Basics of Ultrasound

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Anthony Tran and Amitabh Gulati

Introduction

The scientific origin behind medical ultrasound can be attributed to the year of 1793 when Lazzaro Spallanzani observed that bats were able to navigate in complete darkness while blindfolded but were unable to do so with waxy ear plugs [1]. Thus, he concluded that the ability to hear was critical for bats to navigate. More than seven decades later, a seemingly unrelated discovery was made by Pierre and Jacques Curie termed the "piezoelectric effect", a physical property of certain solids (e.g., crystals) that enable the conversion of mechanical energy to electrical energy in a reversible manner [2]. The application of the piezoelectric effect with the concept of sound as a navigation tool took shape during World War I (1914–1918), in efforts to detect submarines [3]. Piezoelectric-compatible crystals were exploited to create a transducer able to receive electrical energy from the ship's engine and in-turn produce mechanical energy in the form of sound waves. These sound waves could be emitted underwater, reflect off surfaces, and bounce back to a receiver on the ship. The returning sound waves could then be reconverted to electrical energy and the amount of time required to receive the echo could be used to calculate the distance between the ship and an object. It was not until nearly three decades after the start of World War I, did the first documented application of sound for human medical diagnosis emerge. Adopting similar ideas from ship navigation, Austrian neurologist (Karl Dussik) attempted to detect brain tumors within a human skull by directing sound waves through patients' heads and analyzing the echos [4]. In the decades following Dr. Dussik's efforts, technological advancements to be further discussed in this chapter have enabled the routine use of sound for diagnostic and image guidance purposes in clinical medicine.

Contemporary utilization of sound for medical diagnosis and procedural guidance utilizes the general concept of a transducer to emit sound, but also to capture reflected sound signals and funnel information to a central processing unit (CPU) for image generation. In order to understand how an image is generated, the basic physical properties of sound need to be introduced.

Sound is described as mechanical energy that propagates longitudinally via compressions and expansions of molecules within a given medium [5]. Sound can be illustrated using a sinusoidal curve to illustrate the cyclic fluctuation of pressure with time (Fig. 10.1). A sound wave has various descriptors including volume (amplitude), distance between two adjacent points in a wave (wavelength), and number of repeated wave cycles that occur in 1 second (frequency) in unit Hertz (Hz). The human hearing range for sound is described to be between 20 Hz and 20,000Hz [6]. An ultrasound, therefore, is sound beyond the audible range of humans. In the context of ultrasound image generation, the amount of detail within an image (resolution) and the depth of the scanning area achieved (penetration) are interrelated

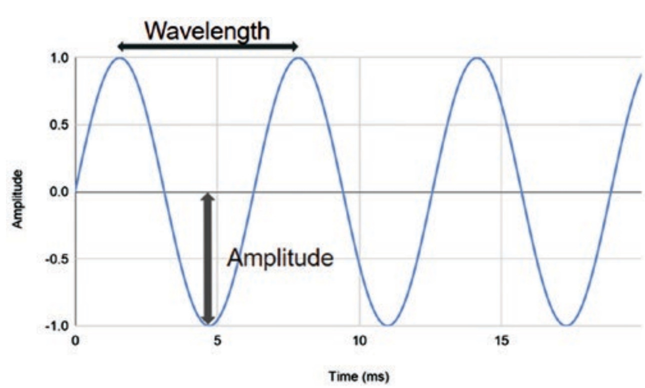

Fig. 10.1 Sound wave characteristics. Wavelength (λ) is the distance between two adjacent points in a wave. Amplitude is the distance from origin to crest/trough

A. Tran
New York-Presbyterian/Columbia and Cornell, Department of Rehabilitation Medicine, New York, NY, USA

A. Gulati (✉)
Memorial Sloan Kettering Cancer Center, Department of Anesthesiology and Critical Care, New York, NY, USA
e-mail: gulatia@mskcc.org

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to ultrasound frequency. While frequency is directly related to resolution, it is inversely related to penetration. That is, higher ultrasound frequencies produce higher resolution images with lower depths of scanning. The behavior of sound within the human body is dependent on the tissue of which the sound is propagating. As sound propagates through tissue, there is gradual loss of energy (attenuation) and some of the sound waves bounce back (reflection) or deflect obliquely while passing from one tissue type to another (refraction). There are various tissue types within a human body and the degree of resistance of an ultrasound beam through a particular tissue type (acoustic impedance) is illustrated in Table 10.1 [7, 8]. Generally, the larger the difference between acoustic impedance between two tissue types, the increased proportion of reflected sound waves which correlate with signal intensity. Typically, ultrasound images are depicted in a gray scale continuum with brighter shades of gray indicating higher intensity and darker shades indicating lower intensity of signal. Therefore, a medical ultrasound image can be thought of as a compilation of reflected ultrasound waves of varying signal intensities from tissues and structures within the body. Let us explore this idea further by evaluating an ultrasound machine.

