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Optimizing Doppler Ultrasound Parameters: The Study of Insonation Angle, PRF, and Dynamic Range in Blood Flow Assessment

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ABSTRACT

Doppler ultrasound is critical in medical diagnostics for evaluating blood flow and detecting vascular conditions. Accurate blood flow velocity measurements depend on insonation angle, Pulse Repetition Frequency (PRF), and dynamic range. This study optimizes these parameters to enhance Doppler ultrasound performance and diagnostic accuracy. A Xario-100 ultrasound machine and the Doppler 403™ flow phantom were used to evaluate the effects of insonation angle, PRF, and dynamic range on measurement accuracy. Insonation angles of 0º and 60º were tested to assess their impact on aliasing and precision. At 0º, significant aliasing occurred, while 90º, aliasing was minimized. PRF settings were adjusted from 14,000 Hz to 17,900 Hz, with higher PRF extending the Nyquist Velocity from 9.8 cm/s to 37.4 cm/s, reducing aliasing and improving high-flow measurement clarity in the dynamic range from 30 dB to 60 dB, with optimal contrast observed at 50 dB. Histogram analysis revealed a balanced pixel intensity distribution at 50 dB, enhancing the Signal-to-Noise Ratio (SNR). The findings demonstrate an insonation angle of 60º, at PRF 17,900 Hz, and a dynamic range of 50 dB optimal Doppler ultrasound performance. Standardizing these parameters can improve diagnostic accuracy, supporting better patient outcomes in clinical practice.

1. INTRODUCTION

Ultrasound imaging is crucial in medical diagnostics due to its non-invasive nature, real-time imaging, and cost-effectiveness (Shung, 2011; Lentz et al., 2021; Alhussein, 2024; Iacob et al., 2024). High-frequency ultrasound is widely used in various clinical applications (Niederer, 2010). Doppler ultrasound plays a pivotal role in assessing blood flow and vascular conditions by measuring the velocity and direction of blood flow within the body (Fish, 1999; Azhari, 2012). The accuracy of these measurements is influenced by the insonation angle, PRF, and dynamic range settings (Gittins & Martin, 2010; Hoyos et al., 2014; Martins et al., 2018), making it essential for diagnosing conditions like arterial blockages and heart valve defects (Revzin et al., 2019).

Accurate Doppler ultrasound performance is vital for reliable diagnostic outcomes (Goldstein, 1991; Russ et al., 2023). Quality assurance and performance testing ensure that ultrasound systems operate within established standards, providing precise diagnostic information (Oglat, 2022). Flow phantoms, such as the Doppler 403 flow phantom, are widely used for these evaluations (Grazhdani et al., 2018; Karaböce & Durmuş, 2024). These phantoms simulate physiological blood flow conditions, offering a controlled environment for assessing ultrasound system performance (Gittins & Martin, 2010; Russ et al., 2023). The Doppler 403 flow phantom specifically det various flow velocities and patterns, making it an effective tool for evaluating measurement accuracy (Jackson & Russell, 2019; Karaböce & Durmuş, 2024).

Among the critical parameters influencing Doppler ultrasound accuracy, the insonation angle plays a significant role (Martins et al., 2018; Revzin et al., 2019). Ideally, a 0-degree angle provides the most accurate velocity measurements, but anatomical constraints often necessitate larger angles, leading to underestimation of blood flow velocity. PRF determines the maximum measurable velocity before aliasing occurs, where the high-speed blood flow appears reversed due to insufficient sampling rates. Increasing PRF raises the Nyquist Velocity, reducing aliasing, but excessively high PRF settings can introduce noise or decrease temporal resolution (Martins et al., 2018). Dynamic range imageRangimageil, with higher settings, enhances the visibility of blood flow but potentially increases noise (Hoyos et al., 2014).

Despite extensive clinical use, ongoing performance testing is needed to adapt to technological advancements and maintain high diagnostic accuracy (Browne, 2014; Grice et al., 2016; Zhou et al., 2017). Previous studies have investigated Doppler ultrasound performance using various flow phantoms (Tsang et al., 2015; Sultan et al., 2022; Jawli et al., 2024; Mencarelli et al., 2024; Paverd et al., 2024; Phani et al., 2024), but limited research has systematically evaluated the combined effects of insonation angle, PRF, and dynamic range rangeasuremenRangeuracy using the Doppler 403 flow phantom (Jackson & Russell, 2019). Existing studies focus on individual parameter adjustments rather than an integrated optimization approach.

