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Ultrafast Divergent Wave Imaging in 2D Echography : A Parametric Study

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Abstract – Ultrafast ultrasound imaging overcomes the inherent limitations of conventional focused line-by-line acquisition by enabling exceptionally high frame rates, which are critical for dynamic tissue characterization and real-time applications. Initially, ultrafast imaging was implemented using unfocused plane waves (PWs) transmitted at multiple steering angles; however, this approach inherently limits the field of view (FOV) due to angular coverage constraints. Divergent wave imaging (DWI) has recently emerged as a promising alternative, wherein virtual sources are placed behind the transducer array to generate spherical wavefronts that insonify a broader region, effectively overcoming the FOV limitations of PW transmissions. In DWI, both the number and spatial distribution of virtual sources significantly influence image quality and frame rate. This study implements DWI using Field II simulations and systematically evaluates the impact of three virtual source distributions—linear, tilted, and curvilinear—under different transmission counts on image quality metrics, including lateral resolution and contrast ratio. The findings provide valuable insights into optimizing DWI parameters for improved image quality while balancing frame rate requirements.

***Keywords*:** Ultrafast Imaging-Divergent wave-Virtual sources-Image Quality-Framerate

1. Introduction

Ultrafast ultrasound imaging has revolutionized medical diagnostics by enabling imaging at thousands of frames per second, which allows visualization of rapid physiological phenomena such as cardiac dynamics, blood flow, and tissue elasticity changes [1]-[4]. Unlike conventional line-by-line ultrasound, ultrafast imaging uses wide unfocalized transmissions to acquire images at high frame rate without compromising image quality. Plane wave imaging is a widely used ultrafast technique where planar wavefronts insonify the entire field of view with a minimal number of transmissions, providing very high frame rates [5]. However, plane waves (PWs) imaging have a limited field of view , therefore divergent wave imaging was introduced to solve the limitation of PWs, first conceptualized by H. Hasegawa and H. Kanai [6], where transmissions are emitted from virtual point sources behind the probe, producing spherical wavefronts that better mimic natural beam divergence and covers a large angular coverage.

Initial implementations of divergent wave imaging demonstrated the ability to generate divergent waves via virtual source synthesis and coherent compounding to achieve improved lateral resolution and contrast. Ghigo et al. [7] explored the influence of virtual source (VS) configurations on image quality in convex array ultrasound imaging. Their findings indicated that performance differences were minimal, which was attributed to the limited number of compounded transmissions used in their study. In contrast, a different strategy was proposed in [1], [8], which generates a broad, unfocused wavefront spanning the entire aperture by applying a simple linear delay profile tailored for convex arrays. This approach creates a wavefront pattern resembling an Archimedean spiral, with its characteristics dependent on the steering angle. Additionally, Liang et al. [9] introduced a Fourier-domain beamforming technique that utilizes tilted diverging wave transmissions.

Although this method enhanced image quality in specific areas, its improvements were confined to zones with a limited azimuthal range.

Despite these advancements, the systematic evaluations of how the distribution and number of virtual sources influence the lateral resolution, contrast, and achievable frame rates in divergent wave imaging is still under investigation . While reducing the number of transmissions increases frame rate, it typically compromises image quality. Conversely, increasing virtual sources improves image fidelity but at the expense of frame rate . To address this, our study implements divergent wave imaging within the Field II [10][11] simulation software using a synthetic phantom. Three virtual source distributions were evaluated—linear, tilted, and curvilinear—and vary transmission counts (20, 10, and 5) to assess their quantitative effects on image quality metrics, specifically lateral resolution (FWHM) and contrast ratio to provide valuable insights into optimizing virtual source configurations for ultrafast divergent wave imaging.

The paper is structured as follows: Section 2 details the simulation setup, phantom configuration, virtual source distributions, and evaluation metrics. Section 3 presents results and discussion on the impact of virtual source geometry and transmission count on image quality. Section 4 concludes the study and outlines future directions in virtual source optimization for ultrafast imaging.

2. Material and Method

Divergent wave imaging is based on transmissions from virtual sources located behind the probe elements, which emit spherical wavefronts covering a wide field of view. Each transmission produces a low-resolution image, and all such images are then coherently compounded to generate a high-resolution composite image . In this section, the simulation setup and data acquisition are described in detail, along with the virtual source distributions employed to generate the divergent waves.

