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Basics of Ultrasound Applications in Anaesthetic Practice

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Abstract

Ultrasound has gained widespread acceptance in the field of perioperative medicine and intensive care. The anaesthesiologist working with ultrasound should have a basic knowledge regarding the physical principles of ultrasound, knobology, the ultrasound anatomy of structures to excel in the performance of a technique. This review throws light upon the minimum knowledge required while using the ultrasound.

Keywords: Anatomy, Physics, Probe, Ultrasound

Introduction

The application of Ultrasound (US) technology has increased in the past decade in anaesthesia, intensive care and emergency medicine practice. Many nerve blocks, airway assessments and vascular procedures are now performed using US. There are no major risks associated with US use as are seen with radiology based devices (ionising radiation) and hence their footprint is seen now-a-days in many operation theatres and intensive care units.

Physics of US

Ultrasound imaging is based on sound waves that are transmitted from, and received by, an US transducer utilizing frequencies of 2– 15 MHz (human hearing operates at 1000 – 20,000 Hz/ 1-20 kHz).

Ultrasound transducers employ an array of piezoelectric elements (Figure 1). Most use artificial polycrystalline ferroelectric materials (ceramics) [e.g. lead zirconate titanate (PZT)], which have piezoelectric properties[1]. Piezoelectricity is the ability of certain materials to generate an electric potential in response to applied mechanical stress. The word is derived from the Greek piezo or piezein, which means to squeeze or press. Each piezoelectric element is wired to allow the application of short high voltage pulses during the transmission of ultrasound waves and the reception of the electronic signal generated during the receive phase. The average 2D transducer utilizes 128 piezoelectric elements.

When a current is applied across the crystal, it expands and contracts as the polarity of the voltage changes. This produces a series of pressure waves (sound waves). This also works in reverse; when the sound waves returns, it squeezes and stretches the crystal generating a voltage change across its surface, which is amplified and forms the receiving signal.

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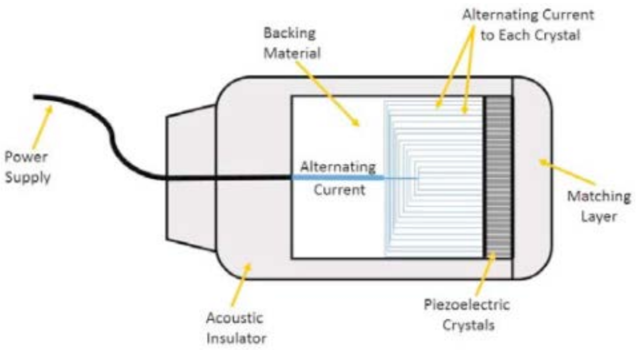

Figure 1. The Ultra sound probe.

The speed of ultrasound waves in human tissues varies but on an average, it is 1540 m/s (Table 1).

Table 1. Propagation velocity across various tissues

Medium	Velocity
Air	**331 m/s**
Brain	**1541 m/s**
Kidney	**1561 m/s**
Liver	**1549 m/s**
Muscle	**1585 m/s**
Fat	**1450 m/s**
Soft Tissue (Average)	**1540 m/s**
Bone (different densities)	**3000 to 5000 m/s**

The transducer-emitted waves strike various interfaces/ tissues in the body in their path. Some of the energy is transmitted and some, reflected (Transmission and Reflection) (Figure 2). Apart from transmission across the tissues and reflection from them, the US waves interact with tissue in three other ways: Scattering, Attenuation and Refraction (Figure 3).

Figure 2. Reflectivity of the US beam.

The main component of interest, the reflected energy, travels back to the transducer where each of its elements acts as a receiver. The reflected ultrasound energy is converted into tiny electrical signals. The ultrasound system processes these signals to produce an image that represents these reflections on the monitor.

The reflectivity is dependent on the difference in acoustic impedance between those structures and also the angle of the US beam. Reflectivity is greatest when the object being visualized is perpendicular to the angle of the US beam. As the angle of incidence decreases from 90^0, the US beam is reflected away from the transducer and will not form part of the image.