The optimization approach explored the impact of insonation angle, PRF, and dynamic range performance. A comprehensive analysis of these parameters using the Doppler 403 flow phantom remains limited. This study aims to fill this gap by systematically assessing the combined effects of insonation angle, PRF, and dynamic range measurement accuracy. By optimizing these parameters, this study seeks to enhance the understanding of Doppler ultrasound performance and contribute to developing standardized testing protocols, ultimately improving diagnostic accuracy in clinical practice.

2. METHOD

2.1 Equipment

Ultrasound Machine: The performance evaluation was conducted using a (Xario 100 TUS-X100S; 225ACBZX00066000; Canon Medical Systems Inc, Tokyo, Japan) ultrasound machine with Linear array transducer (PLU-1204 BT) frequency 12 MHz and frequency Range 5 MHz – 18 MHz, Field of view/angle approx. 38 mm. Xario 100 is an energy-saving system offering high imaging capabilities with a 19-inch LCD monitor, the largest in its class for displaying high-resolution, high-quality images. The machine's technical specifications include a maximum imaging depth of 40 cm and Doppler modes (Color Doppler, Spectral Doppler, Power Doppler). This system radiates ultrasonic waves from a probe into the human body, receives the reflected waves from the human body with the same investigation, processes the received signals, and displays them on an image display. The device is capable of scanch as convex, sectoral, and linear.

Doppler 403 Flow Phantom: The Doppler 403™ flow phantom (Model 1425B - Gammex Inc – Sun Nuclear Corporation, Middleton, USA) simulates blood flow. This phantom includes anatomically accurate vessels of varying diameters (5 mm inner diameter, one horizontal at 2 cm depth, one diagonal at 40^o from 2 to 16 cm deep). It provides adjustable flow rates (constant and pulsatile) and a speed of sound 1550±10 m/s, essential for comprehensive Doppler testing. The Doppler 403™ flow phantom helps assess system velocities using precision flow rates and proprietary blood-mimicking fluid (High Equivalency Gel™ Multi-frequency Tissue-mimicking material). This phantom helps ensure that all transducers and system settings are thoroughly tested across the frequency range from 2 to 18 MHz (Sun Nuclear Corporation, 2020).

2.2 Experiment Setup

This study's experimental setup involved using the Xario 100 ultrasound machine equipped with a Linear array transducer (PLU-1204 BT) to scan high-quality images for analysis. The transducer was set to a frequency of 5 MHz to achieve an optimal balance between resolution and penetration. The transducer was positioned to ensure consistency so the phantom targets were viewed in the same left-to-right image plane orientation. Fluid was pumped through a vessel in a continuous loop to simulate blood flow. The flow rate on the phantom was set to a mid-range of 5 ml/s (Figure 1).

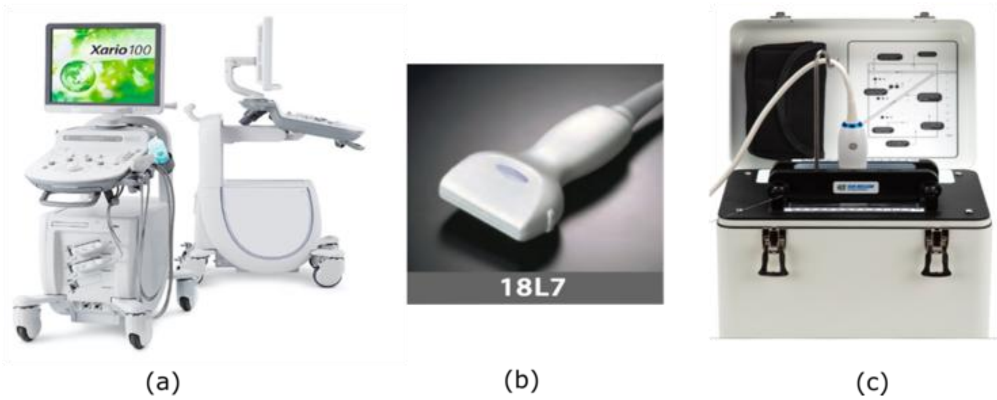

Figure 1. (a) Ultrasound Machine (Model: Xario 100 TUS-X100S), (b) Transducer: Linear array transducer (PLU-1204 BT), (c) Doppler 403 Flow Phantom (Model: 1425B)