Table 10.1 Acoustic Impedance based on material type

Material	Acoustic Impedance (Mrayl)
Air	0.0004
Water	1.48
Fat	1.34–1.38
Liver	1.65
Blood	1.61–1.65
Muscle	1.62–1.71
Skull bone	6.0–7.8

Equipment Ultrasound machines come in many different shapes and sizes. Fortunately, there are commonalities with ultrasound machines that often remain consistent regardless of make. An ultrasound transducer enables real-time interrogation of a field of interest using emitted and receiving reflected sound waves (Fig. 10.2a). The recovered signal from the transducer is processed at a CPU (Fig. 10.2b) for image generation. The image can be displayed on a monitor (Fig. 10.2c) and/or sent to a storage device where a keyboard (Fig. 10.2d) is helpful to input information detailing a study.

Fig. 10.2 Ultrasound machine components may differ in shape and size, a comparison of major functional components between two different manufacturers. Transducer (**a**). CPU (**b**). Monitor (**c**). Keyboard (**d**)

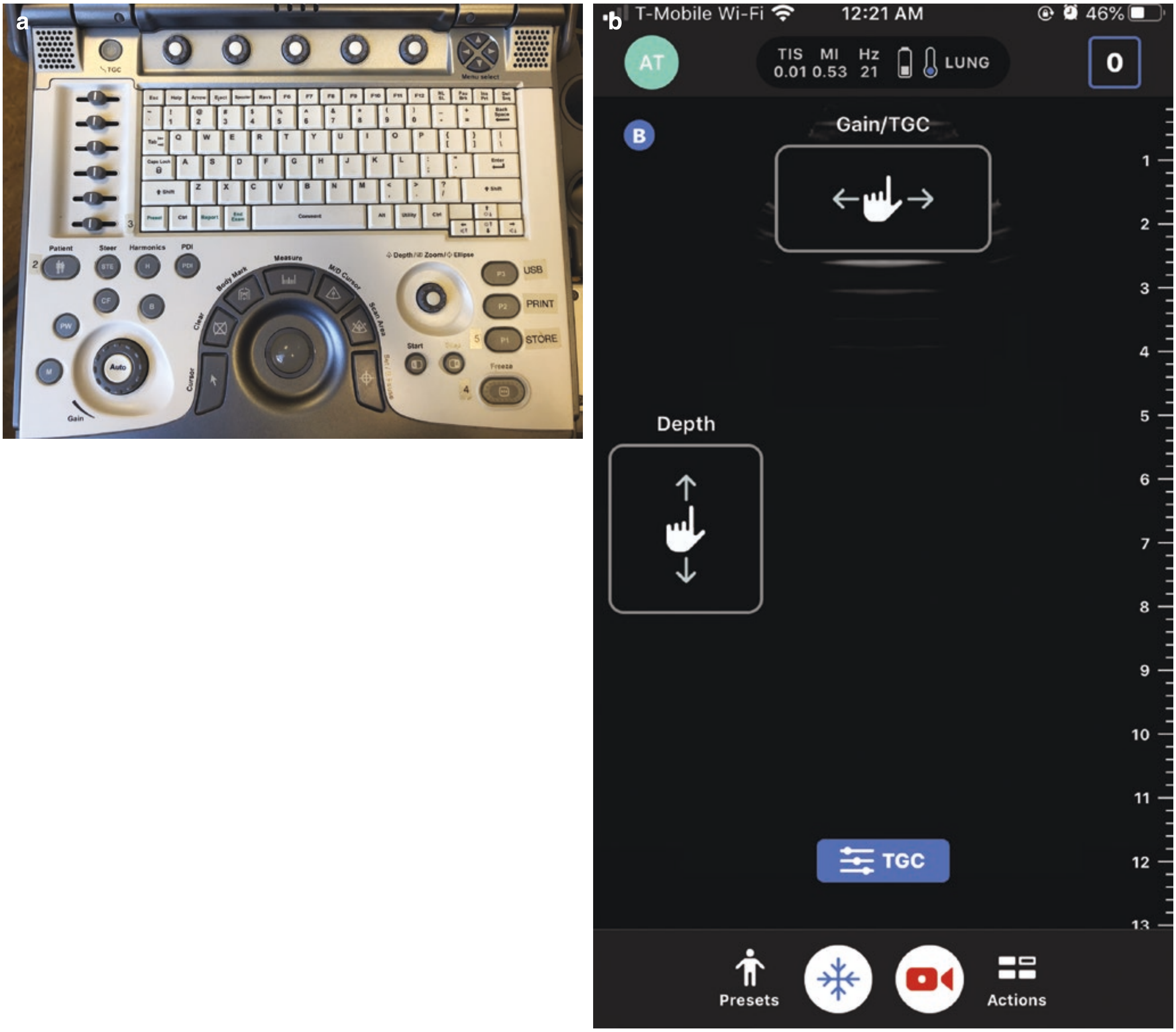


Fig. 10.3 Basic ultrasound knob comparison between two different manufacturers. Power button (**a**). Depth control (**b**). Gain control (**c**). Freeze button (**d**)

In regards to the control panel of an ultrasound machine (Fig. 10.3), there are numerous knobs. The knobs that are typically reproduced from machine to machine include a power button (toggle on/off) (Fig. 10.3a), depth (to adjust shallowness/deepness of an image's field of vision) (Fig. 10.3b), gain (to adjust darkness/brightness of sound signal) (Fig. 10.3c), and freeze (to hold an image at a current selected frame) (Fig. 10.3d). Now that a basic layout of an ultrasound machine has been established, let us learn how to handle a transducer and use the machine.

