Advanced BME Laboratory (AM5019)
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21 December 2021

EXPERIMENT 1:
Estimate the Resolution and contrast of an Ultrasound System

OBJECTIVES:

i. Estimate the axial and lateral resolution from images obtained from three different ultrasound systems operating at different frequencies for the tissue mimicking phantom.
ii. Understand the dependency of frequency on resolution.
iii. Compute the contrast ratio and contrast to noise ratio for the images obtained from different ultrasound systems.

THEORY:

Electronic transducers:
Electronic transducers are made from a large number of small, identical crystal elements which are arranged in a suitable geometrical configuration to provide the desired field of view. Movement of the beam is affected by exciting the crystal elements in an orderly fashion. The crystal elements may be pulsed individually, or one at a time (sequential pulsing). Alternatively, the instantaneous beam may be provided by a small segment of crystals excited together (segmental pulsing). The choice between sequential and segmental pulsing is dictated by the need to provide a suitable beam shape that optimizes the spatial resolution and allows a desired tissue depths to be imaged.

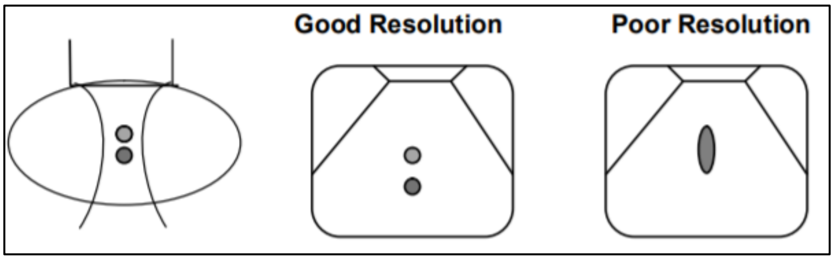
Different geometrical configurations have been used in multi crystal arrays. In linear array transducers, the crystal elements are arranged in a row and generate rectangular fields of view. They may be activated either sequentially or segmental. In an annular array transducer, the crystal elements are arranged in concentric rings. For electronic beam sweep, the set of typically 5 - 10 ring elements is pulsed sequentially to move the beam from the innermost ring outwards. A phased array system may have the same geometrical configuration as either a linear array or an annular array, but the procedure of activating the crystal elements is different. In phased array transducers, all the crystal elements are pulsed almost instantaneously as one group, excepting for very short time delays between the activations of individual crystal elements. The carefully controlled electronic time delays are programmed into the pulsing of each crystal element to facilitate movement and focusing of the beam. For each pulsing of the array, a phased array system produces only one scan line over the whole area of the array. The number of scan lines contributing to the image is increased by sweeping the beam electronically through different directions using the short time delays.

Resolution:

Resolution of an image can be defined as the minimum distance between two points in the image that can be differentiated. A more precise definition of resolution would be: the ability of a medical imaging system to accurately depict two distinct events in space, time, or frequency as separate and are called spatial, temporal, or spectral resolution, respectively. Given the PSF (Point Spread Function- the output corresponding to a single point source) of a medical imaging system, the resolution can be quantified using a measure called the full width at half maximum (FWHM). This is the (full) width of the PSF at one-half its maximum value. Provided there is no geometric scaling, the FWHM equals the minimum distance that two points must be separated in space in order to appear as separate in the recorded image.

Spatial Resolution:

1. Axial Resolution:

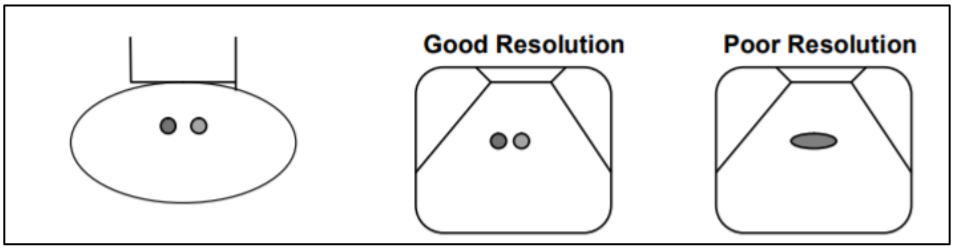


Axial/longitudinal resolution refers to spatial resolution in the direction of beam propagation. It can be described as the instrument's ability to resolve two reflecting boundaries that are closely spaced in the axial (or longitudinal) direction. The theoretical value of axial resolution is given by:

$$\boldsymbol{AR = \frac{Q\lambda}{4}}$$

Q is the quality factor which is given by $Q = \frac{f}{\Delta \mathrm{f}}$, where f is the centre frequency of the transducer and Δf is the bandwidth of the transducer. Therefore, a higher frequency and short pulse length will provide a better axial resolution. Transducers of high frequency have thin piezoelectric elements that generate pulses of short wavelength. However, a drawback of high-frequency pulses is that they are attenuated well in soft tissue. This means that they may not be reflected back sufficiently from deep structures, for detection by the transducer.

