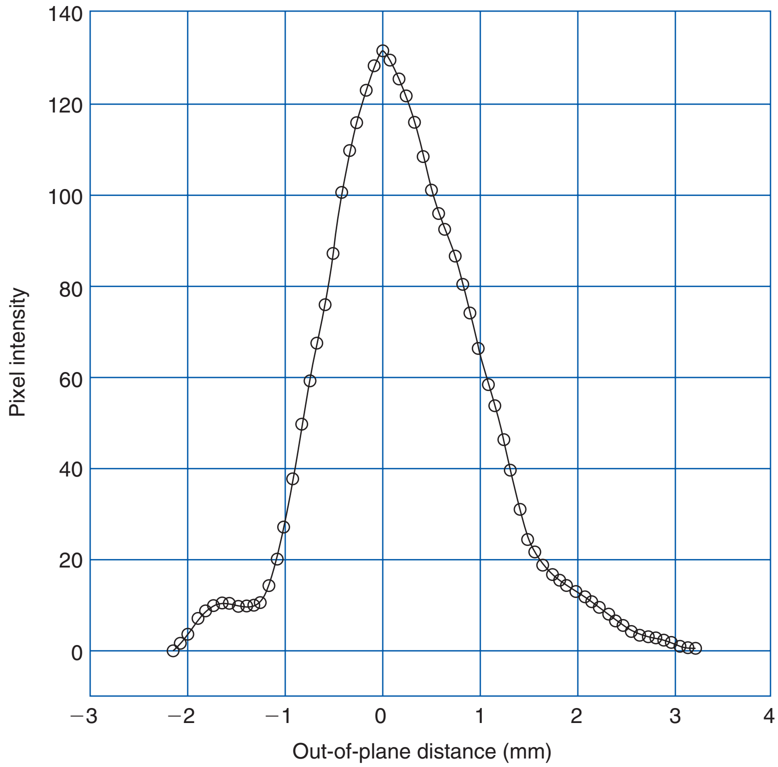

FIGURE 5.2 The beam profile is shown as a function of the distance from the central ray. Because needle diameters are substantially less than those of the slice plane, a strong relationship between needle diameter and visibility is expected.

CHAPTER 6

Anisotropy

See Video 1.1 on ExpertConsult.com.

Isotropic means equal in all directions. Anisotropic implies angle dependence. The latter term has been used to indicate the change in amplitude of received echoes from a structure when the angle of insonation is changed. Anisotropy is a discriminating feature between nerves and tendons. Tendons are more anisotropic than nerves are, meaning that smaller changes in angle (approximately 2 degrees) alter the echoes from tendons than the changes in angle (approximately 10 degrees) that alter the echoes from nerves. The anisotropy of nerves also is important because during interventions it can be challenging to maintain nerve visibility while manipulating the transducer to image the block needle.[1] With training, practitioners learn to naturally manipulate the transducer to fill in the received echoes from nerves. The amplitude of the received echoes from peripheral nerves is usually largest when the sound beam is perpendicular to the nerve path. Other structures, such as muscle, also exhibit anisotropy.[2]

Clinical Pearls

- Anisotropy means that the backscatter echoes from a specimen depend on the directional orientation within the sound field.
- Anisotropy can be quantified by specifying the transducer frequency and the decibel change in backscatter echoes with perpendicular and parallel orientation of the specimen.
- Nerves, tendons, and muscle all exhibit anisotropy. Of these structures, tendon echoes are the most sensitive to transducer manipulation.

References

1. Soong J, Schafhalter-Zoppoth I, Gray AT. The importance of transducer angle to ultrasound visibility of the femoral nerve. *Reg Anesth Pain Med*. 2005;30:505.
2. Rubin JM, Carson PL, Meyer CR. Anisotropic ultrasonic backscatter from the renal cortex. *Ultrasound Med Biol.* 1988;14:507–511.