Transducers The basic types of transducers are linear (Fig. 10.4a), curvilinear (Fig. 10.4b), and phased. Transducer types vary in frequency and footprint, defined as the area of a transducer to which ultrasound rays are emitted. Each transducer has an indicator (a raised bump) on one side and by convention, the indicator is oriented to reflect the left side of the monitor. The upper limit of frequencies that can be achieved by any one transducer depends on the type, and may even vary within a particular type depending on the manufacturer. Generally, the order of relatively high to low frequencies based on type is considered to be: Linear > Curvilinear > Phased. Typically, the relatively high frequency transducers (e.g., linear) are used for superficial structures (e.g., bone, ligaments, and muscle) due to better resolution at shallower depths (poor penetrance). The curvi-

Fig. 10.4 Linear transducer (**a**) with view of footprint along with accompanying field of vision of a left forearm. Curvilinear transducer (**b**) with view of footprint along with accompanying field of vision of a left forearm

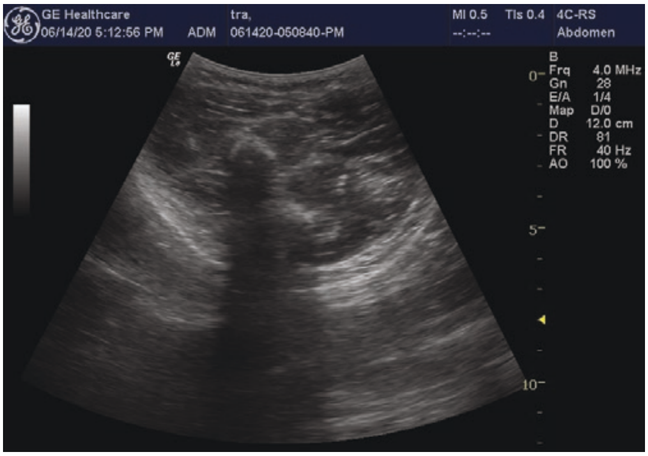


Fig. 10.4 (continued)

linear probes emit ultrasound at a relatively lower frequency allowing for deeper penetration and a wider depth of field (given the shape of its footprint). As a result, the curvilinear transducer is the preferred type for intra-abdominal structures. Phased transducers have a compact footprint enabling visualization from a narrow vantage point, such as in-between ribs to evaluate the thoracic cavity or via a subxiphoid view for cardiac examination (echocardiogram).

Medical ultrasound is highly user-dependent; a number of transducer motions have been described [9] and are demonstrated in Fig. 10.5.