2. Lateral resolution



Lateral/Transverse resolution is measured in the plane perpendicular to the beam's direction.
The spacing in the transverse plane at which the points are resolvable is known as the lateral resolution (LR). The lateral resolution depends on the beam width of the ultrasound wave at that particular depth. The width of the beam and hence lateral resolution varies with distance from the transducer. At the transducer, beam width is approximately equal to the width of the transducer. Then, the beam converges to its narrowest width which is half the width of the transducer, at a perpendicular distance from the transducer called the near-zone length. The region of space subtended by the beam is called the near zone (Fresnel's zone). At a distance greater than the near-zone length i.e., the far zone (Fraunhofer's zone), the beam diverges such that it becomes the width of the transducer, when the distance from the transducer to the reflector is twice the near-zone length. Here, lateral resolution decreases. Lateral resolution is high when near-zone length is long. Near-zone length is given by the following equation- $\boldsymbol{\frac{D^2}{4\lambda}}$, where D is the width of the transducer and λ is the wavelength of the pressure wave. Short wavelength i.e., high frequency of transducer increases the near-zone length. When low-frequency transducers are utilized, lateral resolution deteriorates: in this situation, near-zone length is short which means that structures beyond the near zone are scanned by a divergent beam. When the piezoelectric elements are operated at different times resulting in a narrow-focussed beam, it leads to a creation of a focal region with high lateral resolution. The beam beyond the focal region is divergent and so there is a reduction in lateral resolution of structures deeper than this point.

Contrast Resolution:

Contrast resolution refers to the ability to distinguish between different echo amplitudes of adjacent structures. Contrast resolution is altered by compression of the range of reflected ultrasound amplitudes, number of layers of bits per pixel, and the use of contrast agents. Pulses of ultrasound vary in amplitude and hence power. The magnitude of the highest to the lowest power is expressed logarithmically, in a decibel range called dynamic range. Compression occurs in the signal processor which reduces the dynamic range, to a ratio of the highest power to the lowest power, by a combination of assigning stronger echo powers to maximum and weaker echo powers to zero. Numerically, the number of decibels of the dynamic range is reduced by compression. High compression with a narrow dynamic range creates an image of high contrast. Conversely, low compression with wide dynamic range displays an image of low contrast and with many shades of grey. Storage of digitized information contained in the pulse waveforms occurs in the image memory. The higher the number of bits to represent an image, the better the contrast.
Considering an ultrasound system to distinguish between a cyst and the background, the contrast ratio (CR) and the contrast to noise ratio (CNR) is defined as:

$$\mathbf{CR = 20\log_{10}}\left(\frac{\mu_c}{\mu_b}\right)$$

$$\mathbf{CNR} = \frac{|\mu_c - \mu_b|}{\sqrt{\sigma_c^2 + \sigma_b^2}}$$

where μ_c and μ_b are the mean values of cyst and background respectively and σ^2_c and σ^2_b are the corresponding variance.

APPARATUS USED:

CIRS – commercial phantom (040GSC): Images of the tissue mimicking phantom were captured using three different systems.

Ultrasound System 1: SonixTouch System (Medical equipment)
Linear array (5 - 14 MHz)
1. Focus is at 20 mm depth
2. 64 elements were excited during transmit and 128 elements were used for data acquisition during the receive.
3. Sampling frequency=40 MHz
4. Transmit frequency= **13.3 MHz**

This machine had higher contrast due to better image filtering.

Ultrasound System 2: VeraSonics System (Research equipment)
Linear array (5 -11MHz)
1. Focus is at 20 mm depth
2. 64 elements were excited during transmit and 128 elements were used for data acquisition during the receive.
3. Sampling frequency = 19.2308 MHz
4. Transmit frequency = **5 MHz**

Ultrasound System 3: BUS Lab developed system (For cardiac imaging)
Phased Array (2 – 4 MHz)
1. Focus is at 20 mm depth
2. 64 elements were excited during transmit and 64 elements were used for data acquisition during the receive.
3. Sampling frequency = 32 MHz
4. Transmit frequency = **2.44 MHz**

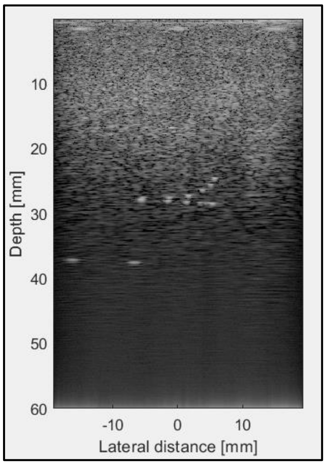
PROCEDURE:

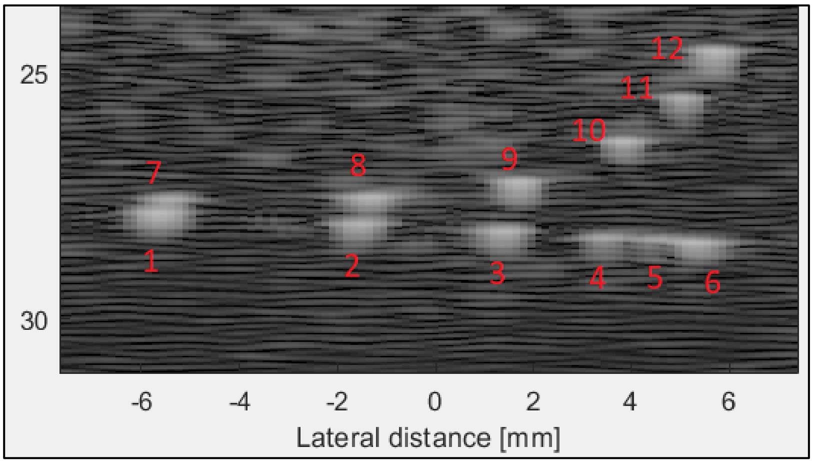
i. Ultrasound B-mode images of the CIRS commercial phantom were acquired from three different systems operating at different frequencies.
ii. The probes were placed perpendicular to the surface of the phantom while acquiring images.
iii. Separate regions of the phantom were imaged for resolution data and cyst regions were acquired for contrast data.
iv. The axial resolution, lateral resolution, contrast ratio, and contrast to noise ratio were estimated for the three systems.
v. To find the lateral resolution, lateral profiles at the appropriate depth was taken and the distance between the peaks was calculated. The minimum distance when the separation between the peaks was greater than or equal to the FWHM was estimated as the lateral resolution.
vi. To find the axial resolution, axial profiles at appropriate widths were taken and the distance between the peaks was calculated. The minimum distance when the separation between the peaks was greater than or equal to the FWHM was estimated as the axial resolution.
vii. The contrast ratio and contrast to noise ratio was calculated using the formulas mentioned above. A rectangular area within the cyst was considered for the cyst pixels, and an area around the cyst was considered for the background pixels as illustrated in the images below.

RESULTS & OBSERVATIONS:

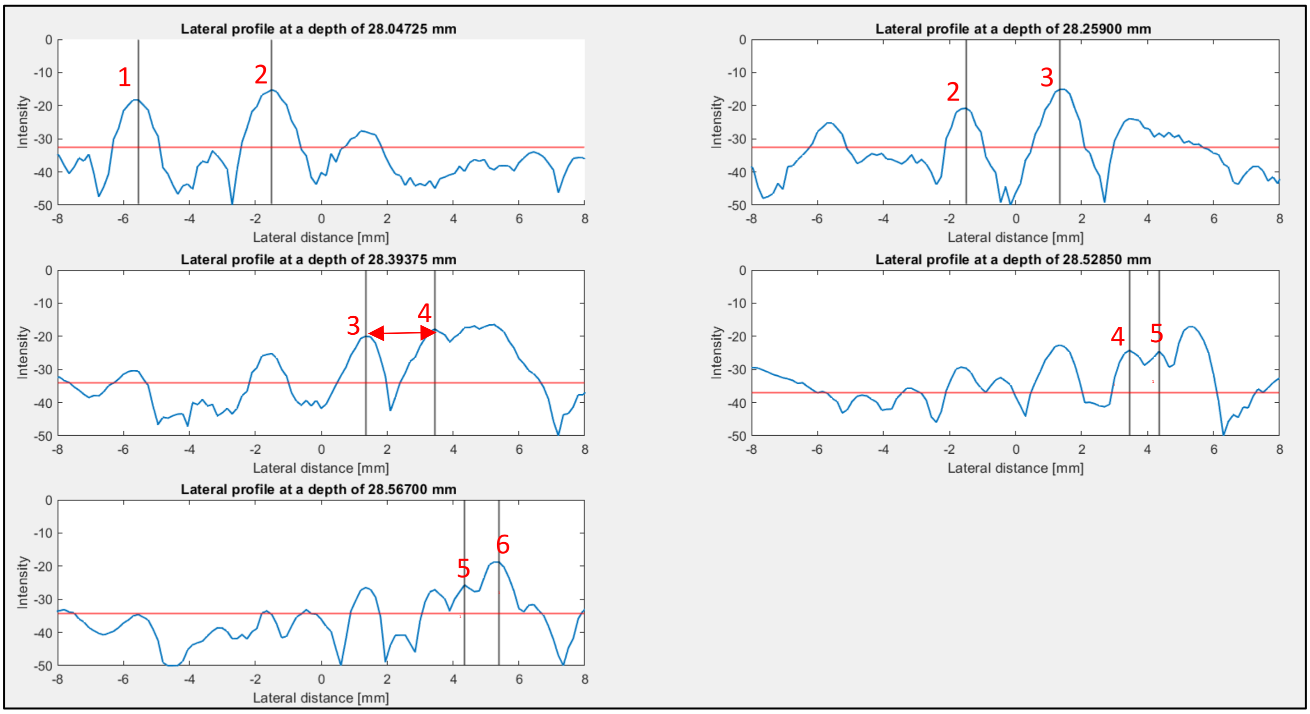
Ultrasound System 1: SonixTouch System: Linear array (5 - 14 MHz)