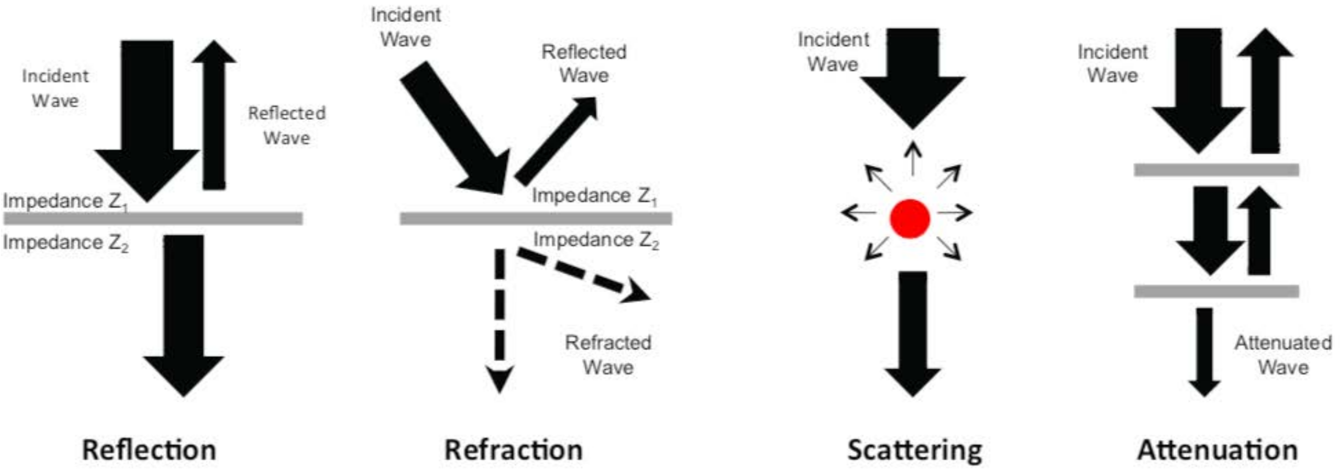

Figure 3. Reflection, refraction, scattering and attenuation of incident US wave.

The Sonographic Appearance of Tissues

The reflection of the sound waves from tissues (echoing) can vary from being anechoic (no reflection- dark/ black), hypoechoic (partial reflection-grey/dark/black) to hyperechoic (maximum reflection- bright /white) (black to white with shades in between). Apart from the image produced by the structure in the area of interest, colours and shades produced by the surrounding structures helps to reconfirm correct identity of the structure. The appearances of different tissues are shown in Table 2.

The Sonographic Appearance of Nerves

Appearance depends primarily on its size and the amount and make-up of the support tissue (epineurium, perineurium). Axons, or in reality fascicles (collection of axons), appear black (hypoechoic) and the supporting tissue appears bright (hyperechoic). (The nerves appear as black bubbles with white borders). The fascicular pattern seems to be typical of large peripheral (e.g. median, ulnar and radial) nerves and is not seen with smaller (e.g. recurrent laryngeal and vagal) nerves. At different levels (roots, trunks, and peripherally), the same nerve may vary in appearance from being hypoechoic (bubbles/holes at the roots) to hyperechoic ovoid, triangular or flattened structures in the periphery. This is possibly because of the changing nature of the fascial covering of the nerve as they divide and pass through different tissues.

In cross sectional view, nerves can have a round, oval, or triangular shape. A single nerve can have all three shapes along its nerve path as it travels between adjacent structures. Ultrasound can easily follow the oblique course of nerves, and this is difficult to accomplish with other imaging modalities such as magnetic resonance imaging[1].

Nerves are not static or fixed structures. They can be affected by the gravity and body position (subarachnoid space), by extremity movements (sciatic nerve rotation in the popliteal fossa), etc., They can be displaced by the pressure of the transducer in superficial blocks; the block needle or the

Table 2. Sonographic appearance of tissues

Tissue	Ultrasound Appearance
Arteries	Anechoic (black circles, tubes), pulsatile (further identified with colour Doppler)
Veins	Anechoic (black circles, tubes), compressible (further identified with colour Doppler)
Tendons (strongly anisotropic) Fibrillar pattern	Longitudinal, tubular structure. Internal architecture, loosely packed continuous blurred bright lines (hyperechoic), pale surface. Transverse, circular structure with pale halo (tendon sheath). Internal architecture hyperechoic (semi-bright) dots (tendon fibrils) loosely packed, within hypoechoic (darkened) surroundings, granular appearance
Nerves (weakly anisotropic) Fascicular pattern	Longitudinal, tubular structures, bright surface. Internal architecture multiply broken bright (hyperechoic) lines. Transverse, circular structure with bright surface (epineurium). Internal architecture multiple hypoechoic black dots (nerve fascicles) with bright outlines within bright surroundings (connective tissue, perineurium), speckled appearance
Fat	Hypoechoic areas with streaks of irregular hyperechoic lines
Fascia	Thin layer hyperechoic structures at tissue boundaries
Muscle	Feather like in longitudinal view-'starry night in cross section'
Pleura (and air)	Thin hyperechoic line(s), one or two with movement (with lung parenchyma hypoechoic, reverberation artefact present)
Lung	Multiple grey echoes, unable to see into lung (The ultrasound beam will not pass through air (whiteout/ dirty picture). It is therefore not possible to see through or into air- filled cavities. It is important to ensure a layer of gel on the probe to provide air-free contact with skin
Bone Periosteum	Hyperechoic ++ line, with shadowing underneath
Cortex and Medulla	Anechoic, black (acoustic shadow, due to reflection of beam by periosteum)
Cysts	Similar to vascular structures, appear as hypoechoic circles in longitudinal view