Settings & Image Adjustment Once an ultrasound image is generated and displayed on the machine's monitor, there are a variety of modes that can be selected from. Three modes will be discussed here: B-mode, M-mode, and Color doppler (Fig. 10.6). B-mode, also known as "Brightness" mode, is a 2D gray scale image that correlates intensities of returning echoes with degrees of brightness, the higher the intensity the brighter the signal. This is often the default ultrasound mode. M-mode, also known as "Motion" mode, provides axial and temporal resolution of an ultrasound image. This mode is able to follow points that are longitudinally adjacent and record the position of these points with successive images over time. This mode is often used in echocardiograms, to evaluate the motion of heart valves over time. Lastly, Color doppler provides information regarding velocity of an area of interest. Often, color doppler is utilized to assess the speed and direction of blood flow within blood vessels and within the heart. Color doppler incorporates "doppler shift", a change in frequency due to movement of a reflector away or towards a transducer. A positive doppler shift denotes an increase in sound frequency due to an object moving towards the transducer, whereas a negative doppler shift denotes a decrease in sound wave frequency due to an object moving away. By convention, red on ultrasound imaging is movement towards the transducer (positive doppler shift) and blue is movement away from the transducer (negative doppler shift).

Ultrasound images are subject to a number of artifacts [10] that can be misleading for an image interpreter. The artifacts that will be highlighted here include: acoustic shadowing, posterior enhancement, anisotropy, and reverberations and mirror image. Acoustic shadowing is a poor signal beyond a structure that is strongly reflective or absorptive of the ultrasound beam (e.g., gallstones within a gallbladder or bone) (Fig. 10.7a). Posterior enhancement is an increased signal intensity deep to structures that transmit ultrasound beams well (e.g., fluid-filled structures) (Fig. 10.7b). Anisotropy is a reflection of ultrasound beam not directly back at the transducer, often seen when scanning structures with many fibrils (e.g., tendons, muscles) and may appear erroneously hypoechoic. Reverberations are ultrasound waves that bounce back and forth from two strong parallel reflectors within the body (Fig. 10.7c). A mirror image artifact is an exact copy of an image from a highly reflective surface.

Ultrasound imaging enables the benefit of real-time evaluation of structures within the human body, void of any ionizing radiation. The risks associated with ultrasound are minimal but include the thermal heating of tissues [11]. The long-term consequences of thermal heating by ultrasound have yet to be fully elucidated or proven to be significant in an adult human. Potential neonatal effects with ultrasound imaging in the obstetric setting have remained inconsistent [12]. Nonetheless, the ultrasonographer in an effort to achieve a clinically relevant ultrasound image should strive to minimize the exposure time to ultrasound waves for all associated participants.

