Ultrasound and Other Innovations for Fluid Management in the ICU

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KEYWORDS

- Image based resuscitation
- Ultrasound
- Echocardiogram

KEY POINTS

- Ultrasound is a user-dependent tool that can help guide therapy.
- The use of ultrasound to guide central line placement decreases complication rates.
- Cardiac ultrasound can help with the diagnosis of cases of hypotension.
- Lung ultrasound and pleura ultrasound are useful adjuncts for diagnosis causes of desaturation.
- Abdominal ultrasound can help in rapid visitation of fluid and intra-abdominal structures.

INTRODUCTION

Guiding therapy for a rapidly deteriorating patient continues to be an issue of interest in critical care. Having a tool that can aid in the decision making to treat shock expeditiously can be lifesaving in some instances. Please see Bracken A. Armstrong and colleagues’ article, “Sepsis and Septic Shock Strategies,” in this issue, for a discussion on the uses of ultrasound to rapidly diagnose causes of deterioration and guide therapy.

ULTRASOUND TO GUIDE THERAPY IN THE ICU

Ultrasound has been introduced in the past couple decades as a tool to guide therapy for critically ill patients. The advantages of this technique are that it offers imaging immediately, it is portable, and it does not carry ionizing energy; therefore, the consequences of repeating the test are minimal. It is, however, operator dependent. Because it is a diagnostic modality that depends on the transition of sound waves into the tissues, anything that interferes with the sound waves can result in poor
visualization. Air is not a good conductor of sound; large individuals can be more difficult to image as well as patients with subcutaneous edema and emphysema. The use of this tools extends from guiding procedures to volume status assessment. This article describes the basics of and technique for performing the test on each organ system.

**FUNDAMENTALS**

Ultrasound is a mechanical wave that requires a medium to travel. In the case of diagnostic ultrasound, these waves travel through human tissue. Fluid is a good conductor of ultrasound and can provide a good interface to visualize organs around what otherwise is not visible. An example of this is visualizing the lung in the presence of a pleural effusion.

Ultrasound machines consist of electric pulse generators, transducers, systems for processing received echoes, and image display screens. The key elements of transducers (probes) are piezoelectric crystals, matching layers, backing material, cases, and electrical cables.

There are several transducer types. This article discusses phased array, linear array, and curved array.

The cardiac probe or phased array transducer has a low-frequency capacity and more penetration to tissues (2–4 MHz on average). It also has small footprints that produce images of sector format through small acoustic windows (eg, cardiac and cranial applications). Because these probes have more crystals than a curvilinear probe, the image is crisper. If an operator does not have a curvilinear probe, the phased array transducer can be used to obtain abdominal images as well.

Linear array transducers are traditionally used to visualize superficial structures because of their higher frequency and lower penetration (7–15 MHz in average). These probes are also useful to evaluate muscle and the pleura.

Curvilinear transducers are optimal for abdominal imaging. They have lower frequencies and higher penetration (2–6 MHz). It is hard to place these probes in the thoracic cavity since their shape against the ribs. If an operator does not have a cardiac probe, however, these can also be used for cardiac visualization.

B mode refers to brightness. It uses the amplitude of the reflected ultrasound signals, which is converted into a gray-scale image. M mode measures the movement of structures along a single line (axis of the ultrasound beam). It is useful in evaluating heart wall or valve motion (echocardiography), hemodynamic status (inferior vena cava [IVC] diameter and motion), and lung sliding or movement of the diaphragm.

Doppler mode measures changes in frequency caused by sound reflections off a moving target (Doppler effect), usually blood, in common bedside practice. There are different versions of Doppler mode, including Doppler duplex, continuous-wave Doppler, and pulsed-wave Doppler (Fig. 2).

**VASCULAR ULTRASOUND**

Ultrasound is used in many settings in critical care medicine in evaluating, diagnosing, and treating vascular disease. Ultrasound is essential in the ICU for procedures done with its guidance for safer and more efficient patient care.

**Arterial**

**Aorta**

Although CT scan is currently the confirmatory study to evaluate for aortic pathology, ultrasound can be used to visualize many different aortic disease processes and often is a useful adjunct in its work-up.
Abdominal aortic aneurysm is a disease in which there is localized enlargement of the abdominal aorta, generally leading to weakening of wall strength and risking rupture. Ultrasound can be used to estimate the anteroposterior and transverse abdominal aortic aneurysm diameter from outer wall to outer wall. It can also visualize thrombus, plaque, intramural hematoma, or leakage with free fluid in the abdomen and/or retroperitoneum.