The experimental procedure included several specific tests. For insonation angles evaluation, the transducer was positioned at 0^o and 60^o relative to the blood flow direction, and images were captured at each setting. These angles were selected because a 0^o angle provides the most accurate velocity measurements, minimizing Doppler shift errors. However, a 0^o angle is rarely achievable due to anatomical constraints. A 60^o angle is commonly used in vascular imaging as a compromise between accuracy and feasibility, as higher angles (>60^o) lead to significant underestimation of velocity due to cosine dependence in the Doppler equation (Ekroll et al., 2013). The Doppler equation is given by:

$$\boldsymbol{f_D = \frac{2f_0 v \cos\theta}{c}} \qquad (1)$$

Where v is the velocity of blood flow, θ is the insonation angle, f_D is the Doppler frequency shift, f_0 is the transmitted ultrasound frequency, and c is the speed of sound in tissue (typically 1540 m/s).

For PRF testing, PRF values were selected based on preliminary experiments to ensure a representative range for clinical Doppler imaging. The PRF was systematically varied, and images were acquired at each setting to assess their impact on Nyquist Velocity and aliasing. Lower PRF settings allow detection of slow blood flow but increase the risk of aliasing, while higher PRF values reduce aliasing but may compromise sensitivity to low-velocity flow (Polak, 1995). The ultrasound system was configured to Color Velocity Imaging Mode with a BART (Blue Away, Red Towards) color scheme to distinguish flow directions relative to the transducer.

In dynamic range testing, settings were adjusted to 30 dB, 40 dB, 50 dB, and 60 dB, with images acquired at each level while maintaining consistent imaging conditions. B-mode and Pulsed-Wave Doppler mode were activated to visualize the horizontal vessel and generate spectral Doppler signals. The vessel contents appeared black in the gray-scale images, confirming the low echogenicity of the blood-mimicking fluid used in the experiment (Oglat, 2022).

2.3 Data Analysis

The study evaluated key parameters to optimize Doppler ultrasound performance, focusing on insonation angles, Nyquist Velocity, dynamic range, and histogram of signal-to-noise ratio (SNR). Insonation angles were systematically tested to determine their impact on the accuracy of blood flow velocity measurements. Nyquist Velocity, influenced by PRF, was assessed to understand its role in preventing aliasing and ensuring accurate velocity measurement (Revzin et al., 2019). The dynamic range, which affects contrast and visibility of blood flow, was varied to evaluate its effect on image quality. Histogram analysis involves computing and analyzing histograms for each image to assess the distribution of pixel values and how the histogram width correlates with dynamic range was calculated to quantify image clarity relative to background noise, with an evaluation of how SNR changes with dynamic range adjustments (Martins et al., 2018).

Data analysis included calculating histograms and computing the mean and variance of pixel values for SNR calculation. Correlation and regression analysis involved plotting SNR against dynamic range and fitting a linear regression model to understand the relationship between these variables. For statistical validation, a one-way analysis of variance (ANOVA) was conducted to compare SNR across different dynamic range settings. A significance level of $p < 0.05$ was used to determine statistically significant differences. The results were analyzed to assess the impact of dynamic range on image quality, focusing on contrast enhancement and noise reduction. Optimal settings were identified based on histogram analysis, SNR calculations, and statistical comparisons.

3. RESULTS AND DISCUSSION

We use a Linear array transducer (PLU-1204 BT). The ultrasound transducer's frequency affects the ultrasound waves' resolution and penetration. A frequency of 5 MHz strikes a balance, delivering adequate resolution for visualizing blood flow and sufficient penetration to assess deeper structures. This frequency is particularly suitable for vascular studies, enabling precise imaging of blood vessels and flow dynamics. Our analysis focuses on the carotid artery to obtain exact and reliable measurements.

