Biomedical Ultrasound Fundamentals of Imaging and Micromachined Transducers

Course Instructor : Karla Mercado-Shekhar

Department of Electronic Systems Engineering

Indian Institute of Science, Bangalore

Lecture - 08

Hello, and welcome to today's lecture where we will be discussing *imaging artifacts*. So, what exactly are artifacts? Just like in any other medical imaging modality, ultrasound also has its own set of artifacts. Artifacts refer to unwanted features in an image that don't correspond to the actual target or anatomy. These can lead to a false representation of the body, causing issues such as structures not appearing in the image, objects being incorrectly located or distorted, or even the appearance of fake objects or features that aren't really present.

In Doppler imaging, artifacts can also result in inaccurate calculations of flow speeds.

So, what causes these artifacts? In broad terms, artifacts can be seen as a type of noise. However, unlike random noise, imaging artifacts are deterministic. They occur when certain assumptions made during image reconstruction are violated. Artifacts can also result from technical or human errors, as well as hardware malfunctions.

There are several different types of artifacts, which can be classified as physical artifacts, system-independent artifacts, or those dependent on the operator.

Let's now go over some common assumptions in image reconstruction that, when violated, can lead to artifacts. For instance, one assumption is that the speed of sound remains constant throughout the tissue being imaged. In most ultrasound systems, the speed of sound is assumed to be 1540 meters per second. However, we know that different tissues have varying sound speeds. A non-uniform sound speed within tissue can cause errors in depth location, meaning that the actual distance of a structure is not accurately portrayed in the ultrasound image.

Another assumption is that the attenuation coefficient is fixed across the tissue. But in reality, tissues are inhomogeneous, and the attenuation of sound waves can vary significantly between different tissue types. This variability can also lead to artifacts in the image.

Another assumption in ultrasound imaging is that the ultrasound beam propagates in a straight line. However, we know that tissue boundaries are not always perfectly perpendicular to the transducer, causing the sound waves to refract or deviate in directions that may not be captured by the transducer.

Another key assumption is that only first-order or single reflections occur. In reality, tissues often cause multiple reflections due to differences in acoustic impedance, leading the ultrasound waves to bounce back and forth between tissue structures. This can introduce distortions or misrepresentations in the resulting image.

It’s also assumed that the ultrasound beam is planar. However, as we’ve previously discussed, the beam is not perfectly planar but has a finite thickness, which affects the beam pattern. Similarly, the assumption that no side lobes are present is not entirely accurate, as spatial and temporal side lobes are commonly observed in ultrasound images. These side lobes can produce unwanted signals and interfere with the main beam, leading to artifacts.

Another assumption is that the transducer is adequately damped. In practice, some transducers exhibit ringing, which can cause range ambiguity and make it difficult to accurately measure the time delay between echoes from different tissue structures.

We also assume that scattering is diffuse, but as we learned in the previous lecture on scattering types, Rayleigh scattering and other forms of scattering can occur depending on the size of the object. Scattering patterns may not always be isotropic and can go in multiple directions, adding complexity to the imaging process.

Additionally, we assume that all transducer elements have equal sensitivity. However, in reality, electronic instruments can have variations in sensitivity across elements, which can influence the image quality.

Time Gain Compensation (TGC) is another operator-controlled parameter that must be adjusted correctly. The sonographer's expertise in dialing the TGC knobs is crucial for optimizing image quality, as improper adjustments can affect how tissue structures are visualized.

Lastly, we assume that no aliasing occurs, especially in Doppler imaging, but aliasing can sometimes present challenges, particularly when measuring blood flow velocities, leading to further inaccuracies in imaging.

If Doppler settings are not configured correctly, aliasing can occur, which can affect Doppler measurements. The first artifact we'll discuss is known as the reverberation artifact, often referred to as the "comet tail" artifact. Let’s explore why that is. This type of artifact typically happens when there is a strong reflector present.

Take, for example, this ultrasound image of a needle inside a phantom. This scenario simulates a procedure known as needle-guided biopsy. The transducer is positioned at the top, transmitting the ultrasound signal. As the signal propagates, it encounters the needle, which has a significant acoustic impedance mismatch compared to the surrounding tissue, making it a highly reflective surface.

As a result, the reflected signal from the needle travels back to the transducer. If the reflection doesn't completely dissipate, the signal may bounce back from the transducer to the needle again, creating what we call multiple reflections. This back-and-forth motion between the transducer and the needle generates these repeated reflections in the image.

