AN INITIAL QUANTITATIVE COMPARATIVE STUDY OF THE AXIAL AND LATERAL SPATIAL RESOLUTIONS OF DIFFERENT ULTRASOUND TRANSDUCERS

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Abstract –
Accurate measurement of the spatial resolution of ultrasound transducers is critical for medical imaging. Spatial resolution places a limit on the amount of detail that can be retrieved in an image and impacts the range of clinical diagnosis errors. High spatial resolution allows precise and clear visualization of anatomical microstructures as well as pathological conditions. It also allows radiologists to detect small abnormalities and deformities. This article compares the spatial resolution of different ultrasound transducers, investigates the effect of spatial resolution with depth for different transducers, as well as the effect of spatial resolution with different frequencies for different type of transducers. The spatial resolution results are from acceptance tests performed between February 2019 and March 2023 for 14 ultrasound scanners equipped with 51 transducers: 22-linear, 23-curvilinear, and 6-sector. An ultrasound phantom was also used (CIRS model 040GSE). In addition, ImageJ was used to calculate the spatial resolution of the different ultrasound transducers at different depths within the phantom quantitatively.

Keywords –
Ultrasound, transducers, spatial resolution, Full-Width-Half-Maximum, ImageJ, phantom

I. INTRODUCTION

Over the decades, the use of ultrasound in medical diagnostics has constantly developed and improved. Nowadays, several people are familiar with ultrasound images from personal experience and prenatal examinations. However, current ultrasound systems are much more complex than before. Modern ultra- sound systems can acquire precise measurements and dimensions of blood movement, as well as generate three-dimensional images of moving objects. These images are produced by a transducer, a device that generates sound waves and receives returning echoes from tissue interfaces. The collection of returned echoes are sampled and computed to produce an image. Post-processing is generated to improve the overall image according to the clinical protocol.

To ensure that the image obtained is of sufficient quality, a quality control (QC) programme is carried out on various types of transducers. This provides verification that the equipment can be put for clinical use. The QC tests evaluate the performance of several clinical imaging parameters; one of which is 'spatial resolution'. Spatial resolution is the ability of an ultrasound system to differentiate between two objects that are relatively close in space [1]. Appropriate tests must be performed for each transducer type, frequency, and depth to analyse the performance and measurements of spatial resolution of ultrasound systems.

A. AXIAL SPATIAL RESOLUTION

The axial resolution is defined as the smallest separation between two closely spaced objects along the direction of the beam axis that can be displayed as two separate objects. The length of the pulse of an ultrasound beam is a contributing element that affects axial resolution. This is recognized as the spatial pulse length (SPL). The shorter the pulse length, the better the axial resolution. In theory, the smallest object spacing that can be determined is 1/2 of the SPL [2]. Conclusively, transducers with higher frequencies offer better image resolution, since the axial resolution is determined by the pulse length [3].

B. LATERAL SPATIAL RESOLUTION

Lateral resolution is defined as the ability of the system to distinguish between two separate points that are perpendicular to the ultrasound's beam axis. Lateral resolution is mainly related to the width of the ultra- sound beam. That is the wider the beam, the poorer the lateral resolution, resulting in structures being unresolved. Therefore, the best lateral resolution is achieved at the focus [1]. As the ultrasound beam diverges above a certain depth, the lateral resolution becomes poor.

C. DIFFERENT TYPES OF ULTRASOUND TRANSDUCERS

Linear array transducers provide a rectangular field of view (FOV) that maintains its width near the surface of the transducer, and hence, they become notably appropriate when the region of interest broadens to the surface. Additionally, a linear array transducer appears from the outside as a shaped block that fits comfortably in the operator's hands, along with a rubber lens on the surface that comes into contact with the patient's skin. There is also a matching layer behind the lens, followed by a linear array that ranges from 128 to 512 regularly spaced, thin, rectangular transducer elements separated by narrow barriers [2]. They are particularly suitable for superficial examinations, such as the neck, veins, and arteries of the limbs.