Aortic dissection is defined as separation of the aortic intima from the media. Transesophageal echocardiography (TEE) is the ultrasound modality of choice to visualize an intimal flap, which is defined as an echogenic band floating in an anechoic lumen. True and false lumens can be distinguished with duplex ultrasound, in which the false lumen shows decreased flow or absent flow in the case of thrombosis.

Peripheral arterial disease can be caused by atherosclerosis, thromboembolism, or vasospasm. It is more common in the lower extremities, with the superficial femoral artery the most common site of stenosis. B mode imaging can be used to visualize arterial wall thickening, lumen narrowing, or filling defects, whereas duplex ultrasound is used to determine the peak systolic velocity, flow direction, and changes in flow (triphasic to biphasic or monophasic).

Pseudoaneurysms are defined as a pulsatile encapsulated hematomas in communication with the lumen of a ruptured vessel via a patent neck, and their walls may consist of adventitia, hematoma, and fibrous tissue. Duplex imaging shows a yin-yang sign, or the bidirectional flow due to swirling of blood within the aneurysm. They are generally caused by catheterization of the vessel or trauma. Pseudoaneurysms can be treated with ultrasound-guided compression (60%–90% success rate) or with injection of thrombin into the neck of the pseudoaneurysm.12–14
Ultrasound to guide arterial line placement
Arterial catheterization can be supplemented by use of ultrasound guidance. Ultrasound-guided arterial catheterization increases first-pass success rates by 71% over landmark techniques. Sites that can be visualized with ultrasound (high-frequency transducer) include the radial, femoral, axillary, and dorsalis pedis arteries.

For the purpose of ICU ultrasound, evaluation of the extremities can help when guiding procedures as well as identifying injury.

Venous
The deep venous system is assessed with ultrasound to evaluate for deep venous thrombosis (DVT). This is executed with a high-frequency linear probe (5–10 MHz) with the use of compression ultrasonography. Studies are performed in a transverse orientation, because errors can be produced in longitudinal axis.

Compressible veins are considered patent and without thrombus, whereas noncompressible veins are diagnostic of thrombus. If a thrombus is visible within the vein, compression is not required and may be rarely associated with dislodgement of the thrombus. Doppler and spectral analysis can be added to study but has not been shown to increase accuracy over compression ultrasound alone. DVT studies can be performed in both the upper and lower extremities.

Fig. 2. Different modes of ultrasound. (A) B mode, also referred to as brightness mode, which is the regular 2-D mode, used to see when performing ultrasound. This particular window shows the subcostal view of the heart, 4 chambers, and the liver superiorly. The right ventricle is the structure located close to the liver edge. (B) M mode or motion. This particular image shows the normal lung with the seashore sign. (C) Color Doppler mode. Notice it is yellow because of the amount of turbulence captured by the image. Color Doppler is red when the structure imaged is moving toward the probe and blue when moving away. Other colors show when turbulence is captured either because of turbulent flow or because of the probe positioning related to the flow itself.

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For upper extremity studies, the patient should be positioned supine, in Trendelenburg position with the arm externally rotated and abducted 90° from the chest. The head should be rotated to the contralateral side and elevated above the extremity to avoid external compression of the distal subclavian vein between the first rib and clavicle. Target vessels are the internal jugular, subclavian, axillary, and brachial veins.

The examination is started by finding the paired brachial veins in the antecubital fossa. Compression should be performed every few centimeters caudal until the subclavian vein is reached. At this point, compression cannot be performed due to the clavicle preventing compression. Although the basilic vein is a superficial vein, a large clot burden at its junction with the brachial vein to form the axillary vein may be of clinical significance. Sequential compression of the internal jugular vein should be performed next in a similar fashion.

To evaluate the subclavian vein, changes in size of the superior vena cava and IVC with respiration and the sniff maneuver should be noted. A collapse of at least 60% should be expected. With complete thrombosis, there should be no response to these respiratory maneuvers as well as asymmetrically dilation when compared with the opposite side.