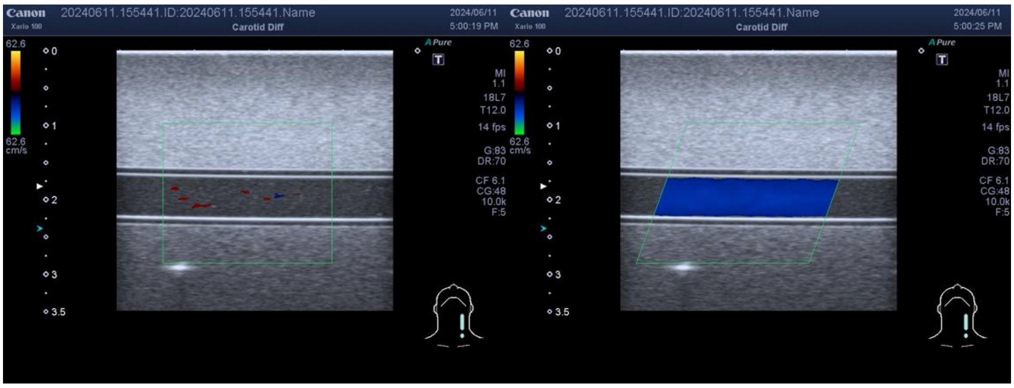

Figure 2. Comparison of blood flow in ultrasound images at 0 degrees (left) and 60 degrees (right) insonation angles. Both images were captured using the following ultrasound settings: Mechanical Index (MI) 1.1, Thermal Index (T) 12.0, frame rate (fps) 14, Gain (G) 83, Dynamic Range (DR) 70, Color Flow (CF) 6.1, Color Gain (CG) 48, PRF 10.0k, and Frequency (F) 5 MHz and Nyquist limit 62.6 cm/s.

In Figure 2, at 0 degrees (left), slight red and blue colors indicate aliasing, which occurs because the Doppler effect is less pronounced at this angle. Optimizing the insonation angle can reduce aliasing. In the image at 60 degrees (right), the blood flow is visible, with the color distribution accurately indicating the velocity and direction of flow. Here, $\cos(60°) = 0.5$, providing a measured Doppler velocity that is half the actual velocity, reducing the risk of aliasing. By positioning the transducer at an optimal angle, such as 60 degrees, the measured Doppler velocity better approximates the actual velocity, reducing measurement errors and minimizing aliasing effects.

Previous studies have consistently demonstrated that the insonation angle significantly influences Doppler measurements and aliasing effects. For instance, a study by (Logason et al., 2001) found that insonation's Doppler angle significantly affects spectral Doppler velocity measurement. This aligns with our findings, where the 0-degree angle resulted in slight aliasing due to the complete Doppler shift being captured, leading to potential measurement inaccuracies. Conversely, (Campbell et al., 2021) reported that using an angle of 60 degrees effectively reduced aliasing by halving the Doppler shift, supporting our observation that optimizing the insonation angle can mitigate aliasing and enhance measurement accuracy.

This study examined how different Pulse Repetition Frequencies (PRF) impact Nyquist Velocity and aliasing in Doppler ultrasound imaging (Figure 3). We used a blood-mimicking fluid with a density of 1.03 g/cc, viscosity of 4.1 cP, and inner tube diameter of 0.5 cm. The flow rate was 5 ml/s, with an average velocity of 25.5 cm/s and peak velocity of 50.9 cm/s, resulting in a Reynolds number of 292.85. PRF determines the Nyquist Velocity, the highest measurable blood flow speed before aliasing occurs. At a PRF of 14,000 Hz, the Nyquist Velocity is only 9.8 cm/s, causing significant aliasing due to the system's inability to handle faster flows. Increasing the PRF to 15,700 Hz raises the Nyquist Velocity to 14.1 cm/s, reducing aliasing and improving image clarity. Further expanding the PRF to 16,000 Hz increases the Nyquist Velocity to 25 cm/s, minimizing aliasing and improving accuracy. At the highest PRF test (17,900 Hz), the Nyquist Velocity reaches 37.4 cm/s, effectively reducing aliasing and allowing precise measurement of very high blood flow velocities.