drug injection, a safety factor to avoid direct nerve injury. They cannot be compressible as the blood vessels are[2].

Tendons can be confused with nerves with similar US appearance but they are present only at the origin and insertion areas. A fibrillar echotexture pattern is seen: fine linear echos resembling fibrils, with hypoechoic areas that are not as prominent (like the fine hairs of a violin's bow). A 10-MHz transducer can differentiate the fascicular and fibrillar echotexture patterns.

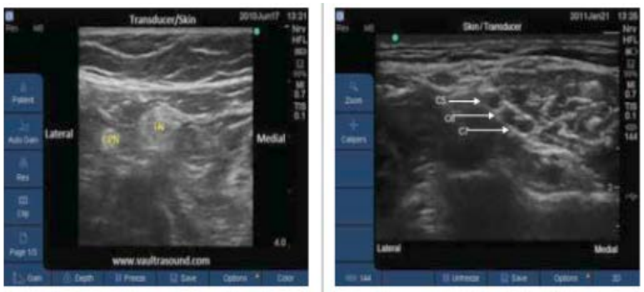

Figure 4. Nerves (Popliteal Fossa, Brachial Plexus).

The sonographic appearance of other tissues is shown in the series of images.

Figure 5. Nerves and Tendons: Both appear hyperechoic near joints, differentiated by following their course into the muscle.

Figure 6. Adipose tissue: Most superficial layer, seen as hypoechoic areas with streaks of irregular hypoechoic lines.

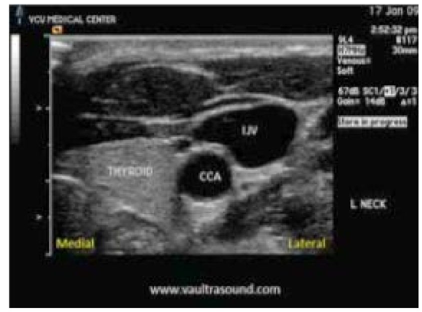

Figure 7. Arteries, Veins and Cysts: Appear as circular anechoic structures in short-axis.

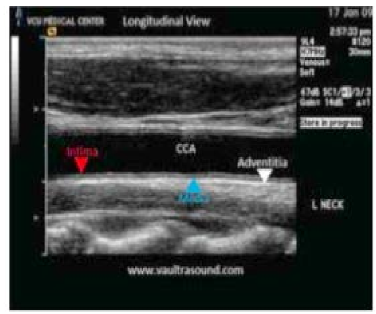

Figure 8. Arteries: *Round* in SAX, tube-like in LAX view. *Pulsatile* in nature and difficult to compress. Display colour on Doppler.

Figure 9. **Veins:** *Ovoid* in SAX, tube-like in LAX. Easily *compressible*. Valves may be visible. Display colour on doppler.

Figure 10. **Muscle:** Heterogeneous on US due to different acoustic impedances between cell structures, water content within the cells and the fascia.

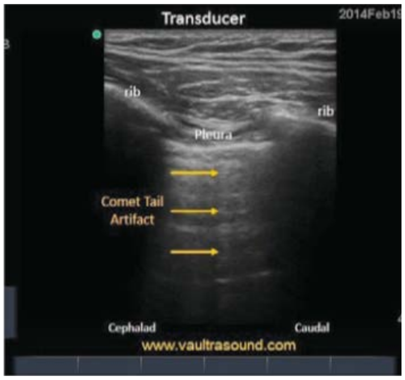

Figure 11. **Pleura:** Appears as a hyperechoic line with "comet tails" beneath it.

Figure 12. **Bone:** A significant reflector, creating a hyperechoic area with significant shadowing beneath it.

