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1 **Verification of effect of interference between multiple scatterers**  
2 **on the evaluation of backscattering coefficient**

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13

14 Abstract

15 Backscattering coefficient (BSC) analysis methods for biological tissues have been clinically  
16 applied, but they are based on the theory of a homogeneous scattering medium. In this paper,  
17 the effect of spatial correlation of waves between scatterers on the backscattering properties  
18 of inhomogeneous mediums containing two types of scattering sources with different  
19 acoustic properties was investigated. In the echo data of a phantoms containing two types of  
20 scatterers acquired by multiple sensors, the power and frequency dependence of the BSC  
21 were different from theoretical calculations due to the interference effects of each scatterer.  
22 The effect of interference between the two types of scatterers was confirmed to be  
23 particularly strong for echoes acquired by the sensor at high intensity and high frequency, or  
24 for higher number densities of strong scatterers.

25

## 26 1. Introduction

27 Quantitative ultrasound (QUS) is useful for noninvasive evaluation of diseases of  
28 various biological tissues such as liver, breast, lymph nodes, skin, and bone. In particular,  
29 amplitude envelope statistics,<sup>1-6)</sup> attenuation coefficients (AC),<sup>7-10)</sup> backscatter coefficients  
30 (BSC),<sup>11-15)</sup> and elastography<sup>16-21)</sup> have attracted attention in clinical practice, and tools for  
31 evaluating QUS parameters which were obtained from these techniques have been  
32 implemented in clinical ultrasound systems.

33 Since backscatter coefficient depends on physical quantities such as the scatterer  
34 diameter, volume fraction, and acoustic impedance ratio of the scatterer and surrounding  
35 medium, the physical quantity to be evaluated can be estimated by comparing the measured  
36 backscatter coefficient with a theoretical model.<sup>22,23)</sup> It has been reported that evaluation of  
37 fatty liver,<sup>24,25)</sup> dermal lymphedema,<sup>26-28)</sup> thyroid tumors,<sup>29,30)</sup> and trabecular bone<sup>31)</sup> is  
38 possible using the backscatter coefficient as an indicator. BSC evaluations using single-  
39 element concave transducers have been widely used in these basic studies.

40 There are also reports of evaluation using multiple frequency bands,<sup>32,33)</sup> plane wave  
41 compound imaging,<sup>34-36)</sup> and spatial synthesis<sup>11,13)</sup> to improve evaluation accuracy. Omura et  
42 al. used multiple ultrasound scanners to acquire signals with two different beamforming  
43 methods, line-by-line beamforming with focused imaging and parallel beamforming with  
44 plane-wave imaging, and verified the variation of BSC.<sup>36)</sup> The calculated BSC was  
45 independent of either the system setting or the beamforming method, and the feasibility of  
46 BSC analysis using plane wave imaging was demonstrated.

47 However, the accuracy of quantitative evaluation is limited even when plane waves  
48 are also used, because multiple types of scattering sources are mixed in biological tissues.  
49 There is a trend to consider the influence of structures in the tissue and interference between  
50 scatterers as the main causes of this problem. Scattering sources in biological tissue are  
51 densely intermingled, with multiple sources within the point spread function (PSF) of the  
52 transducer. Therefore, backscatter characterization is usually based on the speckle signal,  
53 which is the interference between the scatterers. In other words, it is necessary to understand  
54 the spatial correlation between scatterers. The effect of spatial correlation in a  
55 homogeneously distributed medium with one type of scatterer is well understood. E.  
56 Franceschini et al. investigated a scattering model from the perspective of explaining  
57 experimental BSCs from cell pellet biophantoms with a single structural and acoustic  
58 parameter set.<sup>37)</sup> They reported that the impedance and size estimated from the scattering  
59 model were satisfactory. On the other hand, spatial correlations between scatterers in

60 heterogeneous media containing a mixture of scatterers with different acoustic properties  
61 have not been well studied. Therefore, the interpretation of backscatter coefficients from  
62 complex biological tissues first requires an understanding of ultrasonic backscatter from a  
63 biological phantom with known scattering conditions, especially the effects of wave  
64 interference caused by the positional correlation of scatterers.

65 In this study, we focused on the effect of interference between scatterers and  
66 compared the backscatter coefficients of phantoms with two different types of scatterers at  
67 different scattering ratios. Using a self-made ultrasonic scanner and a single concave  
68 transducer, the backscatter coefficients at low and high frequencies were evaluated. We also  
69 evaluated them using a research platform scanner and a very high-frequency linear array  
70 probe. In particular, signals were acquired using the parallel beamforming method with plane  
71 wave imaging and BSC analysis was performed.

72

## 73 **2. Materials and Methods**

### 74 **2.1 Tissue-mimicking phantoms of multiple types of scatterers**

75 Seven different rectangular phantoms (8 cm in width  $\times$  2 cm in length  $\times$  4 cm in  
76 height) were prepared as reference and evaluate phantoms. The solvents of each phantom  
77 were 2 wt% agar (A1296; Sigma-Aldrich, MO, USA) and distilled water. The weak  
78 scatterers were nylon spheres with an average particle size of 5  $\mu\text{m}$  (ORGASOL 2001 EXD  
79 NAT 1; Arkema, Colombes, France), and the strong scatterers were acrylic spheres with an  
80 average particle size of 20  $\mu\text{m}$  (MX-2000; Soken, Aichi, Japan). The intrinsic acoustic  
81 impedances are 1.493 and 1.665 Mrayl, respectively. These scatterers were mixed at various  
82 volume fractions as shown in Table I.

83 Phantom A and B are homogeneous media with only one type of scatterer. They  
84 were created as reference medium which the spatial correlations between scatterers are  
85 known for comparison with phantoms which contain two types of scatterers. Phantom A was  
86 created so that the scattering intensity was equivalent to that of a normal liver. Phantom B is  
87 a case in which only fat droplets are present, which is not possible in actual living tissue.  
88 Phantoms C, D, and E are groups in which fat droplets (strong scatterers) are mixed in  
89 different fractions within the normal liver (weak scatterers),<sup>38)</sup> while phantoms D, F, and G  
90 are groups in which fat droplets are constant and liver components are different fractions.  
91 By comparing the BSCs of these phantoms, the fraction (distribution) of the two types of  
92 scatterers and the effects of scattering and mutual interference from each scatterer can be  
93 evaluated.

94

## 95 **2.2 Data acquisition using the laboratory-made scanner**

96 Three-dimensional RF echo signals were observed using a laboratory-made  
97 ultrasonic scanner and two types of single-element concave transducers [transducer I (V327;  
98 Olympus, Tokyo, Japan) and transducer II (PT35; TORAY, Tokyo, Japan)]. The center  
99 frequency and -6 dB bandwidth are  $10 \text{ MHz} \pm 3 \text{ MHz}$  and  $30 \text{ MHz} \pm 10 \text{ MHz}$ , respectively.  
100 The depth of focus and f-number are 19.7 mm, 10mm, and 2.10, 1.85, respectively. For echo  
101 data acquisition, pulser receiver I (Model 5800; Olympus, Tokyo, Japan) for V327 and  
102 pulser receiver II (DPR500; JSR Ultrasonics, NY, USA) for PT35] for PT32 were used to  
103 excite negative impulses to the element for transmission. After the echo signals were  
104 received, they were band-pass filtered at 1-35 MHz and 30-300 MHz, respectively, by the  
105 receiver circuit in each pulser receiver. Each echo signal was quantized at 12-bits by the  
106 oscilloscope (HDO6104; Teledyne LeCroy, NY, USA) set to the sampling frequency of 250  
107 MHz. The PSF near the focus of each transducer is shown in Table II. The transducer was  
108 fixed to a triaxial linear rail (MTN100CC, Newport) and mechanically scanned in the lateral  
109 and slice directions. The phantom was fixed in degassed water at 22-24°C. Echo signals were  
110 acquired by irradiating ultrasound from the top surface. The depth of field of each transducer  
111 was 17.8-21.5 mm for V327 and 9.7-10.7 mm for PT35, so the phantom surfaces were set to  
112 17 mm and 9 mm, respectively, in order to cover the analysis area within the depth of field.  
113 The scan pitch was 30  $\mu\text{m}$  in both lateral and slice directions. Three-dimensional RF echo  
114 signals of 4096 in depth  $\times$  501 in lateral  $\times$  101 in slice pixels were acquired for all phantoms.  
115 All data acquisition and motor stage control were controlled by LabVIEW (National  
116 Instruments, TX, USA).

117

## 118 **2.3 Data acquisition using the research-platform scanner**

119 Two-dimensional RF echo signals were acquired using the research-platform  
120 scanner (Vantage256; Verasonics, WA, USA) and a linear array probe (L39-21gD;  
121 Verasonics, WA, USA). The center frequency and -6 dB bandwidth were  $25 \text{ MHz} \pm 9 \text{ MHz}$ .  
122 The element pitch and the number of elements were 0.055 mm 128 channels, respectively.  
123 The focus depth in the elevation direction was approximately 6.5 mm. Each echo signal was  
124 quantized at 14-bits with the sampling frequency set to 4/3 times the center frequency. In  
125 addition, the acquired data were up-sampled by a factor of 3 in the depth direction to produce  
126 data with a sampling frequency that is effectively 4 times the center frequency. The PSF at  
127 the highest resolution point is shown in Table II. RF data of each B-mode plane of each

phantom were acquired by plane wave imaging with parallel beamforming. Plane waves were steered at 11 angles ( $0^\circ$ ,  $\pm 1^\circ$ ,  $\pm 2^\circ$ ,  $\pm 3^\circ$ ,  $\pm 4^\circ$ , and  $\pm 5^\circ$ ), and the analysis signal was generated by combining them after delay and sum (DAS).