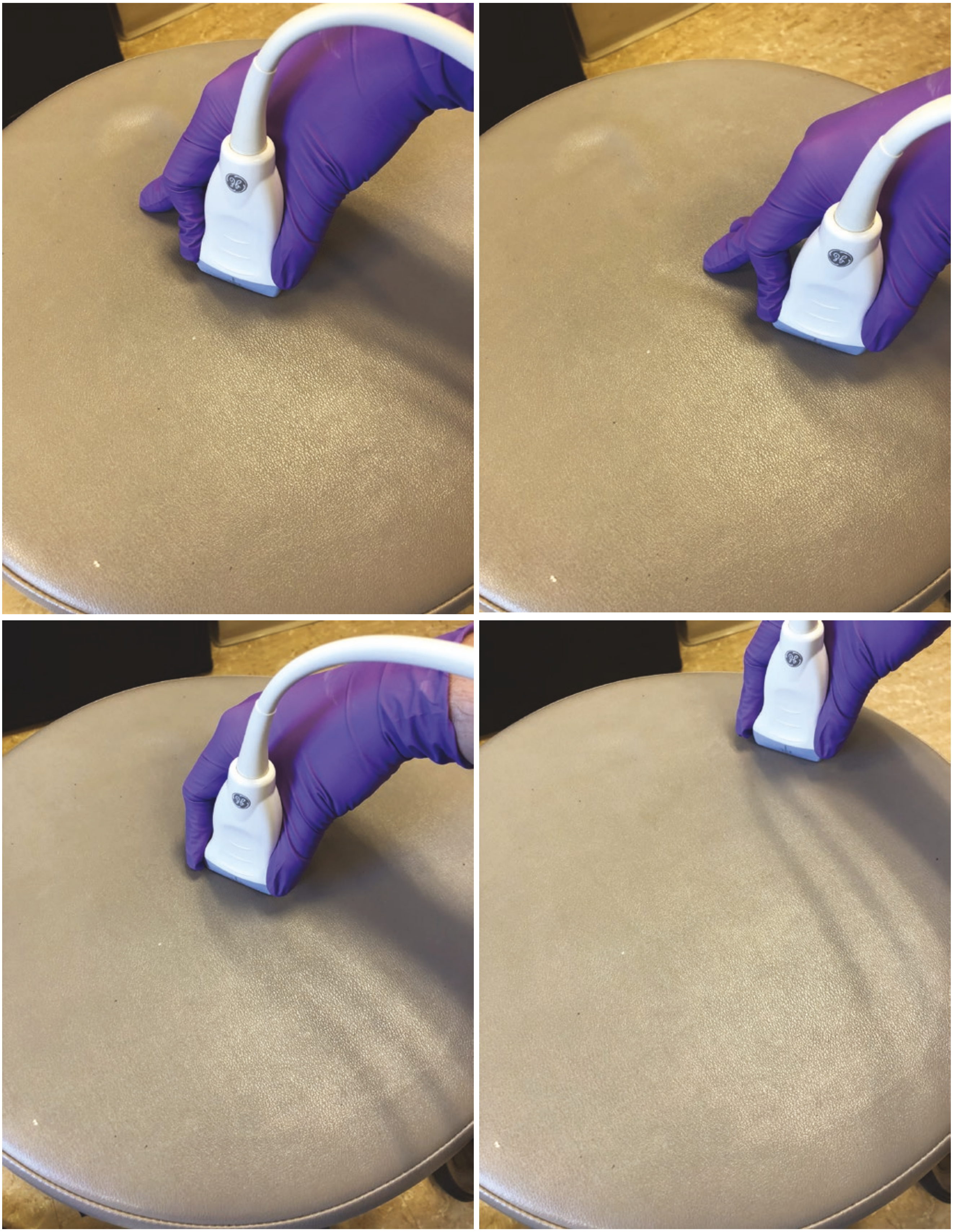
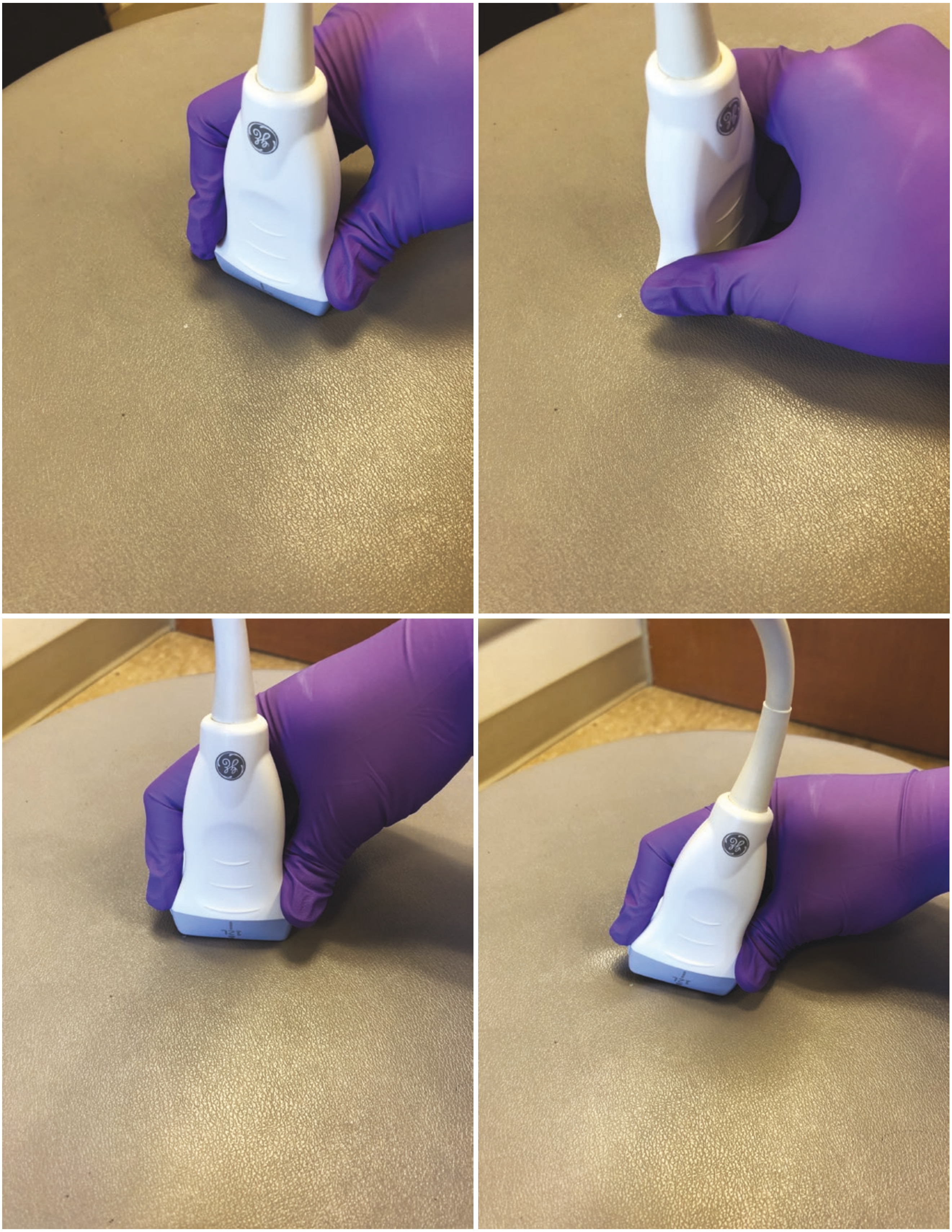