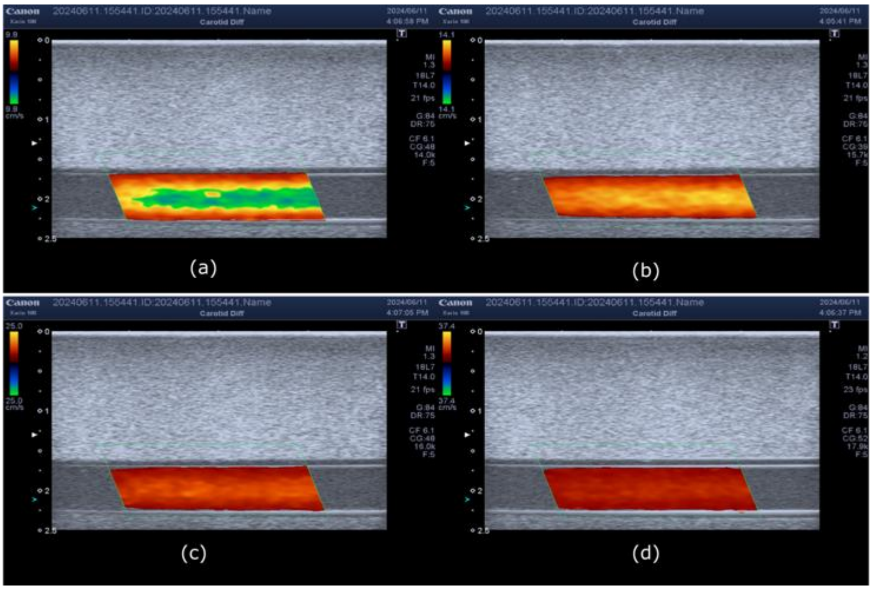

Figure 3. Nyquist velocities at different Pulse Repetition Frequencies (PRF) with a transducer frequency of 5 MHz: (a) Nyquist Velocity: 9.8 cm/s at PRF: 14,000 Hz; (b) Nyquist Velocity: 14.1 cm/s at PRF: 15,700 Hz; (c) Nyquist Velocity: 25 cm/s at PRF: 16,000 Hz; (d) Nyquist Velocity: 37.4 cm/s at PRF: 17,900 Hz

These findings align with Okada et al. (2023), who showed that increasing PRF extends the Nyquist Velocity range and reduces aliasing. Similarly, Martins et al. (2018) reported that higher PRFs allow for more accurate measurement of fast blood flow, the importance of setting PRF according to expected flow velocities to minimize aliasing, supporting our recommendation for optimizing PRF in Doppler ultrasound imaging.

Figure 4 illustrates the impact of dynamic range variations on blood flow visibility and contrast in ultrasound imaging. A higher dynamic range improves tissue differentiation and flow intensity, resulting in more precise and detailed imaging. All images were acquired using consistent ultrasound settings: Mechanical Index (MI) = 1.2, Thermal Index (T) = 14.0, frame rate (fps) = 14, and Gain (G) = 83 to ensure that observed differences are solely due to dynamic range adjustments.

Dynamic range plays a crucial role in ultrasound imaging by optimizing contrast and preserving detail across the full spectrum of signal intensities. At 30 dB (Image a), contrast and detail are reduced, making blood flow less distinct and limiting tissue differentiation. Increasing to 40 dB (Image b) enhances visibility, though subtle differences remain challenging to discern. A 50 dB dynamic range (Image c) provides a clearer view, enhancing the distinction between flow variations and surrounding tissues. The highest setting, 60 dB (Image d), offers optimal contrast and detail, ensuring the most precise blood flow visualization with excellent differentiation. Increasing the dynamic range from 30 dB significantly enhances contrast and detail, thus improving the accuracy and effectiveness of Doppler ultrasound imaging for diagnostic assessment.