131

## 132 2.4 Speed of sound and attenuation coefficient calculation

133 The speed of sound and the attenuation of each phantom were evaluated by the  
 134 reflection method before BSC analysis. 3-D RF echo signals were acquired using a single-  
 135 element plane transducer III (V312; Olympus, Tokyo, Japan) in the same setting as  
 136 transducer I in 2.2. The center frequency and -6 dB frequency bandwidth are  $10 \text{ MHz} \pm 3$   
 137 MHz. Echo signals were also acquired using transducer II under similar conditions. An  
 138 acrylic plate was placed on top of the sound absorber, and the echo signals were acquired  
 139 with and without the sample while maintaining the positional relationship between the  
 140 transducer and the acrylic plate.<sup>39)</sup> The transducer was set at the depth at which the signal  
 141 from the acrylic plate was maximum. The speed of sound was calculated from the time of  
 142 flight (TOF) based on the time difference between the maximum amplitude returned from  
 143 the sample and the acrylic plate as follows:

$$c_p = c_0 \left( 1 + \frac{t_{ref} - t_r}{t_b - t_s} \right), \quad (1)$$

144 where  $t_s$  is the TOF from the sample surface,  $t_b$  is the TOF from the back,  $t_r$  is the TOF  
 145 from the acrylic plate after the sample passed through, and  $t_{ref}$  is the TOF from the acrylic  
 146 plate at the same position as during the measurement.  $c_0$  is the speed of sound of water. The  
 147 thickness  $d$  of the sample was calculated by  $d = c_0(t_b - t_s)/2$ . The attenuation rate of the  
 148 phantom,  $\alpha$  [dB/cm], was calculated using the power spectra with and without the sample  
 149 as follows:

$$\alpha(d, f) = \frac{8.686}{4d} \ln \frac{P_s}{P_{ref}}, \quad (2)$$

150 where  $P_s$  is the power spectrum through the phantom and  $P_{ref}$  is the power spectrum  
 151 without the sample.  $\alpha$  is the total attenuation at an arbitrary frequency  $f$ . The attenuation  
 152 rate can be considered to be the same as the absorption rate when the frequency is somewhat  
 153 low, when absorption attenuation can be considered to be dominant, or when scattering is  
 154 ignorable in a relatively homogeneous medium. In particular, in the frequency band between  
 155 1 MHz and 10 MHz used in clinical used ultrasonic diagnostic equipment, it can often be  
 156 approximated as proportional to the first power of the frequency. Therefore, the attenuation  
 157 coefficient  $\alpha_0$  [dB/cm/MHz] can be written as  $\alpha(f) = \alpha_0 f + b$ . On the other hand, the

158 frequency dependence of attenuation is considered to be an important characteristic in the  
 159 frequency band above 10 MHz, and the dependence of attenuation on frequency is described  
 160 as  $\alpha(f) = \alpha_0 f^n + b$ , where  $n$  as well as  $\alpha_0$  is considered to vary.<sup>40)</sup> Therefore, the  
 161 parameters when approximated by the equations  $\alpha(f) = \alpha_0 f + b$  and  $\alpha(f) = \alpha_0 f^n + b$   
 162 were calculated for the signals measured with transducer III and transducer II, respectively,  
 163 using the least-squares method with a -6 dB bandwidth.

164

## 165 **2.5 Backscatter coefficient analysis using reference phantom method**

166 Backscatter coefficient was calculated using the reference phantom method.<sup>41)</sup> The  
 167 reference phantom method assumes that the attenuation properties and backscatter  
 168 coefficient of the phantom used as the reference medium and the attenuation properties of  
 169 the analysis medium are known. By using a medium with known scattering conditions as a  
 170 reference signal, the backscatter coefficient can be evaluated robustly by correcting the  
 171 sound field of the transmitting and receiving systems when evaluating a medium with  
 172 complex beam diffraction effects such as a linear array probe or a medium with complex  
 173 scatterer structures such as biological tissue. The array probe can be used to evaluate  
 174 backscatter coefficient with high robustness. For this reason, array probes are widely used.  
 175 In this study, a region of interest (ROI) was set up to analyze local RF signal characteristics,  
 176 and the backscatter coefficient for each ROI was estimated. The ROI size was 10 times the  
 177 wavelength at the center frequency of the transducer in the depth direction and 10  
 178 uncorrelated echo lines in the lateral direction. Backscatter coefficient was estimated as

$$BSC(f) = \frac{\overline{P(f)}}{\overline{P_r(f)}} BSC_r(f) \exp \left\{ \frac{4(\alpha - \alpha_{ref})f \left( x_0 + \frac{\Delta z}{2} \right)}{8.686} \right\} \quad (3)$$

179 where  $\overline{P(f)}$  represents the average of the power spectrum of the analyte in the ROI and  
 180  $\overline{P_r(f)}$  represents the power spectrum of the reference medium. The frequency response of  
 181 the measured echo signal includes a component of attenuation that occurs during ultrasonic  
 182 wave propagation. Therefore, the last section corrects for the attenuation up to the analysis  
 183 window.  $\alpha$  and  $\alpha_{ref}$  are attenuation coefficients,  $x_0$  is the distance from the scattering  
 184 medium surface to the start of the analysis window, and  $\Delta z$  is the size of the analysis  
 185 window.<sup>42)</sup>

186 In the frequency range from 1 MHz to 10 MHz,  $n = 1$ , since the attenuation can  
 187 be assumed to be proportional to the power of one of the frequencies.  $BSC_r(f)$  is the  
 188 theoretical value of the backscatter coefficient of the reference medium. In this study, the

189 reference phantom was evaluated as Phantom A. The theoretical values were calculated by  
190 the mathematical model as follows:

$$BSC_r = m \int_0^{\infty} p(r) \sigma_{b\_elastic}(k, r, \gamma) S(k, r, \varphi) dr, \quad (4)$$

191 where  $m$  is the number density of scatterers.  $p(r)$  is the probability density function of  
192 scatterers, which can be assumed by performing calculations for each scatterer diameter  
193 when there is a distribution of scatterer diameters and finally performing weighted integrals.  
194  $\sigma_{b\_elastic}(k, r, \gamma)$  is the Farn model<sup>43)</sup>, which assumes that the scatterers are elastic and  
195 transverse waves propagate. It assumes that the scattering body is elastic and shear waves  
196 propagate.  $S(k, r, \varphi)$  is the structure factor and assumes that the scatterer is dense and the  
197 randomness of the scatterer's position is impaired.  $r$ ,  $k$ ,  $\gamma$  and  $\varphi$  are the particle size,  
198 wavenumber, acoustic impedance ratio, and volume fraction of the scatterer, respectively.

199 In order to verify the effect of interference between the two types of scatterers, the  
200 deviation between the evaluated backscatter coefficient and the theoretical value of the  
201 backscatter coefficient was calculated. The theoretical value of the backscatter coefficient  
202 was calculated in the same way as in equation (4). The average deviation was defined as

$$\text{Deviation} = \frac{1}{\text{BW}} \sum_{f \text{ in BW}} \{BSC(f) - BSC_{ref}(f)\}, \quad (5)$$

203 where BW indicates the frequency band used in the analysis.

204

### 205 3. Results

#### 206 3.1 BSC evaluation of phantoms with one type of scatterer

207 To understand the characteristics of the phantoms used for reference, phantom A  
208 and B which contain only one type of scatterer were measured with three single-element  
209 concave transducers and linear probe. B-mode images of phantom A and B acquired using  
210 transducer I, transducer II, and the linear array probe are shown in Fig. 1. Each B-mode  
211 image was normalized by the maximum value of phantom B. Because the acoustic  
212 impedance of scatterer 2 is higher than that of scatterer 1, the amplitude of phantom B is  
213 larger in each transducer.

214 In phantom A, the number of scatterers present is 749, 28.9, and 88 relative to the  
215 PSFs of the transducer I, transducer II, and linear array probe, respectively, which is  
216 confirmed to be speckle (Fig. 1(a-1)-(c-1)).

217 In phantom B, on the other hand, the number of scatterers present is 7.02, 0.27, and  
218 0.82, respectively, so that scatters acquired with transducer I are speckles, while those



219 acquired with transducer II and the linear array probe can be identified as point sources (Fig.  
220 2(a-2)-(c-2)).

221 The amplitude envelopes of phantom A and B acquired by each sensor are shown  
222 in Fig. 2. The F-values of transducers I and II are 2.10 and 1.85, respectively, and the sound  
223 pressure gradient of transducer II is steep. Therefore, the signal below 12 mm is equivalent  
224 to the amplitude value in the water region, and the S/N ratio is not sufficiently high (Fig.  
225 2(b)). On the other hand, the data measured by the linear array probe shows a high signal  
226 intensity, and a high S/N ratio is guaranteed even in deep areas (Fig. 2(c)).

227 The frequency spectrum of phantom A and B acquired by each sensor are shown in  
228 Fig. 3. Each frequency spectrum is normalized by the maximum value of each phantom.  
229 Transducer I has a narrow effective bandwidth (Fig. 3(a)), while transducers II and linear  
230 array probes have a wide effective frequency band in the very high frequency range (Fig. 3  
231 (b), (c)).

