

Diagnostic and Interventional Musculoskeletal Ultrasound: Part 1. Fundamentals

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Musculoskeletal ultrasound involves the use of high-frequency sound waves to image soft tissues and bony structures in the body for the purposes of diagnosing pathology or guiding real-time interventional procedures. Recently, an increasing number of physicians have integrated musculoskeletal ultrasound into their practices to facilitate patient care. Technological advancements, improved portability, and reduced costs continue to drive the proliferation of ultrasound in clinical medicine. This increased interest creates a need for education pertaining to all aspects of musculoskeletal ultrasound. The primary purpose of this article is to review diagnostic ultrasound technology and its potential clinical applications in the evaluation and treatment of patients with neurologic and musculoskeletal disorders. After reviewing this article, physicians should be able to (1) list the advantages and disadvantages of ultrasound compared with other available imaging modalities, (2) describe how ultrasound machines produce images using sound waves, (3) discuss the steps necessary to acquire and optimize an ultrasound image, (4) understand the different ultrasound appearances of tendons, nerves, muscles, ligaments, blood vessels, and bones, and (5) identify multiple applications for diagnostic and interventional musculoskeletal ultrasound in musculoskeletal practice. Part 1 of this 2-part article reviews the fundamentals of clinical ultrasonographic imaging, including relevant physics, equipment, training, image optimization, and scanning principles for diagnostic and interventional purposes.

INTRODUCTION

Physiatrists have been pioneers in the field of ultrasound for over 5 decades. In 1951, a group of 24 physiatrists recognized the emerging clinical importance of ultrasound technology and eventually founded the American Institute for Ultrasound in Medicine (AIUM) [1]. During the following years, physiatrists continued to lead the medical community with respect to therapeutic ultrasound [2,3]. However, diagnostic applications in the musculoskeletal system remained limited due to poor resolution and lack of real-time imaging capabilities [1]. By the 1980s, real-time ultrasonographic imaging became widely available, facilitating a more efficient, interactive, and clinically useful examination [1]. High-frequency transducers were introduced in the late 1980s, providing the detailed anatomic imaging necessary to effectively evaluate the musculoskeletal system [1]. Following these technological advancements, radiologists and sonographers began to explore the diagnostic potential of musculoskeletal ultrasound [4,5]. Continued improvements in resolution coupled with equipment price reductions subsequently brought musculoskeletal ultrasound into the practices of physiatrists, rheumatologists, orthopedic surgeons, and other clinicians, who began to directly apply the technology to diagnose and manage musculoskeletal disorders. Physicians in general, and physiatrists in particular, have been prescribing therapeutic ultrasound for over 50 years and have now revisited ultrasound within the context of its diagnostic capabilities. Today, many practitioners have already integrated ultrasound into their practices to diagnose tendon, nerve, muscle, ligament, and joint disorders, as well as guide therapeutic procedures. As musculoskeletal ultrasound continues to proliferate, it is imperative that any interested physician acquire a basic understanding of what diagnostic and interventional musculoskeletal ultrasound is and how it may apply to the care of their patients.

This 2-part article [6] will familiarize physicians with ultrasound technology and its potential clinical applications in the evaluation and treatment of patients with neurological

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Table 1. *Advantages of musculoskeletal ultrasound*

High-resolution soft tissue imaging
Ability to image in real-time
Facilitates dynamic examination of anatomic structures
Can interact with the patient while imaging
Minimally affected by metal artifact (ie, implants and hardware)
Ability to guide procedures (eg, aspirations, injections)
Enables rapid contralateral limb examination for comparison
Portable
Relatively inexpensive
Lacks radiation
No known contraindications

and musculoskeletal disorders. After reviewing this article, physicians should be able to: (1) list the advantages and disadvantages of ultrasound compared to other available imaging modalities, (2) describe how ultrasound machines produce images using sound waves, (3) discuss the steps necessary to acquire and optimize an ultrasound image, (4) understand the different ultrasound appearances of tendons, nerves, muscles, ligaments, blood vessels, and bones, and (5) identify multiple applications for diagnostic and interventional musculoskeletal ultrasound in musculoskeletal practice. Part 1 will review the fundamentals of clinical ultrasonographic imaging, including relevant physics, equipment, training, image optimization, and scanning principles for diagnostic and interventional purposes .

WHAT IS MUSCULOSKELETAL ULTRASOUND?

Musculoskeletal ultrasound involves the use of high-frequency sound waves (3-17 MHz) to image soft tissues and bony structures in the body for the purposes of diagnosing pathology or guiding real-time interventional procedures. Modern-day ultrasound machines provide exquisitely detailed images of the musculoskeletal system, delivering sub-millimeter resolution that is superior to comparative magnetic resonance imaging (MRI) studies in most cases [7]. High-resolution scanning produces detailed anatomic images of tendons, nerves, ligaments, joint capsules, muscles, and other relevant structures throughout the body. Consequently, physicians can use ultrasound to diagnose tendinosis, partial- or full-thickness tendon tears, nerve entrapments, muscle strains, ligament sprains, and joint effusions, as well as guide real-time interventional procedures to treat these pathologies as clinically indicated.

In addition to higher resolution, musculoskeletal ultrasound provides several distinct advantages relative to radiography, computed tomography (CT), and MRI when performing focused examinations of the musculoskeletal or

neurological system (Table 1). Most important, ultrasound is a hands-on, dynamic, and interactive examination [8]. The clinician uses the information gained from the history, physical examination, and available diagnostic testing to define the clinical question and identify the region for examination. Static ultrasonographic imaging is supplemented with sonopalpation—precisely localizing the structures over which the patient is maximally tender by palpating under the transducer and eliciting patient feedback. With the assistance of the patient, joint and tendon motion, muscle contraction, and provocative testing may all be performed during ultrasonographic visualization to reveal clinically important pathologies, such as dislocating ulnar nerves, snapping iliopsoas tendons, or dislocating biceps tendons [9-11]. Ultrasound is generally unaffected by metallic artifacts (eg, metatarsal plate in the foot, suture anchors) and delivers no radiation to the patient or the user, an important consideration when evaluating females of child-bearing age. Unlike radiographs, CT, and MRI, ultrasound can be readily used to complete a comparative examination of the contralateral extremity when clinically indicated. Finally, ultrasound can provide precise, real-time guidance for interventional procedures. Compared with radiographs and CT scans, ultrasound can demonstrate soft tissues with great detail, enabling safe and accurate needle guidance for interventional procedures. Similar to ultrasound, MRI provides excellent soft tissue visualization, but the requirement for nonferromagnetic instrumentation coupled equipment size and expense currently limit MRI use for real-time interventional procedures.