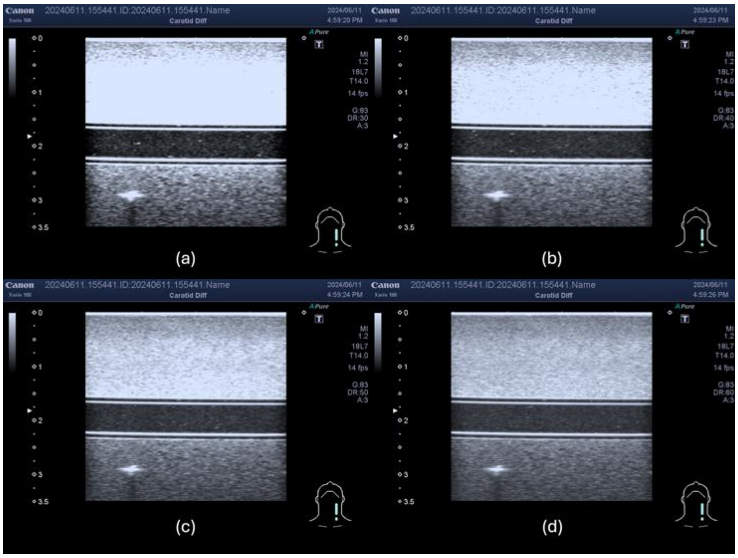

Figure 4. Comparison of blood flow in ultrasound images at different dynamic ranges: (a) 30 dB – High contrast, low detail, (b) 40 dB – improved contrast and visibility, (c) 50 dB – clearer flow differentiation, and (d) 60 dB – best contrast and detail. All images were acquired with MI = 1.2, TI = 14.0, fps = 14, and G = 83.

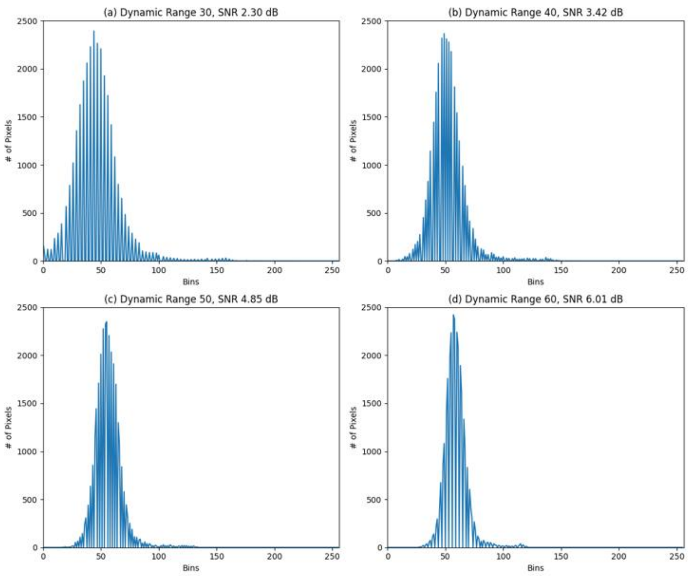

Figure 5. Analysis of Dynamic Range, SNR, and Histogram Characteristics.

Dynamic Range measures the range between the mRanrangend maximum intensity levels that an imaging system can capture. A higher dynamic range allows for a broader range of intensity values to be represented in an image. SNR measures the ratio of the signal to noise, with a higher SNR indicating clearer images with less noise relative to the signal. The data indicates that as dynamic range increases, SNR improves, suggesting that a higher dynamic range contributes to better signal quality relative to noise. A wide histogram indicates that pixel values are distributed over a broad range, implying effective utilization of the dynamic range. Conversely, the histogram suggests that pixel values are concentrated within a limited range, which may mean less effective use of the dynamic range or potential Ranrangeuch as low contrast.

Figure 5. a (dynamic range 30, SNR 2.30 dB) and 5.b (dynamic range 40, SNR 3.42 dB) show the relatively low dynamic range and SNR. Broad histograms, low dynamic range, and SNR suggest

that the images may not capture a broad range of details and could have significant noise relative to the signal. In contrast, Figure 5.c (dynamic range 50, SNR 4.85 dB) and 5.d (dynamic range 60, SNR 6.01 dB) indicate that although the dynamic range and SNR are hRanrangehe image's contrast and detail may still be limited, potentially leading to lower contrast and detail. In general, higher dynamic ranges and SNRs contribute to better image quality. A higher dynamic range allows for capturing more information, while a higher SNR indicates less noise relative to the signal. A wide histogram is typically associated with better dynamic range utilization and usually reflects good contrast and detail, whereas a narrow histogram may indicate poor contrast or limited detail extraction. SNR improves as the dynamic range increases, which suggests better image quality. To optimize image quality, it is essential to ensure that higher dynamic ranges and SNR are effectively translated into better image contrast and detail, avoiding situations where a narrow histogram limits the effectiveness of high dynamic range and SNR.