To study the lower extremity, patient position should be supine, reverse Trendelenburg position with flexion of the knee and external rotation of the hip. The popliteal vein can be imaged in prone position, with knee flexion of 45° or in lateral decubitus position. Compression ultrasound begins in the groin at the level of the inguinal ligament to identify the common femoral vein (CFV). The probe is the sequentially moved every few centimeters, checking for compressibility. The important compression points needed for an adequate study include

- CFV at inguinal ligament
- Junction of great saphenous vein and CFV
- Bifurcation of CFV into superficial femoral vein and deep femoral vein
- Popliteal vein
- Trifurcation of popliteal vein

The examination can also include compression ultrasound of the whole length of the superficial femoral vein and below-the-knee veins, including the soleal, gastrocnemius, and peroneal veins, although thrombus in these veins is often observed and not treated initially unless symptomatic or multiple.

**Central line placement under ultrasound**

Ultrasound-guided central venous access greatly improves patient safety by reducing complications by reducing the number of attempts and duration. A linear array transducer (7–15 MHz) is generally used due to the high resolution and superficial location of the veins.

Vascular scanning prior to the procedure helps identify anatomy and any abnormalities, such as thrombosis or anatomic barriers (small size and location in relation to artery). Veins are typically elliptical or ovoid, thin walled, and readily collapsible, whereas arteries are circular, thick walled, less compressible, and pulsatile.

Internal jugular vein cannulation via ultrasound guidance is the standard of care currently in the ICU. Multiple studies show an increase successful placement and first attempt rates, along with decreased arterial puncture rate. This can be performed with transducer in longitudinal or transverse mode.

The procedure is done with direct visualization of needle entering the vein while at the same time getting flashback of venous blood in the syringe. A wire is then inserted into the needle and advanced with no resistance. Using a Seldinger technique, a
dilator and then the catheter itself are placed into the vein and secured in place with sutures. Cardiac monitoring should be performed to watch for ectopy when advancing the wire or the catheter.

Femoral vein catheterization is assisted by ultrasound guidance with many of the same features as internal jugular cannulation. It improves first attempt rates and decreased arterial puncture rates. The procedure is performed in a similar fashion to jugular vein catheterization.

Subclavian vein cannulation can also be guided under ultrasound when done distally because the clavicle can produce shadowing allowing for poor visualization of the vessel.\textsuperscript{16} (Fig. 3).

**ABDOMINAL ULTRASOUND**

Abdominal ultrasonography is performed with a phased array (1–5 Mhz) or curvilinear (1–3 Mhz) probe. It can be used in the diagnosis and treatment of many different organ pathologies.

In trauma management, the focused assessment with sonography for trauma (FAST) examination is commonly used a screening test to evaluate for fluid in the abdomen in the unstable patient. It consists of 4 views: subxyphoid, perihepatic, parasplenic, and pelvis.

The subxyphoid view is used to evaluate for pericardial effusion and cardiac function. Perihepatic views can visualize fluid in the right pleural cavity, subphrenic, and

![Fig. 3. Central line placement. (A) Sagittal view and (B) wire in the vessel.](image)
Morison pouch, with the perisplenic view showing any fluid in the left upper quadrant or paracolic gutter. The pelvic view visualizes fluid by the pelvic organs, including bladder, uterus, and rectum (Fig. 4).

Ultrasound can be used as both a diagnostic and therapeutic tool in the management of ascites. Ascites can be tapped or drained under ultrasound guidance at the bedside.

Ultrasound is also the first line of imaging recommended in the work-up of biliary conditions. In evaluating the gallbladder, the probe is placed in the right upper quadrant, just below the costal margin in a transverse or longitudinal orientation. In these windows, biliary pathology, including gallstones, gallbladder sludge, thickened gallbladder wall, pericholecystic fluid, and dilated common bile ducts and stones, can be diagnosed.

The urinary system can also be evaluated using ultrasound. Renal ultrasound is performed in the midaxillary line, in approximately the ninth interspace for the right kidney and slightly more cephalad for the left kidney (seventh to eighth interspaces) in both longitudinal and transverse orientations.

Renal imaging includes visualization of the outer renal parenchyma and inner hypoechoic renal sinus. Generally, the ureter and collecting system in not easily visualized under ultrasound but with obstruction can be seen as hydronephrosis. Duplex imaging of the kidney is also performed and can evaluate renal artery flows and intraparenchymal flow and resistive index, which can be useful in the work-up of acute renal failure.