Fig. 10.5 (**a**) Sliding: probe motion side to side in the long axis; (**b**) Sweeping: probe motion forward and backward along the short axis; (**c**) Rotating: circular motion of probe; (**d**) Rocking: angling probe towards or away from the indicator; (**e**) Fanning: short-axis tilting of probe; (**f**) Compressing: downward pressure along probe, often to evaluate tissue/structural changes (e.g., delineating a compressible vein vs. an incompressible artery)



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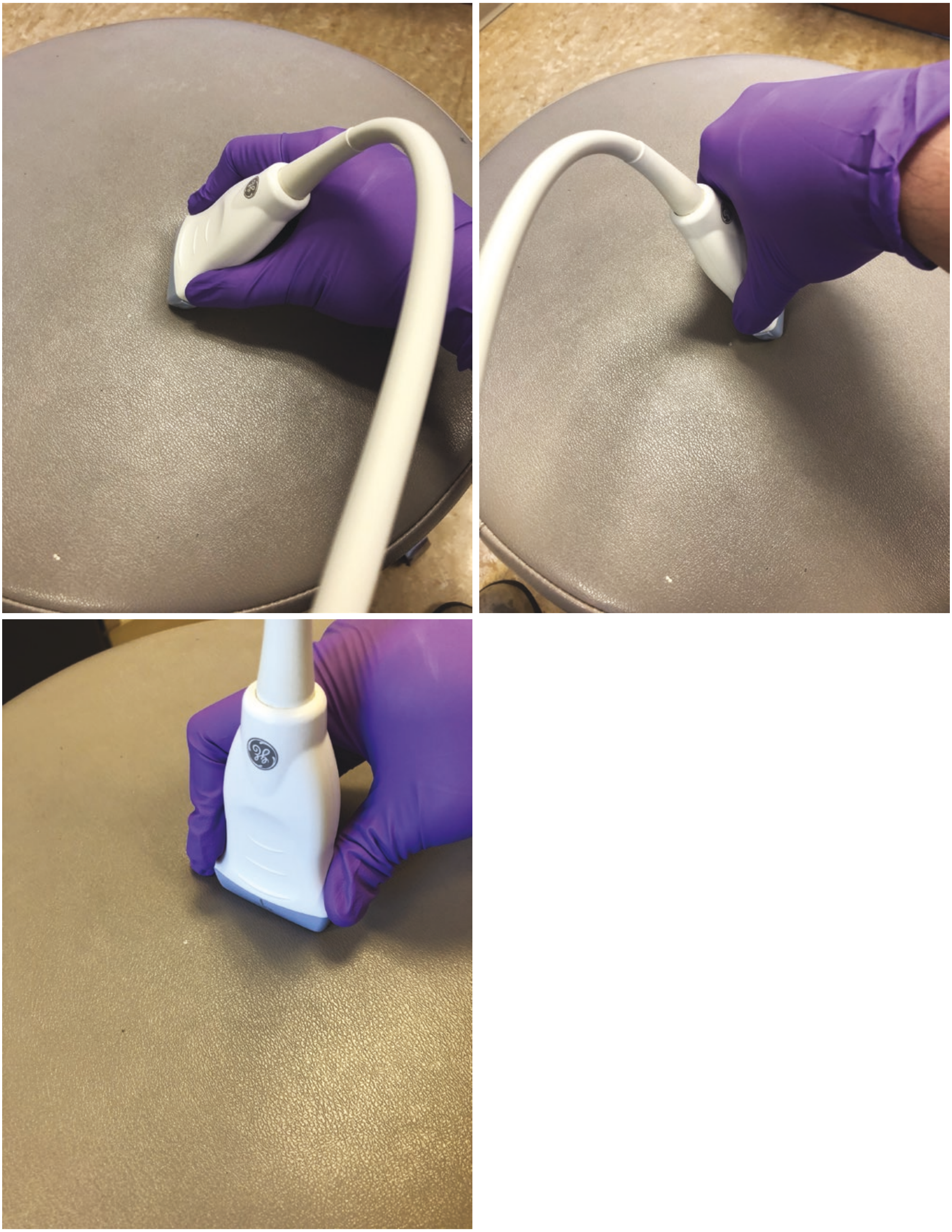