Curvilinear arrays, on the other hand, are characterized by the fact that the arrangement of PZT elements ahead of the front is curved or bent rather than following a straight line. Nonetheless, the maximum useful size of the active element group of a curvilinear array is smaller than that of a linear array with elements of the same size. As a result, the width of the beam in the focal zone is larger providing poorer performance lateral resolution than the linear array transducer. This is mainly due to the fact that as the number of active elements increases, the outermost elements move further and further away from the centerline of the array until they can no longer transmit or receive any data at all in that direction [2]. In addition, curvilinear arrays have the advantage that the FOV becomes wider with increasing depth inside the patient. Therefore, they are often used for abdominal applications [2].

Finally, a sector (or phased array) transducer produces a cone-shaped image or fan-like FOV arrangement, where the sound waves emerge from a small vertex. Cardiac imaging is the most common application of sector transducers [2]. The different transducers are shown in Fig. 1.

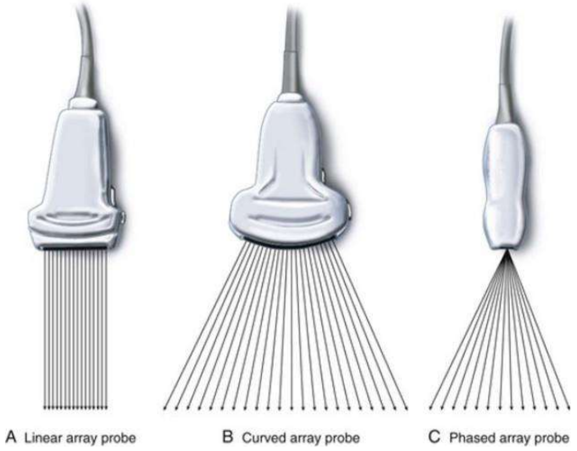

Fig. 1: Different transducer types

D. *AAPM AND IPEM 102 STANDARDS*

According to AAPM ultrasound Task Group No.1, the preferred way to quantify the spatial resolution is by measuring the FWHM. AAPM has suggested several performance criteria values for axial and lateral spatial resolution. It stated that the axial resolution should generally be 1 mm or less for transducers with central frequencies over 4 MHz and 2 mm or less for those with central frequencies under 4 MHz. However, when measuring the spatial resolution using the FWHM method, AAPM suggests that the FWHM of the axial resolution should be less than 0.45 mm for transducers having central frequencies higher than 4 MHz, and an FWHM of less than 0.9 mm for transducers having central frequencies lower than 4 MHz. The lateral resolution can be evaluated by measuring the width of a filament target at different depths; near, mid, and far-field zones of the transducer [4]. The recommended tolerances for the lateral resolution are shown below in Figure 2. It was noted that IPEM 102 does not have any specific tolerances for spatial resolution during acceptance testing, except for routine QA.

		Lateral resolution		
Depth (cm)	Transducer frequency (f) (MHz)	Response width or spacing between targets (mm)	FWHM (mm)	FWTM (mm)
>10	<3.5	≤4	≤2	≤4
<10	$3.5 \leq f < 5$	<3	<1.5	<3
<10	≥5	<1.5	<0.8	<1.5

Table 1: AAPM recommended lateral resolution requirements

II. MATERIALS AND METHODS

In this study, multiple ultrasound scanners from various manufacturers that were accepted in the last four years were used. The scanners used were equipped with different transducers; linear, curvilinear, and sectors of various shapes, including hockey stick and endocavity/endovaginal probes. Also, a dedicated ultrasound phantom with appropriate features was used for testing spatial resolution. Furthermore, standard operation procedures (SOPs) documents authorized by the Medical Physics Department were utilized to perform acceptance QA physics tests on ultrasound systems and to conduct data analysis. These documents have operating instructions on how to perform several tests, as well as to analyse the ultrasound images quantitatively.

A. *ACQUIRING PHANTOM IMAGES FOR DIFFERENT TRANSDUCERS*

In the first part of the test, ultrasound images were acquired using a dedicated ultrasound phantom. The images were acquired following the IPEM 102 method to test the spatial resolution for Ultrasound Systems' [5]. An example of the obtained ultrasound image is shown in Fig. 2.