Sampling frequency= 40 MHz; Transmit frequency= 13.3 MHz





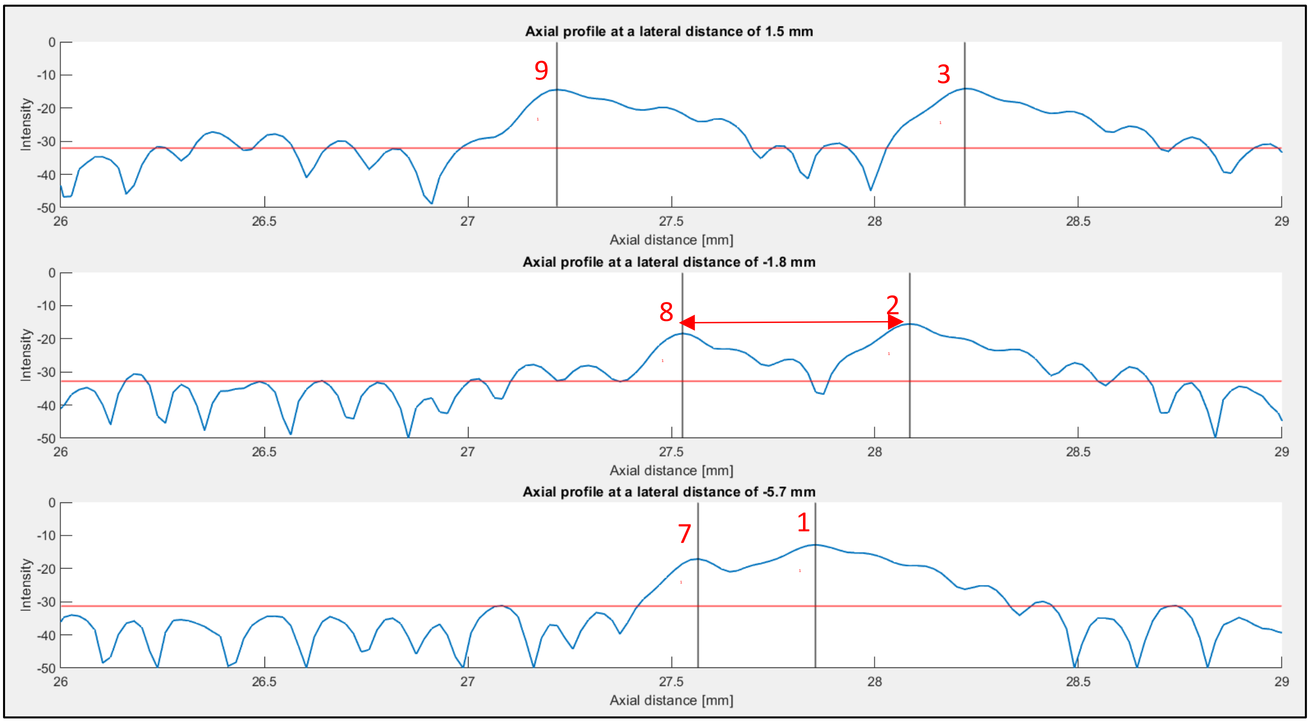
Lateral Resolution



From the lateral profiles, the points 1-2, 2-3, 3-4 can resolved as the separation between the intensity peaks is greater than the FWHM. The points 4 -5, 5-6 cannot be resolved as the distance between their intensity peaks lie at less than FWHM.

Therefore, from the manual observation in this case, the **lateral resolution** is the separation between points 3 – 4 = 3.45 – 1.35 = **2.1 mm**

Axial Resolution

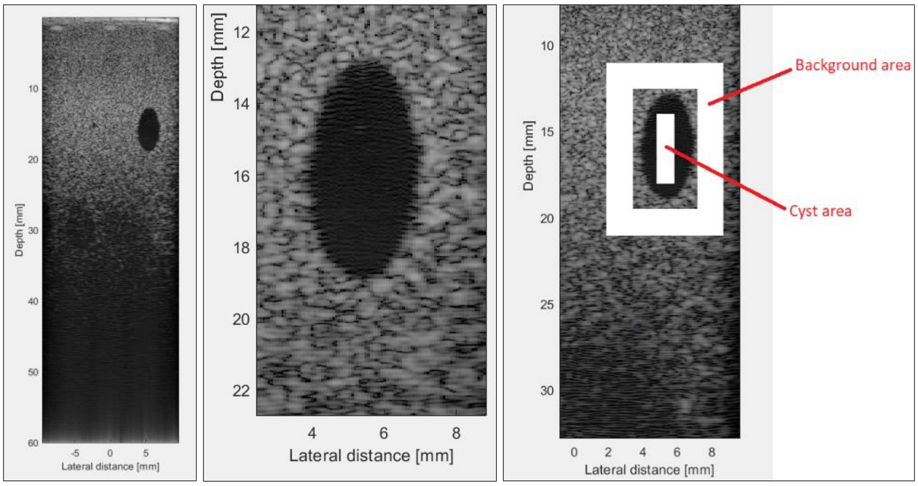


From the axial profiles, the points 9 - 3 and points 8 – 2 can be resolved as the separation between the intensity peaks is greater than the FWHM.

From subplot 3, the points 7 – 1 cannot be resolved as the distance between their intensity peaks lie at less than FWHM.