232 The results of the backscatter coefficient estimation for phantom A and B using each  
233 single-element transducer and their respective theoretical values are shown in Fig. 4.  
234 Phantom A is self-referencing, so the sound field and attenuation corrections can be  
235 performed with high accuracy, and the results are in agreement with theoretical values. For  
236 Phantom B, the results for transducer I agreed with the theoretical values, confirming the  
237 high precision of the evaluation (Fig. 4(a)). However, in the high-frequency band, there was  
238 no complex frequency dependence as in the theoretical values, and the deviation was large.  
239 (Fig. 4(b), (c)).

240

## 241 **3.2 BSC evaluation of phantoms with two types of scatterers**

### 242 **3.2.1 Effects of increasing strong scatterers**

243 Based on the trend of the backscatter coefficient evaluation results for phantoms  
244 with only one type of scatterer mixed in, the effect of the number density of strong scatterers  
245 on the backscattering characteristics was confirmed. B-mode images of phantom C, D, and  
246 E acquired using transducer I, transducer II, and linear array probe are shown in Fig. 5.  
247 Normalization method of B-mode images was the same as in Fig. 1(a-2)-(c-2). Comparing  
248 phantom C, D, and E in transducer I, the amplitude increases as the scatterer number density  
249 increases (Fig. 5(a)). In transducer II, the amplitude did not change as the number density  
250 increased (Fig. 5(b)). On the other hand, in the linear array probe, the amplitude of the  
251 phantom decreases as the number density increases. In particular, strong scatterers are  
252 recognizable as point sources, and the amplitude of strong scatterers decreases gradually

253 (Fig.5(c)).

254 The amplitude envelopes of phantom A, B, C, D, and E in each sensor are shown in  
255 Fig. 6. For comparison, Figure 6 also presents results for phantom A and B. Since the signal  
256 intensity from the surface waves is similar for both phantoms, it can be assumed that the  
257 intensity of the incident ultrasound signal of the phantoms in this study is similar (Fig. 6 (a),  
258 (b)). This is because the number density of scatterers in the phantom in this study is  
259 sufficiently small, and the reflected wave signal from the phantom surface does not include  
260 the reflected wave from the scatterers, but is considered to be the reflection from the  
261 surrounding medium, the agar phantom. In the amplitudes acquired by the linear array probe,  
262 the scatterer number density increases in the order of phantom B, D, and E, but the  
263 amplitudes are lower in the order of phantom B, D, and E (Fig. 6 (c)).

264 The frequency spectrums of phantom A, B, C, D, and E observed with transducer I,  
265 II, linear array probe are shown in Fig. 7. The power was normalized by the maximum value  
266 of each phantom. The bandwidth widens as the scatterer number density increases in  
267 transducer I. Both phantoms were speckle signals, and the total power of the signal increased  
268 as the number density increased (Fig. 7 (a)). In transducer II and the linear array probe, the  
269 bandwidth is narrower than in phantom A because the signal from the strong scatterer is  
270 acquired as a point scattering source. In phantom C and D and E, the higher number density  
271 of scatterers in the PSF increases the signal at lower frequencies, while the signal at higher  
272 frequencies decreases due to greater scattering attenuation (Fig. 7 (b), (c)).

273 The estimated and theoretical backscatter coefficients for phantom C, D, and E at  
274 each transducer are shown in Fig. 8. The theoretical value of the two-scatterer mixed  
275 phantom is the value obtained by substituting the probability density function of the scatterer  
276 particle size for each phantom into the probability density function in eq. 5. In other words,  
277 it is the sum of the theoretical values of the backscattering coefficients of each scatterer. That  
278 is, it is the sum of the theoretical values of the backscattering coefficients of each scatterer.  
279 Thus, interference between each scatterer is taken into account, but the effect of mutual  
280 interference between the two types of scatterers is not taken into account. There was no  
281 difference in the frequency dependence of each phantom in transducer I. As the number of  
282 strong scatterers increases, the value of the backscatter coefficient is higher, and the values  
283 for phantom C and D are consistent with the theoretical values (Fig. 8 (a)). In transducer II,  
284 the estimation results are similar for the phantom with two mixed scatterers, as in phantom  
285 B, with a large deviation from the theoretical value. In particular, the properties of phantom  
286 D are strongly consistent with phantom B (Fig. 8 (b)).<sup>38)</sup> The results of the evaluation with

287 the linear array probe show a lower value compared to Phantom B, although the deviation  
288 from the theoretical value is large. Comparing phantom C, D, and E, the backscatter  
289 coefficients show lower values as the scatterer number density increases (Fig. 8 (c)).

290 The deviation between the estimated backscatter coefficient and the theoretical  
291 value calculated by the mathematical model is shown in Fig. 9. Although Phantom B has  
292 only one type of scatterer, the deviation from the theoretical value is so large that it is difficult  
293 to compare with the deviation calculated by eq. 7. Therefore, the deviations of the other  
294 phantoms were normalized at each frequency so that the deviation of phantom B was zero,  
295 and the mean and standard deviation were calculated. The theoretical value of the backscatter  
296 coefficient is a model that does not take into account the interference between the two types  
297 of scatterers, whereas the measured evaluation results include their effects, and the deviation  
298 indicates the degree of such interference. A smaller standard deviation indicates a smaller  
299 frequency-dependent deviation. Since the evaluation of phantom A is self-referencing and  
300 the evaluation is highly accurate in all modalities, the deviation of phantom A is not  
301 calculated. The mean and standard deviation of the deviation in transducer I are within 3 dB,  
302 indicating a high degree of agreement with the theoretical values. The mean deviation for  
303 transducer II and the linear array probe was lower with increasing scatterer number density,  
304 and the standard deviation of the deviation was larger for the linear array probe.

305

### 306 **3.2.2 Effects of increasing weak scatterers**

307 To confirm the effect of increasing of week scatterers, phantom D, F, and G were  
308 compared. B-mode images of phantom D, F, and G acquired using transducer I, II, and the  
309 linear array probe are shown in Fig. 10. Normalization method of B-mode images was the  
310 same as in Fig. 1(a-2)-(c-2). In Fig. 10, it is confirmed the amplitudes of transducer I are  
311 similar for an increasing number of weak scattering sources (Fig. 10(a)). B-mode images  
312 acquired with the transducer II and linear array probes show a low-contrast image with a  
313 small amplitude of the strong scattering source as the weak scatterer increases (Fig. 10(b),  
314 (c)).

315 The amplitude envelopes of phantom D, F, and G using transducer I, transducer II,  
316 and linear array probes are shown in Fig. 11. The amplitude envelopes of phantom A and B  
317 are also shown for comparison. The similarity of phantom B, D, and F in the signals acquired  
318 with transducer I indicates that the strong scatterer is dominant in the reflected signal.  
319 Phantom G has a sufficiently high number density of weak scatterers, and many scatterers  
320 are mixed in near the phantom surface. Because the reflected waves from the scatterers are

321 included in the surface wave signal of the phantom, the surface waves are larger than those  
322 of other phantoms and the signal inside the phantom is also lower (Fig. 11(a)). The signal  
323 intensities of phantom B, D, F, and G acquired with transducer II are comparable, and the  
324 amplitude gradient of the signal below the focus is steeper as the number density increases  
325 due to scattering attenuation (Fig. 11(b)). Signals acquired with the linear array probe show  
326 an increase in scatterer number density but lower amplitude when compared to phantom B,  
327 D, and F. Phantom G is difficult to compare with other phantoms, because the intensity of  
328 the incident signal is smaller than the other phantoms due to the larger surface waves in Fig.  
329 11(a). However, comparison of phantom B, D, and F suggests that the scattering intensities  
330 are not simply additive (Fig. 11(c)).

331         The frequency spectrums of phantom A, B, D, F, and G acquired using each sensor  
332 are shown in Fig. 12. For transducer I, the frequency bandwidth tended to narrow as the  
333 number of weak scatterers increased (Fig. 12(a)). For the transducer II and linear array  
334 probes, as in Fig. 7(b),(c), the low-frequency signal increased with each increase in scatterer  
335 number density, but the high-frequency signal decreased due to high-frequency attenuation  
336 (Fig. 12(b),(c)).

337         The estimated backscatter coefficients of phantom D, F, and G acquired by each  
338 sensor and the theoretical values calculated by the mathematical model are shown in Fig. 13.  
339 The theoretical values for a phantom with two mixed scatterers are calculated in the same  
340 way as in chapter 3.2.1. Phantom B, D, F and G were similar in transducer I (Fig. 13(a)).  
341 The deviation from the theoretical value was large for transducer II, while results for B, D,  
342 and F were similar. On the other hand, phantom G shows lower values than the other  
343 phantoms, and the difference is larger than the difference between the theoretical values (Fig.  
344 13(b)). In the linear array probe, as in transducer II, the deviation from the theoretical value  
345 is large but low as the scatterer number density increases. The frequency dependence is also  
346 different in the frequency range from 25 MHz to 35 MHz, where the slope becomes smaller  
347 as the number density increases (Fig. 13(c)).