In dynamic range, PRF settings range from 14,000 Hz to 17,900 Hz, with higher PRF extending the Nyquist Velocity from 9.8 cm/s to 37.4 cm/s, reducing aliasing and improving clarity in high-flow measurements. The histogram analysis revealed that a dynamic range of 50 dB resulted in a more balanced pixel intensity distribution, enhancing SNR compared to lower settings. This improvement in SNR contributes to better visualization of blood flow, particularly in regions with subtle flow variations. Furthermore, the insonation angle of 60°, combined with PRF 17,900 Hz and a dynamic range of 50 dB, provided optimal Doppler ultrasound performance by reducing aliasing artifacts and enhancing flow differentiation.

Our results align with previous research on the impact of dynamic range on ultrasoundRanrangeuality. Meiburger et al. (2020) demonstrated that increasing the dynamic ranges improves contrast and detail in ultrasound images, which is consistent with our findings. Similarly, studies by Gauthier et al. (2011) and Rindal et al. (2019) reported that increasing the dynamic range from 30 dB significantly enhanced tissue and blood flow differentiation, mirroring our results. Additionally, the correlation between dynamic range and SNR observation study corroborates findings, which showed that a higher dynamic range contributes to better image quality and more explicit signal representation (Yang & El Gamal, 1999). These studies collectively underscore the importance of optimizing dynamic range settings to achieve the best possible imaging outcomes.

Figure 6 shows a positive correlation between dynamic range and SNR. As dRanrangeange increases, SNR also improves, indicating that systems with higher dynamic ranges better distinguish signals from noise. The linear regression model quantifies this relationship, allowing us to estimate SNR for various dynamic ranges. A study was conducted to assess the effect of dynamic range on SNR. The results showed a statistically significant difference in SNR across the different dynamic range settings ($F = \infty$, $p < 0.05$), indicating that increasing the dynamic range significantly ranges SNR. Post-hoc analysis was not required due to the apparent trend of increasing SNR with higher dynamic ranges. These findings suggest that optimizing the dynamic range enhances the image by improving contrast and reducing noise, which is crucial for accurate visualization of blood flow in ultrasound imaging.

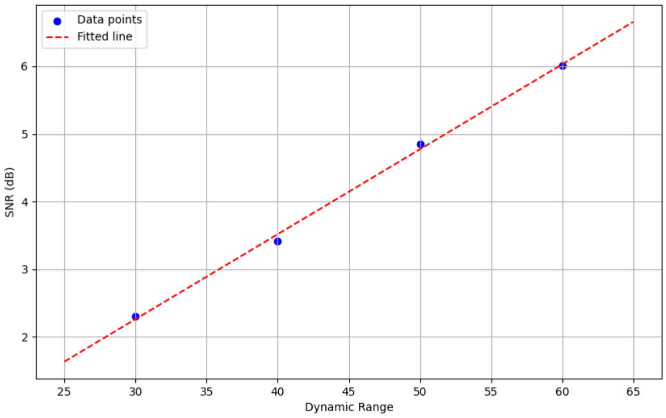

Figure 6. Correlation between dynamic range and SNR with a linear regression model.

4. CONCLUSION

Optimizing insonation angle, PRF settings, and dynamic range significantly. The Doppler ultrasound performance can be boosted by reducing aliasing and improving blood flow visualization. An insonation angle of 60° provides a practical balance between minimizing aliasing and maintaining measurement accuracy. Increasing PRF from 14,000 Hz to 17,900 Hz extends the Nyquist velocity from 9.8 cm/s to 37.4 cm/s, effectively reducing aliasing and enabling more precise measurement of high-flow velocities. Dynamic range adjustments from 30 to 60 dB revealed that 50 dB offers the best contrast and a more balanced pixel intensity distribution, leading to an improved SNR. These findings underscore the importance of optimizing dynamic range settings to enhance image clarity and diagnostic precision.

Standardizing these parameters can improve diagnostic accuracy, ensuring more reliable Doppler measurements in clinical practice. Future studies are needed to validate these findings in clinical settings using patient data, particularly for different vascular conditions, to refine and optimize Doppler ultrasound imaging techniques.

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