Physicians should recognize several clinically relevant limitations of musculoskeletal ultrasound (Table 2). Perhaps the most important limitations pertain to field of view and penetration. Ultrasound provides a very high quality picture of a relatively small area. Clinicians should use ultrasound to confirm or characterize pathological changes within a defined body region. A patient presenting with “diffuse ankle pain” is not optimal for ultrasound examination; such a patient would be better served with CT, MRI, or bone scan, depending on the clinical circumstances. Conversely, ultrasound could be considered the initial test of choice to evaluate a patient presenting with posteromedial ankle pain suspected of having posterior tibial tendinopathy. As discussed later, ultrasound’s limited resolution at greater depths and inability to penetrate bone limit its ability to adequately image deep body regions, morbidly obese patients, areas deep to bones, and central intra-articular regions [7]. Finally, as an interactive and technologically intensive examination, musculoskeletal ultrasound is also limited by both the ultrasound machine and the skill of the examiner using it. These factors will be discussed subsequently.

Table 2. *Disadvantages of musculoskeletal ultrasound*

Technical	Examiner	Equipment
<ul style="list-style-type: none"> • Limited field of view • Incomplete evaluation of bones and joints • Limited penetration 	<ul style="list-style-type: none"> • Operator dependent • Lack of educational infrastructure • Lack of certification or accreditation process 	<ul style="list-style-type: none"> • Cost • Variable quality

MUSCULOSKELETAL ULTRASOUND: THE PREREQUISITES

Musculoskeletal ultrasound is perhaps the most operator-dependent imaging modality currently available. The primary reason for this is the need to physically acquire an acceptable image, using appropriately adjusted equipment, with specific attention to transducer positioning, all within the context of an in-depth understanding of neurological and musculoskeletal anatomy. To successfully integrate diagnostic or interventional musculoskeletal ultrasound into clinical practice, the practitioner must therefore acquire the necessary equipment, education, and scanning skills.

Ultrasound Equipment

All ultrasound machines consist of a transducer (or probe) attached to the main body of the machine via a cord [7] (Figure 1). The transducer contains a linear array of very thin crystals, each of which is linked to the machine's electrical system [7]. To generate an ultrasound wave, the machine applies a rapidly alternating electrical current to the transducer crystals, which in turn vibrate. The vibrating crystals generate a sinusoidal sound wave, which is a form of mechanical energy. This transformation of electrical to mechanical energy is known as piezoelectricity (piezoelectric = "pressure electric") [7]. The generated sound wave can be characterized by its frequency, wavelength, amplitude, and propagation speed. The material properties of the piezoelectric crystals and their thickness determine the range of frequencies that the transducer can generate [7]. The frequency and



Figure 1. Commonly used ultrasound transducers in musculoskeletal ultrasound. Left, High-frequency (15-7 MHz), small-footprint, linear array transducer, also called a "hockey stick" transducer. Center, High-frequency (17.5 MHz) linear array transducer. Right, Low- to medium-frequency (5-2 MHz) curvilinear array transducer. Both linear transducers are used for superficial imaging, whereas the curvilinear transducer's lower frequency facilitates examination of deeper regions such as the hip (Phillips iU22 Ultrasound Machine; Philips Medical Systems, Bothell, WA).

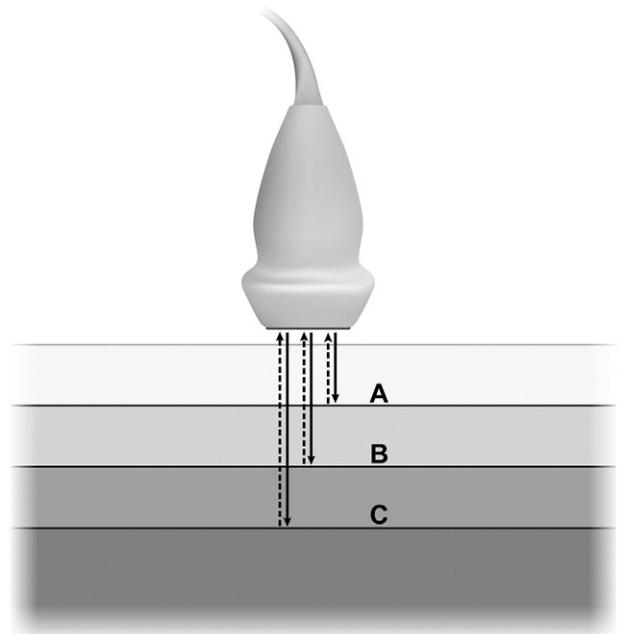


Figure 2. A generated sound wave passes through the body until it encounters an acoustic interface (lines A, B, and C). At each acoustic interface, a portion of the sound wave's energy is reflected, whereas the remainder is transmitted (solid lines traveling away from the transducer = sound waves traveling through tissues, dotted lines traveling back toward transducer = reflected sound waves). The reflected sound energy can be detected by the transducer and used to generate an ultrasound image.

amplitude (ie, intensity) of the generated sound waves are determined by the frequency and amplitude of the electrical current used to stimulate the crystals.

Because sound requires a medium in which to travel, the sound waves pass through ultrasonographic coupling gel into the body. The sound waves travel deep into the body until they encounter an acoustic interface. Acoustic interfaces occur at any point in which there is a change in the stiffness or density of adjacent tissues. The acoustic interface reflects a portion of the sound wave's energy, while allowing some of it to pass and penetrate deeper into the body [7] (Figure 2). The reflected sound wave is detected by the transducer, which then functions as a receiver. Via reverse piezoelectric effect, the received mechanical sound energy is transformed into an electrical signal for processing. The ultrasound machine records the amplitude of the returning beam as well as the depth of the reflecting structure. The depth of the reflector can be calculated using the equation "Distance = Velocity \times Time," wherein the speed of sound in human tissue is a relatively constant 1540 m/s, and the time is known because the ultrasound machine records the time each sound pulse is generated and returns [7]. By alternately generating and recording the amplitudes and travel times (ie, reflector depth) of sound beams over 7000 times per second, the ultrasound machine can use sophisticated computer software to generate a 2-dimensional black-and-white image of the

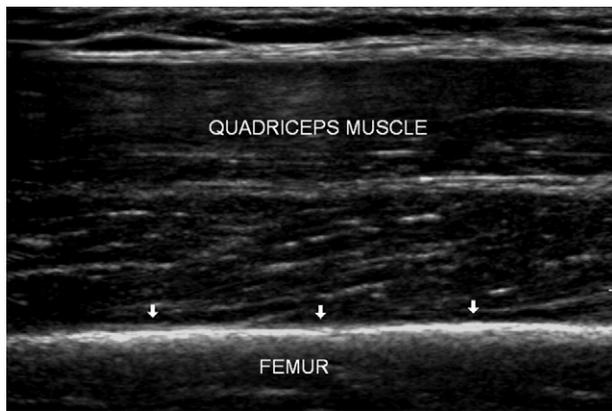


Figure 3. Longitudinal image of the anterior thigh. The large differences between the material properties of bone (femur) and the overlying muscle tissue (quadriceps) cause a large amount of sound energy to be reflected at this acoustic interface. Consequently, the bone appears bright, or “hyperechoic,” relative to the darker, or “hypoechoic,” overlying muscle. Left screen = proximal, right screen = distal, top screen = superficial, bottom screen = deep, and arrows denote hyperechoic surface of femur.

body. This process is also referred to as pulsed ultrasound, used to generate a B-mode image.