348         The deviation between the estimated backscatter coefficient and the theoretical  
349 value calculated by the mathematical model is shown in Fig. 14. The same as in Fig. 9,  
350 normalized by Phantom II. For all modalities, the mean value of the deviation was higher as  
351 the scatterer number density increased. In addition, the standard deviations of the deviations  
352 are larger for transducer I, transducer II, and the linear array probe, in that order.

353

## 354 4. Discussion

355           In this study, the effect of the interference state between different scatterers on the  
356 backscattering characteristics was examined by changing the ratio of the scatterers in a  
357 medium with multiple types of scatterers. The amplitudes were evaluated for the medium  
358 with a fixed amount of weak scatterers and an increased amount of strong scatterers, and for  
359 the medium with a fixed amount of strong scatterers and an increased amount of weak  
360 scatterers, as shown in Figs. 5(c) and 10(c). The amplitude is low even in shallow areas as  
361 the number density increases due to the weaker interference caused by the mixture of two  
362 types of scatterers. As shown in Fig. 5(a) and Fig. 10(a), the intensity of the surface wave  
363 does not change between phantoms, indicating that it is not due to the reflection of the  
364 surface wave.

365           As shown in Fig. 8(a) and Fig. 13(a), the theoretical model for a phantom with two  
366 types of scatterers does not consider the interference between the two types of scatterers.  
367 Therefore, the mutual influence between the two types of scatterers is small in the theoretical  
368 value. On the other hand, in the actual measurements, as shown in Figs. 8(b) and 13(b), the  
369 scattering from the strong scatterer is sufficiently larger than that from the weak scatterer,  
370 and the signal from the strong scatterer is dominant in the two-scatterer mixed phantom.  
371 Therefore, the interference signal between the weak scatterers is small, and it is assumed that  
372 the backscattering coefficient is estimated low in Figure 8(c) because the strong scatterers in  
373 the analysis region are weakened by the interference with the surrounding weak scatterers  
374 and the contrast is reduced. This can be understood from the fact that the slope as well as the  
375 power is smaller, as shown in Fig. 13(c). In other words, it is due to the effect of weaker  
376 interference from strong scatterers and more dominant signals from weak scatterers.

377           As shown in Fig. 9 and Fig. 14, the standard deviation of the deviation is larger for  
378 each increase in the number density of scatterers in the order of transducer I, transducer II,  
379 and the linear array probe, and the data acquired with the linear array probe shows the largest  
380 deviation from the frequency dependence, indicating the influence of interference. The  
381 deviation in transducer II shows the difference between the theoretical values and is not due  
382 to the effect of interference, because the difference between the phantoms in the backscatter  
383 coefficient evaluation results is small as shown in Fig. 8(b) and Fig. 13(b). The standard  
384 deviation of the deviation in transducer I is small, indicating that the frequency dependence  
385 of the deviation is highly consistent despite the difference in power. Thus, interference  
386 between the two types of scatterers has a significant effect on the backscattering  
387 characteristics when evaluated with a high intensity and high frequency sensor.

388

## 389 **5. Conclusions**

390 In order to understand the influence of wave interference caused by the correlation  
391 of scatterer positions, we compared the backscattering characteristics of a phantom with a  
392 mixture of two types of scatterers when the ratio of the scatterers was changed, using several  
393 sensors. The signal acquired with a single transducer showed only a small influence of  
394 interference, while the signal acquired with a linear array probe of high intensity and high  
395 frequency showed a weaker influence of interference, which became more pronounced as  
396 the number density of scatterers increased. However, the scattering intensity of actual  
397 biological tissue differs significantly from that of the simulated biological samples used in  
398 this study and has a more complex scatterer distribution, so the frequency dependence of the  
399 BSC is also assumed to have more diverse variations. In future works, we will evaluate the  
400 scattering intensity of real biological tissue as well as media with heterogeneous scatterer  
401 distribution and structure, which are closer to the scattering intensity of biological tissue.

402

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406

407 **References**

- 408 1) T. Yamaguchi, H. Hachiya, *J. Med. Ultrason.* **37** [4], 155 (2010).
- 409 2) S. Mori, S. Hirata, T. Yamaguchi, and H. Hachiya, *Jpn. J. Appl. Phys.* **57**, 07LF17  
410 (2018).
- 411 3) K. Tamura, J. Mamou, K. Yoshida, H. Hachiya, and T. Yamaguchi, *Jpn. J. Appl.*  
412 *Phys.* **59**, SKKE23 (2020).
- 413 4) M. Omura, K. Yoshida, S. Akita, and T. Yamaguchi, *Jpn. J. Appl. Phys.* **57**, 07LF15  
414 (2018).
- 415 5) Y. Sato, K. Tamura, S. Mori, D. Tai, P. Tsui, K. Yoshida, S. Hirata, H. Maruyama,  
416 and T. Yamaguchi, *Jpn. J. Appl. Phys.* **60**, SDDE06 (2021).
- 417 6) Y. Ujihara, K. Tamura, S. Mori, S. Hirata, K. Yoshida, H. Maruyama, and T.  
418 Yamaguchi, *Jpn. J. Appl. Phys.* **62**, SJ1043 (2023).
- 419 7) Y. Koizumi, M. Hirooka, N. Tamaki, N. Yada, O. Nakashima, M. Kudo, and Y.  
420 Hiasa, **14** [8], 1 (2018).
- 421 8) Y. Fujiwara, H. Kuroda, T. Abe, K. Ishida, T. Oguri, S. Noguchi, T. Sugai, N.  
422 Kamiyama, and Y. Takikawa, *Ultrasound Med. Biol.* **44** [11], 2223 (2018).
- 423 9) Y. Fujiwara, H. Kuroda, T. Abe, K. Ishida, T. Oguri, S. Noguchi, T. Sugai, N.  
424 Kamiyama, and Y. Takikawa, *Ultrasound Med. Biol.* **44** [11], 2223 (2018).
- 425 10) S. Kyung, I. Joo, S. Y. Kim, J. K. Jang, J. Park, H. S. Park, E. S. Lee, and J. M. Lee,  
426 *Ultrasonography* **40** [1], 136 (2021).
- 427 11) W. Saito, M. Omura, J. A. Ketterling, S. Hirata, K. Yoshida, and T. Yamaguchi, *Jpn.*  
428 *J. Appl. Phys.* **61**, SG1049 (2022).
- 429 12) T. Oguri, M. Omura, W. Saito, K. Yoshida, and T. Yamaguchi, *Jpn. J. Appl. Phys.*  
430 **60**, SDDE24 (2021).
- 431 13) T. Mizoguchi, K. Yoshida, J. Mamou, J. Ketterling, and T. Yamaguchi, *Jpn. J. Appl.*  
432 *Phys.* **59**, SKKE17 (2020).
- 433 14) M. Omura, K. Yoshida, S. Akita, and T. Yamaguchi, *J. Med. Ultrason.* **47** [1], 25  
434 (2020).
- 435 15) S. C. Lin, E. Heba, T. Wolfson, B. Ang, A. Gamst, A. Han, J. W. Erdman, W. D.  
436 O'Brien, M. P. Andre, C. B. Sirlin, and R. Loomaba, *Physiology and behavior* **176**  
437 [1], 139 (2016).
- 438 16) D. Ito, T. Oguri, N. Kamiyama, S. Hirata, K. Yoshida, and T. Yamaguchi, *Jpn. J.*  
439 *Appl. Phys.* **60**, SDDE11 (2021).
- 440 17) K. Osato, T. Oguri, N. Kamiyama, S. Hirata, K. Yoshida, and T. Yamaguchi, *Jpn. J.*

- 441 Appl. Phys. **62**, SJ1054 (2023).
- 442 18) M. Minagawa, H. Hasegawa, T. Yamaguchi, and S. Yagi, Jpn. J. Appl. Phys. **57**,  
443 07LE07 (2018).
- 444 19) S. Fujii, M. Yamakawa, K. Kondo, T. Namita, and T. Shiina, Jpn. J. Appl. Phys. **58**,  
445 SGGE07 (2019).
- 446 20) I. Sporea, S. Bota, M. Peck-Radosavljevic, R. Sirli, H. Tanaka, H. Iijima, R. Badea,  
447 M. Lupsor, C. Fierbinteanu-Braticevici, A. Petrisor, H. Saito, H. Ebinuma, M.  
448 Friedrich-Rust, C. Sarrazin, H. Takahashi, N. Ono, F. Piscaglia, A. Borghi, M.  
449 D'Onofrio, A. Gallotti, A. Ferlitsch, A. Popescu, and M. Danila, European Journal  
450 of Radiology **81** [12], 4112 (2012).
- 451 21) J. E. Brandenburg, S. F. Eby, P. Song, H. Zhao, J. S. Brault, S. Chen, and K. An,  
452 Archives of Physical Medicine and Rehabilitation **95** [11], 2207 (2014).
- 453 22) E. Franceschini, and R. Guillermin, J. Acoust. Soc. Am. **132** [6], 3735 (2012).
- 454 23) E. Franceschini, R. Monchy, and J. Mamou, IEEE Trans. Ultrason. Ferroelectr.  
455 Freq. Control **63** [9], 1321 (2016).
- 456 24) G. Ghoshal, R. J. Lavarello, J. P. Kemmerer, R. J. Miller, and M. L. Oelze, Ultrasound  
457 Med. Biol. **38** [12], 2238 (2012).
- 458 25) Z. F. Lu, J. A. Zagzebski, and F. T. Lee, Ultrasound Med. Biol. **25** [7], 1047 (1999)
- 459 26) E. Saegusa-Beecroft, J. Machi, J. Mamou, M. Hata, A. Coron, E. T. Yanagihara, T.  
460 Yamaguchi, M. L. Oelze, P. Laugier, and E. Feleppa, J Surg Res. **183** [1], 258 (2013).
- 461 27) K. Tamura, J. Mamou, A. Coron, K. Yoshida, E. J. Feleppa, and T. Yamaguchi, IEEE  
462 Trans. Ultrason. Ferroelectr. Freq. Control **64** [10], 1501 (2017).
- 463 28) M. Omura, K. Yoshida, S. Akita, T. Yamaguchi, Jpn. J. Appl. Phys. **59**, SKKE15  
464 (2020).
- 465 29) R. J. Lavarello, W. R. Ridgway, S. Sarwate, and M. L. Oelze, Ultrasound Med. Biol.  
466 **61** [6], 515 (2015).
- 467 30) M. L. Oelze, J. Mamou, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **63** [2], 336  
468 (2016).
- 469 31) K. Lee, J. Acoust. Soc. Am. **145** [5], EL393 (2019).
- 470 32) M. McCormick, E. Madsen, M. Deaner, and T. Varghese, J. Acoust. Soc. Am. **130**  
471 [2], 737 (2011).
- 472 33) B. Raju, and M. Srinivasan, Ultrasound Med. Biol. **27** [11], 1543 (2001).
- 473 34) M. Herd, T. Hall, J. Jiang, and J. Zagzebski, Ultrasound Med. Biol. **23** [1], 1 (2012).
- 474 35) M. Omura, R. Nagaoka, K. Yagi, K. Yoshida, T. Yamaguchi, and H. Hasegawa, Jpn.