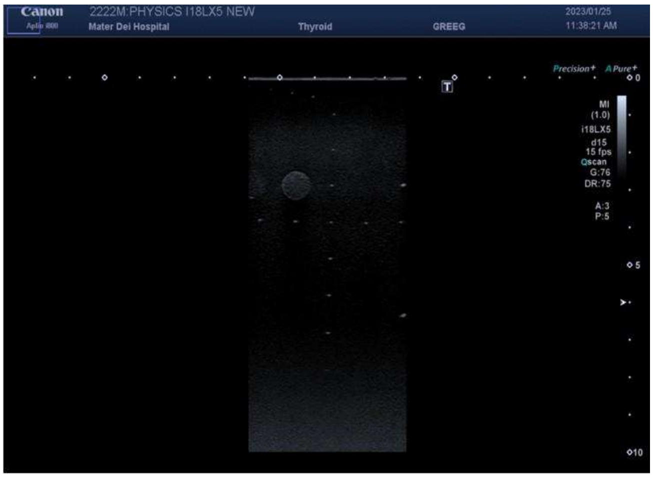

Fig. 2: An ultrasound image using a linear transducer on the *Canon Aplio i8000*

B. DATA COLLECTION TOOL

An evaluation of the axial and lateral spatial resolution was carried out between February 2019 and March 2023 for 13 ultrasound scanners equipped with 51 transducers; 22 were linear, 23 were curvilinear, and 6 were sector. Moreover, one phantom: CIRS Model 040GSE, and one software package: Image J, were also used in this study. Subsequently, all transducers utilized were broadband, with 5– 20 MHz frequencies for linear transducers, 3–9 MHz for curvilinear transducers, and 3-5 MHz for sector transducers. A list of all the tested ultrasound scanners is presented below in Table 2.

C. CIRS MODEL 040GSE

A Multi-Purpose, Multi-Tissue Ultrasound Phantom model 040GSE manufactured by CIRS was utilized during acceptance testing. The Model 040GSE is equipped with features enabling it to operate with diagnostic ultrasound devices. The phantom is filled with Zerdineâ, a gel material miming soft human tissue's acoustic properties. A wide range of transducer sizes and frequencies may be used with the phantom [6].

The phantom is split into two sections of different attenuation coefficient: each 0.5 dB/(cmMHz) and 0.7 dB/(cmMHz). Several small targets are positioned at known intervals in horizontal and vertical directions to check the precision and accuracy of the distance measurements and spatial resolution. The CIRS Model is certified to ISO 9001:2008 standards and backed with a certificate of compliance [6]. This phantom was chosen since it was the one used in acceptance testing, and it was the one readily available at that time. Other commercial phantoms that could have been used are; '*GAMMEX Sono 410 SCG*', '*ATS 539*', and *'GAMMEX 405GSX'*.

Table 2: A list of evaluated ultrasound systems and transducers

Manufacturer	**Model**	**Linear**	**Curvilinear**	**Sector**
Canon	*Aplio i800 (2)*	i18LX5 (2)	6MC1 (2)	-
		L24LX8 (2)	i8CX1 (2)	-
	Aplio a550	11L3	8C1	-
		-	11C3	-
	a450	-	11C3 (2)	-
Hitachi	*Arietta 65*	L64	C251	-
Toshiba	*Aplio a400*	-	6C1	-
Philips Healthcare	*Sparq (3)*	L12-4 (3)	C5-1 (3)	S5-1
		-	-	S5-2 (2)
	Lumify SMT-T590 (6)	L12-4 (3)	C5-2	S4-1 (2)
	EIPQ Elite 5G	L12-3	C5-1	-
		Hockey Stick L15-7io	-	-
	CX50 POC	L12-3	C5-1 (2)	-
		-	-	-
GE Healthcare	*Voluson S10*	-	C1-5RS (3)	-
		-	Endocavity IC9-RS	-
	Vivid iQ	12L-RS (2)	-	M5Sc-RS
		Hockey Stick L8-18i-RS	-	-
Esatote	*MyLAB X7*	SL3116	-	-
		L4-15	-	-
		Hockey Stick IH6-18	-	-
BK Medical	*bk3000-01*	Hockey Stick IH6-18	6C2	-
			Endocavity E14C4t	-