Therefore, from the manual observation in this case, the **axial resolution** is the separation between points 8 – 2 = **0.5583 mm**

Contrast

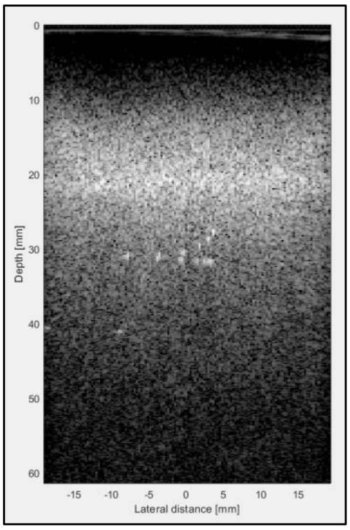


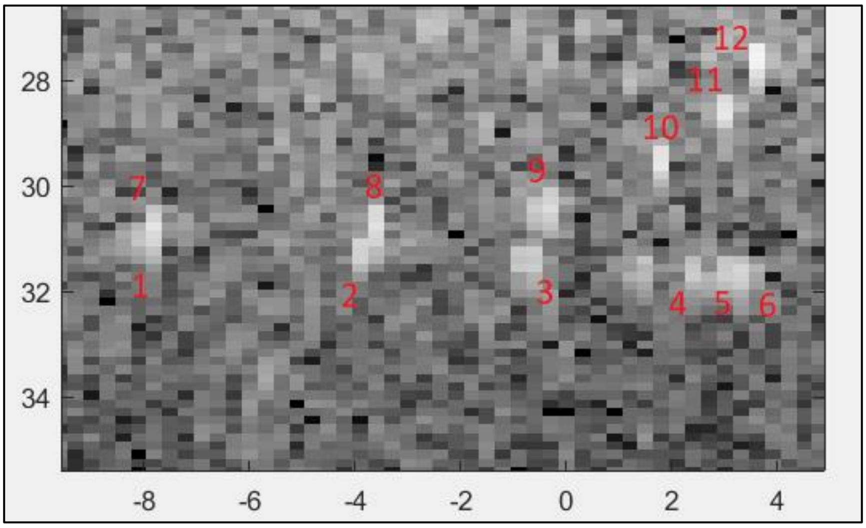
$$CR = 20 * \log_{10} \frac{\mu_c}{\mu_b} = 20 * \log_{10} \frac{-44.3065}{-28.9543} = 3.6951$$

$$CNR = \frac{|\mu_c - \mu_b|}{\sqrt{\sigma_c^2 + \sigma_b^2}} = \frac{|-44.3065 - (-28.9543)|}{\sqrt{1.4721^2 + 5.9324^2}} = 2.5117$$

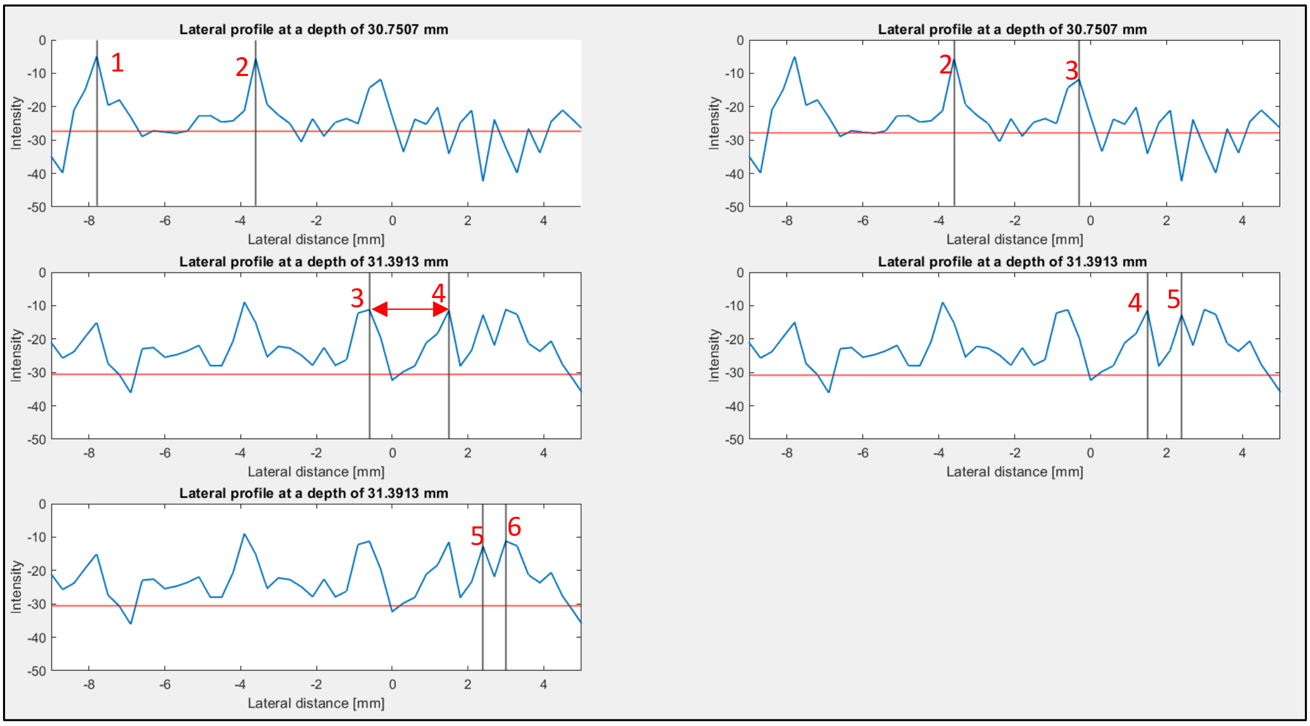
Ultrasound System 2: VeraSonics System: Linear array (5 -11MHz)