Frequency of US Waves

The wavelength and frequency of US are inversely related, i.e., ultrasound of high frequency has a short wavelength and vice versa. Sound absorption is directly proportional to the frequency of the US beam-less frequency, less attenuation and more frequency, more attenuation. As low-frequency waves are less attenuated, they will penetrate tissues better than high frequencies.

High-frequency (probe) gives good resolution but lacks the ability to penetrate, whereas low-frequency (probe), although penetrating deeper, has reduced resolution[3].

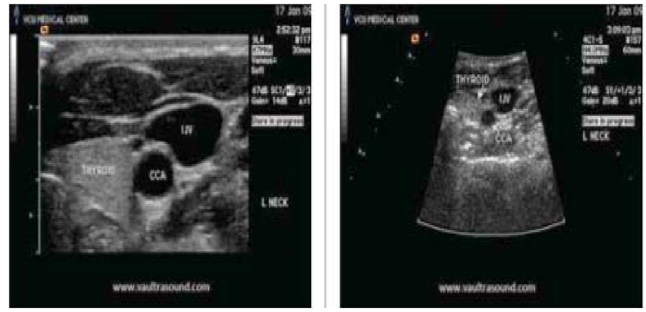

Figure 13. High vs low frequency images.

The Types of Probes

The most commonly used probe in regional anaesthesia practice is the high-frequency, linear array probe (5-10 MHz), as this gives good spatial resolution for the nerves and plexuses, which are usually superficial (1- 5cm deep). A low-frequency curvilinear probe (2-5 MHz) can be useful for deeper nerves and plexuses, but it is limited by its poor spatial resolution at increasing depth. Most machines have pre-set factory setting (e.g. musculoskeletal, vascular, nerve) to optimize tissue visibility and picture quality. Further adjustment of depth and gain will focus the beam to the correct level and allow an improved grey/white scale. Access may be limited by the size of the probe (footprint) and therefore smaller probes may be needed in certain anatomical locations and patients (supraclavicular, paediatrics).

Linear-array transducers have a high scan line density and therefore produce the best image quality (Figure 14). These transducers, in particular the high-frequency broad band linear probes, have proven the most useful for nerve imaging. *Images from linear arrays are displayed in rectangular format.* When a linear transducer is needed but the space at the block site is small, a compact linear ("hockey stick") transducer can be very useful.

Curvilinear arrays produce images in sector format. These transducers are useful when the working room

Table 3. Characteristics of Low vs high frequency views

High Frequency	Low Frequency
• More cycles / Sec • Higher Resolution Images • Increased attenuation • Imaging limited to shallow depths	• Fewer Cycles / Sec • Greater Tissue penetration but lower resolution • Less attenuation allows for imaging of deeper structures

at the anatomic site for the block is limited (e.g., the infraclavicular region) (Figure 15). Curved probes are easier to rock and provide a broader view.

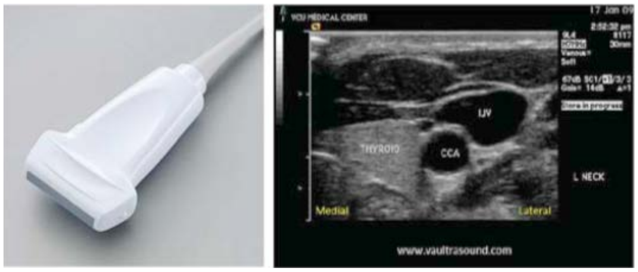

Figure 14. Linear array probe and rectangular display.

Figure 15. Curved array probe and sector display.

Imaging Planes for Nerves by US

Nerves can be imaged in the short axis or the long axis (transverse and longitudinal). In short-axis view (SAX), the nerve is visualized in section and in long-axis the nerve is visualized longitudinally (Figure 16)[5].

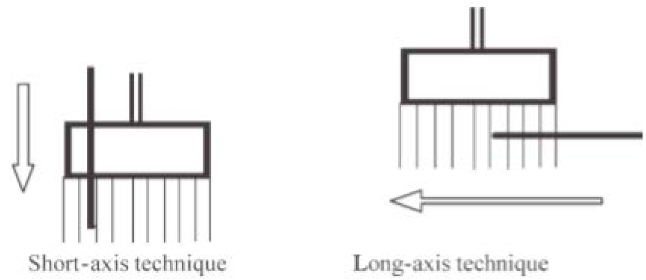

Figure 16. The SAX and LAX views.

Generally, short axis is used because: 1. It is easy to identify peripheral nerves with this approach 2. The fascial barriers which surround the nerves are seen with good resolution 3. The distribution of drugs around the nerve is visualised, in real time 4. Even if the probe position is disturbed to an oblique position, the focus is not lost.