2.1. Simulation Setup and Data Collection :

The RF data were generated using the Field II simulation software [10][11] , employing a convex array probe and a synthetic phantom comprising multiple reflectors and cysts positioned at various depths and lateral locations. A schematic overview of the simulation setup is presented in Figure 1. The transducer was simulated with a center frequency of $f0=3$ MHz and a two-cycle excitation pulse, while the received signals were sampled at a frequency of $fs=30$MHz. The acquired RF data were subsequently processed using a delay-and-sum beamformer, followed by envelope detection and logarithmic compression to reconstruct the final B-mode images. The synthetic phantom included point reflectors located at lateral positions $x=[-20,0,20]$mm and depths of $[10,30,50]$ mm, as well as anechoic cysts with radii of 3 mm, 4 mm, and 5 mm positioned at $x=[-20,0,20]$ mm and depths $[20,40,60]$ mm. Data were generated using three distinct virtual source distributions—linear, tilted, and curvilinear—which are described in details in the following subsection. For each distribution, the number of transmissions was varied from 20 to 10 and 5 to increase the frame rate and evaluate the corresponding effects on image quality.

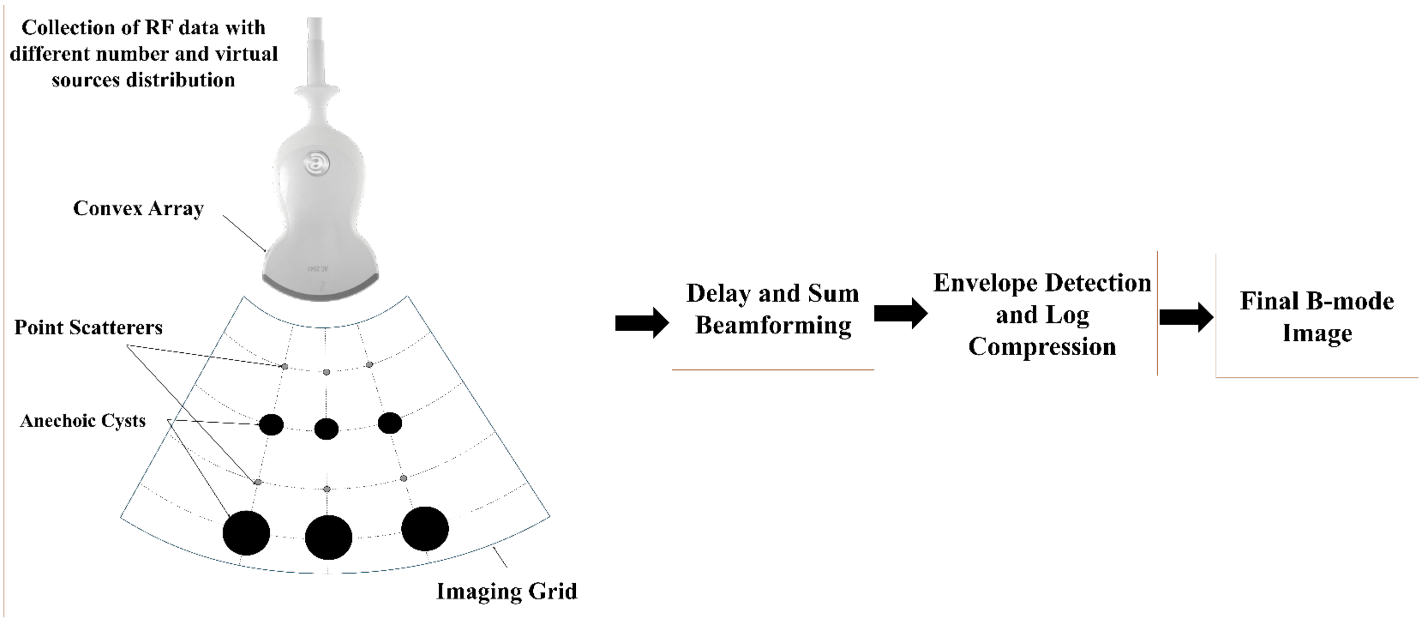

Figure 1 : Schematic representation of the simulation setup for divergent wave ultrasound imaging using a convex array probe.

