Interventional ultrasound in clinical medicine

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INTERVENTIONAL ULTRASOUND IN CLINICAL MEDICINE

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Abbreviations

BI-RADS - Breast Imaging Reporting and Data System
CLABSI - Central Line-Associated Bloodstream Infection
CRC - Colorectal Cancer
CT - Computed Tomography
EUS - Endoscopic Ultrasound
FAST - Focused Assessment with Sonography for Trauma
FFP - Fresh Frozen Plasma
FNA - Fine Needle Aspiration
GI tract - Gastrointestinal Tract
HCC - Hepatocellular Carcinoma
ICU - Intensive Care Unit
IVUS - Intravascular Ultrasound
MRI - Magnetic Resonance Imaging
PICC line - Peripherally Inserted Central Catheter line
POCUS - Point-of-Care Ultrasound
PT - Prothrombin Time
PTT - Partial Thromboplastin Time
RaCeVA - Rapid Central Vein Assessment
RCC - Renal Cell Carcinoma
SLDs - Spring-loaded core needle biopsy devices
TSH - Thyroid Stimulating Hormone
US - Ultrasound
US-TTNB - Ultrasound-guided transthoracic needle biopsy
VAB - Vacuum-assisted biopsy
VABB - Vacuum-Assisted Breast Biopsy

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Abstract

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The properties of ultrasound, a known medical tool, allow the use of sound waves with high frequencies to penetrate the body and interpret tissue properties based on their densities. Ultrasound is used in clinical medicine because of its benefits, but is also widely used in several interventional procedures, and is known as interventional ultrasound. In those procedures, ultrasound serves as the eyes of the operator, and by that, interventional ultrasound decreases complications as well as makes the procedure quicker and safer.

This paper presents a comprehensive overview, beginning with the general physical properties of ultrasound that help recognize normal and pathological anatomical structure and what is interventional radiology. Then, be discussed the comprehensive use of interventional ultrasound in the field of medicine. Those will include the indications, steps in the process, and complications of several interventional procedures, with emphasis on the importance of ultrasound in guidance of those techniques. Some key applications of interventional ultrasound include vascular access and vascular procedures, biopsies, and injections. Those interventions will be discussed for different body systems with organs with emphasis on how the use of ultrasound is significant for those procedures to be more successful.

In addition, some limitations will be mentioned, and their solutions in the developing field of interventional ultrasound. Those include the approach to improving the clinical skills of the operator, the anatomical barriers of the patient, and the technological aspect of ultrasound in the future of clinical and interventional medicine.

Keywords: Interventional ultrasound, interventional medicine

Sažetak

Naslov: Intervencijski ultrazvuk u kliničkoj medicini
Autor: Eliran Rond

Svojstva ultrazvuka, poznatog medicinskog alata, omogućuju korištenje zvučnih valova visokih frekvencija za prodiranje u tijelo i tumačenje svojstava tkiva na temelju njihove gustoće. Ultrazvuk se koristi u kliničkoj medicini zbog svojih prednosti, ali se također široko koristi u nekoliko interventnih postupaka, i poznat je kao interventni ultrazvuk. U tim postupcima, ultrazvuk služi kao oči operatera, i time interventni ultrazvuk smanjuje komplikacije, ali i čini postupak bržim i sigurnijim.

Ovaj rad pruža sveobuhvatan pregled, počevši od općih fizičkih svojstava ultrazvuka koja pomažu u prepoznavanju normalne i patološke anatomije i što je interventna radiologija. Zatim će biti raspravljeno o sveobuhvatnoj upotrebi interventnog ultrazvuka u medicini. To će uključivati indikacije, korake u procesu i komplikacije nekoliko interventnih postupaka, s naglaskom na važnosti ultrazvuka u vođenju tih tehnika. Neki ključni primjeri primjene interventnog ultrazvuka uključuju vaskularni pristup i vaskularne postupke, biopsije i injekcije. Ti će se zahvati raspravljati za različite tjelesne sustave s organima s naglaskom na to kako je upotreba ultrazvuka značajna za uspješnost tih postupaka.

Osim toga, spomenut će se neka ograničenja i njihova rješenja u razvijajućem području interventnog ultrazvuka. To uključuje pristup poboljšanju kliničkih vještina operatera, anatomsku barijeru pacijenta i tehnološki aspekt ultrazvuka u budućnosti kliničke i interventne medicine.

Ključne riječi: Intervencijski ultrazvuk, interventna medicina

Introduction

Humans can hear in frequency between 20Hz to 20kHz, while ultrasound machines operate at frequencies above 20kHz, which gives the meaning to its name. This machine uses sound pulses that move differently in each type of material based on its density, and this principle allows interpretation of the tissue characteristics.

Several aspects and properties of ultrasound machines can be used in order to make several invasive procedures safer and easier. Therefore, the main goal is discussion of how those properties work, used, and influence those procedures.

Literature review

1. Principles of ultrasound in medicine

The basics of ultrasound physics will be discussed in several aspects. First, the characteristics of sound as it travels through matter. Then, the modes of ultrasound. Finally, the use of ultrasound in medicine.

1.1 Basic physics of sound waves

There are some characteristics of sound waves propagation as sound can be reflected, refracted, or absorbed when transmitted into the body.

- Reflection happens when sound passes through materials with different densities, causing sound waves to move backwards. Reading of the reflected waves helps the computer to create an image of the tissue.
- Refraction happens when sound changes direction when it passes through material as the speed of sound changes in this transition, causing bending of the waves. This by itself can cause inaccuracies in the interpretation of the ultrasound image.
- Absorption occurs when sound energy is converted into thermal energy, with greater absorption of this energy occurring in tissues such as bones. It can lead to acoustic shadowing which occurs when sound energy is reduced due to reflection or absorption. Acoustic shadowing is represented by the black area behind the material. This is in contrast to acoustic enhancement in which ultrasound waves will penetrate fluid-filled tissue, and a white area will appear behind it (figure 1). It can be useful for distinguishing cystic from solid lesions (1).
- Attenuation occurs when sound is decreased in intensity over distance. This can affect image quality in the form of lateral resolution, with higher-frequency waves attenuating more quickly when comparing lower-frequencies. This principle allows the operator to choose the desired frequency to balance the quality and depth of the tissue. More superficial tissues will be seen with high-frequency waves and deeper tissue with low-frequency waves. Other types of resolutions

are axial resolution that relates to discerning structures along the path of the beam and temporal resolution that depends on the frame rate.

Those characteristics of ultrasound allow different visualization of tissue based on its echogenicity. Dense materials or tissues reflect more sound, creating bright "white" images termed hyperechoic, as seen with bones. Some tissue appears “gray”, termed isoechoic or hypoechoic. Fluids transmit sound waves, resulting in "black" images termed anechoic. Air on the other hand is a strong reflector, making it challenging to visualize structures behind it and leaves shadowing (2).