In the ultrasound image, we can observe these repeated reflections, which gradually fade in amplitude as they extend deeper into the tissue. These reverberation artifacts can create the illusion of false targets in the reconstructed image. In this case, the artifact makes it seem as though there are structures present that don't actually exist, as they are simply echoes from the strong reflector.

The next artifact is acoustic shadowing. This occurs when the ultrasound beam encounters a structure with high attenuation, which affects the reconstruction of the image. When this happens, structures located behind the highly attenuating object appear darker than they should.

For instance, here we see an ultrasound image of a gallbladder stone. The gallbladder typically contains a fluid-like substance, but when a stone is present, it creates a significant acoustic impedance mismatch with the surrounding tissue, making it a strong reflector. The result is a bright echo from the stone, and because the sound cannot pass through the stone effectively, the area behind it appears as a dark shadow, which is characteristic of acoustic shadowing.

Much of the ultrasound signal is reflected back to the transducer, and only a small portion of it passes through and gets transmitted beyond the stone. This results in the shadowing artifact that appears behind the stone. This effect isn’t just limited to stones—bones, metal implants, and calcifications in the body can also cause similar shadowing because of their high acoustic impedance mismatch with surrounding soft tissues.

On the other hand, another type of artifact is known as acoustic enhancement. This occurs when the ultrasound beam interacts with a structure that has low attenuation, resulting in distal structures appearing brighter than they should. A typical example is seen in this ultrasound image of the bladder. The bladder is mostly fluid-filled, and as the ultrasound beam propagates through the tissue and reaches the bladder, very little attenuation occurs. As a result, a significant portion of the sound energy is scattered back from the distal tissues.

To clarify the terms: proximal refers to areas close to the transducer, and distal refers to areas further from the transducer. So, when you have a fluid-filled structure like a bladder or cyst, it can cause acoustic enhancement in the distal part of the tissue.

Another type of artifact is caused by beam diffraction, which can result in non-uniform brightness or resolution across the image. For example, in this ultrasound image of wire targets, a focused ultrasound beam concentrates energy in a specific region. In this case, the focus is around the middle, where the echogenicity (brightness) is much higher compared to areas outside the focal region.

As the ultrasound beam moves away from the focal point, it spreads out. This beam spreading leads to attenuation of the signal, meaning echoes from targets outside the focal region may appear weaker or less clear. The next artifact to discuss is the range or ambiguity artifact.

Here's how this occurs: In this example, we have a transducer imaging a region of interest with a structure of interest within that area. There might also be a stronger reflector located outside of the region of interest. The transducer sends out a pulse, which interacts with the tissue, and the pulse repetition frequency (PRF) is typically set so that the echoes from the deepest part of the region of interest have enough time to return to the transducer. Once this happens, the transducer moves to another lateral or horizontal position, and the same process repeats.

However, if the PRF is too high, the echoes from deeper structures may not fully dissipate before the next pulse is transmitted. If there is a strong reflector in the deeper region, it can lead to what's known as a range ambiguity artifact. In this case, the echo from the strong reflector doesn't fade away completely, and as the next pulse is transmitted, the previous echo interacts with it. This can cause deeper structures, which are not part of the original region of interest, to appear in the ultrasound image.

Another common type of artifact is side lobe artifacts. These can occur in single-element transducers, while grating lobes happen in transducer arrays. Both can create additional beams beyond the primary sound beam, leading to objects being incorrectly displayed in the horizontal position of the ultrasound image. For instance, in this ultrasound image of a bubble cloud—which consists of microbubbles located in one spot—there is high echogenicity in the center, representing the bubble cloud. However, due to the presence of side lobes, additional echogenic signals appear on either side of the bubble cloud. These signals are not representative of the actual bubble cloud but are artifacts caused by the side lobes.

Another artifact is edge refraction artifacts. Consider this ultrasound image of a gallbladder, which is fluid-filled. When the ultrasound beam propagates through the tissue and encounters the edge of a structure, refraction can occur at these edges. As the beam refracts, the signal gets redirected, preventing it from returning to the transducer. Consequently, the edges of the structure appear darker in the ultrasound image. This is due to the beam's diversion, which results in no signal being reconstructed at the edge, producing the edge refraction artifact.