- 475 J. Appl. Phys. **61**, SG1067 (2022).
- 476 36) M. Omura, H. Hasegawa, R. Nagaoka, K. Yoshida, and T. Yamaguchi, J. Med.  
477 Ultrason. **47** [1], 35 (2020).
- 478 37) E. Franceschini, R. Guillermin, and F. Tourniaire, J. Acoust. Soc. Am. **135** [6], 3620  
479 (2014).
- 480 38) H. Kutsuzawa, S. Hirata, K. Yoshida, E. Franceschini, and T. Yamaguchi, Proc. Symp.  
481 Ultrason. Electron2023.
- 482 39) R. Kuc, M. Schwartz, IEEE Trans. Sonics Ultrason. **25** [5], 353 (1979).
- 483 40) N. Suzuki, in *Chouonnpabinran* (Handbook of Ultrasound), ed. Ultrasound  
484 Handbook Editorial Committee (Maruzen, Tokyo, 1999) pp421-422 [in Japanese].
- 485 41) L. Yao, J. Zagzebski, and E. Madsen, Ultrason. Imaging **12** [1], 58 (1990).
- 486 42) M. Oelze, W. D. O'Brien, J. Acoust. Soc. Am. **111** [5], 2308 (2002).
- 487 43) J. J. Faran, J. Acoust. Soc. Am. **23**, 405 (1951).

## Figure Captions

**Fig. 1.** (Color Online) B-mode images of (a-1)-(c-1) phantom A and (a-2)-(c-2) phantom B acquired with (a) transducer I, (b) transducer II, and (c) linear array probe

**Fig. 2.** (Color Online) Amplitude envelopes of phantom A and B acquired using (a) transducer I, (b) transducer II, and (c) linear array probe

**Fig. 3.** (Color Online) Power spectrums of phantom A and B acquired using (a) transducer I, (b) transducer II, and (c) linear array probe

**Fig. 4.** (Color Online) Backscatter coefficients of phantom A and B acquired using (a) transducer I, (b) transducer II, and (c) linear array probe and theoretical values

**Fig. 5.** (Color Online) B-mode images of (a-1)-(c-1) phantom C, (a-2)-(c-2) phantom D and (a-3)-(c-3) phantom E acquired with (a) transducer I, (b) transducer II, and (c) linear array probe

**Fig. 6.** (Color Online) Amplitude envelopes of phantom A, B, C, D and E acquired using (a) transducer I, (b) transducer II, and (c) linear array probe

**Fig. 7.** (Color Online) Power spectrums of phantom A, B, C, D and E acquired using (a) transducer I, (b) transducer II, and (c) linear array probe

**Fig. 8.** (Color Online) Backscatter coefficients of phantom A, B, C, D and E acquired using

(a) transducer I, (b) transducer II, and (c) linear array probe and theoretical values

**Fig. 9.** (Color Online) Deviation between the estimated backscatter coefficients for phantom B, C, D, and E and the theoretical values calculated by the mathematical model

**Fig. 10.** (Color Online) B-mode images of (a-1)-(c-1) phantom D, (a-2)-(c-2) phantom F and (a-3)-(c-3) phantom G acquired with (a) transducer I, (b) transducer II, and (c) linear array probe

**Fig. 11.** (Color Online) Amplitude envelopes of phantom A, B, D, F and G acquired using (a) transducer I, (b) transducer II, and (c) linear array probe

**Fig. 12.** (Color Online) Power spectrums of phantom A, B, D, F and G acquired using (a) transducer I, (b) transducer II, and (c) linear array probe

**Fig. 13.** (Color Online) Backscatter coefficients of phantom A, B, D, F and G acquired using (a) transducer I, (b) transducer II, and (c) linear array probe and theoretical values

**Fig. 14.** (Color Online) Deviation between the estimated backscatter coefficients for phantom B, D, F, and G and the theoretical values calculated by the mathematical model

**Table I.** Phantom composition and acoustic properties

Phantom	A	B	C	D	E	F	G
Volume fraction of scatter 1 [%]	0.5	-	0.5	0.5	0.5	2	5
Volume fraction of scatter 2 [%]	-	0.3	0.1	0.3	0.5	0.3	0.3

Scatterer 1: nylon with diameter of 5  $\mu\text{m}$ , scatterer 2: acrylic with diameter of 20  $\mu\text{m}$ .

**Table II.** PSF near focus for each sensor

	Axial [ $\mu\text{m}$ ]	Lateral [ $\mu\text{m}$ ]
V327	109	300
PT35	42	95
L39-21gD	80	120