An acoustic interface that reflects a large amount of sound energy will appear brighter (or whiter) on the screen, whereas less reflective interfaces will appear darker. Because the reflectivity of the acoustic interface depends on the differences in material properties of its constituent tissues, it is not surprising that more sound energy is reflected at interfaces composed of very different tissues. For example, a large amount of sound energy is reflected at the interface between bone and muscle, resulting in bone appearing very bright (or

white) on the display screen [7] (Figure 3). Examiners should understand the concept that all ultrasound images are not based on the absolute material properties of a tissue but rather on the relative material properties of that tissue compared with adjacent regions. This concept is not only important diagnostically but can be manipulated to the clinician’s advantage. For example, during interventional ultrasound, injecting a small quantity of local anesthetic around the needle tip will significantly increase the relative differences in material properties of the needle compared with its surroundings, thus increasing the conspicuity of the needle; the needle appears brighter when surrounded by fluid compared with the same needle surrounded by muscle or connective tissue (Figure 4).

Modern-day ultrasound machines differ significantly in performance, size, and cost (Figure 5). Purchase prices can range from \$20,000 to over \$100,000, depending on quality of the machine and the number of probes purchased. Despite the wide cost range, each model has been engineered using the basic principles previously discussed. When assessing an ultrasound machine’s capabilities, the importance of imaging frequency cannot be overemphasized. In simple terms, higher-frequency sound waves produce better spatial resolution [7]. Spatial resolution is the ability to distinguish 2 structures as separate structures. Thus, smaller values for resolution (ie, 0.1 mm, also called high resolution) are desirable over larger values (ie, 1 cm). High-quality ultrasound machines used for musculoskeletal applications are capable of scanning at frequencies greater than 10 MHz, providing spatial resolutions of less than 1 mm [7]. The ability to scan at high frequencies is necessary but not sufficient to produce high-resolution images. The intricacies of sound beam generation and signal detection and processing result in significant performance differences between machines that look very similar on pa-

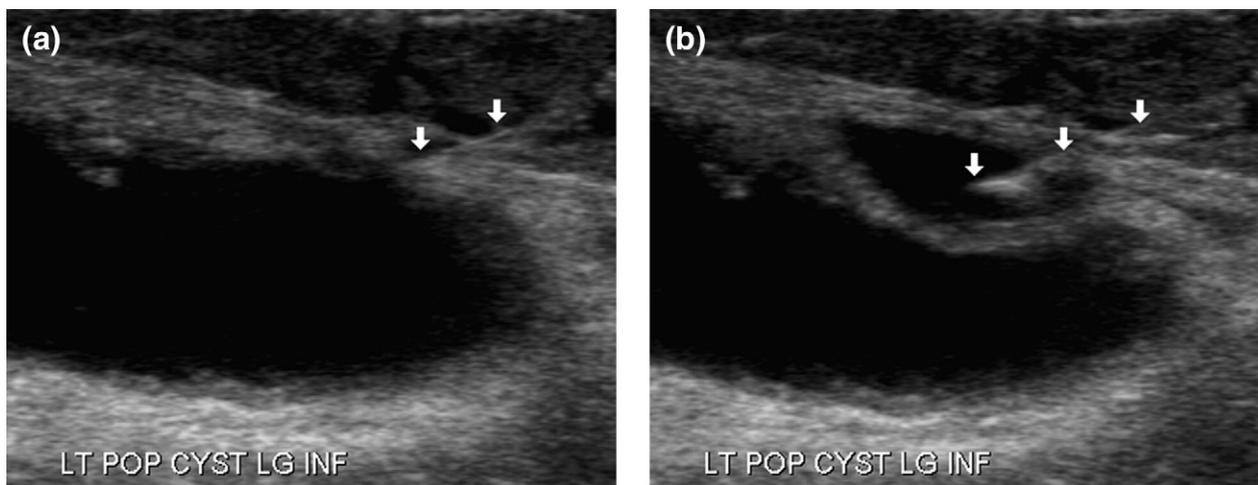


Figure 4. Longitudinal view of a popliteal cyst in the posterior left knee. (a) A 27-gauge needle (arrows) is barely conspicuous at the cyst capsule margin due to the similar echogenicity of the connective tissue and the needle. (b) Delivery of local anesthetic (1% lidocaine) creates a more reflective acoustic interface (needle vs fluid), dramatically increasing the conspicuity of the needle (arrows). LT, left; POP CYST, popliteal cyst; LG, longitudinal. Orientation similar to Figure 3, with right side of screen being inferior (or distal). (Philips iU22 Ultrasound Machine; Philips Medical Systems, Bothell, WA).

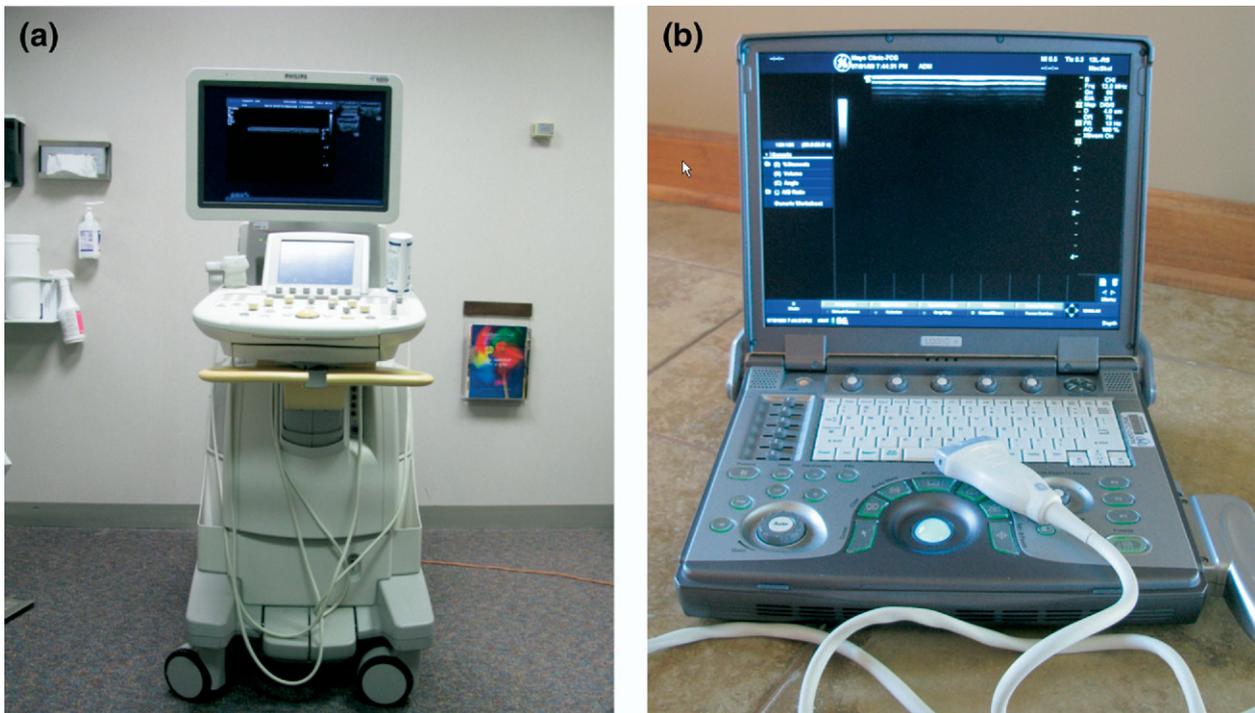


Figure 5. (a) Cart-based premium ultrasound system (Philips iU22 Ultrasound Machine; Philips Medical Systems, Bothell, WA). (b) High-quality portable laptop ultrasound system (GE LogiqQ; GE Healthcare, Wauwatosa, WI).