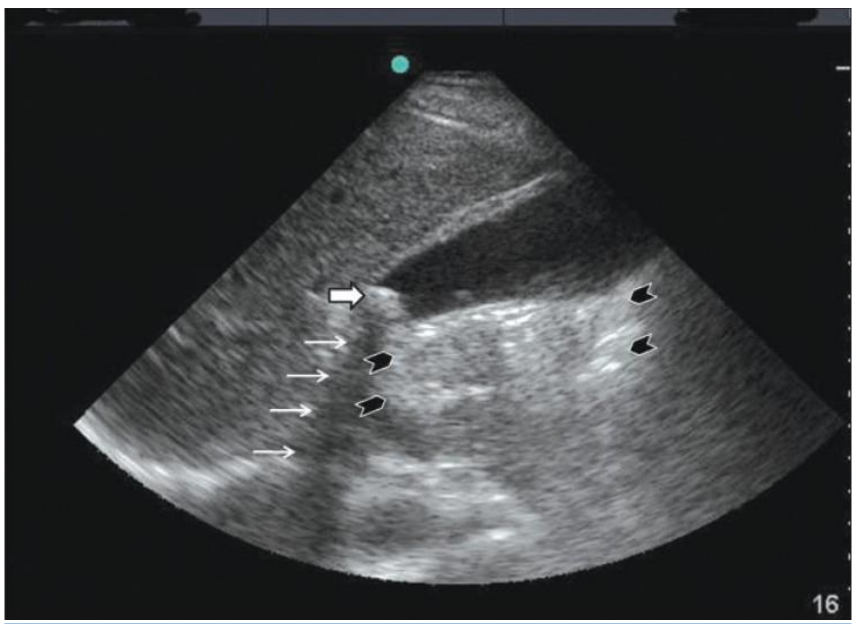

Figure 1. A gallstone at the neck of the gallbladder (white thick arrow) causing a shadow artifact behind it (white thin arrows). Posterior enhancement is shown behind the gallbladder (black arrowheads) (1)

1.2 Properties of ultrasound machines

Medical ultrasound machines use piezoelectric crystals to send and receive ultrasound waves. The crystals oscillate when current is applied and they can create current when sound is reflected back, creating information that can be presented and interpreted. The presentation of the tissue characteristics can be seen in several modes:

- A-mode is the simplest mode, where the transducer displays echoes as a function of depth. Therapeutic ultrasound aimed at a specific tumor or stones, is also A-mode, to allow for pinpoint accurate focus of the destructive wave energy.
- B-mode produces two-dimensional black and white images of different body planes.
- M-mode, which stands for motion mode, captures a rapid sequence of B-mode scans to visualize and measure motion in the form of video and is used mainly for the heart.
- Doppler mode which is used to measure and visualize blood flow, usually displayed as different colors and intensities depending on direction of flow. Microbubbles can be used as intravenous contrast agents in those cases. They increase blood signal strength, making Doppler signals easier to detect (3).

In addition, those modes can be presented differently depending on the type of transducer. There are also different shapes of transducers, each with different properties:

- Linear transducers feature one line of crystals that produce a rectangular beam shape, giving it a good resolution. They are ideal for vascular examination and breast imaging.
- Convex transducers have a curvilinear arrangement creating a convex beam shape, allowing good depth at the cost of decreased resolution. Those properties make them good for abdominal and musculoskeletal imaging.
- Phased array transducers, known for their phased array crystal arrangement, are often used for cardiac and abdominal imaging.

- Endocavitary transducers, such as endovaginal probes, are designed for internal examinations (4).

1.3 Types of ultrasound techniques used in medicine

Several types of techniques exist in medical practice:

- Conventional ultrasound is the most common type used in medicine and is mainly used for diagnostic purposes. Conventional ultrasound is indicated for assessing internal organs such as the liver, gallbladder, pancreas, kidneys, and urinary system. It can be used for monitoring pregnancy, uterus, and ovaries and for assessing the central nervous system in newborns for conditions such as hydrocephalus.
- Point-of-care ultrasound is an imaging protocol that is conducted at the patient's bedside. It aims to narrow the differential diagnoses. For example, POCUS of the abdominal aorta helps determine the diameter for diagnosing abdominal aortic aneurysms while POCUS of the biliary system helps in the detection of cholecystitis and cholelithiasis. Focused Assessment with Sonography for Trauma, also known as FAST, is a specific subset used primarily in trauma and helps identify conditions such as free fluid in the abdominal cavity. Rapid diagnosis is important for appropriate treatment, especially when time is a big factor.
- Duplex ultrasonography combines blood vessel ultrasound with a Doppler mode to determine anatomy and blood flow to identify occlusions, aneurysms, and venous insufficiency.
- Endoscopic ultrasonography, which will be discussed in details later, is a more invasive technique that aims to investigate internal organs through insertion of ultrasound probe into body cavities, such in transesophageal echocardiogram, transrectal ultrasound of the prostate, and transduodenal ultrasound of the pancreas.
- Contrast-enhanced ultrasound that was mentioned before, can be used for example in detection of a patent foramen ovale (2).

1.4 Advantages and disadvantages

Although not as detailed as other imaging modalities such as MRI, ultrasound has many other advantages, making it more commonly used in daily practice for many conditions. It is an effective and noninvasive technique that enables real-time diagnosis. It is safe, as sound waves do not use ionizing radiation, making them a suitable alternative to x-ray and CT scans, especially for children and pregnant women. It is also portable and cost-effective, and recent developments have further enhanced its utility (5).

Even though it is commonly used due to its advantages, it has several limitations, such as inferiority in details when compared to CT or MRI, the need for interpretation skills, limitation in reaching deep or dense structures and artifacts. Further disadvantages will be discussed under “Challenges and Limitations in Ultrasound-Guided Interventions”.

2. Interventional radiology

Interventional radiology is an evolving medical field that includes diagnostic and therapeutic procedures that use medical imaging modalities in order to guide the insertion of devices such as needles and catheters. It can be used in many different medical fields and is usually performed by an experienced radiologist.

Arterial interventions, such as angioplasty, stenting, and atherectomy, diagnose and treat peripheral artery diseases through minimally invasive endovascular techniques. Aortic aneurysm repair can be achieved through endovascular aortic repair and is compared to conventional surgery by safety, effectiveness and efficiency. Interventional radiology also has a role in treating acute hemorrhage with procedures such as transarterial embolization. Biopsies, fluid drainage, and injections can be performed with ease as imaging modalities help guide the path for reaching the target locations. Reproductive organs are manipulated, such as uterine fibroid embolization (6).