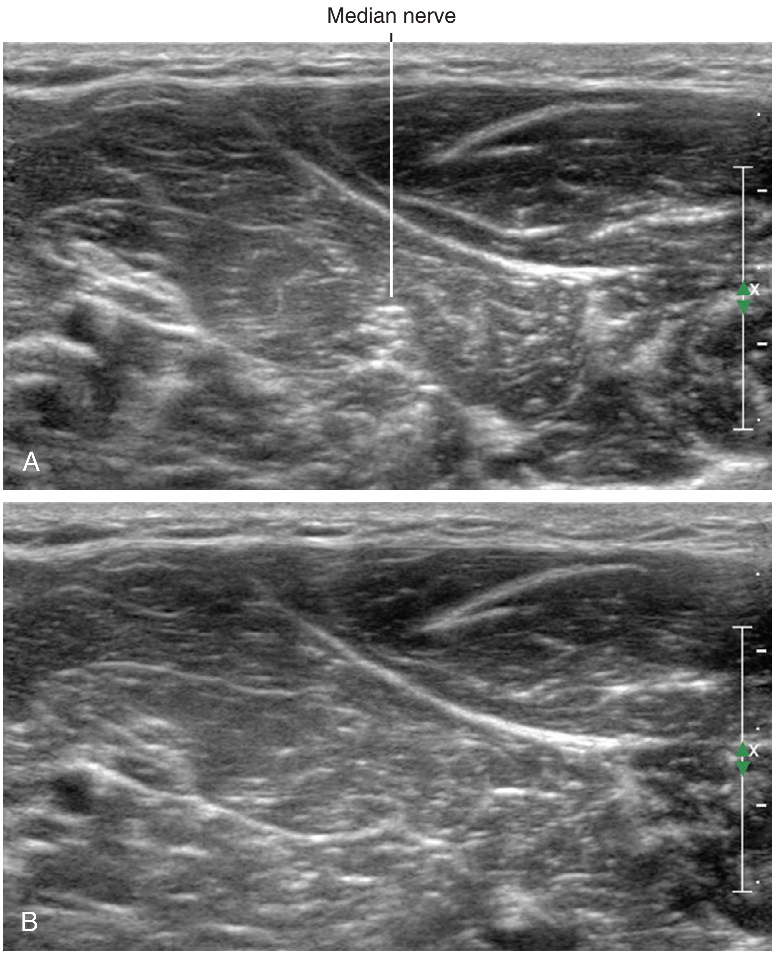

FIGURE 6.1 Anisotropy of the median nerve (A and B). With inclination of the transducer (tilting), the received echoes from the median nerve disappear.

CHAPTER 7

Spatial Compound Imaging

See Video 1.1 on ExpertConsult.com.

In conventional sonography, tissue is insonated from a single direction. Spatial compound imaging combines multiple lines of sight to form a single composite image at real-time frame rates. The ultrasound beam is steered by a different set of predetermined angles, typically within 20 degrees from the perpendicular.

One benefit of the use of spatial compound imaging is the reduction of angle-dependent artifacts (Table 7.1). *Speckle* is the granular appearance of a sonographic image that results from scattering of the ultrasound beam from small tissue reflectors. This speckle artifact results in the grainy appearance observed on sonograms, representing noise in the image. Improved image quality may be obtained by using spatial compound imaging, which can reduce speckle noise.

There is a central triangular region of overlap within the field of view where all angles mesh together for full compounding. The corners of the image receive only a subset of all the lines of sight; therefore not all the benefits of spatial compounding are manifest. Some machines allow the stray lines of sight (those off the rectangular field of view) to form a trapezoidal image format. This is sometimes useful to view the approaching needle with in-plane technique.

Spatial compound imaging was first designed to eliminate angle-dependent artifacts.[1] This can be accomplished with a narrow range of beam angles. The larger the range of angles subtended by spatial compounding, the smaller the region within the field of imaging that will receive all the lines of sight (i.e., the region of full compounding).

Ultrasound imaging near bone may be improved by spatial compound imaging. This has relevance to imaging for some blocks (e.g., neuraxial, paravertebral, lumbar plexus, intercostals, sacroiliac joint). Although ultrasound waves cannot penetrate mature bone (even with low-frequency ultrasound), spatial compound imaging allows better definition of the bone surface.

Linear test tool images can be used to reveal the number of lines of sight used in spatial compound imaging. These images are generated with a smooth metal surface, such as that of a paper clip, solid metal stylet, or a US nickel. Metal is used because it is relatively nonattenuating,

TABLE 7.1 Advantages and Disadvantages of Spatial Compound Imaging

Advantages	Disadvantages
Reduction of angle-dependent artifacts (e.g., posterior acoustic enhancement and speckle)	Frame averaging (persistence or motion blur effect)
Needle tip imaging	Limited range of angles (typically <20 degrees)
Nerve border definition	
Fascia contours	
Imaging around bone	
Wider field of view with stray lines of sight	

yet produces an echo. Smooth metal is used so that the test tool does not damage the transducer. For these measurements, high receiver gain and a single focal zone near the surface are used. As long as the test tool contact is less than the receiver aperture, the width of the displayed echoes will not change.

Clinical Pearls

- The use of spatial compound imaging can improve imaging of nerve borders and the block needle tip.
- One potential disadvantage of compound imaging is that needle reverberations occur over a broader range of angles and can prevent imaging of deeper structures.
- Compound imaging is being developed for both linear and curved arrays.
- Sliding the transducer along the known course of the nerve is a well-established technique to improve small nerve imaging. However, frame rate reduction that occurs with spatial compound imaging can cause problems with this technique.
- If compound imaging is not an advantage for a particular imaging situation, it can be turned off.