per. Not all 10 MHz machines produce the same high-quality B-mode image. The situation is similar to televisions, in which 2 televisions of similar apparent resolution can produce significantly different qualitative images. In general, larger, more expensive ultrasound machines will generally produce the highest-quality images, although smaller and less costly systems may produce images sufficient for many clinical applications. The first step in initiating a search for an ultrasound machine is to define how the machine will be used in practice. The projected clinical use will determine the minimal acceptable picture quality. Thereafter, each practitioner should consider the interrelated factors of resolution/performance, size (and therefore portability), and cost when narrowing the search. Special imaging features may be a consideration. Virtually all machines now offer high-sensitivity Doppler imaging, allowing detection of abnormal blood flow in diseased tendons or identification of vessels during interventional procedures [12]. Some machines offer spatial compounding, frequency compounding, harmonic imaging, or extended field of view (or panoramic imaging). Discussion of advanced imaging features is beyond the scope of this article and interested readers should consult the appropriate references [7,13]. As a final step, physicians should use each machine during a live demonstration, preferably in a side-by-side comparison. Subtle but potentially important differences will emerge in picture quality and usability during such demonstrations. It is prudent not to purchase an ultrasound machine without personally evaluating it during a live demonstration.

Education

Physicians contemplating incorporation of musculoskeletal ultrasound into their practices must embrace the concept of self-directed learning; currently, no educational infrastructure exists [14-16]. Consequently, physicians must pursue 1 or more of the increasing number of continuing education courses teaching musculoskeletal ultrasound skills. Furthermore, on-line educational opportunities and resources are starting to emerge (Table 3). Continuing educational experiences must be supplemented by regular practice to refine scanning skills and having routine access to an ultrasound machine will accelerate the learning curve. Not surprisingly, one typically does not develop competency at musculoskeletal ultrasound without regular practice—thus the necessity to either rent or purchase a machine. Practically, it may take several months until the machine is being used in a manner that will generate income to offset the initial capital outlay.

Despite the educational challenges, many physicians have already successfully acquired the equipment and skills nec-

Table 3. Educational websites for musculoskeletal ultrasound

American Institute for Ultrasound in Medicine (AIUM): www.aium.org
European League Against Rheumatism (EULAR): www.doctor33.it/eular/ultrasound/Guidelines.htm
European Society of Skeletal Radiology (ESSR): www.ESSR.org
University of Michigan Ultrasound: www.med.umich.edu/rad/muscskel/mskus/index.html

essary to integrate musculoskeletal ultrasound into their practices. If current trends continue, formal educational opportunities will likely increase in quantity and quality. The development of formal curricula and training programs is certainly feasible [14-16].

Scanning Skills

Physicians seeking to integrate musculoskeletal ultrasound into their practices must develop and refine their abilities to manipulate the transducer and optimize images using basic machine controls. Skillful transducer manipulation using a variety of movements—sliding, tilting, rotating, and heel-toeing—ensures that the region of interest has been scanned in total, and the target structures investigated with the appropriate angle of insonation [17].

Ultrasound generates a 2-dimensional picture of a 3-dimensional structure. Similar to CT, ultrasound represents a “slice” through the body. Consequently, the transducer must be moved from one end of a structure to the other in order to execute a complete examination. For example, a single ultrasound image generated with the transducer parallel to the supraspinatus tendon approximately 1 cm posterior to the anterior edge of the tendon fails to reveal a full-thickness supraspinatus tear, subsequently revealed by sliding the transducer anteriorly (Figure 6). All regions of interest must be scanned to avoid errors of omission.

Anisotropy is commonly encountered during the musculoskeletal ultrasound examination, and is a major pitfall for inexperienced clinicians. Anisotropy occurs when an otherwise normal but smooth structure appears “dark” on ultrasonographic imaging due to the fact that the ultrasound beam did not encounter the structure perpendicular to the plane of that struc-

ture [17,18]. When sound encounters a smooth structure such as a tendon, the tendon behaves like a mirror. A beam that encounters the tendon perpendicular to its surface will be reflected directly backward and toward the transducer, whereas a beam encountering the surface at any angle is reflected obliquely and away from the transducer. In the former case, the tendon will appear normally bright, or hyperechoic, while in the latter case, the tendon appears artifactually dark, or hypoechoic, because the transducer did not “see” the obliquely reflected beam (Figure 7). Because tendinosis and tearing manifest as dark, or relatively hypoechoic, regions within a tendon, anisotropy may be mistaken for actual pathology, resulting in a false-positive diagnosis [17,18]. Thus, during the musculoskeletal examination, examiners should avoid anisotropy by continually manipulating the transducer to direct the generated beam perpendicular to the target structure. Similarly, the examiner should manipulate the transducer and reexamine any potential region of abnormality to confirm that it does not represent anisotropy. In both situations, a combination of tilting and heel-toeing is typically used. As the examiner gains scanning experience, these transducer manipulations will become automatic and will occur effortlessly while simultaneously sliding or rotating the transducer.

Physicians must also develop basic skills in image optimization. Variation of ultrasound machine parameters can significantly influence the machine’s performance. Reassuringly, many ultrasound manufacturers have developed presets for various musculoskeletal applications (eg, superficial, intermediate, deep, nerve, etc). However, the existence of these presets does not preclude the need for the examiner to complete several important steps to produce the most clinically useful picture.