D. IMAGEJ

ImageJ is a free, open-source software built specifically for processing radiological images. ImageJ has the capacity to provide statistical information and data from line profiles. Therefore, this software tool was used in this project to measure the spatial resolution in the axial and lateral directions by implementing the FWHM method. This software tool was chosen since it is flexible, easily accessible, and preferred by medical physicists at that time. Other software tools that could have been used are; '*MATLAB*', *'Python'*, and *'UltraIQ'*.

E. DATA ANALYSIS TECHNIQUE: OBTAINING THE FWHM FROM A LINE PROFILE

In order to obtain the spatial resolution in the axial and lateral directions using the FWHM method, a line profile was drawn across the nylon filaments on the ultrasound. Then, a dedicated Image J plug-in tool for FWHM was used to calculate the FWHM for each depth.

III. RESULTS

The data collected was presented in a series of scatter plots using Microsoft Excel to analyse the performance of each ultrasound transducer's axial and lateral spatial resolution. These graphs were investigated and related to the objectives of the study. Both of spatial resolution FWHM results were plotted against depth. These plots made evaluating and assessing various variables easier. However, the graphs plotted were based on the limited number of probes available.

A. RESULTS FOR AXIAL RESOLUTION

A graph of the axial resolution against depth was plotted for the three different transducers at different frequencies. The FWHM results of the transducer with the same frequency were averaged to obtain the most accurate and precise analysis as possible.

Linear transducers operating at frequencies 5 to 8 MHz showed the highest axial resolution (~0.54 mm) at the shallowest depth (10 mm). The axial resolution continued to increase with depth (Figure 5). Transducers with 9 and 10 MHz frequencies showed better axial resolution (~0.4 mm) than those with lower frequencies. The poorest axial resolution was measured at a depth of 90 mm for the 10 MHz transducer (~0.57 mm). Conversely, linear transducers with higher frequencies (15 to 20 MHz) had the best axial resolution at lower depths than other frequency ranges. Moreover, it was noted that the resolution of the 20-MHz transducer was worse than that of the 9- and 19-MHz transducers, especially at 40 mm depth (Fig.3).

On the other hand, for curvilinear probes, the axial resolution was broader for transducers operating at frequencies from 3 to 6 MHz. Moreover, the axial resolution decreased rapidly at 120 mm depth in this frequency range. However, even with increasing depth, transducers operating at higher frequencies (8.5 and 9 MHz) showed better overall axial resolution. The best resolution (~0.54 mm) was observed for the 8.5 MHz probe at 10 mm depth (Fig.4).

Finally, the best axial resolution for the sector transducers was observed for the 5 MHz transducers, especially at depths above 100 mm. However, the 3 MHz probe also had the poorest resolution, with increasing depths (Fig.5).

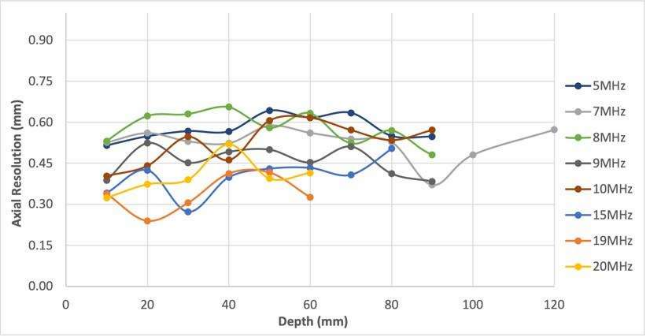

Fig. 3: Axial resolution (mm) against depth (mm) for linear transducers with different frequencies