The next artifact is the mirror artifact, which occurs when reflections from structures near strong specular scatterers produce a duplicated object in the image. To explain this, imagine standing in front of a mirror while a camera takes a photo of you. In the photo, you see both yourself and your reflection because of the mirror. A similar phenomenon happens in ultrasound images. For example, in this liver ultrasound image, the transducer sends a signal that encounters a strong specular scatterer, which produces a bright echo. This specular scatterer acts as a mirror, creating a duplicate of the structure in the image at another location.

In addition to mirror artifacts, there are challenges in visualizing specular structures in ultrasound images. Specular scatterers are not always perpendicular to the transducer. Take this liver image, for example. The diaphragm, acting as a specular scatterer, appears less echogenic when it’s not perfectly horizontal. This occurs due to the oblique angle of incidence, where the incident ultrasound wave hits the boundary at an angle. The reflected wave bounces back at the same angle, meaning less of it returns to the transducer. As a result, parts of the diaphragm that are more oblique to the transducer appear less bright compared to those more perpendicular.

Another artifact is the transducer ringing artifact. This happens when the transducer has a high Q factor, causing it to "ring" for a longer time, especially in the near field. For example, if you look at this signal pattern, the ring down artifact from the transducer signal is visible, along with the echo. If the object being imaged is far from the transducer, the time difference between the echo and the ring down artifact is measurable. However, if the object is close to the transducer, the echo signal from the structure can interfere with the ring down artifact, making it difficult to identify the scatterer at that location.

This phenomenon is referred to as the transducer ringing artifact. Doppler imaging, which we use to assess blood flow velocity in moving structures like blood vessels, can also produce artifacts. As we know, the Doppler signal depends on the angle between the incident ultrasound beam and the direction of blood flow. Typically, Doppler ultrasound imaging is performed at angles between 30 and 60 degrees, because angles greater than 60 degrees tend to produce inaccurate Doppler frequency shifts.

However, tissue motion can also introduce artifacts in Doppler, known as flash artifacts. When tissue moves, the Doppler ultrasound may misinterpret it as a moving structure. For instance, in this image of a beating heart, there's a vessel at the center, but you also see a color map signal around the tissue, indicating motion in the surrounding area. This is an example of an artifact caused by tissue movement.

While artifacts are often undesirable, not all of them are detrimental. In fact, some can provide valuable diagnostic information. Sonographers are trained to recognize and interpret these artifacts to aid in clinical diagnosis. For example, artifacts can help differentiate between a cyst and a tumor.

Previously, we discussed an example of a cyst, and here’s an example of a renal cyst. The acoustic enhancement artifact seen distal to the cyst is actually helpful, as it allows sonographers to confirm the presence of a cyst due to the enhanced signal beyond it.

Another useful artifact is observed when detecting calcifications in tissues. Since calcified structures have a high acoustic impedance mismatch compared to surrounding tissue, they produce a higher echogenic region at the site of the calcification, helping to identify these structures in the image.

Here’s an example of calcification in the liver. You can observe a bright echogenic signal originating from the calcification, accompanied by distal shadowing due to the high acoustic impedance of the calcified region. This shadowing effect helps confirm the presence of calcification in the liver.

Another example comes from lung ultrasound. In a healthy lung, it's challenging to image beyond the pleural line due to the air-filled nature of the lung. However, ultrasound becomes useful in cases where the lung is fluid-filled or fibrotic (a buildup of proteins in the tissue). In this lung ultrasound, you can see the pleural line, which encases the lung. Regions of healthy lung, which is primarily air-filled, cause some shadowing. But when there’s fibrotic tissue, the ultrasound signal penetrates deeper, propagating further into the lung.

The high echogenic regions visible here are known as B-lines on lung ultrasound, which are particularly useful for detecting conditions like fluid-filled lungs. This was especially significant for diagnosing patients with COVID-19, as these B-lines indicated the presence of fluid-filled lungs, a common symptom.

To summarize, in today’s lecture we explored various artifacts in ultrasound imaging, their formation, different types, and sources. We also discussed how they can degrade image quality and how signal processing techniques can help correct them, which we will cover in future lectures. However, not all artifacts degrade image quality—some, like those identifying cysts or calcification, are quite helpful in clinical diagnosis.

That wraps up this lecture! Looking forward to seeing you in the next one. Goodbye!