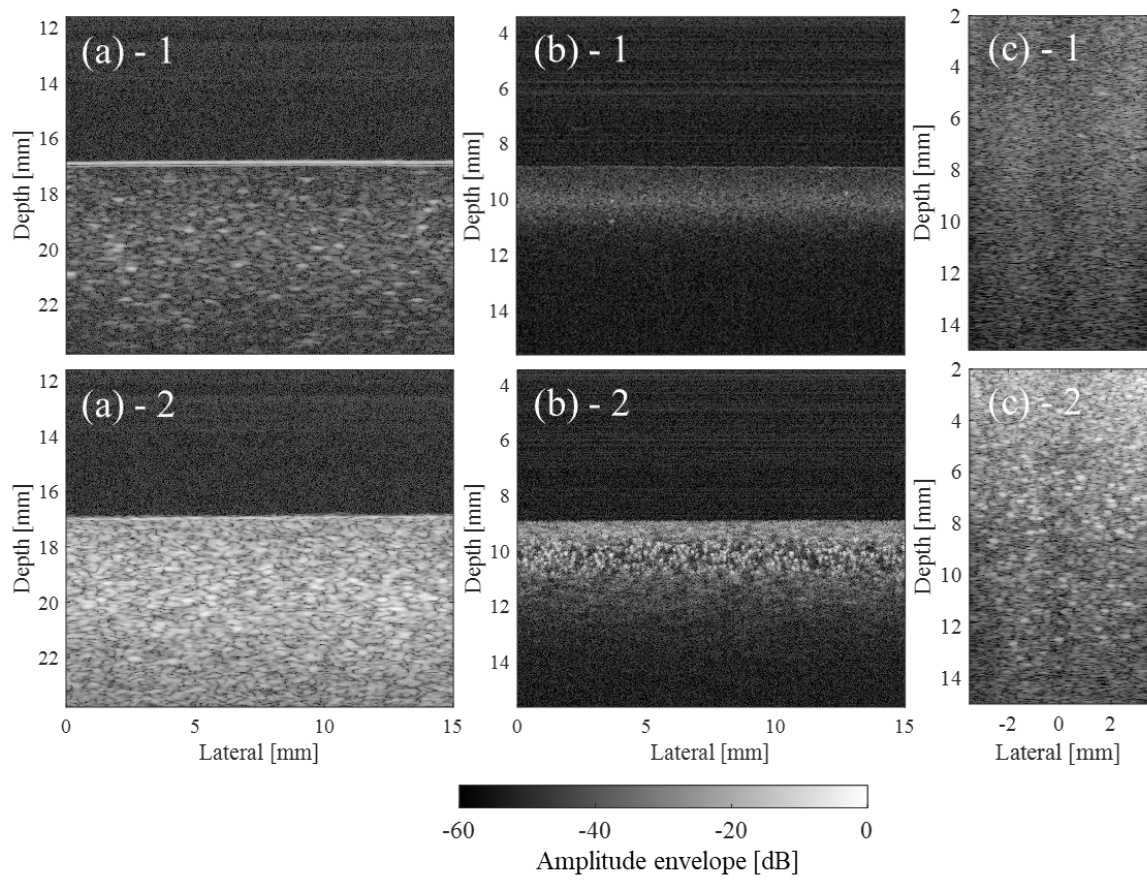


Fig. 1

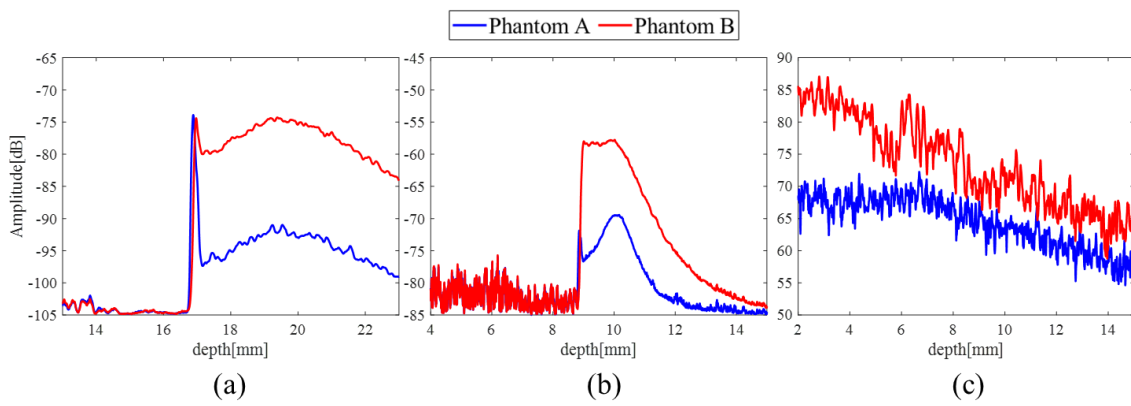


Fig. 2

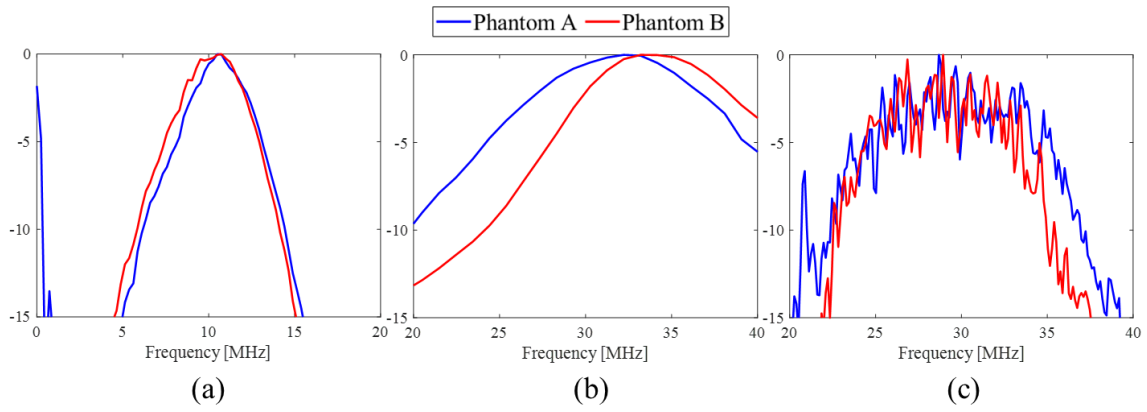


Fig. 3

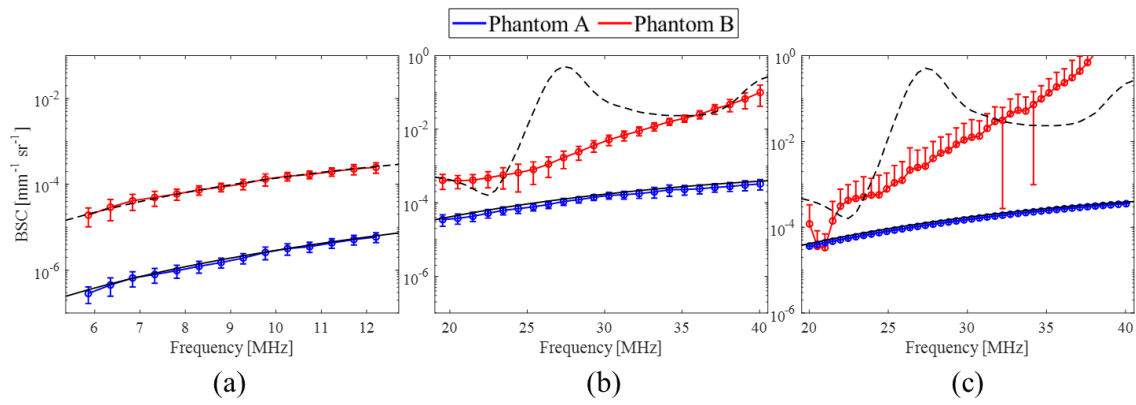


Fig. 4

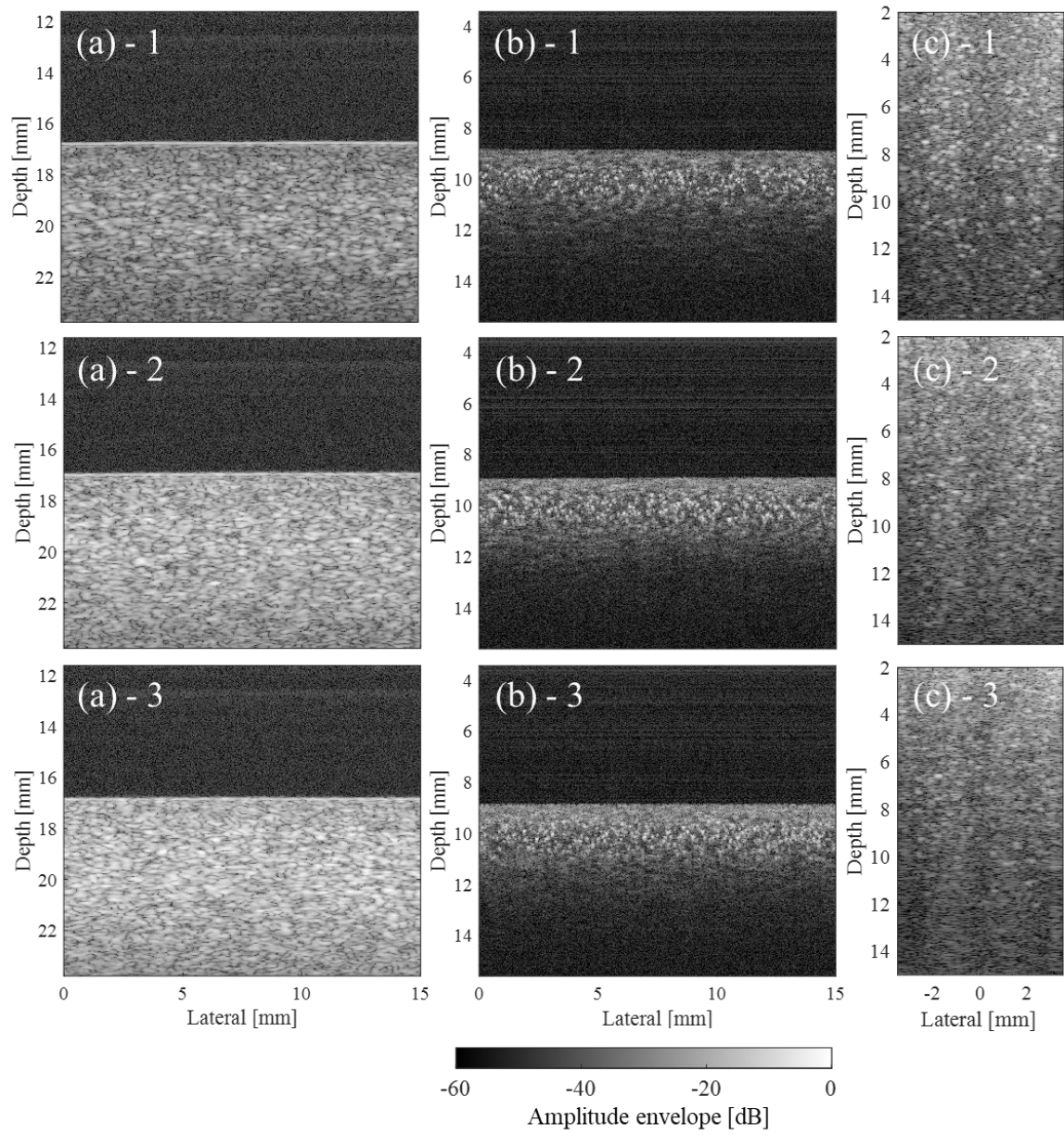