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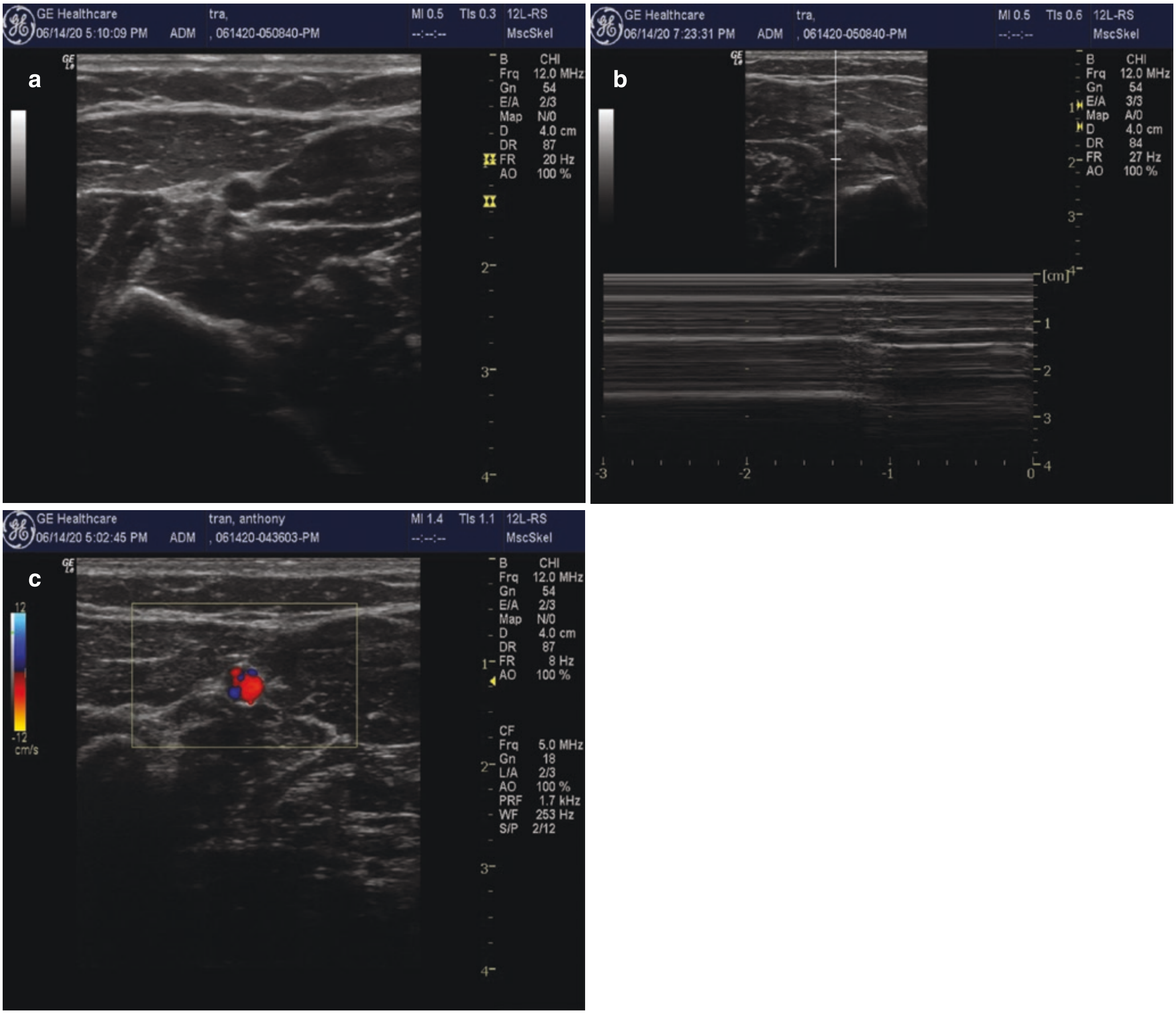