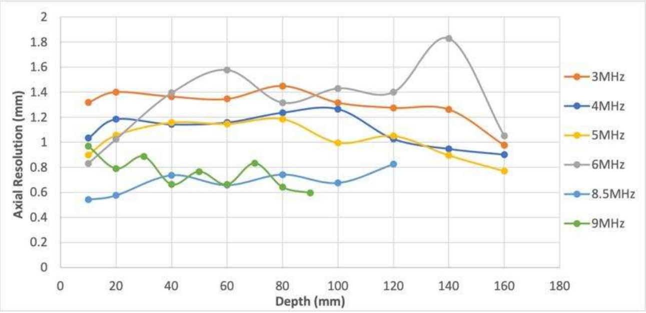

Fig. 4: Axial resolution (mm) against depth (mm) for curvilinear transducers with different frequencies

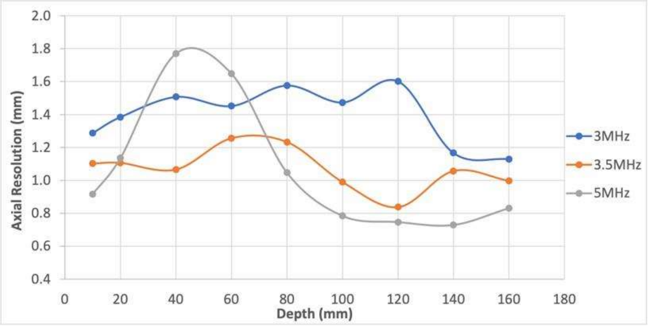

Fig. 5: Axial resolution (mm) against depth (mm) for sector transducers with different frequencies

B. RESULTS FOR LATERAL RESOLUTION

The linear transducers with 5-8 MHz frequencies showed worse lateral resolution, especially at depths of 50-70 mm and 100 mm, as shown in Fig.6. For transducers operating at 7 MHz, the lateral resolution deteriorated rapidly at 40-60 mm depths. Since only two transducers were tested at this frequency and different protocols were used, it might have impacted the final result. However, the 9 and 20 MHz transducers had the best lateral resolution, at most 1.19 mm. On the other hand, curvilinear probes with low frequencies (3-5 MHz) had the worst lateral resolution on average, even with increasing frequencies, even with increasing depth. However, the best lateral resolution was exhibited by the transducers operating at frequencies of 6 and 8.5 MHz (Fig.7) Finally, as expected, sector transducers at higher frequencies experienced a better lateral resolution than the lower frequencies, even with increasing depth. It was also found that the lateral resolution at 10 mm for 3 MHz sector probes was better than that of 3.5 MHz probes. The lack of limited 3.5 MHz transducers may have influenced this observation (Fig.8).

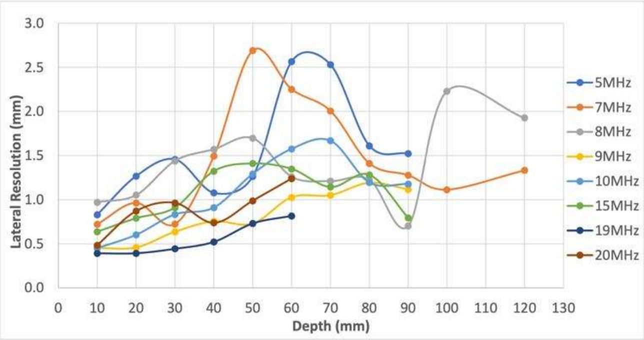

Fig. 6: Lateral resolution (mm) against depth (mm) for linear transducers with different frequencies

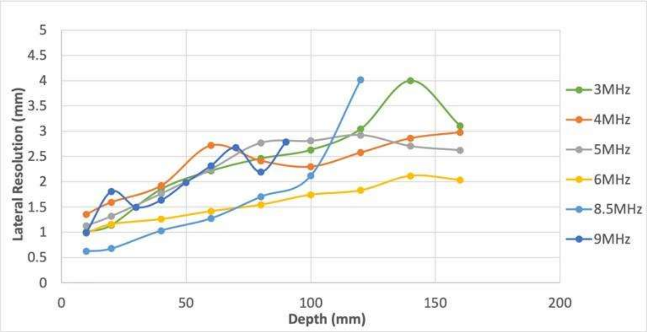

Fig. 7: Lateral resolution (mm) against depth (mm) for curvilinear transducers with different frequencies