2.2. Distribution of Virtual Sources:

Three distinct virtual source distributions were employed to generate the divergent wave transmissions, each designed to optimize the insonified field and influence the resultant image quality. The linear distribution, depicted in Figure 2(a), consists of virtual sources positioned along a fixed axial plane at −20 mm, uniformly spaced across the lateral axis. This configuration produces a set of planar virtual sources aligned parallel to the transducer elements, facilitating relatively straightforward wavefront propagation and coverage of the imaging field. The tilted distribution, illustrated in Figure2 (b), involves virtual sources arranged along an oblique axial plane with positions varying laterally between approximately -12mm +12mm, and axially between −11 mm and −9 mm. This inclination aims to better match the natural curvature of the wavefront and enhance angular coverage while potentially improving the focusing characteristics. Finally, the curvilinear distribution, shown in Figure 2(c), features virtual sources arranged along a concave curve with lateral positions extending beyond ±25 mm and axial positions forming an arc peaking at approximately −10 mm. This distribution closely mimics the geometry of a curved array transducer, aiming to emulate a natural focusing effect and maximize the in sonification uniformity over a wide angular range. Each distribution offers unique trade-offs in terms of spatial coverage, beam shape, and image quality, and their comparative evaluation is essential for optimizing divergent wave imaging performance.

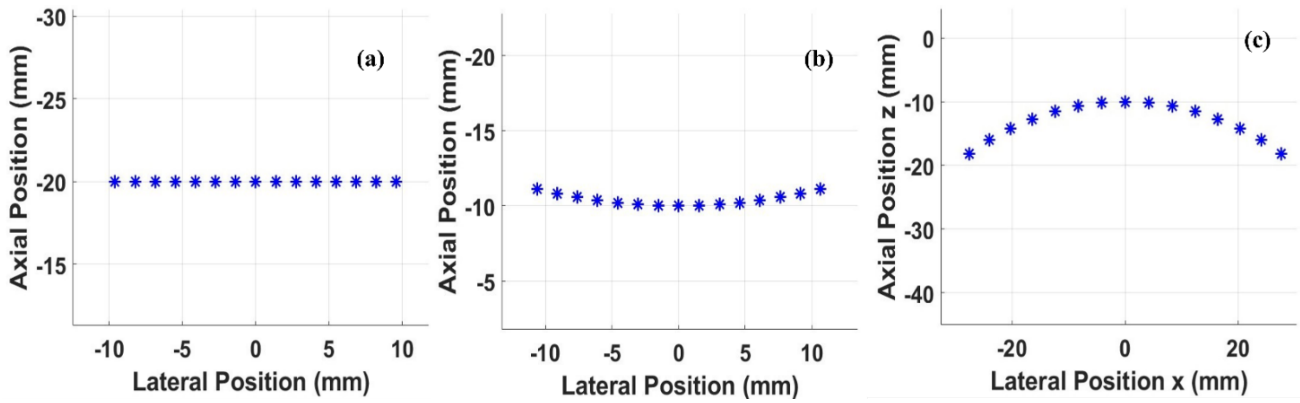

*Figure 2: **:** Virtual source distributions : (a) illustrates the linear distribution with virtual sources positioned uniformly along a fixed axial depth of -20 mm. (b) depicts the tilted distribution, where the virtual sources are arranged along a curved line with varying axial positions around -10 mm, simulating an angular tilt relative to the probe surface. (c) presents the curvilinear distribution, characterized by virtual sources positioned on a concave arc*

2.2. Evaluation Metrics :

The evaluation of image quality in ultrafast ultrasound imaging relies on quantitative metrics that characterize resolution and contrast performance. In this study, lateral resolution and contrast ratio (CR) were selected as the primary metrics, as axial resolution is predominantly governed by pulse duration and bandwidth, which remain constant across all experiments. Lateral resolution quantifies the system's ability to distinguish two closely spaced reflectors along the lateral direction. It is commonly measured as the Full Width at Half Maximum (FWHM) of the lateral point spread function (PSF) corresponding to point reflectors located on the central imaging axis. Contrast ratio is used to assess the ability to differentiate anechoic cyst regions from the surrounding tissue. It is defined as the logarithmic ratio of the mean echo intensity inside the cyst region to that in the adjacent background region, expressed in decibels (dB):

$$CR = 20\log_{10}\left(\frac{\mu_{\text{in}}}{\mu_{\text{out}}}\right),$$

where µin and µout represent the mean pixel intensities within the cyst and background regions, respectively. Higher CR values indicate better contrast and improved visibility of anechoic structures. Both metrics were computed along the central axial line of the imaging field for each virtual source distribution and transmission count.