Sampling frequency = 19.2308 MHz; Transmit frequency = 5 MHz





Lateral Resolution

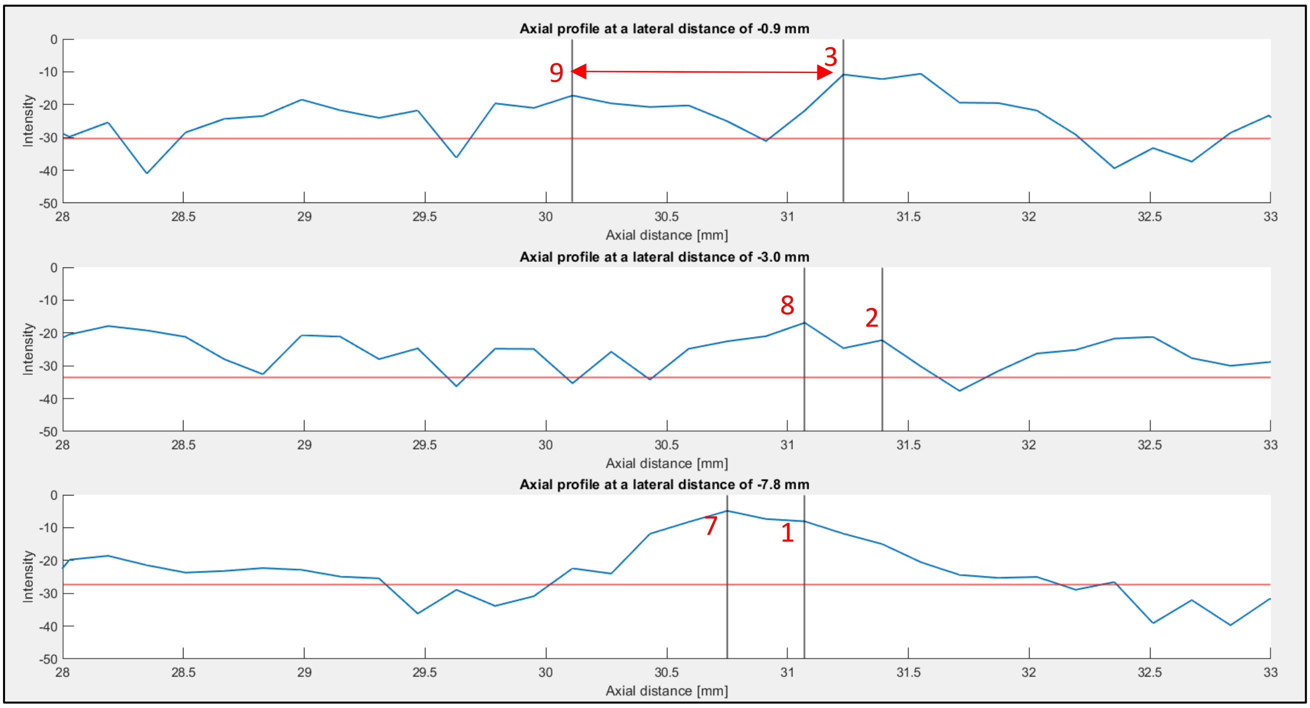


From the lateral profiles, the points 1-2, 2-3, 3-4, can resolved as the separation between the intensity peaks is greater than the FWHM.

The points 4-5 and 5-6 cannot be resolved as the distance between their intensity peaks lie at less than FWHM.

Therefore, from the manual observation in this case, the **lateral resolution** is the separation between points 3– 4 = 1.5 – (- 0.6) = **2.1 mm**

Axial Resolution

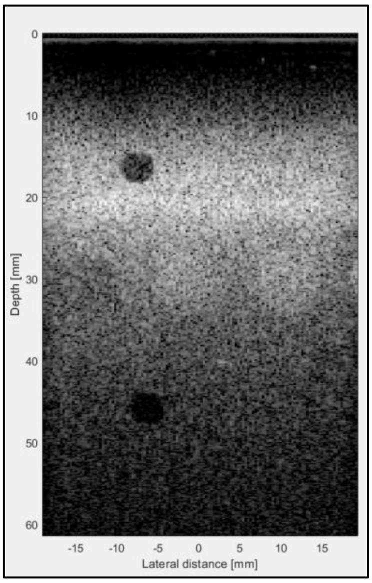


From the axial profiles, the points 9 - 3 can be resolved as the separation between the intensity peaks is greater than the FWHM.

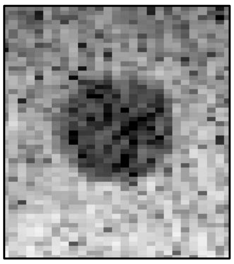
The points 8 - 2 and 7 – 1 cannot be resolved as the distance between their intensity peaks lie at less than FWHM.