Bladder ultrasound can be used to evaluate for urinary retention and work-up of low urine output. Anatomic causes, such as tumor, clot, diverticulum, and stones, can be easily visualized. A fluid-filled bladder is best to delineate the bladder wall if needed.

Scrotal ultrasounds are performed with a high-frequency linear transducer (7–15 MHz). They are used in the evaluation of epididymis, testicular torsion, and scrotal trauma. Using B-mode and Doppler signals, evaluation of arterial and venous flow, testicular vascularity, and scrotal fluid hydrocele or hemaatocele can be performed.²,³,¹³,¹⁴,¹⁷

LUNG AND PLEURA

Ultrasound examination of the pleural cavity, when compared with CT or x-ray technology, is inexpensive and avoids ionizing radiation exposure.
The performance of bedside ultrasound precludes the need to transport acutely ill patients. The quality and sensitivity of ultrasound imaging for the diagnosis of pneumothorax are exceptional, in contrast to portable chest x-ray films that can have a sensitivity as low as 30% in some series.

Ultrasound has also proved effective in determining the presence and cause of effusions, based on the internal fluid echogenicity and associated changes in pleura and adjacent lung parenchyma.

A lines result from ultrasound reverberations that take place between the pleural interface and the transducer surface, producing repetitive horizontal hyperechoic lines, depicted distal to the pleura at equally spaced intervals. This is found in normal lung imaging.

B lines (also known as comet tails or lung rockets) are ultrasound artifacts caused by the reflection of ultrasound beams within thickened interlobular septa just under the pleura and are seen as hyperechoic vertical lines arising from the pleural line. A predominance of B lines can be indicative of pulmonary edema. B lines are 3 mm or less apart in cardiogenic or fluid overload whereas B lines that are 7 mm apart generally represent interstitial pulmonary edema (Fig. 5).

Lung sliding is defined as the motion of the visceral pleura against the parietal pleura as a result of inspiration and expiration. M mode (seashore sign) is viewed as continuous hyperechoic horizontal lines above the pleura representing the static chest wall, followed by a granulous pattern below the pleural line. This sandy pattern is created by the moving lung tissue during respiration.

Pneumothorax can be evaluated using ultrasound in clinically stable and unstable patients. Lung point is an ultrasound imaging finding in which the boundary of the noncollapsed part of the lung moves into the air-filled thorax replacing the signs of pneumothorax. The presence of lung point together with the lack of lung sliding 100% specific for identifying pneumothorax.

Lung pulse refers to subtle lung tissue motion (vibration) normally caused by the cardiac pulse. This appears as distinctive vertical bands in M mode and is most easily

Fig. 5. An example of (A) A lines, as horizontal lines; these are an artifact produced by air in the thoracic cavity. (B) B lines; these are also called comet tails, start at the pleural surface, and shine down into the thoracic cavity. Abundance of B lines can be seen in patients with pulmonary edema.
viewed with a hyperinflated lung. The absence of lung pulse may imply the loss of lung tissue and is an additional clue for pneumothorax.

Pleural effusion is usually seen in the lateral and posterior basal windows as a hypoechoic or anechoic space with the compressed lung base floating within. Septations within the effusion, swirling appearance, bilayer effect, and increased echogenicity are highly suggestive of exudate, empyema, or hemothorax. Under ultrasound guidance, this fluid can drained via thoracentesis or with placement of a chest tube. The chest tube can be placed via Seldinger technique with many different sizes of tube available, from 16F to 28F. The chest tube can also be placed via the tradition open technique after visualization of the fluid under ultrasound.  

**Pneumothorax**

Use of ultrasound for detection of pneumothorax is extensively validated. The presence of lung sliding in an area spanning 3 intercostal spaces has been shown to have a negative predictive value of 100% by Lichtenstein and colleagues. Another prospective study by the same group in 73 ICU patients revealed that presence of A lines (horizontal artifacts) had a sensitivity and a negative predictive value of 100% and a specificity of 60% for the diagnosis of pneumothorax. When the presence of A line and absent lung sliding are combined, they had a sensitivity and a negative predictive value of 100% and a specificity of 96.5%.  