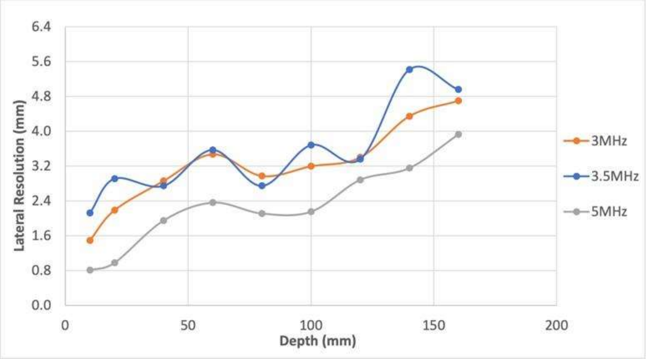

Fig. 8: Lateral resolution (mm) against depth (mm) for sector transducers with different frequencies

IV. DISCUSSION

This study evaluated and compared the axial and lateral spatial resolution of the linear, curvilinear, and sector array transducers. The effect of spatial resolution with depth was also investigated. This was done with the equipment previously, and conclusions were drawn from the scanners and transducers considered in this study. It is interesting to note that the results from previous literature are consistent with some key findings from this study. This is essential as it confirms and strengthens the reliability of the study's results.

Firstly, it was concluded that linear transducers provide better axial and lateral spatial resolution than curvilinear and sector array transducers. The axial resolution of linear transducers at 5 and 9 MHz did not exceed 0.64 and 0.52 mm, respectively, while the lateral resolution did not exceed 2.56 and 1.05 mm on average. On the other hand, the worse axial and lateral resolution was observed for curvilinear (C) and sector (S) probes, with a maximum axial resolution of 1.19 mm (C) and 1.77 mm (S) and a maximum lateral resolution of 2.71 mm for curvilinear and 3.92 mm for sector probes.

Linear transducers provide better axial and lateral spatial resolution due to their shape and design. Linear transducers theoretically have a narrow beam and provide a rectangular field of view, which allows them to produce a thin, highly focused beam that can be guided precisely to the area of interest in the patient. This concentrated beam improves axial resolution by minimizing the distance between the two scanned objects or structures, resulting in better distinction between them. In addition, the design of a linear transducer allows the beam to be focused in a specific direction, which helps to decrease the scattering of the ultrasound beam. As a result, the ultrasound image becomes more accurate and focused, providing better differentiation between adjacent structures. Subsequently, better lateral resolution is achieved, thus agreeing with this study's first objective.

Secondly, the relationship between spatial resolution and depth was also examined. Theoretically, the axial resolution is determined by the SPL of the ultrasound waves. The SPL of an ultrasound wave is governed by the period of the electrical pulse used to generate the wave and not by the distance travelled. Therefore, SPL is independent of depth, so the axial resolution should remain constant at any depth. In this study, it was noted that the maximum deviation of the FWHM measurement of the axial resolution was less than 1 mm along the depth. The linear transducers experiencing less deviation than the curvilinear and sector transducers.

On the other hand, lateral resolution was found to deteriorate with increasing depth. Theoretically, the ultrasound beam initially converges, reaches the focal zone and then diverges as it penetrates deeper into the tissue. This causes the ultrasound beam to widen at the far field, making it more difficult to identify two adjacent structures. Thus, the lateral resolution is poorer with depth. This could also be observed visually from the acquired ultrasound image, where the first few nylon filaments are well resolved, while the others became increasingly blurred with depth. This may happen because the beam's intensity decreases due to partial waves being reflected and attenuated across the tissues. In this way, the second objective of this study was addressed.