Peripheral nerves have an internal fascicular pattern characterized by hypoechoic (dark) fascicles surrounded by hyperechoic (bright) connective tissue (cervical nerve roots-ventral rami have a monofascicular appearance on ultrasound scans). The fascicular echotexture results in the "honeycomb" appearance of nerves on short axis (transverse) scan.

The Imaging Approaches

Apart from the technical aspects related to the probes for transfer of beam (SAX and LAX), two approaches related

Table 4. Choice of transducer[4]

Structure	Requirements
Abdominal organs (liver, kidneys, etc.)	3–5 MHz required for adequate penetration to deep structures. Curved array gives good intercostal/ subcostal access with a wide field for both deep and superficial structures
Vascular	Linear array for superficial vessels. Allows good skin contact and wide field of view for superficial, linear structures, 5–12 MHz
Nerves	10–15 MHz, small footprint linear array for superficial structures such as the median nerve/ brachial plexus. Lower frequency (4–7 MHz) may be required for deeper structures such as the adult sciatic nerve and infraclavicular brachial plexus
Cardiac	Small footprint phased array. Ease of access via limited intercostal/parasternal spaces. Wide field of view (adults 1.5–4 MHz, pediatric 3.5–8 MHz) Transesophageal imaging requires specialist transducer. Adults 3–10 MHz, pediatric 4–10 MHz

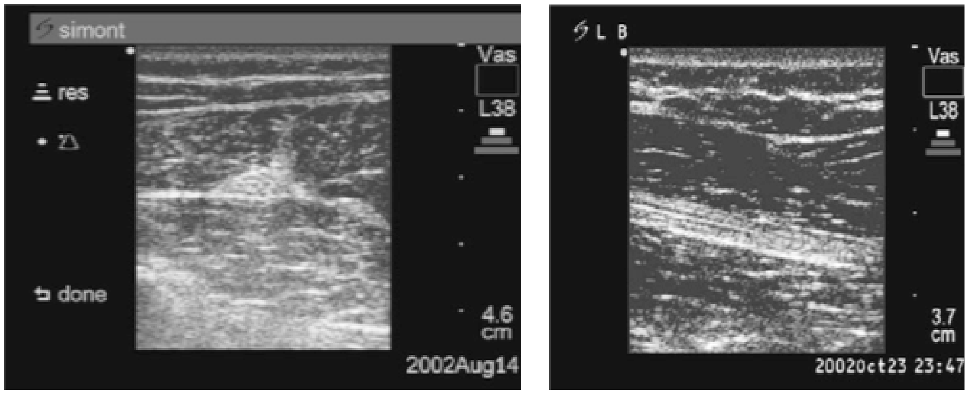

Figure 17. Sciatic nerve- short axis and long axis view.

to the nerve / vessel location are used- the Out of Plane (OOP) and In Plane Approach (IP) (Figure 18). (2)

The Out-of-plane technique: Here the insertion direction is such that the needle crosses the plane of imaging near the target. The target is centered within the field of view and the depth noted. Sliding and tilting of the transducer allows the needle tip to be followed and localised / fixed in the field of scan.

The In-plane Needle Approach: When this approach is used, the needle is visualised in its entirely (shaft and tip) in the field of scan. While scanning, the imaged needle path should be maximized by placing the target on one side of the imaging field of view away from the approaching needle. The transducer can be manipulated as necessary to bring the needle into the plane of imaging. The IP approach requires longer needle insertion paths than the OOP approach and can therefore cause more patient discomfort. Optimal visualization of the needle occurs when the needle is parallel to the active face of the transducer and the tip is better seen with the bevel directly facing (or averting) the active face of the transducer.

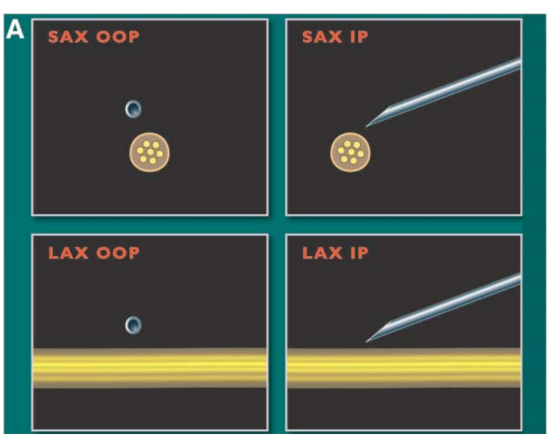

Figure 18. Out of plane and in plane approach.