Reference

1. Baad M, Lu ZF, Reiser I, Paushter D. Clinical significance of US artifacts. *Radiographics*. 2017;37:1408–1423.

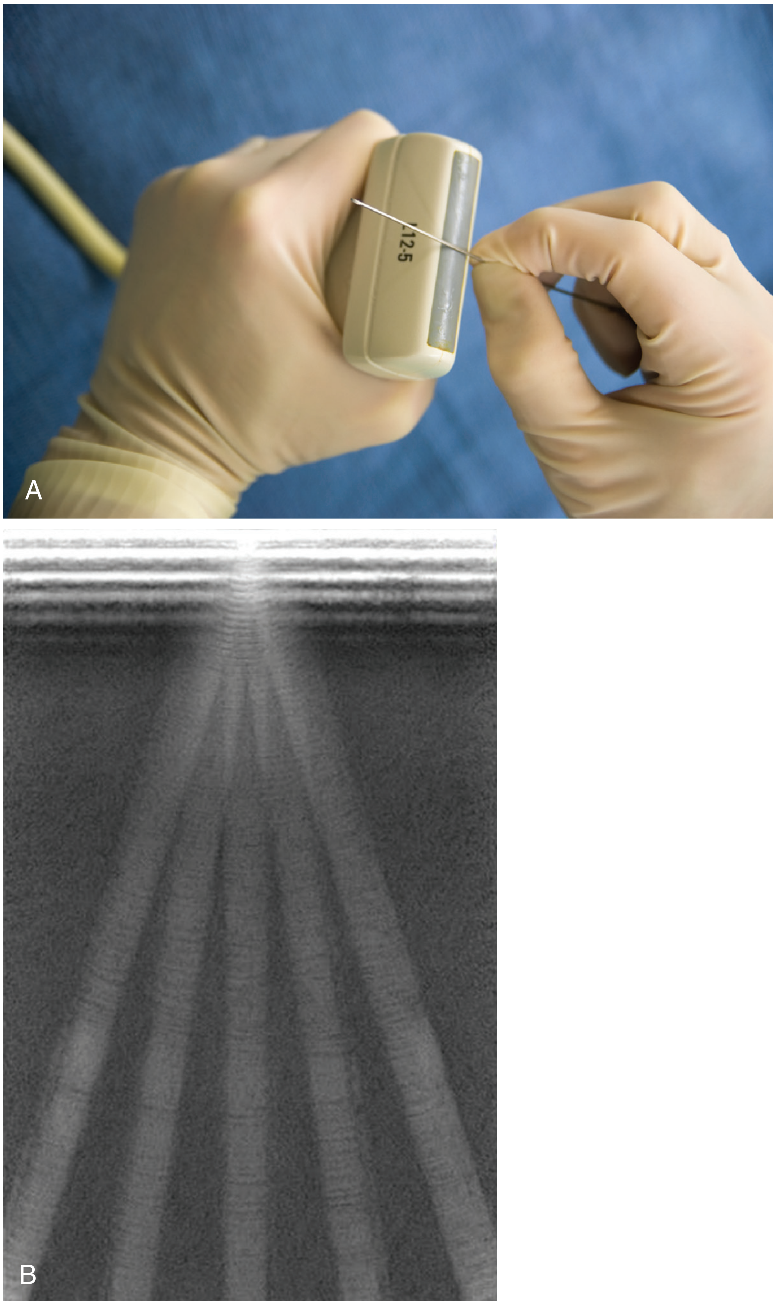

FIGURE 7.1 Spatial compound imaging. Some forms of ultrasound imaging use multiple lines of sight by electronically steering the beam to different angles. This sonogram was obtained by placing a linear array test tool (the solid metal stylet of a 17-gauge epidural needle) over the active face of the transducer to isolate a single element (A and B). The displayed test tool image consists of the receiver apertures of the transducer. In this case, five lines of sight are used to form a compound image.

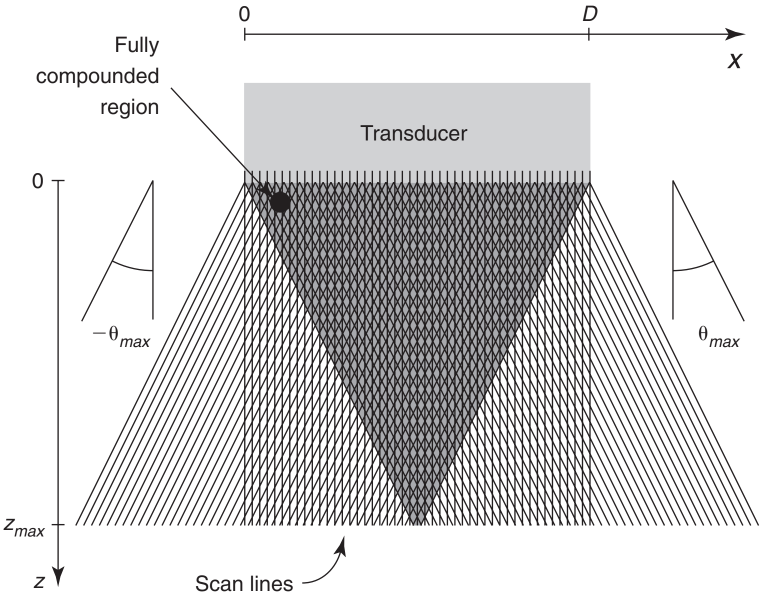

FIGURE 7.2 Conceptual illustration of transducer and associated scan lines for recording of three single-angle images. (Adapted from Jespersen SK, Wilhjelm JE, Sillesen H. In vitro spatial compound scanning for improved visualization of atherosclerosis. *Ultrasound Med Biol*. 2000;26:1357–1362.)