Interventional ultrasound is also known as ultrasound-guided intervention, is diagnostic or therapeutic minimally invasive procedures guided by real-time ultrasound imaging (7). It plays an important role in guiding many procedures in many target organs and systems. Many of those interventions will be discussed in this thesis.

3. Ultrasound-guided vascular access

3.1 General information

Vascular access is important for blood sampling, hemodynamic monitoring, and medication administration. It can be obtained in peripheral veins, central veins, or intramedullary bones. Peripheral access is widely used for medical analysis, and the sample is sent to the lab. It is also used first in resuscitation. Arterial access is needed for accurate blood pressure monitoring, cardiac output monitoring, and frequent blood gas sampling. In addition, it is used in procedures such as embolization, stenting, ablations, and angioplasties. Complications can arise, such as infection, thrombosis, and tissue damage. In order to minimize complications and increase success rate, ultrasound can be used and is called “Real-time ultrasound guidance”. Furthermore, intravascular ultrasound probes can be used to enhance the mentioned procedures as well.

Ultrasound aids in distinguishing veins from arteries based on characteristic appearances, such as echogenicity, thin walls, and greater compressibility. Veins are easily compressible while arteries are not. Doppler ultrasound is another tool to enhance this differentiation by showing pulsation. In order to perform ultrasound-guided artery catheterization, the operator needs to use a high-frequency linear transducer and identify the vessel (8). When the vessel is identified and there is a route, the needle is inserted and aligned along the transducer's middle allowing visualization of the needle tip and its way to the desired vessel.

In regard to venous access, especially central venous catheters, ultrasound can be used in critically ill patients in the ICU. Without the use of ultrasound, the landmark technique is applied, and it involves specific insertion points. For example, in the case of the internal jugular vein, the needle should be placed between the sternocleidomastoid muscle's two heads, approximately 5 cm above the medial clavicle while turning the patient's head to enhance these landmarks. In the case of femoral vein, the needle should be inserted below the inguinal ligament and medial to the pulsation of the femoral artery (9). However, complications can occur using this technique, and the risk rises even more after more than three attempts. Therefore, limited attempts can reduce complications but also can be reduced by using ultrasound guidance (10). Ultrasound assists in the evaluation of veins through a procedure called Rapid Central Vein Assessment (RaCeVA). This approach provides a thorough understanding of venous anatomy, size, and position. Therefore, ultrasound can help ensure the safety and precision of venous access procedures (11).

Once the needle is inside the blood vessel, it is mainly used for blood analysis and administration of fluids or medication. In addition, some other procedures can be done through a vein. An example is venography, in which dye is injected to evaluate blood flow through the veins and especially used to diagnose deep vein thrombosis. For this procedure, although ultrasound can be used for venous access, it is usually done with the use of CT, MRI, and fluoroscopy and not directly by ultrasound.

As for arterial access, it is needed for some procedures and ultrasound guided access can be used to minimize complications and save time. On the one hand, blood gas analysis can be taken once access is achieved. On the other hand, more invasive procedures such as embolization, stenting, ablations, and angioplasties can be performed. For example, in interventional oncology, radiofrequency ablation is a technique that uses high-frequency currents through a thin needle into the tumor. This is used in a variety of diseases including hepatocellular carcinoma or metastasis, lung carcinoma or metastasis, renal cell carcinoma, and bone metastasis (12). Although ultrasound waves are not directly used in the procedure, they can help to minimize complications and help the operator to see through it. Therefore, ultrasound-guided vascular access allows interventional radiologists, vascular or trauma surgeons, cardiologists and neuroradiologists to perform a variety of life saving procedures that all start by gaining ultrasound-guided vascular access.

3.2 Vascular procedures complications

When gaining arterial access, some complications can occur and they can also be corrected with the use of ultrasound-guided procedures, for example hematomas, pseudoaneurysms, fistulas and dissections of the femoral artery. Those complications are relatively common, some can occur in up to 15% of patients, especially those receiving anticoagulation therapy. Therefore, there is a need for a low threshold for the use of ultrasound in detecting and treating them (13). Although not entirely preventable, those complications can be minimized with the use of ultrasound-guided access.

Following vascular access, mainly arterial, hematomas can form. They often resolve within days, usually not requiring surgical intervention. However, femoral artery access can result in significant complications. Bleeding can occur if blood is not contained by the connective tissue around the vessel, and extravasation of blood into surrounding tissues can cause hematomas. They can be minor but potentially also massive and extend into the retroperitoneal space, resulting in hypotension and flank pain. In addition, arteriovenous fistulas can occur, which are abnormal connections between arteries and veins (14). Furthermore, pseudoaneurysms are formed when there is disruption in all layers of the arterial wall, allowing arterial blood to move into the surrounding tissue forming hematoma. They frequently occur in the femoral artery after percutaneous procedures.

For pseudoaneurysms, ultrasound can be used to treat them (15). First, it is used to evaluate the size, shape, and location of the pseudoaneurysm. Once identified, an ultrasound-guided intervention involves the application of pressure on the pseudoaneurysm until there is a complete cessation of blood flow within the pseudoaneurysm. Thrombin is then injected. Finally, doppler ultrasound is used to evaluate the postoperative process. If pseudoaneurysm reappears, this procedure can be repeated. Complications of subclavian central vein placements when inappropriately placing the catheter include lung puncture, leading to pneumothorax or hemothorax, and myocardial perforation, leading to pericardial tamponade, as well as brachial plexus injuries and bleeding complications (16).

As for central line bloodstream infection (CLABSI), another complication of central line access, factors that increase its risk include poor hygiene, severity of illness, and duration of therapy. Although CLABSI can be reduced by the use of PICC lines, avoidance of femoral lines in adults, proper preparation of the skin with chlorhexidine and alcohol, and adhere to strict hand hygiene, the use of ultrasound can reduce the risk as well. Two meta-analyses suggest that using real-time two-dimensional ultrasound for central venous catheter placement reduces infections and number of cannulations attempts, and is preferable over Doppler ultrasound guidance (17).

Therefore, in addition to the variety of procedures that can be done when vascular access is performed, ultrasound-guided access ensures procedural safety, increases success rates, and prevents complications. Those advantages with minimal disadvantages represent the high success rate and evolution of ultrasound-guided procedures.

3.3 Other vascular procedures

Ultrasound is not only used in vascular access, but it can also be used for enhancing the effectiveness of thrombolysis. Ultrasound energy separates the fibrin strands, increasing its surface area and allowing more contact between the lytic agent and the clot. By that it makes fibrinolysis more efficient (18).