Fig. 10.6 Ultrasound images demonstrating various mode types. B-mode (**a**). M-mode (**b**). Color Doppler (**c**)

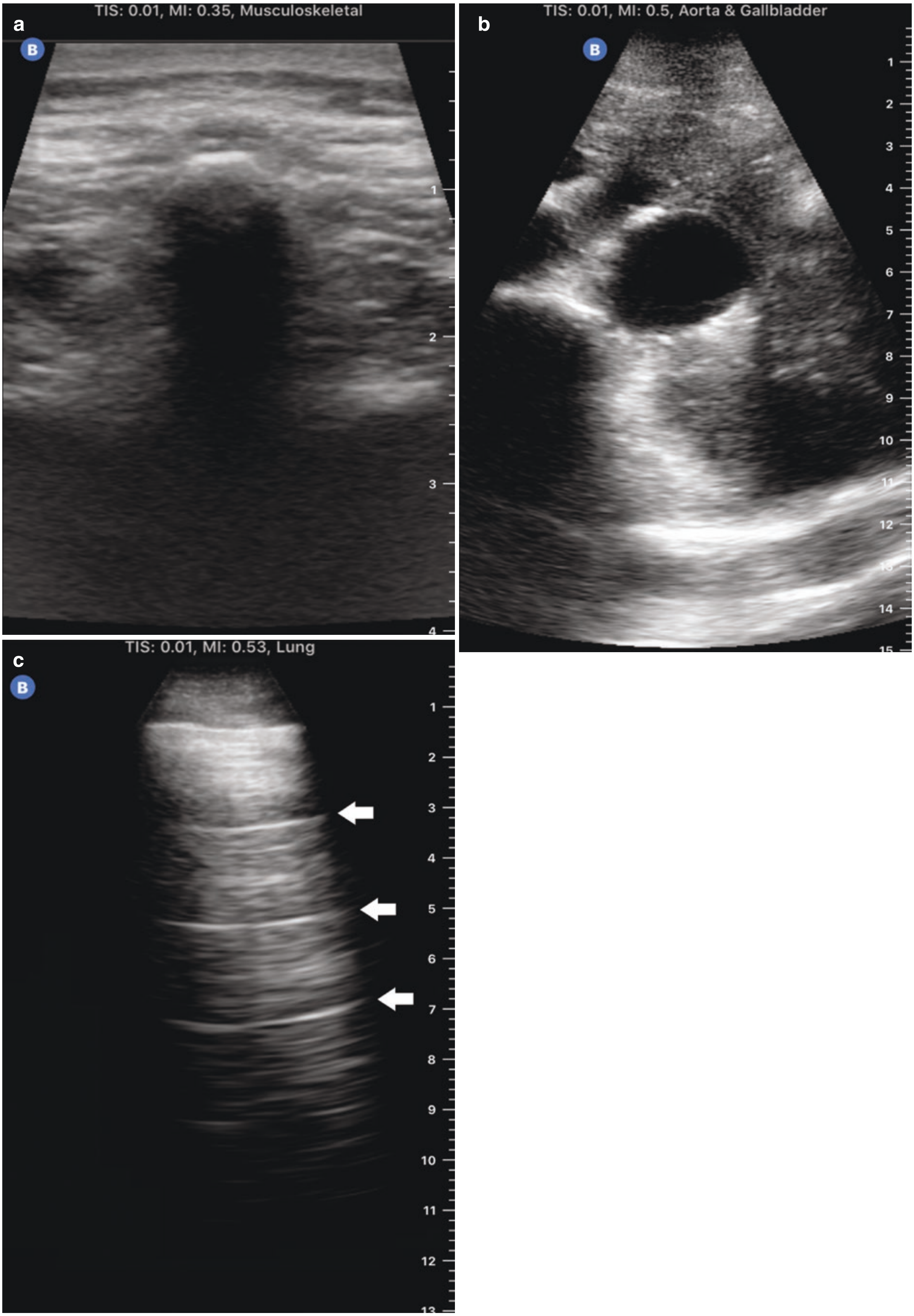

Fig. 10.7 Ultrasound images demonstrating various artifacts. Axial view of a lumbar spinous process with acoustic shadowing (**a**). Axial view of an abdominal aorta with posterior enhancement (**b**). Right lung with reverberation artifact (**c**, arrows)

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