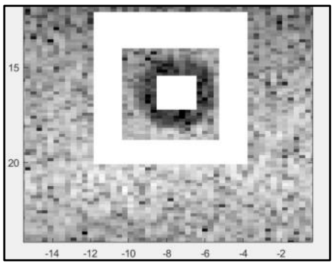
Therefore, from the manual observation in this case, the **axial resolution** is the separation between points 9 – 3 = **1.1212 mm**

Contrast



Top
cyst



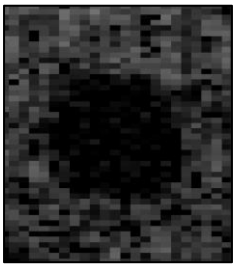


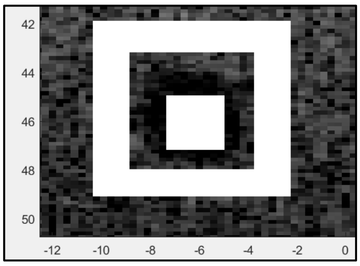
Cyst (Top):

CR = $20 * \log_{10} \frac{\mu_c}{\mu_b} = 20 * \log_{10} \frac{-38.7772}{-19.6751}$ = 5.8932

CNR = $\frac{|\mu_c - \mu_b|}{\sqrt{\sigma_c^2 + \sigma_b^2}} = \frac{|-38.7772 + 19.6751|}{\sqrt{5.9066^2 + 8.2403^2}}$ = 1.8841

Bottom
cyst





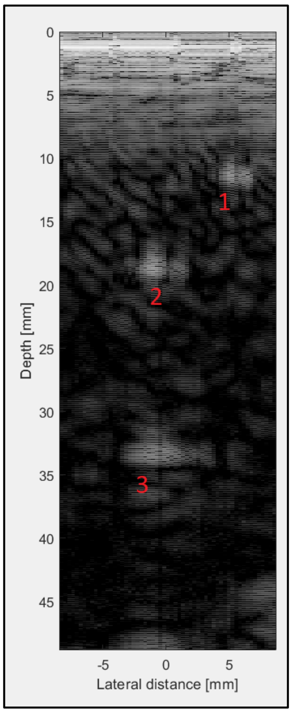
Cyst (Bottom):

CR = $20 * \log_{10} \frac{\mu_c}{\mu_b} = 20 * \log_{10} \frac{-49.1251}{-39.9191}$ = 1.8025

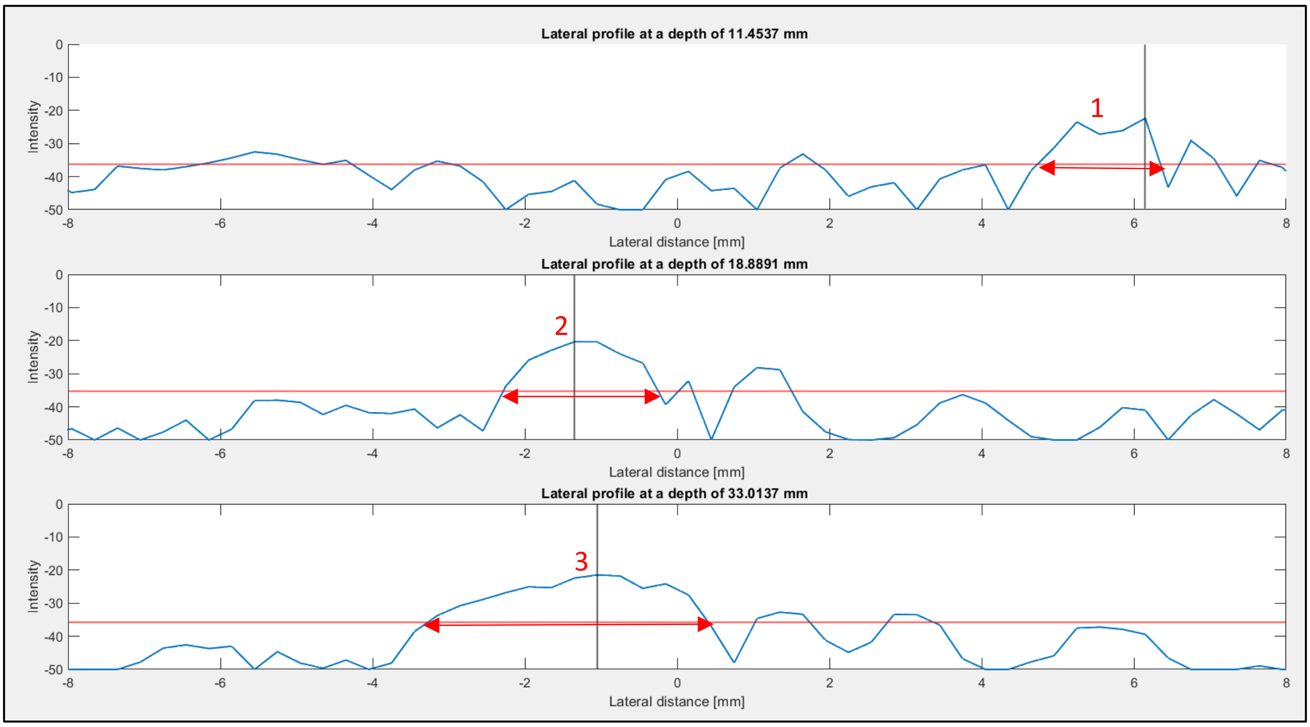
CNR = $\frac{|\mu_c - \mu_b|}{\sqrt{\sigma_c^2 + \sigma_b^2}} = \frac{|-49.1251 + 39.9191|}{\sqrt{1.3578^2 + 5.2441^2}}$ = 1.6995

Ultrasound System 3: BUS Lab System: Phased Array (2 – 4 MHz)