Also in coronary artery interventions, ultrasound can be helpful in other aspects than vascular access. A relatively new procedure allows utilization of Intravascular ultrasound (IVUS) for visualizing the coronary arterial wall using a catheter with a small transducer located on its tip. It is particularly beneficial for assessing plaque morphology as it provides precise measurements of the vessel and plaque size. It separates between the vessel layers, which are bright echo from the intima, dark zone from the media, and multiple bright echoes from the adventitia. It also shows the plaque within the wall of the vessel (19). By that it helps guide coronary interventions and allows proper stent placement. Its main disadvantage is the limitations in flexibility making them less suitable for tortuous vessels.

4. Ultrasound-guided biopsies

4.1 General information

A biopsy is a medical procedure where a sample of tissue or cells is extracted for examination to diagnose diseases. The tissue is processed, stained, and examined under a microscope by a pathologist. There are different types of biopsies, including excisional, incisional, and needle aspiration biopsies, and they can be taken from almost every organ in the body, as well as with the use of different biopsy devices (20). Ultrasound can be used to guide those procedures.

During ultrasound-guided procedure, the patient lies on their back or side on a table, and the radiologist or surgeon uses the ultrasound device to locate the mass. Before the insertion of the biopsy device, there is a need for sterilizing the biopsy site and the use of local anesthesia to minimize discomfort as the procedure can be painful.

4.2 Breast biopsy

Many breast pathologies require further evaluation as some can have malignant lesions with high mortality rate, and early diagnosis can reduce those rates. Others on the other hand can be simple cysts or abscesses that are both diagnosed and treated by needle aspiration. In all those cases, ultrasound is usually used to invade through the skin and reach the target tissue. Those biopsies are then sent for further analysis in order to guide appropriate treatment decisions based on the diagnosis. Therefore, ultrasound makes the procedure safer and easier.

An important note of the use of ultrasound for breast pathologies is that before its use to guide invasive procedures, in patients younger than 30 years old, ultrasound is the first line imaging modality in case of breast mass. The reasons are a combination of the facts that the lesions cannot be effectively visualized using mammography in this age, the low probability of presence of cancerous lesions in this age, and in order to decrease radiation in younger patients. The findings can be classified according to the

Breast Imaging Reporting and Data System (BI-RADS) system. BI-RADS 1 or 2 means simple cyst and usually requires follow up or aspiration, or solid lesion requiring follow-up. BI-RADS 3 means a more complex cyst or solid mass requiring follow-up and biopsy in case of enlargement. BI-RADS 4-5 require ultrasound-guided biopsy (21). Under ultrasound each mass has some characteristics based on its echogenicity. The must be seen in two different planes and the mass is reviewed based on its margins whether circumscribed or spiculated, echo pattern whether anechoic, hypoechoic, isoechoic or hyperechoic, whether it is homogenous or heterogenous, vascularity, and calcifications (22).

There are several types of biopsies that can be taken. On one hand, fine-needle aspiration biopsy is a relatively simple procedure in which a thin needle is directed into the mass. On the other hand, core needle biopsy is a more complex procedure in which a thin, hollow needle is used to remove multiple tissue samples. Although ultrasound is effective to guide those procedures, sometimes the biopsy is taken under other modalities such as MRI-guided biopsy.

There are 2 basic types of devices commonly used in ultrasound-guided biopsies, spring-loaded core needle biopsy devices (SLDs) and vacuum-assisted biopsy (VAB or VABB when related to the breast) devices. In SLD, the needle is aligned parallel to the transducer, allowing visualization of the needle transversely. Then, a 90 degrees rotation of the transducer shows a different angle, and allows visualization of the needle in the center of the target. It allows confirming the position in the mass (Figure 2). When the needle is in the correct position, the spring-loaded mechanism allows the needle to quickly be inserted, capturing tissue core. A real-time ultrasound imaging is used continuously to monitor the needle's location. In VAB on the other hand, the target is vacuumed into the device. Compared to a VAB device in which the needle is inserted only once, the SLD needle is usually used without an introducer and must be inserted multiple times. The properties of the mass, the technique used in the biopsy, and the goals are eventually what helps to choose between the SLD or VAB devices, but ultrasound is still needed for those procedures in order to help with proper guidance and safety (23). In some studies, comparing VABB and SLD in ultrasound-guided breast biopsy, It was shown that 8-gauge VABB is superior to the 14-gauge SLD. It reduces the false negative rate for diagnosing invasive breast carcinoma (24).