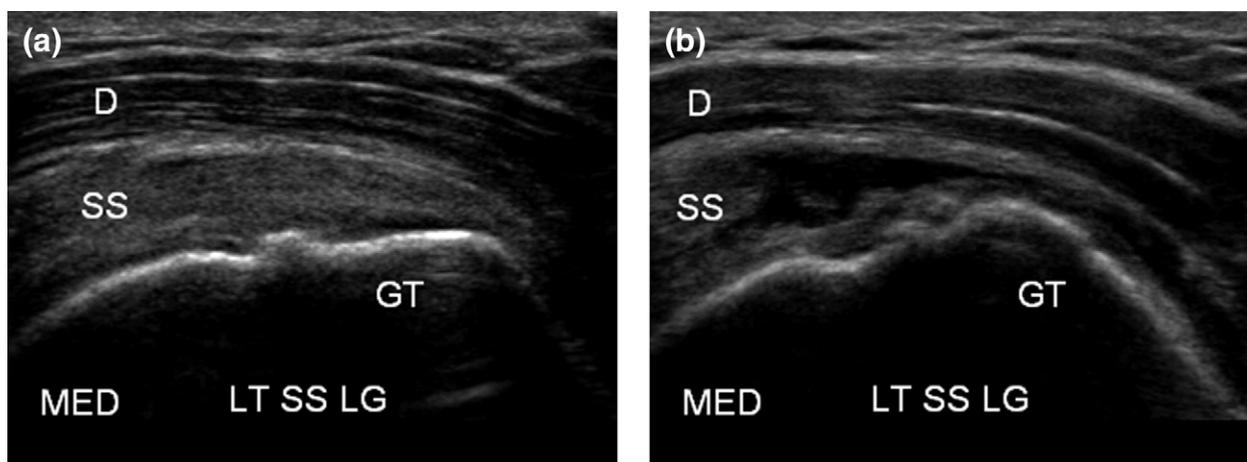


Figure 6. Longitudinal ultrasound image of the supraspinatus tendon. This image is oriented similar to an oblique coronal MRI scan. (a) Essentially normal “hyperechoic” supraspinatus tendon (SS) lying deep to the more “hypoechoic” deltoid muscle (D) and superficial to the humeral head and greater tuberosity (GT). (b) Sliding the transducer just 1 cm anteriorly reveals a full-thickness tear of the supraspinatus tendon. Failure to scan the entire anteroposterior dimension of the supraspinatus would have resulted in a false negative examination. Image obtained with a 17.5 MHz linear array transducer (Philips iU22 Ultrasound Machine; Philips Medical Systems, Bothell, WA). LT, left; LG, longitudinal. Left screen = medial (MED), right screen = lateral, top screen = superficial, bottom screen = deep.

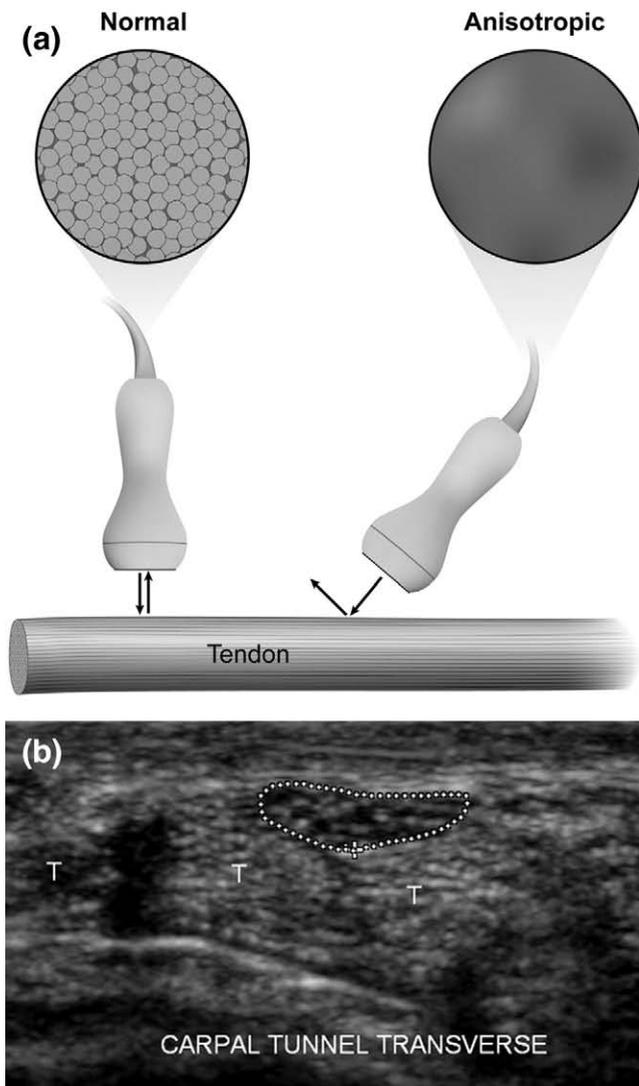


Figure 7. (a) The transducer on the left is perpendicular to the tendon, resulting in a clearly defined normal image of the tendon. The transducer on the right is at an angle to the tendon, which results in a poorly defined, hypoechoic or anechoic image referred to as anisotropy. (b) Transverse ultrasonographic view of the proximal carpal tunnel. The median nerve is outlined and appears in cross-section as a mixed density honeycomb structure. Several hyperechoic, fibrillar finger flexor tendons (T) lie deep to the nerve. (c) Tilting the transducer slightly results in tendon anisotropy. Tendons exhibit greater anisotropy than nerves and essentially “disappear,” whereas the nerve (outlined) remains visible. Images obtained with a 15-7 MHz small footprint linear array (ie, “hockey stick”) transducer (Phillips iU22 Ultrasound Machine; Philips Medical Systems, Bothell, WA). Left screen = radial, right screen = ulnar, top screen = superficial, bottom screen = deep.

First, the examiner must select the appropriate transducer. Transducer choice is determined primarily by the depth of the target region. There is an inverse relationship between frequency and penetration depth [7]. Although high-frequency transducers produce the best resolution, they exhibit the lowest penetration into the body. Consequently, one should always choose the highest-frequency transducer that can adequately image the target structure(s) at the appropriate depth. The superficial location of most musculoskeletal structures renders them amenable to examination using high-frequency (>10 MHz) linear array transducers, which can typically penetrate up to 6 cm (Figure 1, center). The phrase “linear array” refers to the linear arrangement of the piezoelectric crystals used in construction [7]. The maneuverability of small-footprint, high-frequency linear array transducers (also called “hockey stick” transducers) provides greater flexibility when examining superficial structures located within curved body regions (eg, peroneal or posterior tibial tendons about the ankle malleoli) or when performing precise ultrasound-guided interventions in superficial regions (Figure 1, left). The larger curved linear array transduc-

ers typically scan at lower frequencies (2-6 MHz) and are commonly used in the hip region (Figure 1, right). Curved transducers may also be necessary to examine shoulders in patients of large body habitus. The ability to image at increased depths comes at a cost. Lower-frequency scanning results in reduced resolution, and the divergent beam geometry of the curved transducer increases the likelihood of encountering anisotropy when imaging smooth, linear structures in the body such as tendons and ligaments.

Following transducer selection, ultrasound gel is placed on the transducer and the transducer applied to the skin. Using the depth control on the console, the examiner then adjusts the depth to a more superficial or deep setting so that the displayed image includes the region of interest without wasting screen space deep to the structure (Figure 8).

The focal zone position is subsequently adjusted so that the focal zone is located at the same length and position as the target structure(s) (Figure 8). All ultrasound beams initially narrow to a minimum width and subsequently widen as they travel into the body. The narrowest point of the beam, or focal zone, represents the region of best lateral resolution [6].