The long axis in plane approach is more suitable for vascular access procedures than nerve blocks as the alignment on nerves can be difficult as they do not always have a straight path and slight movement of the transducer can result in loss of the nerve image. Furthermore, with the long axis IP approach, the needle is constrained to come down directly on the nerve and therefore may increase the chance of injecting into the targeted structure.

Usually for the purposes of introducing a needle, the SAX is preferred, as it is easier to hold the nerve in view while introducing the needle[6]. The needle can then be introduced either along the long axis of the probe (long-axis technique, LAT) or across the short axis of the probe (short-axis technique, SAT).

Doppler and Colour Doppler Use in Ultrasound

(Pulsed Wave Doppler, Continuous Wave Doppler and Colour Flow Doppler)

Doppler is used to evaluate blood flow where the ultrasound transducer is both the source and receiver of ultrasound waves. The blood flow is in motion relative to the imaging transducer. It is based on the Doppler Effect- a change in the observed frequency of a wave, as of sound or light, occurring when the source and observer are in motion relative to each other, with the frequency increasing when the source and observer approach each other and decreasing when they move apart – this is also called Doppler Shift. If the source is moving toward the receiver, the frequency goes up. If the source is moving away from the receiver, the frequency goes down (Figure 19).

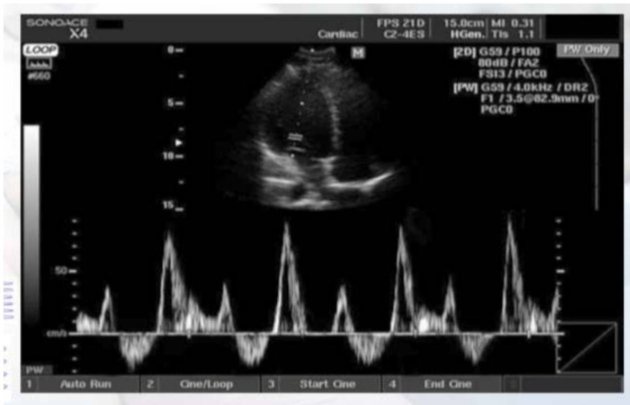

Figure 19. Doppler flow assessment.

Pulsed Wave Doppler (PW): The system produces short bursts of ultrasound waves (TX) and listens to the reflected waves (RX) in between, displayed by B mode images (Figure 20). The same crystals are being used for transmission and receiving of the US waves. PW allows us to sample at a specific depth along the Doppler line. This is represented by the sample volume ('Gate'). It provides display direction, velocity and quality of the flow and of accurate velocity and clear audible signal.

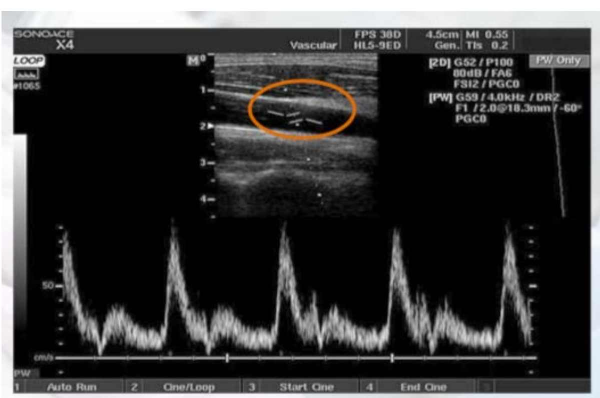

Figure 20. Pulsed wave doppler.

Continuous Wave Doppler (CW): Uses different piezoelectric elements to send and receive US waves. One element constantly sends ultrasound waves of a single frequency while another constantly receives the reflected waves. No B-mode image is acquired or displayed (Figure 21). Doppler can display flow at any velocity and cannot position the sample to listen at a specific depth. It samples everything along the Doppler line.

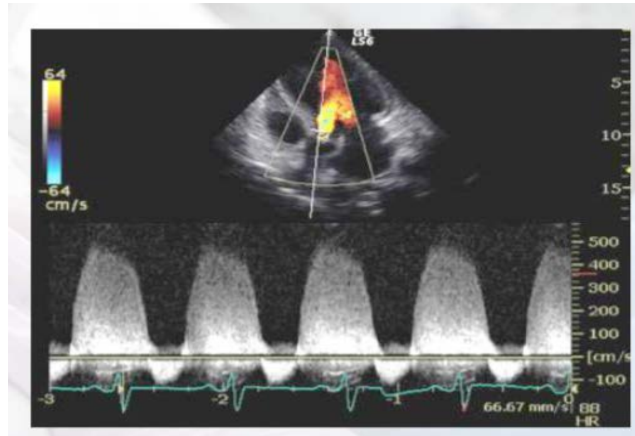

Figure 21. Steered CW doppler in cardiac imaging.