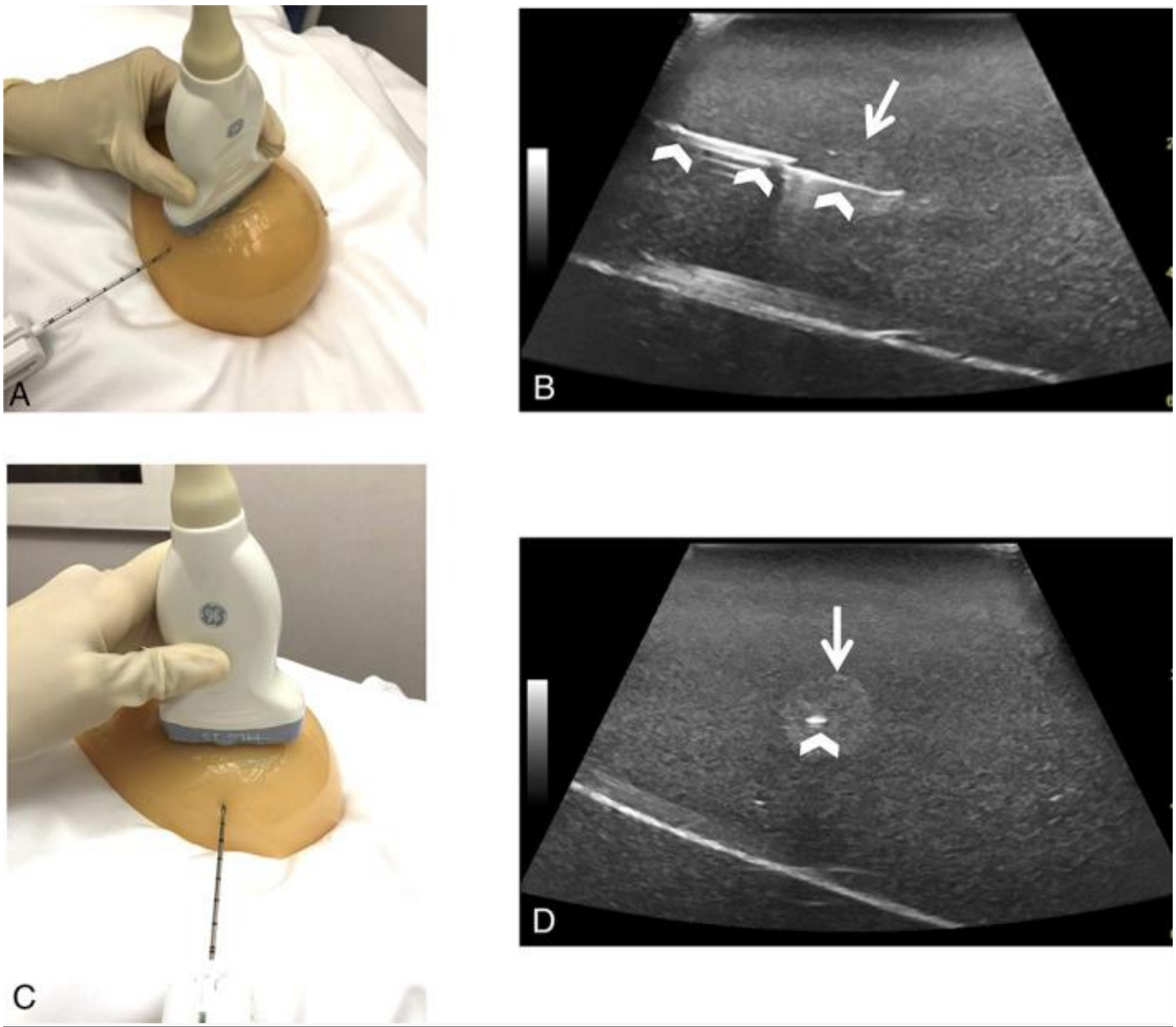

Figure 2. A, the needle is parallel and aligned with the transducer. B, Corresponding transverse US image in which the needle (arrowheads) and target (arrow) are marked. C, Rotation of the transducer 90° makes the transducer orthogonal to the needle and longitudinal with the lesion. D, Corresponding longitudinal US (24)

There are some potential complications which are bleeding, which is the most common one, hematoma formation, infection and abscess formation, pneumothorax, milk fistula formation, cosmetic deformity and seeding of tumor (25). Those complications are reduced by using ultrasound.

4.3 Thyroid biopsy

Thyroid nodules are common abnormal growths in the thyroid gland. While most of them are benign and consist of cysts and adenomas, some are malignant. Therefore, investigation is needed, and sometimes fine-needle aspiration cytology is done, which is usually guided by ultrasound.

First, TSH and radioiodine uptake scans help to evaluate nodules, and classify them as hot or cold. Ultrasound is done in parallel and helps in distinguishing between those nodules based on some characteristics. Solid hypoechoic nodules with irregular margins, microcalcifications, and nodules larger than 1cm all indicate high risk for malignancy. Sometimes, it is difficult to find the transition from the nodule and the surrounding thyroid parenchyma, and the edges do not always mean there is abnormality. In addition, many benign nodules are hypoechoic and cannot indicate malignancy (26).

Ultrasonographic features that are associated with an increased risk of thyroid cancer
Hypoechogenicity
Solid composition
Punctate echogenic foci (microcalcifications)
Coarse calcification (macrocalcifications)
Interrupted eggshell calcification with soft tissue extrusion
Infiltrative/irregular margins
Taller-than-wide shape
Associated suspicious lymphadenopathy
Ultrasonographic features that are associated with a lower risk of thyroid cancer
Isoechoic or hyperechoic
Spongiform appearance
Simple cysts
Comet-tail artifact within a cystic component of a nodule
Uninterrupted eggshell calcification

Figure 3. Ultrasound features associated with thyroid cancer risk in adults (27).

Once fine-needle aspiration is done, the cytology results are influenced by several factors, such as the person performing the cytology, how the specimen is prepared, and the method used for aspiration. The latter factor mentioned is improved by using ultrasound during the biopsy, which allows a live imaging of the needle's position within the nodule, enhancing the precision and reducing diagnostic errors.

After preparation for the biopsy, the freehand method is used in which the needle is inserted by the guidance of the transducer. It can be parallel to the beam or at an angle. The parallel approach allows visualization of the needle path, therefore making the procedure easier to maneuver. However, many operators prefer to perform the oblique approach, which is simple, fast and safe. This approach allows visualization of the tip as a transverse spot. When the needle is in the nodule, and it is confirmed on the screen the tissue sample is taken. Doppler ultrasound can be used mainly to avoid puncturing blood vessels (28).

Ultrasound guidance makes the procedure safer and cheaper, making it the preferred choice for thyroid biopsy. It decreases complications, such as local pain and hematomas, and it shows a better rate of correct diagnosis (29).

4.4 Lungs biopsy

Although ultrasound is not the primary method for evaluating the lungs due to its inability to penetrate well tissue with air, it can still be used in diagnosis of certain conditions. In a healthy lung, ultrasound can show the sliding motion of the visceral pleura and the lung against the parietal pleura during breathing and cardiac cycles (30). Therefore, it can also identify abnormal conditions such as effusions, pneumothorax and some peripheral masses. Ultrasound waves are reflected in the lung's pleura of healthy individuals, which creates A-line, which creates horizontal and parallel lines. As the interstitium thickens, B-line is formed, which are perpendicular lines (figure 4). Consolidations can also be seen if they are close to the pleura.

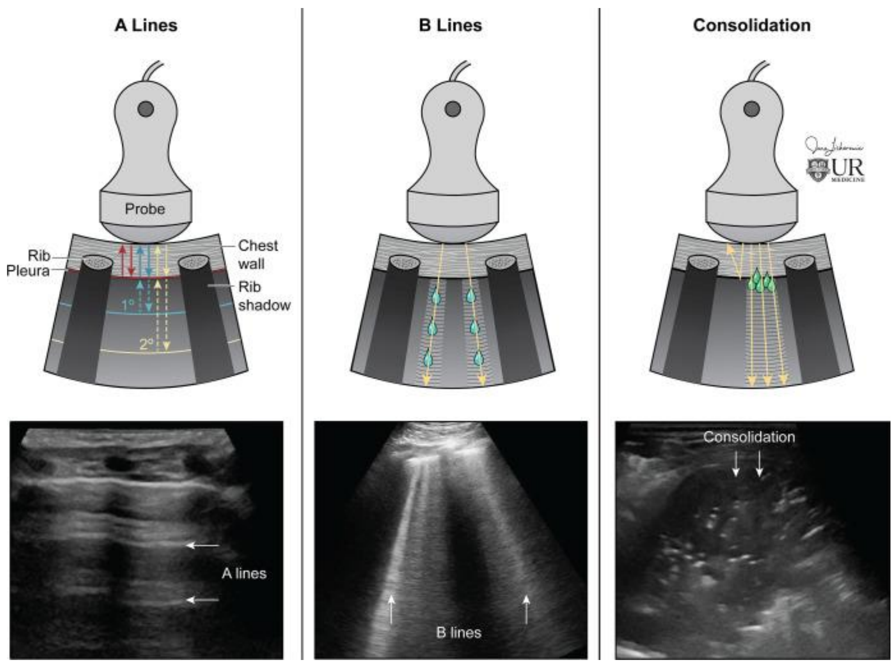

Figure 4. Ultrasound findings in different conditions affecting the lung (30)