**Technique**

Using the linear high-frequency probe, start scanning obtaining images from the second intercostal space on the midclavicular line. Then lower the probe to the fourth intercostal space on anterior axillary line. Continue to the sixth intercostal space on the midaxillary line and, the eighth intercostal space on the posterior axillary line. Air usually rises to the top when a patient is supine. Scanning patients from top down allows for a prompt diagnosis.

**Fluid in the Pleural Space**

Gravity brings the fluid down to the back with a patient in supine. This can allow for rapid visualization in the most dependent anatomic locations, such as fluid in the thoracic cavity (Fig. 6).

**Technique**

Use the low-frequency probe (curvilinear or phased array). Place it in the posterior axillary line on the vertical position with the cursor pointing superiorly. This view in both sides allows for visualization of the diaphragm and the lung. If there is a pleural effusion, the fluid and the lung bathing in this fluid can be seen.

**Other Lung Pathology**

The excessive presence of B lines can signify pulmonary edema. With the low-frequency probe it is possible to visualize a consolidation or a complete lobe collapse. Once an operator is comfortable using this tool, more diagnostic applications become available.  

**CARDIAC**

All cardiac imaging should be performed with a phased array, low-frequency probe (typically 2–5 MHz). The ideal windows for this test are parasternal long axis, parasternal short axis, apical 4-chamber, subxyphoid long axis, and subxyphoid IVC.
To perform the parasternal long axis view, the transducer marker should point toward the right shoulder with the probe placed next to the sternum, between the third and fifth intercostal spaces. The resultant view allows 2-D and M-mode evaluation of structures, including the left ventricle, outflow tract, and aortic root. Color Doppler is usually also applied to the aortic and mitral valves. Zoomed views of the aortic and mitral valves may also allow more detailed structural and functional evaluation. By angling the transducer, it may also be possible to acquire right ventricular inflow and pulmonary artery long axis views. From the parasternal long axis view, the proximal ascending aorta is potentially visualized by moving the transducer up 1 interspace.

The parasternal short axis view is done by rotating the probe is rotated until it is at 90° from the initial long axis position. This window is used to observe the left ventricle, in particular contractility and filling. Right ventricular enlargement can be seen in this window, such as in cases of massive pulmonary embolism and right heart failure.

The apical 4-chamber window is best viewed with patients in left lateral decubitus position but is often not possible in ICU patients due to hypotension, trauma, or critical illness. This window is obtained by placing the probe horizontally over the point of maximal impulse, generally under the left nipple. This view allowed to evaluate left and right ventricular function, valvular function, and atrial anatomy.

The subxyphoid long axis window is viewed with the probe placed in the epigastric area just underneath the xiphoid process and angled cranially pointing toward the left shoulder. This window can view all 4 chambers of the heart in the same plane as well as assess for pericardial effusion. It is used as part of the FAST examination and, therefore, is most commonly used as an initial evaluation by surgeons. (Figs. 7 and 8).

**Inferior Vena Cava Long Axis Views**

There is enough literature to prove or disprove the usefulness of the IVC size and variation for fluid status management. This is a dynamic measurement; I changes with the intrathoracic pressure so the size of the vessel and collapsibility have to be taken into clinical context.
A flat IVC (collapsing >50% with respiratory variation) along with an empty heart (kissing ventricles) are diagnostic of hypovolemia in hypotensive patients. Increased intrathoracic pressure can cause an increase IVC size even in the face of hypovolemia. Therefore, a full IVC cannot rule out hypovolemia, and other clinical parameters should be measured, such as urine output, strove volume variation, and so forth. IVC can be visualized in the subcostal view, right midclavicular line, or posterior midaxial line.1,2,8,11,20–25

Diagnostic Uses in Cardiac Ultrasound

Pericardial effusion/tamponade can be viewed in the subcostal, parasternal, and apical views. The size of effusion can be approximated by the distance between the pericardium and epicardial border and can be serous or hemorrhagic depending on history and clinical setting (Fig. 9). Pericardial tamponade occurs when the effusion causes a compression of the right ventricle, resulting in a decrease in cardiac filling and, therefore, cardiac output. This causes equilibration of pressures in the heart chambers.