3. Results and Discussions

3.1 B-mode Image of Synthetic Phantom:

The B-mode images acquired from the synthetic phantom are represented in Figure 3 with 60 dB dynamic range and their corresponding lateral resolution and contrast ratio for the reflectors and anechoic cysts located at the central axes (x=0) are represented in Figure 4 and Figure 5 respectively .Lateral resolution degradation with decreasing number of transmissions was observed across all virtual source distributions, consistent with the expected trade-off between frame rate and image quality in ultrafast ultrasound. Linear distribution demonstrated the highest baseline lateral resolution, with a FWHM of approximately 0.9 mm at a shallow depth of 10 mm using 20 transmissions. This resolution gradually decreased to 1.8 mm at 50 mm depth. Reducing the number of transmissions to 10 and 5 increased the FWHM by 22% and 50% at 10 mm, and by 22% and 50% at 50 mm, respectively, indicating significant degradation in spatial resolution at higher depths (Fig. 4).Curvilinear distribution exhibited a slightly broader lateral resolution, starting at 1.1 mm at 10 mm depth with 20 transmissions and increasing to 2.0 mm at 50 mm depth. The reduction in transmissions to 10 and 5 resulted in 18% and 45% deterioration at shallow depth, and 25% and 50% at deeper regions. This distribution's wider beam geometry likely accounts for the broader baseline FWHM values. Tilted distribution presented intermediate performance, with an initial FWHM of 1.0 mm at 10 mm depth and 1.9 mm at 50 mm for 20 transmissions. The FWHM increased by approximately 20% and 47% at 10 mm, and 21% and 47% at 50 mm when transmissions were halved to 10 and reduced to 5, respectively. The results underscore the critical balance between frame rate and resolution. While all configurations exhibit resolution deterioration when transmissions decrease, the linear distribution offers superior lateral resolution across all depths, which is particularly advantageous for applications demanding high spatial accuracy.

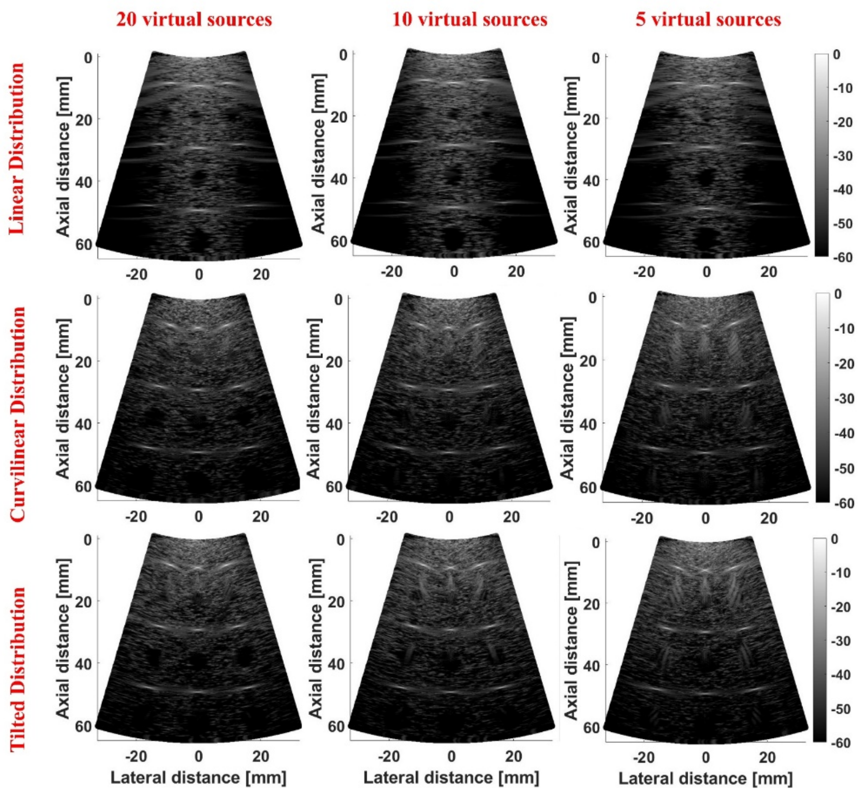

Figure 3 : B-mode Images of Synthetic phantom obtained with three different virtual source distributions—linear, curvilinear, and tilted—and varying numbers of transmissions (20, 10, and 5). The axial and lateral dimensions are indicated in millimeters, with dynamic range set to 60 dB.