***Colour Flow Doppler*:** Colour Doppler provides a method to visualize blood flow and differentiate it from surrounding tissue. It provides information about the presence of blood flow, its direction and speed. It utilizes pulse-echo Doppler flow principles to generate a colour image. This colour image is superimposed on the 2D grayscale image. The red and blue colours provide an indication of the flow velocity and direction. Blue represents flow away from the transducer and red, towards the transducer ('BART') (Figure 22).

For both red and blue colours, the darker the shade, the slower the flow and lighter the shade, the faster the flow.

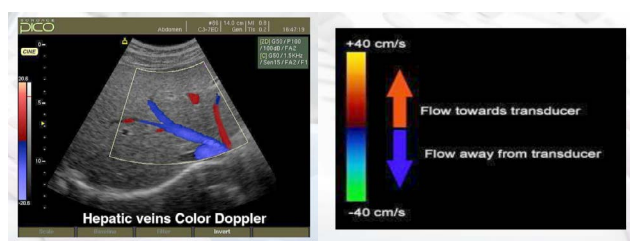

Figure 22. The direction of flow relative to transducer- 'BART'.

The Needle Visibility

The insertion angle and gauge of the needle influence the ultrasound visibility of the needle[7]. Steeper angles cause reduced needle visibility due to backscatter received by the US transducer[8]. Entering the skin with the needle close to the transducer disturbs the surface contact and forces steep angles to the target. Large-bore needles are easier to visualize for two reasons. First, the larger cross-sectional area makes the needle easier to locate. Second, larger needles are less flexible and therefore less likely to bend out of the plane of imaging. Larger needles cause increased tissue damage and patient discomfort. Needle tip and shaft visibility is improved by keeping the needle shaft at more than 55° to the US beam while keeping the needle tip at 0 or 180° to the US beam. Advances in needle technology to improve the reflective signal have included dimpling, roughing, scoring, and the application of a polymeric coating to the needle with the aim of increasing the return of the US signal to the transducer[9].

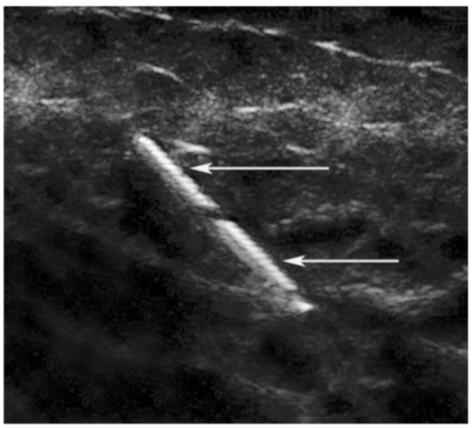

Figure 23. An echogenic needle; arrow indicates cornerstone technology.

Needles with piezoelectric polymer sensors at the tip, beam steering technology and the use of proprietary software algorithms within the US machine software to adjust the needle-beam angle to 90^0 are other developments[10].

Advantages of using US

The following are the advantages of using US for regional anaesthesia and for vascular applications.

1. Allows real-time direct visualization of nerves and surrounding anatomical structures and their relationships (arteries, veins, lung, other nerves) and hence increased success rate.
2. Allows direct visualization of the spread of local anaesthetic during injection.
3. Avoidance of complications (e.g., intraneuronal or intravascular local anaesthetic injection, pleural injury, etc.,).
4. Avoidance of painful muscle contractions during nerve stimulation.
5. Reduction of the dose of local anaesthetic: Also reducing risk of toxicity.
6. Faster sensory onset time.
7. Improved quality of block.
8. Safe to perform under general anaesthesia, (e.g. children) and even to be repeated if ineffective.
9. Close supervision possible during training.
10. Has steeper learning curve.
11. Cheaper compared with other imaging modalities, can be performed in the operating theatre and carries no radiation risk.
12. Portability
13. Allow for patient variability (e.g. size, shape, anatomical variations).
14. Can be used in patients with neuropathy do not respond normally to PNS.
15. Can assess catheter position.

The Procedure in Brief

All adjustable US variables, i.e. penetration depth, the frequencies, and the position of the focal zones, must be optimized for the type of block to be performed.