Figure 8. Transverse (axial) view of an ultrasound guided aspiration of a complex prepatellar bursitis. An 18-gauge needle is entering from the medial side of the knee (left screen = lateral, right screen = medial, top screen = superficial, bottom screen = deep). Numerical scale on right side of screen depicts imaging depth, set at 3 cm for this procedure. The depth was adjusted using a console control to avoid “wasted space” deep to the target structure(s). The focal zone is depicted by the vertical bar just to the left of the depth scale (delimited by the arrows). As an alternative to adding or subtracting focal zones, this machine provides the user the capability of adjusting the length (ie, tissue depth covered) of a single focal zone. The user uses the console controls to move the focal zone to the region of interest, then changes its length to encompass the target structure(s). Temporal resolution is represented by frame rate, appearing as FR in the left upper corner of the image. In this case, the ultrasound image is being updated 32 times per second (32 Hz), providing “real-time” imaging of dynamic processes such as this aspiration. The gain is represented as a percent value and is depicted in the middle left side of the screen, in this case 83%. Using console controls, the overall gain can be increased toward 100%, providing maximal amplification (likely resulting in image “white out”), or reduced toward 0%, providing essentially no amplification (likely resulting in image “black out”). Image obtained with a 12-5 MHz linear array transducer (Phillips iU22 Ultrasound Machine; Philips Medical Systems, Bothell, WA).

Lateral resolution refers to the ability to distinguish 2 adjacent structures that occur next to each other within the imaging region. Although lateral resolution also benefits from higher-frequency scanning, it can be further enhanced by moving the focal zone into the region of interest through electronic manipulation. Additional focal zones may be added to define multiple target levels of interest. However, the addition of a focal zone requires generation and detection of a separate ultrasound beam, reducing temporal resolution. *Temporal resolution* refers to the ability to identify the position of a structure at any point in time and is reflected on the display screen as frame rate (Figure 8). A faster frame rate reflects better temporal resolution. As focal zones are added, or imaging depth increased, the rate at which the ultrasound machine can produce complete, updated B-mode images is reduced. One must manage frame rates based on the clinical situation. Higher frame rates (typically more than 20 frames/s) are necessary to detect rapidly occurring events

such as a snapping iliopsoas tendon or to track needle movement and injectate flow during an ultrasound guided injection [19]. At frame rates less than 16 frames per second, the displayed image degrades, and real-time capabilities are significantly compromised [7].

After choosing the focal zone number and location, the examiner then adjusts the overall gain (Figure 8). The overall gain control equally amplifies all of the echoes returning from the scanned region [7]. The gain should be adjusted to provide optimal visualization of the target region. Too much gain will result in “whiting out” of the image, whereas too little gain will render the target region too dark to assess. Although the optimal overall gain for a particular scan is somewhat subjective, blood flowing within vessels, simple fluid collections, and regions beyond bone should appear black or nearly black when the overall gain is adjusted appropriately.

Finally, the examiner adjusts the depth gain compensation (DGC, also called time gain compensation, or TGC) [7]. The DGC typically appears as a series of slide dials, each representing the gain at a different depth in the image (Figure 9). By sliding a specific DGC control to the left or right, one can decrease or increase the gain, respectively, in that specific region of the scanned image. Thus, DGC is a depth-specific variation of overall gain. Depth gain compensation exists to correct for the normal attenuation of sound waves that occurs as the waves propagate through body tissues. Although reflected sound beams are required for image generation, most of the sound traveling through the body is actually absorbed and dissipated as heat [6]. Attenuation results in a reduction of the acoustic energy (expressed in decibels [dB] and increases as a function of depth and frequency [6]. This rela-



Figure 9. Console controls of modern-day cart-based ultrasound machine (Phillips iU22 Ultrasound Machine; Philips Medical Systems, Bothell, WA). The depth gain compensation (DGC) slide controls are on the right hand side of the picture. In this case, 8 DGC slides are available, each independently adjusting the gain at a specific level in the ultrasound image (top slide = superficial, bottom slide = deep). Moving a slide to the left will decrease the gain at that level, whereas moving it to the right will increase the gain at that level.

relationship explains why high-frequency transducers demonstrate limited penetration. In addition, attenuation results in the lower (ie, deeper) part of the displayed ultrasound image appearing darker than the upper (ie, superficial) part, all other parameters being equal. Depth gain compensation allows correction for this depth-related intensity dropoff. Although many modern ultrasound machines automatically adjust the DGC internally based upon the imaging depth, ultrasound machines that lack automatic DGC or examiner preference may dictate adjustment of these controls manually.

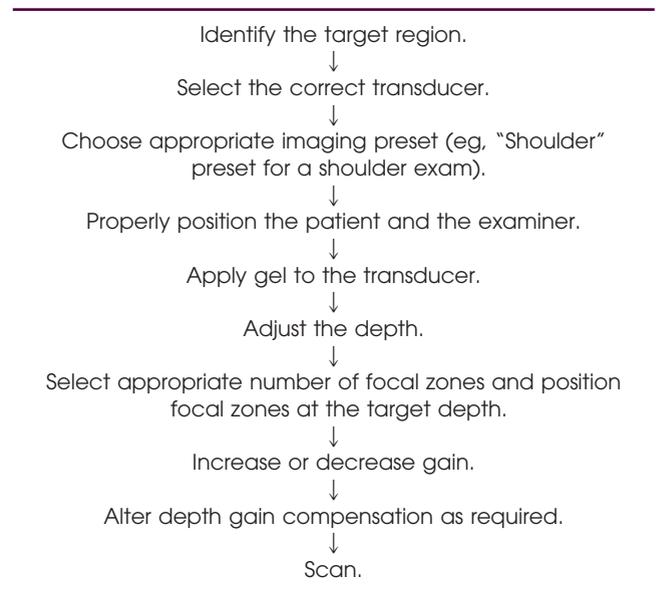
In summary, it is essential that physician performing diagnostic or interventional musculoskeletal ultrasound acquire high-quality ultrasound equipment and the skills to effectively use it. Whereas equipment can be purchased at a distinct point in time, skill acquisition requires enthusiasm, dedication, and training.