Fig. 5

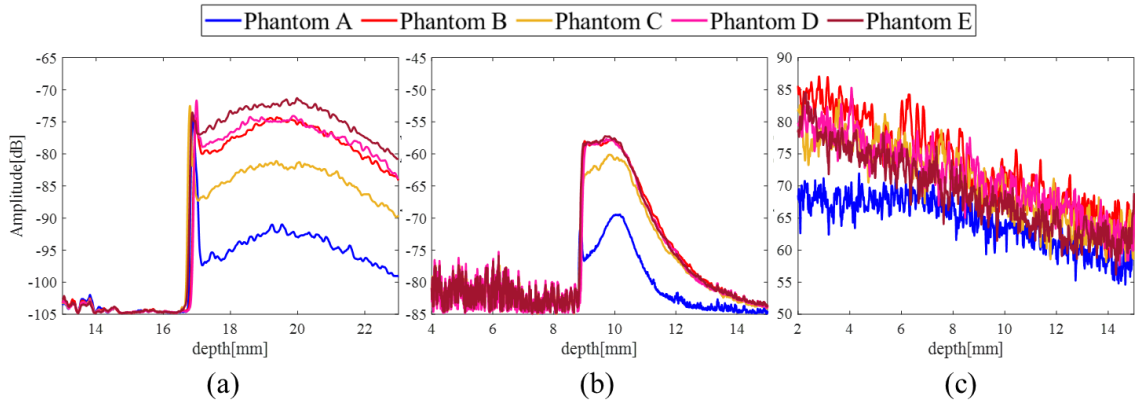


Fig. 6

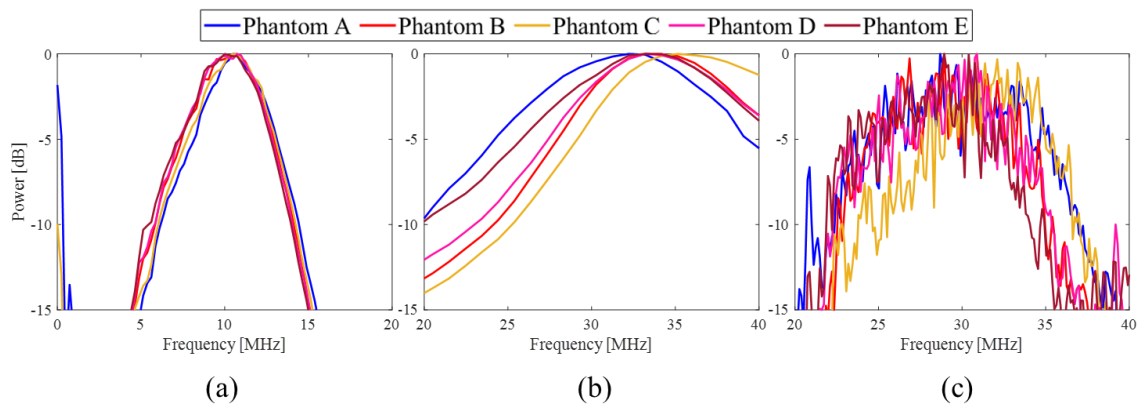


Fig. 7

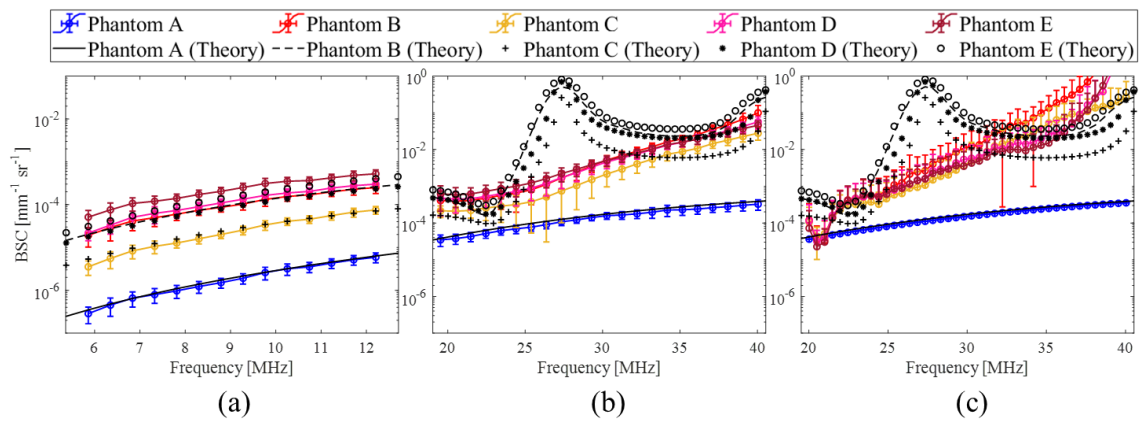


Fig. 8



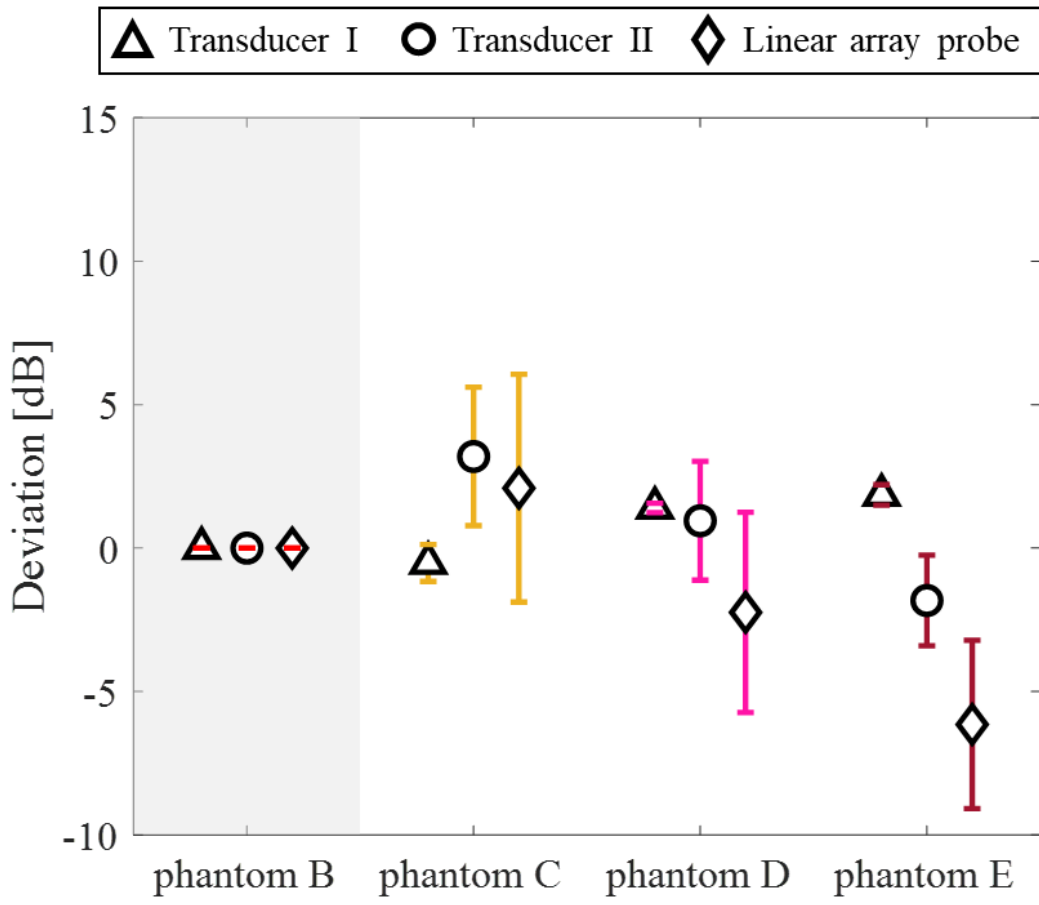


Fig. 9