Contrast ratio analysis revealed parallel trends with lateral resolution findings, highlighting the influence of transmission number and virtual source geometry on tissue differentiation capabilities. For the linear distribution, CR values at 10 mm depth were approximately -25 dB for 20 transmissions, deteriorating to -18 dB for 5 transmissions—a 28% reduction in contrast. At 50 mm, CR degraded from -30 dB to -25 dB, representing a 17% loss.The curvilinear distribution showed slightly lower contrast performance, with CR dropping from -23 dB to -16 dB (30% decrease) at shallow depths and from -29 dB to -23 dB (21% decrease) at 50 mm depth upon reduction of transmissions. The tilted distribution yielded intermediate CR values, with a 29% reduction from -24 dB to -17 dB at 10 mm depth and a 20% decrease from -30 dB to -24 dB at 50 mm depth when the transmission count dropped from 20 to 5 . The contrast degradation is consistent with the decrease in transmit aperture synthesis due to fewer transmissions, which limits the system's ability to suppress speckle and noise artifacts, thereby impairing anechoic cyst visibility.

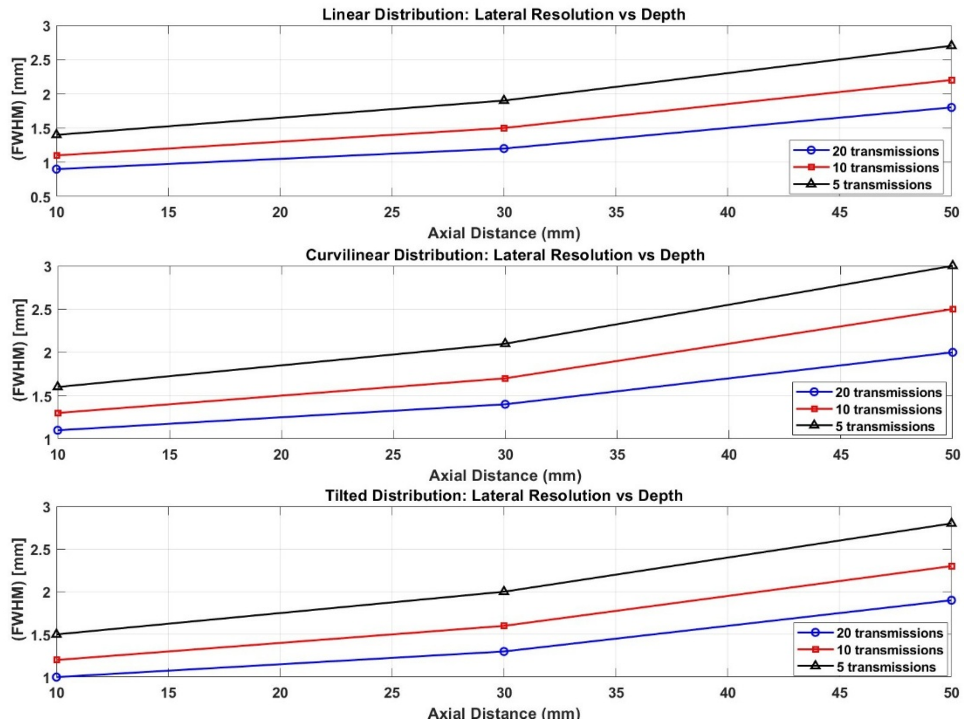

Figure 4: Quantitative analysis of lateral resolution measured as full width at half maximum (FWHM) for reflectors located along the central lateral axis of the synthetic phantom images as function of depth . The plots compare three virtual source distributions—linear, curvilinear, and tilted—across three frame rates corresponding to 20, 10, and 5 transmissions.