The patient should be appropriately starved, IV access secured, basic monitoring attached and resuscitation equipment and drugs available. A skilled assistant should be present. If the patient is awake, the site of needle insertion should be anaesthetized with local anaesthetic.

Air is the worst medium for ultrasound (99% of the beam is reflected from an air-tissue interface obscuring any view of deeper structures) and it is therefore important to ensure an adequate layer of gel on the probe and remove all air from the injectate to prevent 'whiteout'.

The ten steps of peripheral US guided nerve block:

1. Visualize key landmark structures including muscles, fascia, blood vessels and bone. (Pre-block scan / Scout scan)
2. Identify the nerves or plexus on short axis imaging
3. Confirm normal anatomy or recognize anatomical variation(s)
4. Plan for the safest and most effective needle approach
5. Use all aseptic precautions: Both the skin and the US probe need to be disinfected. Most conventional

disinfectants can be used on US probes. A sterile US jelly will provide aseptic conditions for the nerve block (a jelly for urinary catheters can also be used). The probe can also be wrapped in a sterile glove. The site is cleaned with alcohol solution (isopropyl alcohol 70%), draped.

6. During needle placement and advancement, the location of the needle tip should be identified real time, at all times. When in doubt about needle-nerve interface, gently move needle to ascertain that the nerve does not move with it (indicating that tip is embedded within epineurium).
7. Consider a secondary confirmation technique, such as nerve stimulation
8. When the needle tip is presumed to be in the correct position, inject a small volume of a test solution: "Hydrodissection" can be utilized to delineate anatomy.
9. Make necessary needle adjustments to obtain optimal perineural spread of local anaesthesia
10. Maintain traditional safety guidelines of frequent aspiration, monitoring, patient response, and assessment of resistance to injection. Aspiration will minimize the risk of intravascular placement of local anaesthetic.

Manipulation of transducer: The effort to get the best image using the probe is dynamic and needs experience. The right location with the right direction, surface pressure and tissue opposition will result in best image catch, with minimum time.

1. Sliding (moving contact). Sliding the transducer along the known course of the nerve using a short-axis view often helps with nerve identification.
2. Tilting (cross-plane, side-to-side). The echobrightness of peripheral nerves will vary with the degree of tilt. Optimizing this angle is critical to promote nerve visibility.
3. Compression. Compression is often used to confirm venous structures. To improve imaging, compression not only provides better contact but also brings the structures closer to the surface of the transducer. Soft tissue is subject to compression and therefore estimates of tissue distances will vary.
4. Rocking (in-plane, toward/away from indicator). Rocking is often necessary to improve needle and anatomic structure visibility when the working room is limited.
5. Rotation. Some rotation of the probe will produce true short-axis views rather than oblique or long-axis views.

Needle Guidance Devices

Needle guides direct the needle in a fixed, predetermined direction to various depths from the transducer surface, depending on the selected angle of the guide relative to the transducer. These vary between manufacturers and may be a fixed part of the transducer or detachable, sterile, single-use plastic, or reusable metal devices. Fixed guides lie within the sterile sheath, while sterile, detachable guides are attached onto the probe over the sterile sheath (Figure 24)[11].

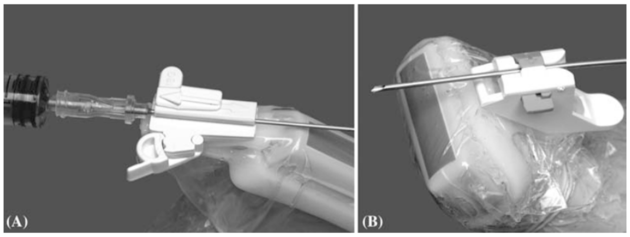

Figure 24. Needle guides: Aligned either along the long axis or the short axis (transverse configuration) of the probe (CISCO© guide & Sonosite© probes).

Guides are designed to be used in either the transverse or the longitudinal plane. Tram lines can be generated electronically on the display to show the approximate path of the needle. These guides are particularly useful for directing needles into deeper structures like the kidney. Longer needles will be required to compensate for the less acute angle of trajectory and the section of needle held in the guide. The direction of the bevel and the flexibility of the shaft may alter the trajectory, particularly with long needles.

Conclusion

The use of ultrasound in different clinical settings is on the rise. As further research and advancements in ultrasonography take place, making it a safer and efficient method, understanding the basics as well as its applications is essential for every anaesthesia provider for better outcomes and patient safety.

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