For pulmonary nodules, ultrasound can visualize them especially if their location is already known from previous radiological modalities such as precious CT scan, and it can be used to guide a biopsy. It is useful for biopsies of the chest wall, pleural, anterior mediastinal, and peripheral lung lesions (31). Because of the ultrasound's ability to give real-time pictures, ultrasound is used to direct the needle into the lesion during the phase of the respiratory cycle, which can complicate biopsies. This is in contrast to CT-guided biopsies that are limited by those cycles (2). Therefore, the main purpose is to avoid lung tissue damage during the procedure.

During the procedure, which is called ultrasound-guided transthoracic needle biopsy (US-TTNB), a sterile transducer is used, and anesthesia is injected. The biopsy is typically performed using an in-plane technique (Figure 6), allowing the visualization of the needle's movement near the lesion. The needle is inserted above a rib to reduce the risk of damaging the intercostal vessels, and a doppler imaging can help avoid those risks. The biopsy itself should be coordinated with the patient's breathing, with instructions given to the patient on how to breathe and when to hold their breath (32).

Complications are mainly pneumothorax and hemorrhage, although less common can occur and include air embolism, tamponade and tumor seeding. A proper use of ultrasound and doppler can help reduce the more common complications (31).

4.5 Hepatobiliary system

There are many hepatobiliary lesions, some of the benign masses and tissue changes may not need biopsy, while other lesions do. Ultrasound-guided procedures of the hepatobiliary system are used to diagnose and evaluate liver, bile duct, and pancreatic lesions and treatment can be planned according to the results.

For the liver, differentiating between hepatic masses can be based on several radiological characteristics, for example size and margins. Most incidental lesions are under 1cm with smooth margins and are benign. Hepatocellular carcinoma (HCC) is the most common primary liver malignancy and is a larger lesion, heterogeneous due to fibrosis, fatty change, necrosis, and calcification (33). Metastatic lesions have different characteristics that help to identify the primary cancer and distinguish between them and benign liver lesions. For example, lung and breast cancer and hypoechoic, colorectal carcinoma (CRC) renal cell carcinoma (RCC) are hyperechoic, and those can have calcifications and different vascularity, especially when contrast-enhanced ultrasound is used (34). In this type of contrast agents are microbubbles, nitrogen gas or sulfur hexafluoride stabilized in a phospholipid membrane (35). However, even if those radiological characteristics exist, biopsy is still needed for confirmation and ultrasound can help guide it as well as primary visualization of the lesion.

Percutaneous liver biopsies, with the guidance of ultrasound, confirm the diagnosis. First, there is the need to find the entrance site, often between the sixth and ninth intercostal spaces. After confirmation by ultrasound, the area is sterilized and anesthetic such as lidocaine is injected. The biopsy is taken using a Tru-Cut biopsy (36) device to obtain a biopsy specimen while the patient holds their breath during the expiration phase. After the procedure, another ultrasound examination is performed to evaluate for bleeding.

Pancreatic lesions are also relatively common and should be evaluated. Endoscopic ultrasound (EUS) and intraductal ultrasound (IDUS) are other two imaging techniques used for assessing bile duct and pancreatic lesions and are minimally invasive compared to percutaneous ultrasonography of pancreatic tumors (37). EUS involves using a thin, flexible endoscope inserted into the GI tract, with an ultrasound probe connected to it. EUS helps understanding the extent of the tumor and the involvement of the regional lymph nodes, as well as guidance of FNA. As with other biopsies, the site is located, and a needle is inserted into the target lesions. IDUS is another method that helps to determine the invasion, and is often better for evaluating the proximal biliary system and the surrounding structures, and also allows biopsy guidance.

Potential complications of those procedures include bleeding, infection, perforation, and pancreatitis. Bleeding, one of the most common complications, may arise with low platelet counts, prolonged PT, or elevated PTT. To minimize risks, patients should be screened for these factors before the biopsy. Abnormal values should be corrected using FFP or platelet concentrate before the procedure (38). As for other invasive procedures, ultrasound helps decrease complications.

5. Ultrasound-guided drainage

5.1 General information

In some diagnostic methods and pathologies, it is indicated to remove fluid or air from spaces within the body. Examples include paracentesis in cases of ascites, thoracentesis in case of pleural effusion or pneumothorax and pericardiocentesis in case of cardiac tamponade. In addition, some joint pathologies require aspirations in order to differentiate between them, such as septic arthritis and gout. Lastly, ultrasound can be used to guide obstetrics procedures in order to drain amniotic fluid. Ultrasound can be used to guide those procedures, allowing enhancement of safety, and reduction of potential complications.

5.2 Body cavities

Ultrasound can help guide drainage of body cavities fluids for diagnostic and for therapeutic purposes. Those cavities are the peritoneum, pericardium and pleura.

First, it can be used to diagnose and treat fluid buildup in the peritoneal cavity, and it is done by paracentesis. This procedure typically involves using ultrasound guidance to ensure correct needle placement. It is used to identify the needle insertion site based on size of the fluid collection and the thickness of the abdominal wall. It should be evaluated in multiple planes to ensure distance from abdominal organs and blood vessels (39). Another importance of ultrasound in this procedure is in patients with a history of abdominal surgery. The location of the paracentesis should be modified in patients with surgical scars so that the needle is inserted several centimeters away from the scar in order to avoid bowel entry with the needle (40).

Under ultrasound, ascites fluid is anechoic in most cases, but hemorrhagic, inflammatory or neoplastic ascites contain debris or septations. After identification for the entry site, a sterile needle is inserted, and fluid is removed. This can be done either through direct aspiration or connecting to a drainage system. Ultrasound-guided techniques increase the success rates and reduce risks for complications such as persistent fluid leak and hepatic encephalopathy. With the removal of large volumes of fluids, albumin should be added to the patient, because it reduces the risk of post paracentesis circulatory dysfunction, hyponatremia, and acute kidney injury (41).