3.2 Discussion:

The virtual source distribution critically affects both lateral resolution and contrast ratio, with the linear distribution generally outperforming curvilinear and tilted configurations in terms of resolution and contrast. The results align with the principle that narrower beamwidths in the linear distribution yield improved spatial focusing and image quality. However, the curvilinear and tilted distributions may provide wider field coverage and are potentially advantageous in scenarios requiring broader angular in sonification. Reducing the number of transmissions from 20 to 5 leads to a significant deterioration in image quality however the frame rate increased from 550 to 2200 at depth of 70mm (Table I), with lateral resolution worsening by up to 50% and contrast ratio declining by approximately 20-30%, depending on depth and distribution type.

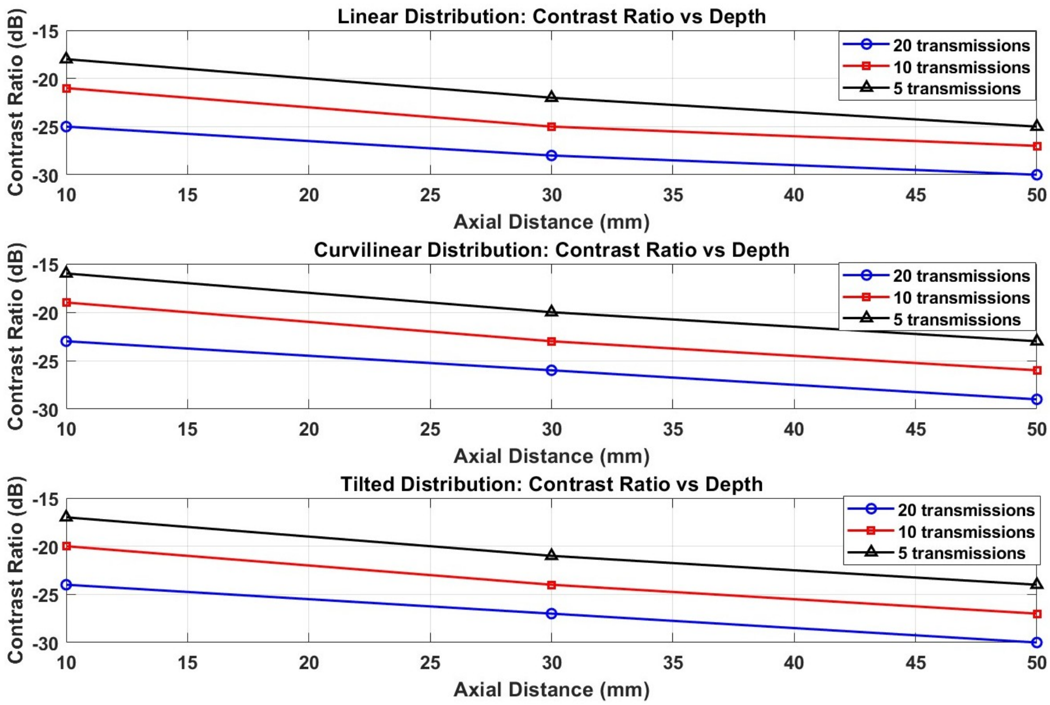

Figure 5 : Contrast ratio (CR) measurements for anechoic cysts located along the central axis of the synthetic phantom images. The plots depict the CR in decibels as a function of imaging depth for linear, curvilinear, and tilted virtual source distributions with 20, 10, and 5 transmissions.

It is worth mentioning that , in the simulation made in this study , no weights has been applied to each virtual source transmission previously introduced in [12].These weights improves the image quality further and can be computed offline and saved in memory with increasing the computational time [13].

Table I : *Frame rates corresponding to different numbers of virtual sources used in divergent wave ultrasound imaging at a depth of 70 mm.*

Number of Virtual Sources	Frame Rate (frames/s)
20	~550
10	~1100
5	~2200

4. Conclusion

This study systematically investigated the impact of virtual source distributions and the number of transmissions on image quality in ultrafast medical ultrasound imaging using divergent waves. Three distinct virtual source configurations—linear, curvilinear, and tilted distributions—were evaluated under varying frame rates corresponding to 20, 10, and 5 transmissions. The analysis focused on two key image quality metrics: lateral resolution, quantified by the full width at half maximum (FWHM) of reflectors at the image center, and contrast ratio (CR) measured from anechoic cysts located at the center of the field-of-view. Looking ahead, future work will include the optimization of the virtual source distributions at high frame rate with low transmission events.

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