Ultrasound can be useful in a hypotensive patient with concern for pulmonary embolism. Right ventricular enlargement with a thin ventricular wall, hemodynamic

Fig. 7. The subcostal or subxyphoid view. The liver is located in the most superior part of the screen. LV, left ventricle; RV, right ventricle.

Fig. 8. (A) Parasternal short window. The blue arrow indicates the left ventricle. The red arrow shows comet tails emanating from the pericardium into the lung tissue. (B) An apical view. LV, left ventricle; RV, right ventricle.
instability, and respiratory distress are highly suggestive of massive pulmonary embolism.

In the correct clinical scenario, trans thoracic echocardiogram (TTE) can be diagnostic of new myocardial ischemia. Signs include regional wall motion abnormalities, new-onset valvular disorders, intracardiac thrombus, and ventricular wall rupture.1,2,8,11,20–25

Furthermore, cardiac ultrasound can be used to guide resuscitation to euvolemia in critically ill patients.15,23 An empty ventricle, hyperdynamic is diagnostic of hypovolemic, in contrast with a full heart with enlargement of the atria and dilation of the IVC, indicating a patient who is not fluid responsive. In some instances, excessive fluid resuscitation can lead to right-sided cardiac dysfunction. An example of a resuscitation protocol guided by ultrasound findings is shown in Fig. 10.

Fig. 9. A parasternal short view of a patient with severe left ventricular hypertrophy. The red arrow indicates the concentric pericardial effusion.

Fig. 10. Initial assessment of volume on admission to ICU. ASAP, as soon as possible; IVF, intravenous fluid; KVO, keep vein open; LTTE: limited transthoracic echocardiogram; PTS, patients; \( SVO_2 \), mixed venous \( O_2 \) saturation; TEG, thromboelastogram.
OTHER INNOVATIONS

Transesophageal Echocardiogram

The gold standard in cardiac imaging is TEE. Because the probe is in the esophagus, the images obtained are sharper and of much better quality than TTE.

TEE allows for visualization of the cardiac chambers, estimation of volume, and getting a sense for cardiac contractility and the overall function of the right and left ventricles.

TEE is more invasive than a transthoracic study; however, for surgeons this is not more difficult than performing an endoscopy at the bedside.

Smaller probes of easier placement have become available but these produce an image of lesser quality.

Some ultrasound machines used by emergency medicine physicians and surgeons have the capability to allow for TEE probes. These are additional tools in the armamentarium of intensivists, and acquiring expertise and credentialing should be available for physicians who treat these difficult patients.26

Transesophageal Doppler

Doppler ultrasound via a probe in the esophagus has been used to measure the blood velocity in the descending aorta. The blood velocity measurement in the descending aorta can be used to calculate stoke volume as a surrogate of intravascular volume.

The flexible probe that is placed in the esophagus has piezoelectric crystals that produce ultrasound images. The probe tip lies along the descending aorta. The velocity of the red blood cells is obtained and converted to flow, using an algorithm. Factors, such as age, gender, weight, and height, are taken into account.

To clarify, this method does not produce 2-D ultrasound images; therefore, the diameter of the descending aorta is not measured but calculated using patient characteristics as well as not having cardiac images to evaluate. It is use merely for volume calculation.27

SUMMARY

The use of ultrasound as a tool to guide therapy in acutely ill patients has been well defined. A few decades ago, the FAST examination was introduced to evaluate for free fluid in the abdominal cavity. In the acute trauma setting, free fluid in most cases is attributable to blood outside of the intravascular space. Blood in the abdominal cavity in the presence of hypotension is an absolute indication for operative exploration. Furthermore, the FAST examination was extended to the pleura to visualize intrapleural fluid and diagnose pneumothorax. Cardiac ultrasound has been shown useful to guide therapy in hypotension.

Because the ultrasound machine is portable, all these anatomic evaluations can be moved to wherever a patient in need is. Therefore, the use of this tool has been extended from the initial phase of resuscitation in the emergency department to the ICU.

In more stable situations, acute care surgeons can also use ultrasound to assist in procedures, evaluate for DVT, and evaluate other intra-abdominal organs.

Other innovations to treat deteriorating patients include transesophageal Doppler and TEE. Physicians who treat these sick patients need to be informed of the uses and applications of these tools to benefit critically ill patients.2,9,26,28–33

REFERENCES