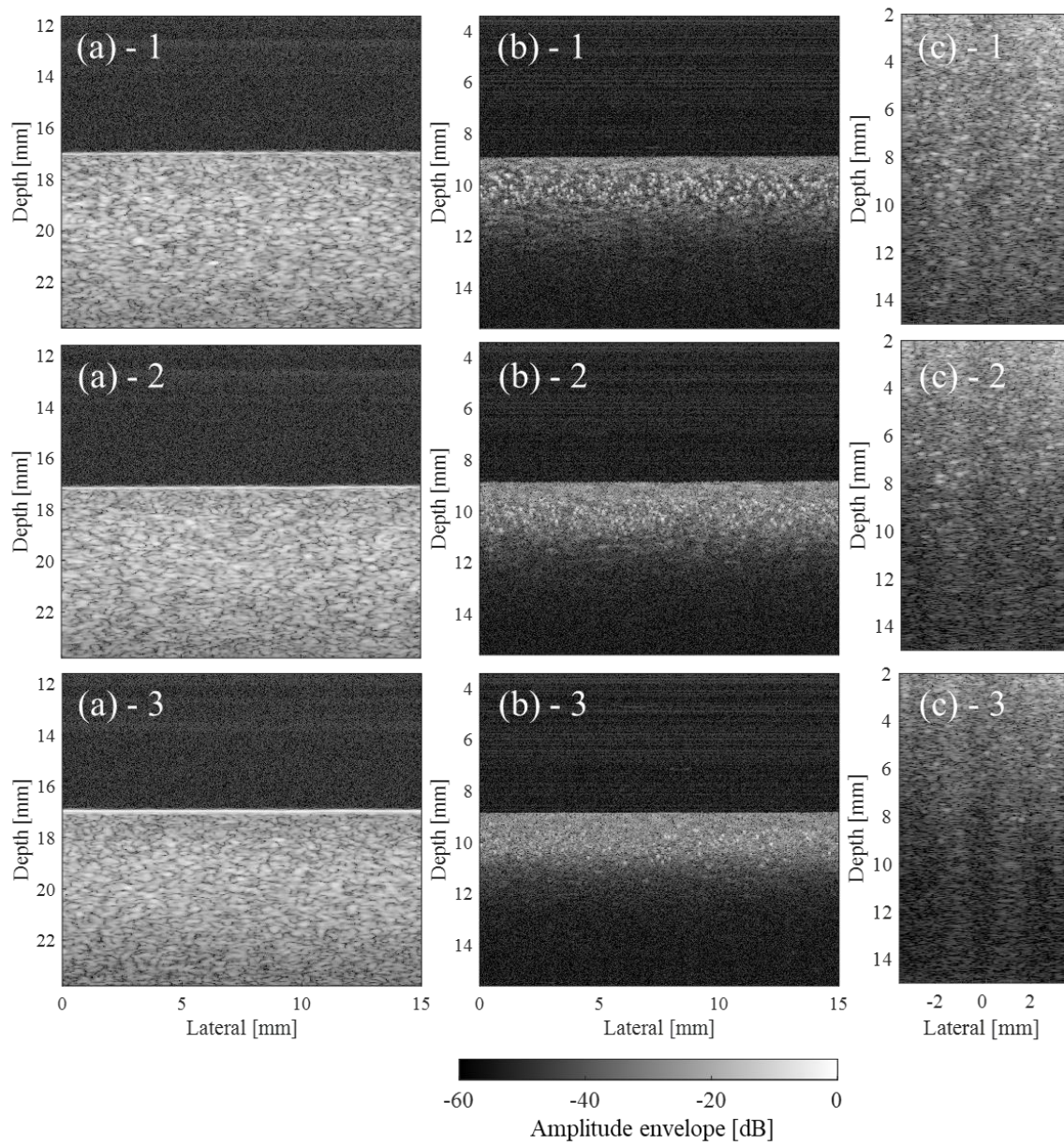


Fig. 10

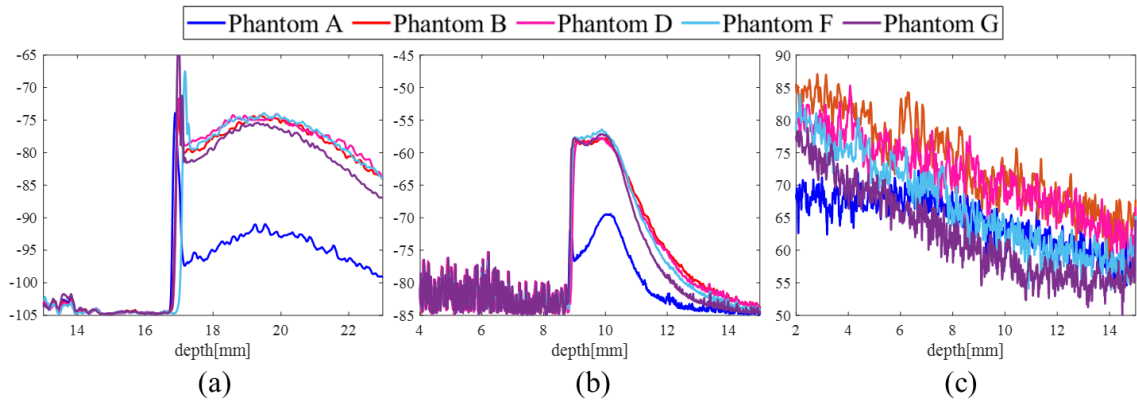


Fig. 11

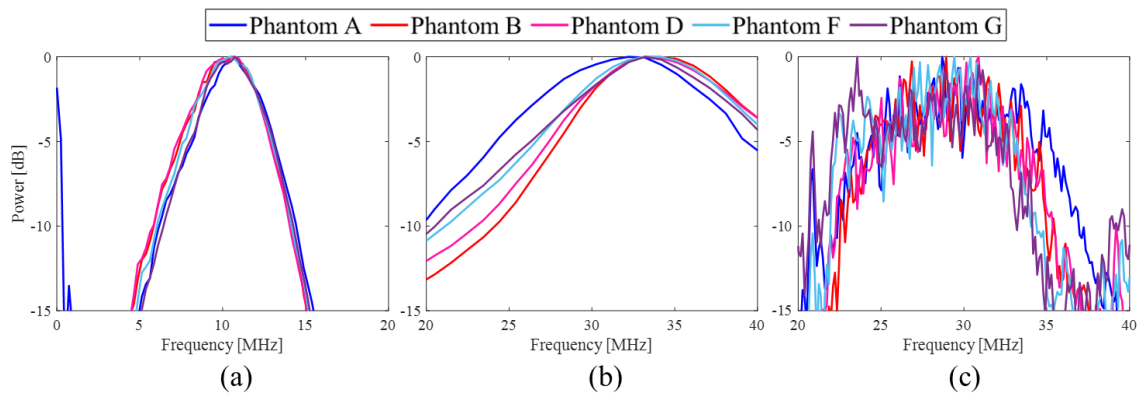


Fig. 12

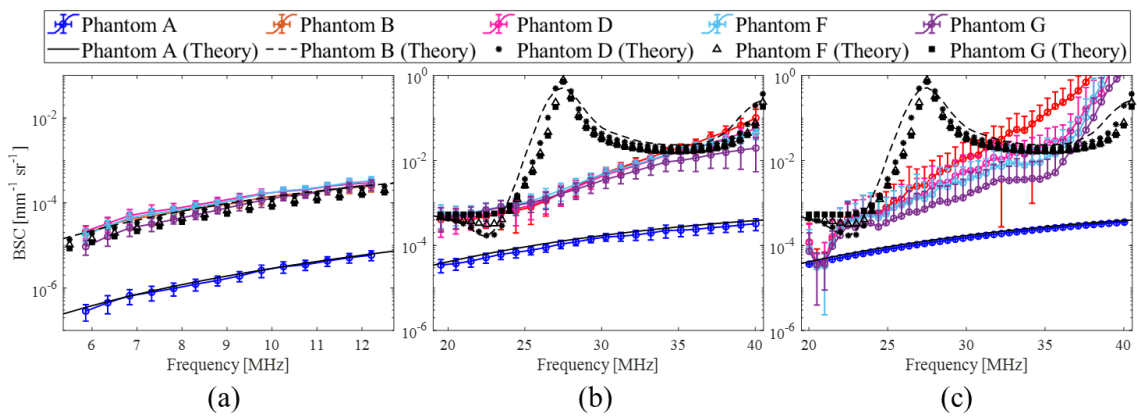


Fig. 13

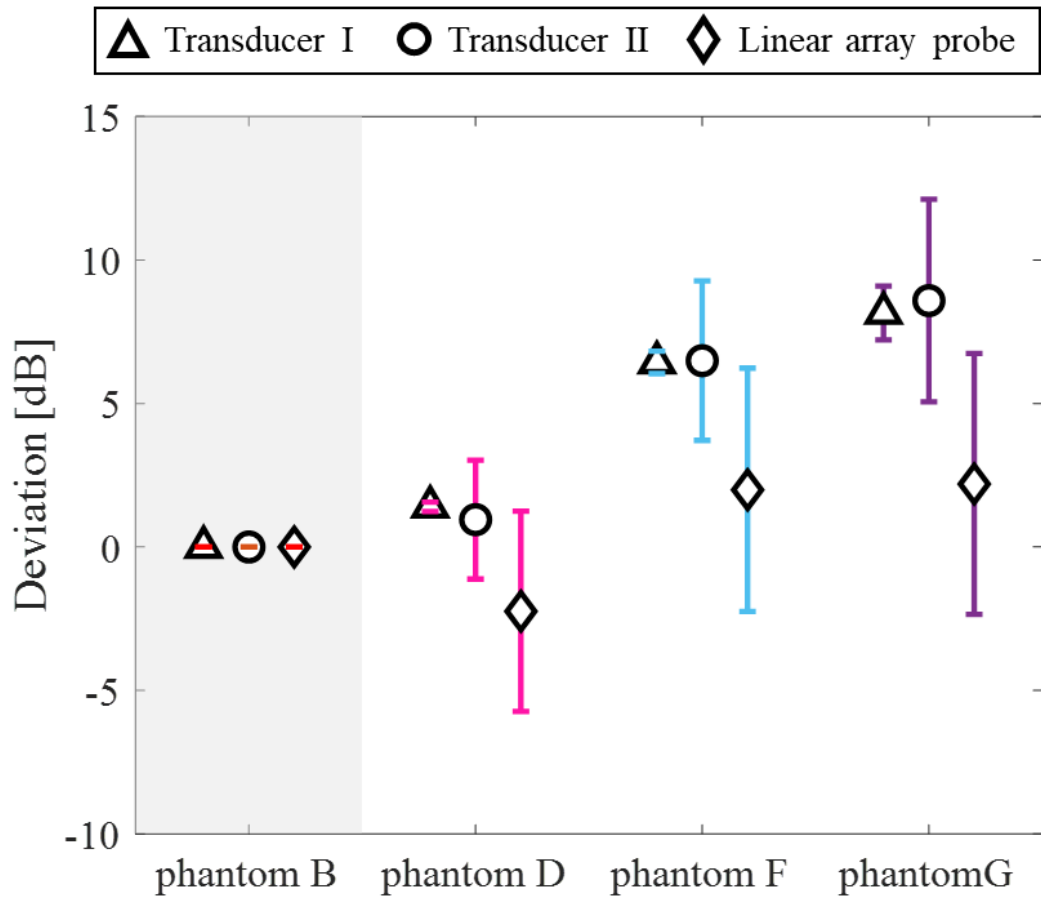


Fig.14