Moreover, it was concluded that the axial and lateral spatial resolution improved at higher ultrasound frequencies. Theoretically, a higher frequency leads to a shorter wavelength and, thus, a shorter spatial pulse length. A shorter pulse length results in a better axial resolution. In addition, at higher frequencies, the beam width at the focus is narrower, resulting in better lateral resolution. Hence, the third and final objective was addressed. To determine if the current standards are still applicable or need to be revised, comparing the study's results with the existing standards is essential. As previously mentioned, there are still no corresponding FWHM standard values for axial resolution. However, the results were compared with the recommendations found in AAPM (Table 1). From the results obtained, the axial resolution for frequencies greater than 4 MHz for linear transducers exceeds an FWHM of 0.45 mm for most transducers. The highest value was obtained for the 8 MHz transducer. This was also observed for curvilinear and sector probes, where the largest FWHM was 1.82 and 1.77 mm for the 6- and 5- MHz transducers respectively. In contrast, for frequencies below 4 MHz, the FWHM values met the recommended AAPM standards. Thus, although some values were within the standards, most results differed widely. Note that the AAPM did not specify the depth at which the FWHM values correspond (for axial resolution), so this assessment is general and hence, it must be more accurate.

When comparing the lateral spatial resolution results with the AAPM standards, it was noted that the lateral resolution at frequencies below 3.5 MHz does not comply with the existing standards. The FWHM exceeded the recommended tolerance of 2 mm for curvilinear and sector transducers operating at 3 MHz, especially after 40 cm (for curvilinear transducers) and 15 cm (for sector transducers) depth. It is good to note that the AAPM does not indicate the FWHM values for lateral resolution for transducers with frequencies greater than 3.5 MHz having depths greater than 10 cm. Since spatial resolution was measured at depths greater than 10 cm, the comparison with the relevant standards (for lateral resolution) was very limited.

The following results imply that the current AAPM standards and recommendations need to be revised and improved accordingly. Both axial and lateral FWHM standards for spatial resolution should be increased, especially for those already mentioned. The medical physics profession needs to recognize these discrepancies and highlight that the current standards need strengthening. Technology constantly evolves, and ultrasound scanner manufacturers continually improve and upgrade their products to achieve optimal spatial resolution.

V. CONULUSSION

The main conclusions of the study were:

a) Linear array transducers exhibited the best axial spatial resolution.
b) Linear array transducers provided better lateral spatial resolution.
c) Axial resolution remained constant with depth across all transducers.
d) Lateral resolution deteriorated with depth for all transducers.
e) Transducers with higher frequencies provided better axial and lateral spatial resolution.

Suggestions for further research are:

a) Repetition of the study with a larger number of ultrasound scanners/transducers as well as using a broader frequency spectrum. This study considered QC images obtained from acceptance testing on all available ultrasound transducers. This can be extended by testing ultrasound scanners/ transducers in all private clinics in Malta as well as in health centres.

b) Replication of the study by comparing different protocols used by different manufacturers. This is a very interesting recommendation for the future because one can compare, for instance, a thyroid protocol with a breast protocol and assess the behaviour of frequency and/or spatial resolution.

c) For a more comprehensive study, this study can be repeated by adjusting the focus to each nylon filament across the depth of the phantom. Since only the results of the acceptance tests were considered, the focus was set at a specific depth. Obtaining images with a focus at each depth can help determine the depth at which the spatial resolution improves or deteriorates.

d) This study can be extended by examining how spatial resolution varies among different manufacturers. In this study, the spatial resolution for some ultrasound transducers varied depending on the manufacturer and model of the probe used. As technology is continually developing, manufacturers are striving to improve ultrasound scanners' spatial resolution through image processing techniques and reconstruction.

The research study's stated objectives were achieved and answered in depth. A quantitative measurement protocol and software analysis for evaluating the spatial resolution performance of ultrasound equipment is the way ahead for quality assurance programmes. Optimized spatial resolution leads to precise localization and identification of microstructures in the imaged region, which is critical for physicians to make an accurate diagnosis and ultimately locate the malignancy or any deformity. It could additionally reduce the need for unnecessary imaging procedures or invasive treatments, which can be expensive, time-consuming, and potentially harmful to the patient. Therefore, ultrasound images with high spatial resolution can improve and enhance patient treatment outcomes.

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