BASIC PRINCIPLES OF DIAGNOSTIC AND INTERVENTIONAL ULTRASOUND

When performing a diagnostic musculoskeletal ultrasound examination, the physician should follow several important steps to optimize the diagnostic yield while minimizing errors (Table 4):

- (1) Define a specific clinically relevant question that may be answered by the ultrasound examination. Clinical applications are discussed in a subsequent section.
- (2) Ergonomically position the physician, patient, and machine. Relaxed patients are generally more cooperative. The examiner should be positioned so that he or she can examine all regions in a relaxed posture while viewing the display screen and manipulating the console controls. If the physician is positioned uncomfortably, fatigue will rapidly ensue and transducer manipulation will be compromised.
- (3) Maintain control of the transducer. Ultrasound is a “hands-on” examination. To effectively manipulate and control the transducer, the physician must have a firm (although not tight) grip on the transducer, and stabilize the transducer on the body using the fingers and the hand (Figure 10). Part of the physician’s fingers or hands should be on the patient’s body to provide a steady foundation for transducer control and a frame of reference for transducer manipulation. Many physicians first learning ultrasound find themselves confused by what they see on the display screen, only to look down and see that their hand (and the transducer) has moved several centimeters away from its starting point.
- (4) Completely evaluate the region of interest to avoid errors of omission [20]. Recall that an ultrasound picture represents a single 2-dimensional slice through a 3-dimensional structure. Multiple slices must be examined to mentally reconstruct the 3-dimensional view of the target region. This process requires the physician to have an in-depth knowledge of regional anatomy. Although 3-di-

Table 4. Steps to perform a diagnostic musculoskeletal ultrasound examination



mensional ultrasound technology is rapidly developing, musculoskeletal applications remain limited at this time. Detailed scanning protocols have been developed and should be used to avoid errors of omission (Table 3).

- (5) Evaluate each target structure in 2 orthogonal planes. Each structure is typically examined longitudinally (long axis) and transversely (short axis). These descriptors are referenced to the specific structure and not necessarily the body. Orthogonal imaging increases the diagnostic sensitivity and minimizes the risk of misinterpreting artifactual changes (eg, anisotropy) as pathology.

When using ultrasound guidance for interventional procedures, the physician must consider all the principles discussed for diagnostic scanning as well as the general principles pertaining to injections and aspirations in the musculoskeletal system [21-24]. In addition, the physician must plan the approach for the intervention considering both the regional anatomy and the ability to visualize the needle en route to the target. Specific technical aspects of ultrasound guided procedures are beyond the scope of this article. However, several principles are applicable:

- (1) Determine the specific procedure and goal (ie, diagnostic or therapeutic).
- (2) Review the regional anatomy. In general, the approach should consist of the shortest distance between the skin and the target while minimizing neurovascular risk and optimizing needle visualization. This step is crucial to minimize complication risk. During the planning process, the projected needle path should be examined with the Doppler ultrasound. Doppler ultrasound detects frequency differences in a transmitted versus reflected sound wave to determine whether the reflective tissue/fluid is moving [7]. Therefore, a preliminary Doppler

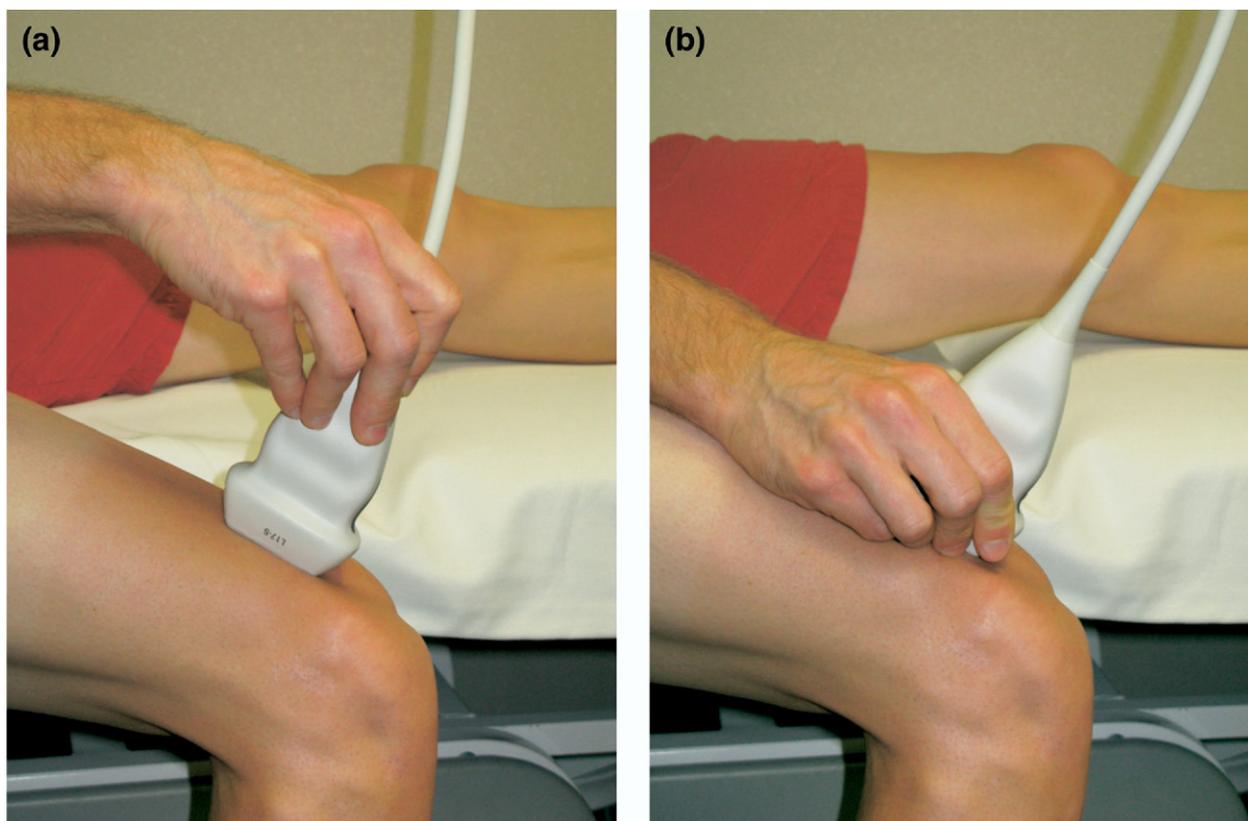


Figure 10. (a) Beginners commonly fail to keep a portion of their hand on the patient's body, making transducer control and manipulation challenging. (b) Maintaining finger or hand contact with the patient's body provides a frame of reference for the examiner, as well as a stable foundation for transducer control.

examination can identify veins and arteries so that they can be avoided during the procedure.

- (3) Use sterile technique. Sterile ultrasound transducer covers and sterile ultrasound gel packets are readily available and recommended.
- (4) Preferentially choose a long-axis approach (also called "in plane"). During a long-axis approach, the needle tip and shaft are co-linear with the long axis of the transducer, providing optimal ultrasonographic visualization of the needle en route to the target (Figure 11). The tip and shaft appear as linear, hyperechoic structures. Long-axis imaging provides the greatest control and safety when performing ultrasound-guided procedures. Alternatively, some situations dictate using a short-axis (or "out of plane") approach, in which the needle shaft is perpendicular to the long axis of the transducer (Figure 11). The needle appears as an echogenic (ie, white) dot within the display as the ultrasound beam cuts an oblique cross-section of the needle shaft. Determining the exact location of the tip during short-axis imaging can be challenging. Consequently, the short-axis approach should only be performed when necessary and by experienced ultrasonographers [22-24].
- (5) Maintain needle tip visualization throughout the procedure. Ultrasound is a powerful tool that can facilitate

completion of precise injections and aspirations while minimizing risk. These benefits necessitate constant awareness of the needle tip position. Needle conspicuity can be increased by (a) maintaining the needle as parallel to the transducer face (and therefore perpendicular to the ultrasound beam) as possible, (b) increasing the contrast between the needle tip and adjacent tissues by injecting a small amount of local anesthetic or sterile normal saline—referred to as *hydrodissection* (Figure 4), (c) gently completing small-amplitude back-and-forth needle motions without advancing it, also known as *jiggling*, or (d) using a larger-gauge needle [21-24]. Although echogenic needles have been developed, currently available data suggest only marginal increases in conspicuity that may not justify their added cost.