Sampling frequency = 32 MHz; Transmit frequency = 2.44 MHz



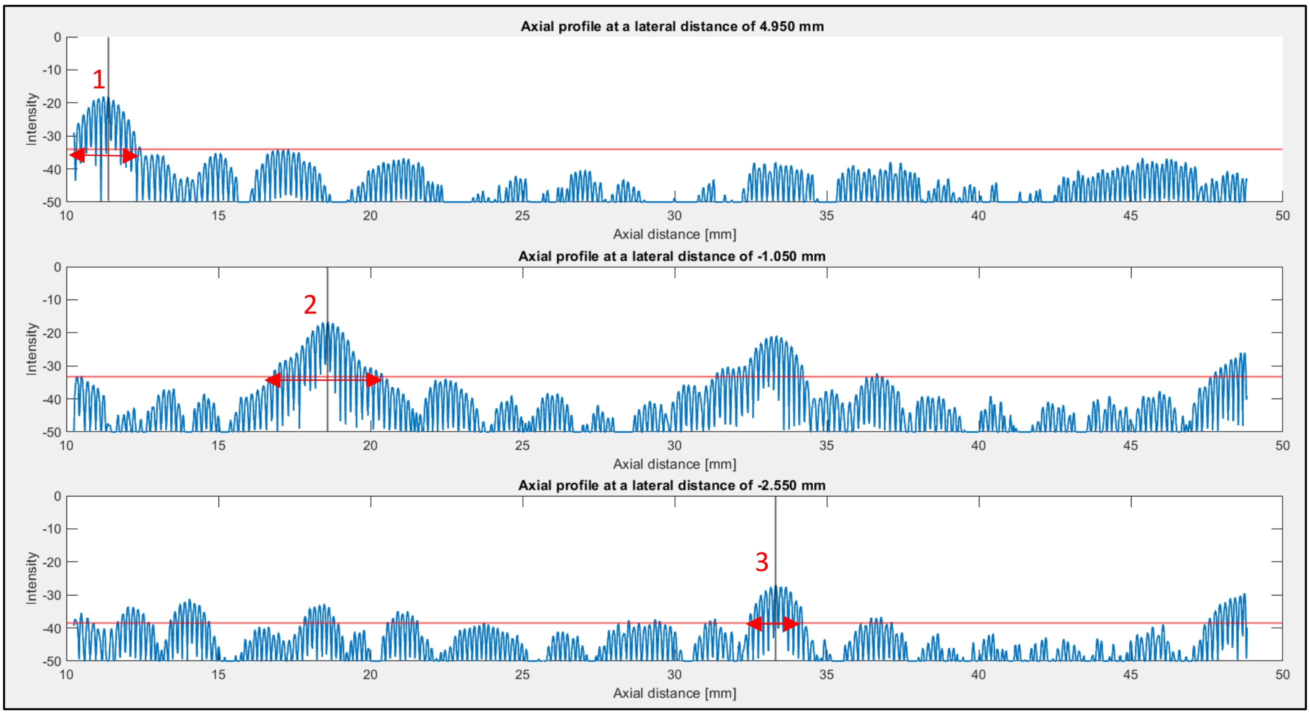
Lateral Resolution at different depths



Point	Depth	Lateral resolution
1	11.4537	1.62
2	18.8891	2.02
3	33.0137	3.67

The lateral resolution has been estimated as the FWHM of a single peak. As the depth increases the lateral resolution degrades. This is expected since the beam width increases as the beam diverges.

Axial Resolution



Point	Lateral distance	Axial resolution
1	4.950	1.995
2	-1.050	3.57
3	-2.550	1.74

The axial resolution has been estimated as the FWHM of a single peak.

Ultrasound System	Transmit frequency used (MHz)	Sampling frequency (MHz)	Axial Resolution (mm)	Lateral Resolution (mm)	Contrast ratio	CNR
SonixTouch System	13.3	40	0.5583	2.1	3.6951	2.5117
VeraSonics System	5	19.2308	1.1212	2.1	Cyst (Top) 5.8932 Cyst (Bottom) 1.8025	Cyst (Top) 1.8841 Cyst (Bottom) 1.6995
BUS Lab developed system	2.44	32	Lateral Dist: 4.95; AR:1.995 Lateral Dist: -1.05 AR:3.57 Lateral Dist: -2.55; AR: 1.74	Depth:11.45; LR: 1.62 Depth:18.89; LR: 2.02 Depth:33.01; LR: 3.67	--	--

CONCLUSIONS:

- The practical axial and lateral resolution have been determined for the three Ultrasound systems.

- As the frequency increases axial resolution improves. Therefore, the highest frequency, in this case 13.3MHz has the best axial resolution (0.5583 mm).

- The focus was set to 20mm for all three systems. The best lateral resolution would have been obtained at this depth. Beyond the focus the beam is diverged which results in poorer lateral resolution.
- For the BUS System, as the depth increases the lateral resolution degrades. This is expected since the beam width increases as the beam diverges.

- The topmost cyst in the Verasonics System has best contrast ratio (CR). At greater depths, the contrast decreases.

- The Sonixtouch system has the best contrast to noise ratio (CNR). This system has good filtering of the signal to eliminate noise.

CRITICAL REMARKS:

In reality, the resolution depends on the point spread function and is affected by other factors such as noise, the correct placement of the transducer perpendicular to the surface, variations in approximated speed of sound in the medium