Second, the pleural cavity is another potential space for pathological fluid accumulation which can be drained via ultrasound-guided techniques. As for other fluid accumulation in cavities, ultrasound can be used to identify effusions or pneumothorax and was discussed under the “lung biopsy” section. Both pleural transudates and exudates can be anechoic and have a simple appearance. In some cases, ultrasound can also show complex effusions with internal echoes or septations and these findings are indicative of an exudate in most cases (2). Once pleural fluid is identified, an appropriate site can be localized for thoracentesis. Most thoracenteses are typically performed by ultrasound-guidance at the bedside. CT imaging-guidance is used for effusions that are small, or those that cannot be readily accessed or have failed ultrasound-guided access, such as loculated effusions. The intercostal space is chosen, and the needle is inserted at an angle perpendicular to the chest wall and directly into pleural fluid. Ultrasound allows several respiratory cycles to be observed in order to ensure that no lung potentially moves close to the needle path (42).

Complications include pneumothorax, bleeding complications and re-expansion pulmonary edema. In an observational cohort study of over 61,000 thoracenteses of which 45% were performed under ultrasound guidance, ultrasound reduced the risk of pneumothorax by 19% and is statistically significant (43).

Third, ultrasound can be used in case of pericardial fluid accumulation, especially when it leads to cardiac tamponade in the emergency settings. Diagnostic techniques such as echocardiography are critical in identifying the presence and extent of the effusion, which is when ultrasound is used before the pericardiocentesis, which is invasive and can be diagnostic and therapeutic. The effusion is visualized as an echo-free space between the heart and the parietal layer of the pericardium. A semi-quantification of the effusion may be obtained measuring the distance between the two pericardial layers (44). Ultrasound guidance is used during the procedure of gaining access to the cavity after the effusion is diagnosed. It is aimed to place the needle correctly and avoid complications. The recommendation is to use echocardiographic guidance rather than no imaging guidance or only fluoroscopic guidance. It is important to identify the location where the effusion is closest to the skin with no intervening vital organs, which allows the operator to select the shortest safe route. In addition, echocardiology guidance allows monitoring the position of the needle during the initial puncture and is easier and more convenient than with fluoroscopy (45).

While pericardiocentesis is generally safe, potential complications can occur, for example injury to the myocardium, arrhythmias, and pneumothorax. Proper training and the use of ultrasound guidance are recommended to minimize risks and improve the procedure's success rate.

5.3 Joints aspirations

As in fluid accumulation in body cavities, ultrasound can also be used in both diagnosis and therapy of fluid accumulation in joints. Arthrocentesis is used in the management of septic arthritis, where synovial fluid is aspirated from a joint, and is recommended for all patients suspected of having this condition. It can help to determine the cause of joint effusions, such as infections or crystal-induced arthropathies, and to identify the presence of hemarthrosis.

Traditionally, arthrocentesis was performed blindly using landmarks to aspirate effusions. However, using a landmark-based approach has some limitations due to variation in anatomy, with success rates ranging from 61 to 78% depending on the joint that is being assessed (46). Ultrasonography adds some advantages over a blind landmark-based approach by direct visualization of the effusion and assessing the route.

There are some different techniques. In the in-plane method (Figure 6), the needle is aligned with the ultrasound probe so that its entire length is visible on the screen and in the out-plane method the needle is inserted perpendicular to the probe (46). Those methods can be used in various joints such as the ankle, elbow, hip, knee, shoulder, and wrist. Each joint has specific anatomical landmarks and preferred probe placement's locations. Ultrasound-guided arthrocentesis enhances the precision of fluid aspiration, minimizing risks, such as injuries to blood vessels and bones.

5.4 Obstetrics

Amniocentesis and amnioreduction are examples of procedures in obstetrics that are invasive and can benefit from the guidance of ultrasound. The aim is to locate the amniotic sac while inserting a needle in order to collect amniotic fluid for genetic testing, diagnose infections, and assess fetal lung maturity. In amnioreduction, the purpose of ultrasound is the same, but in this case the procedure aims to remove fluid of polyhydramnios.

In amniocentesis, a detailed ultrasound is performed to assess the gestational age, placental location, fetal position, and amniotic fluid volume. Under ultrasound, the placenta appears as a uniformly echogenic structure along the uterine wall, with a deep hypoechoic band separating it from normal uterine myometrium (47). After finding the proper pathway of the needle insertion, the skin is entered, and the fluid is collected. The transducer is placed in a way that the ultrasound beam is directed at a 15 to 20-degree angle from the planned track of the needle, and it must be ensured that fetal parts, umbilical cord, or placenta are not present in the region of needle insertion (Figure 5). Amnioreduction involves a similar process but the volume aspirated is different (48).

Figure 5. Ultrasound showing needle insertion during amniocentesis (48)

Complications can occur, especially if the procedure is done earlier than indicated which is why amniocentesis is done after 15 weeks of pregnancy. Those complications include miscarriage, infection, injury to the fetus, rhesus disease and club foot. Most miscarriages occur within three days to two weeks after the procedure and are due to infection, bleeding, or damage to the amniotic sac. The chance of having a miscarriage after 15 weeks is about 1% and the other complications are rare as well (49). Ultrasound aims to decrease those complications and allow easier procedures for both the operator and the patient.

6. Ultrasound-guided injections

6.1 General information

Some injections, including intra-articular injections and nerve blocks, are minimally invasive procedures that can be guided by ultrasound imaging. For intra-articular injections, ultrasound helps to direct the needle into joint spaces in the same way it is used in arthrocentesis which was explained before in this article. Nerve blocks involve the injection of local anesthetics near nerves to manage pain, and ultrasound guidance allows avoiding damaging vessels and nearby tissues.

6.2 Injections

With similarities to arthrocentesis and amniocentesis regarding the procedure and complications, ultrasound-guided insertion of needles can also be used to inject medications or fluids rather than aspirate the content of the desired cavity. Steroids can be injected into the joint cavity in conditions such as osteoarthritis, and fluid can be injected into the amniotic cavity, such in amnioinfusion in case of severe oligohydramnios. The way in which ultrasound is used in guidance of the minimally invasive procedure and the associated risks were discussed before.

6.3 Nerve blocks

Nerve blocks involve Injection of local anesthetics around nerves in the peripheral nervous system in order to achieve pain control. Ultrasound guidance enhances the success and safety of those procedures by allowing visualization of needles and nerves, and the blood vessels that travel in their proximity.

Meta-analysis that includes 23 trials with over 2000 nerve blocks, ultrasound guidance is compared with nerve stimulation alone, which is the detection of nerve response to an electrical nerve stimulator. The analysis shows that ultrasound guidance reduced the rate of vascular puncture, pain during the procedure, and the need for analgesic with statistical significance. There was no difference in the rate of postoperative neurologic complications (50). Ultrasound is especially beneficial for patients with complex anatomical challenges such as previous surgical scarring or obesity, and those with coagulopathies to decrease further complications.