- (6) Recognize the limitations of the physician, equipment, and technique. Interventional ultrasound is technically demanding. Not only must the physician control the transducer and machine, but he or she must also precisely guide the needle to the target. Most interventional musculoskeletal ultrasound is performed using the "free-hand technique" in which the physician holds the transducer in one hand and the needle in the other [20-23]. Although needle guides are available, their lack of versatility limits their application in clinical practice. The

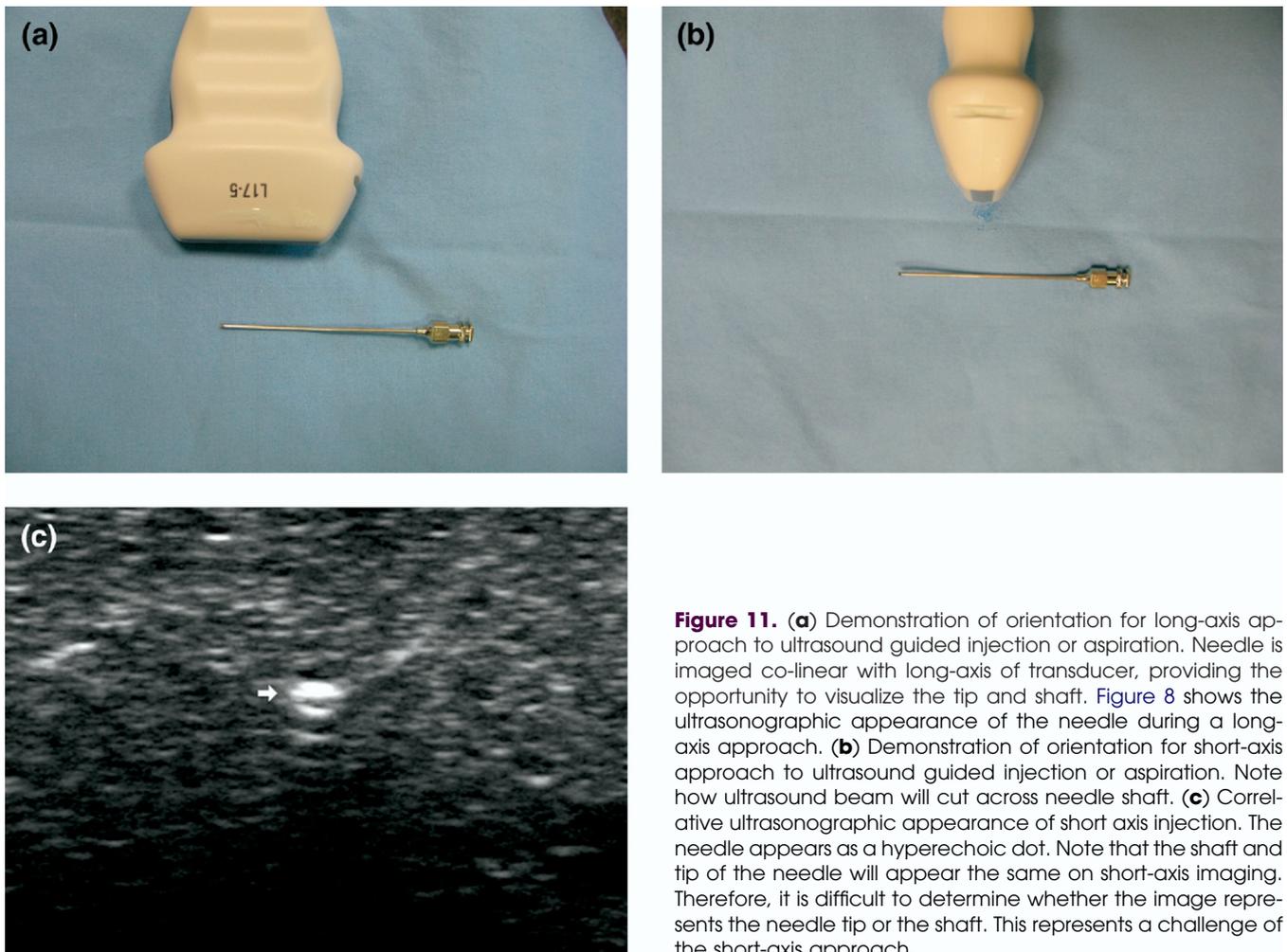


Figure 11. (a) Demonstration of orientation for long-axis approach to ultrasound guided injection or aspiration. Needle is imaged co-linear with long-axis of transducer, providing the opportunity to visualize the tip and shaft. Figure 8 shows the ultrasonographic appearance of the needle during a long-axis approach. (b) Demonstration of orientation for short-axis approach to ultrasound guided injection or aspiration. Note how ultrasound beam will cut across needle shaft. (c) Correlative ultrasonographic appearance of short axis injection. The needle appears as a hyperechoic dot. Note that the shaft and tip of the needle will appear the same on short-axis imaging. Therefore, it is difficult to determine whether the image represents the needle tip or the shaft. This represents a challenge of the short-axis approach.

technical demands of interventional musculoskeletal ultrasound dictate that each physician should recognize the limits of his or her skill when deciding which procedures may be appropriate. Limitations in ultrasound machine performance may similarly limit the examiner's ability to perform certain procedures on specific machines. Finally, some procedures may not be feasible to complete under ultrasound guidance. Failure to define a safe path to a target site while simultaneously visualizing the needle would preclude using ultrasound. In addition, the risk-benefit ratio of performing certain procedures under ultrasound guidance is currently unfavorable in the authors' opinion, particularly when superior alternative options exist. One example would be the use of ultrasound to perform cervical transforaminal epidural injections [25].

CONCLUSIONS

Musculoskeletal ultrasound has emerged as a powerful clinical problem-solving tool that can be used by physicians to diagnose and treat patients presenting with a variety of musculoskeletal complaints. Part 1 of this 2-part article has presented the fundamentals of ultrasound scanning, including physics, equipment,

training, image optimization, and scanning principles. Physicians must acquire an in-depth understanding of these basic concepts to effectively integrate musculoskeletal ultrasound into clinical practice. Part 2 of this 2-part article will specifically focus on the clinical applications of musculoskeletal ultrasound, both diagnostic and interventional.

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