The procedure involves visualization of the nerve and the surroundings. The normal nerve, in the transverse section, reveals small hypoechoic areas separated by hyperechoic septae. The hypoechoic areas represent nerve fascicles while the septae represent the perineurium. The longitudinal sections can also be used (51). Blood vessels can be visualized by doppler. With 2 main approaches, the in-plane technique (Figure 6) involves the visualization of the needle parallel to the transducer and in the out-of-plane approach, the needle appears in the cross section as a small dot, and those procedures were already explained. Out-of-plane technique is often used for deeper blocks where it is more difficult to visualize the entire length of the needle to the target nerve. When the needle is in the target, the operator injects the anesthetic (50).

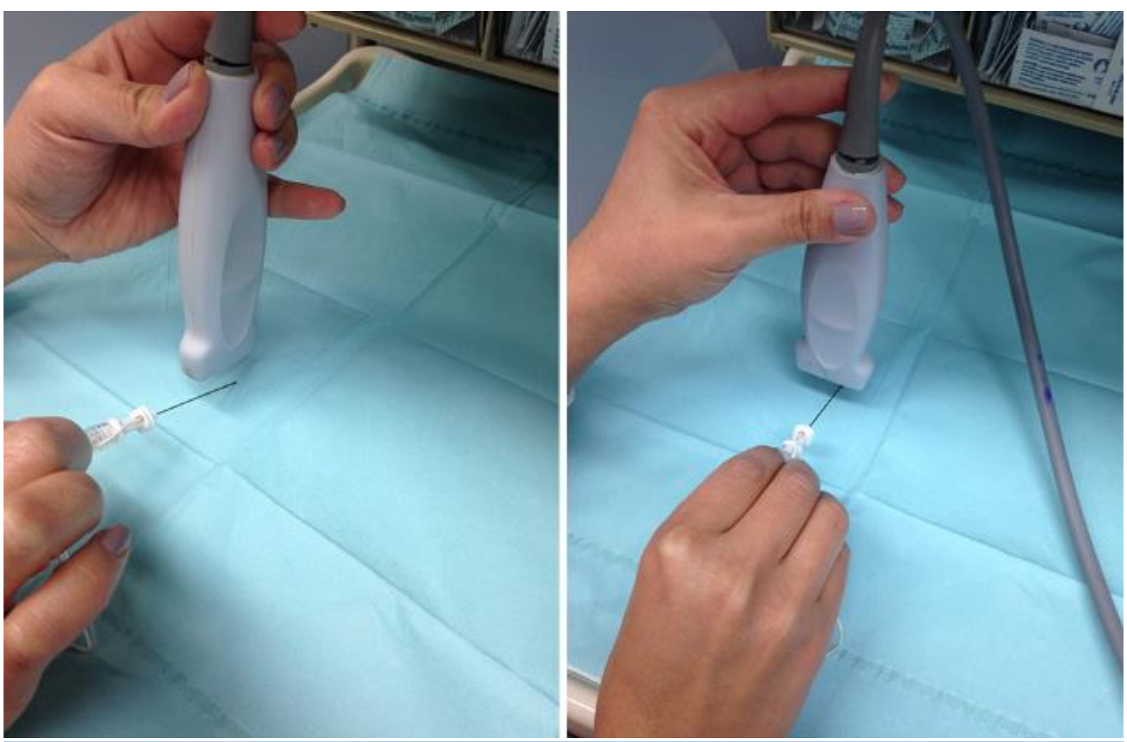

Figure 6. In-plane needle placement (left) and Out-of-plane needle placement (right) (50)

Complications are punctures of blood vessels, injections into the blood circulation, and damaging the nerve fibers. The use of ultrasound has reduced those complications but has not eliminated them (52).

7. Challenges and Limitations in Ultrasound-Guided Interventions

Although ultrasound is a safe technique, it has some limitations. Those limitations can be related to the patient, the modality and the operator,

First, some patient-related or anatomical characteristics of the target location for the ultrasound can limit its performance. As was discussed under the general characteristics of ultrasonography, the waves do not penetrate every tissue, especially in obese patients. Some other limitations are deep organs or those surrounded by complex structures. In order to improve some of those anatomical limitations, there are some innovations in the field of 3D ultrasonography (53). It allows a better understanding of the patient's anatomy and helps the guidance of some intervention better than the 2D ultrasound.

Second, the operator's experience can limit the use of ultrasound, as some physicians are not well familiar with ultrasound's usage and interpretations. interpretation of ultrasound images can vary based on the operator's ability to manipulate the transducer and interpret what they see. Some solutions include targeted training programs and subspecialties that aim to reduce complications. For example, a gastrointestinal radiologist who performs endoscopic ultrasound, percutaneous biliary drainage or gastrostomy insertion (54).

Third, this imaging modality itself still does not have the same resolution as other imaging modalities. Ultrasound cannot help visualizing every detail, and complications can occur even with its guidance. Artifacts, such as shadowing from bone or gas can obscure critical anatomical structures (53). In addition, unlike CT and MRI, which can image large areas or entire organs at once, ultrasound can only view small sections at a time. Therefore, ultrasound remains inferior to other imaging modalities when complex structures are needed to be invaded during medical procedures or when there are barriers to visualization of the target organ.

Conclusion

Ultrasound is an important tool used in clinical diagnostic medicine and is known for its benefits and almost no adverse effects when compared to other imaging modalities. Although known for its role in visualizing tissue changes due to pathologies, invasive ultrasound can also be used for a variety of interventional diagnostic and therapeutic techniques in order to help the operator to visualize and gain insight about the procedure. As a result, it decreases complications and promotes safety.

Ultrasound is used for guiding vascular access, which is important in many medical procedures, from medication and fluid delivery to tumor embolization and assisting in fibrin clot destruction due to some ultrasound physical properties.

It is also used in other procedures such as biopsies and injections. Some techniques involve placement of ultrasound on the skin surface while others involve intravascular, endoscopic or intraductal probe insertion.

Although many advantages are associated with ultrasound use in interventional and clinical medicine, some limitations also exist, and include technological, operator skills and anatomical barriers. Some of those limitations are answered by promoting subspecialization programs and the continuous improvement of its interpretation properties. Therefore, ultrasound has a high chance of becoming an even more important tool both in clinical and interventional medicine.

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Biography

Eliran Rond was born in Israel on the 4 of January 1995. From a young age he was exposed to the doctor’s life as both of his parents work as medical doctors. His majors were physics and computer science, but he realized that his real dream is to become a doctor and save lives. He finished 3 years in the navy and began studying general medicine at the University of Zagreb that lasted during 2018-2024. During his second year of medicine, he received the Dean’s award. During medical school, he worked in a radiology high-tech company and was exposed to several imaging modalities and their interpretations.