Side lobe free medical ultrasonic imaging with application to assessing side lobe suppression filter

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Abstract

When focusing using an ultrasonic transducer array, a main lobe is formed in the focal region of an ultrasound field, but side lobes also arise around the focal region due to the leakage. Since the side lobes cannot be completely eliminated in the focusing process, they are responsible for subsequent ultrasound image quality degradation. To improve ultrasound image quality, a signal processing strategy to reduce side lobes is definitely in demand. To this end, quantitative determination of main and side lobes is necessary. We propose a theoretically and actually error-free method of exactly discriminating and separately computing the main lobe and side lobe parts in ultrasound image by computer simulation. We refer to images constructed using the main and side lobe signals as the main and side lobe images, respectively. Since the main and side lobe images exactly represent their main and side lobe components, respectively, they can be used to evaluate ultrasound image quality. Defining the average brightness of the main and side lobe images, the conventional to side lobe image ratio, and the main to side lobe image ratio as image quality metrics, we can evaluate image characteristics in speckle images. The proposed method is also applied in assessing the performance of side lobe suppression filtering. We show that the proposed method may greatly aid in the evaluation of medical ultrasonic images using computer simulations, albeit lacking the use of actual experimental data.

Keywords Filter evaluation · Main lobe · Side lobe · Side lobe suppression · Speckle · Ultrasonic image

1 Introduction

A typical method of evaluating the focusing performance of a medical ultrasound imaging system is to observe the point spread function (PSF) of a point target. From the PSF, we can examine the distribution of a main lobe at a focal point where an ultrasound energy is concentrated as well as side lobes due to the leakage of the energy around a focal point [1, 2]. In the PSF, it is easy to separately evaluate the influence of the main and side lobes as they are clearly separated in the spatial domain. To characterize

an ultrasound field characteristic quantitatively, the full width at half maximum of a main lobe or a peak side lobe level relative to the main lobe maximum was used [3–5].

Echoes from a region in which random scatterers are widely distributed form a speckle noise pattern due to signal interference in the coherent summation process [6]. Since the main and side lobe signals reflected from widely distributed point scatterers superpose each other, the side lobe signal component that is not eliminated in the focusing process reduces the contrast of an ultrasonic image.

To reduce the effect of side lobes in a focusing system, aperture apodization was employed which multiplies weighting factors to the transmit and receive channels [7]. Recently, adaptive minimum variance beamforming methods have significantly improved the resolution of ultrasonic images [3, 4, 8–10]. They use adaptive apodization to maintain the main lobe signal while reducing the side lobe levels. Ultrasonic images were improved by measuring the relative magnitude of side lobes based on the fact that the correlation of side lobes between the

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receive channel data is small [11, 12]. Jeong et al. improved the image quality by utilizing the spatial frequency characteristic of side lobes and thus estimating side lobe levels [13–16].

Previous works [8–10] quantified the performance of side lobe suppression filters using the contrast ratio (CR) which is the difference between the average brightness of a hypoechoic cyst and the background brightness of a region where side lobes are filtered out, the contrast-to-noise ratio (CNR), which is the CR divided by the background brightness, or the signal-to-noise ratio (SNR), which is the signal brightness divided by the background brightness. These metrics require one to select the main and side lobe regions in a speckle image very carefully. In an experimental situation, echoes from all scatterers in the ultrasound transmit field of view are superposed and received at the same time, making it impossible to separate a potpourri of echoes from individual scatterers. As a consequence, in contrast to a point target, the evaluation of image quality in a speckle region indirectly measures the effect of suppressing side lobes. Accordingly, the accurate computation of the main and side lobe signal magnitude to assess ultrasound image quality is still a challenging research topic in ultrasonic imaging.

In this paper, we propose several new metrics for assessing ultrasound image quality. Using computer simulation, we construct an ultrasound image by adding together signals reflected from a number of scatterers. In this process, echoes from the main and side lobes can be discriminated so that the main and side lobe signals can be separated to construct the main and side lobe images separately. The superposition of the main and side lobe images in terms of RF data yields the conventional image. Metrics such as the average brightness of the conventional, main lobe, and side lobe images, the conventional to side lobe image ratio (CSR), and the main and side lobe image ratio (MSR) are presented.

We have investigated the point spread function and speckle characteristics of the conventional, main lobe, and side lobe images using computer simulations. By applying the proposed image quality metrics to those three types of images, we evaluated the performance of side lobe suppression filtering. We show that the main and side lobe images can be used as a gold standard to assess the image quality, as well as in investigating and improving the performance of side lobe suppression filtering.

2 Separation of main and side lobes in point target imaging

We obtained PSFs through computer simulations. Using a 5 MHz, 64-channel linear array with an element width of 0.31 mm, we imaged a point located at a depth of 30 mm,

where the transmit focal point was set to 50 mm. A Gaussian pulse of three cycles was transmitted. Simulation programs were written in MATLAB. In a conventional focusing system, the signal at an imaging point is obtained by applying both transmit focusing time delays to ultrasonic signals that are fired from the transmit elements and receive focusing time delays to ultrasonic echoes that arrive at the receive elements after reflection from a large number of scatterers. All the receive channel data are added together to construct ultrasonic images. In the computer simulation of a 64-channel system, computing a focused signal from a point scatterer requires the summation of signals for each of 4096 combinations of the transmit and receive elements.

Since the position of every scatterer is available in computer simulation, it is straightforward to separate echoes from scatterers in the main lobe region from those in the side lobe region. As shown in Fig. 1, two images can be separately constructed, one image using echoes from scatterers in the main lobe region (signal paths shown in solid line) and the other using echoes from scatterers in the side lobe region (signal paths shown in dotted line). The main and side lobe images refer to those constructed using echoes from the main and side lobes, respectively. The main lobe width is defined as twice the distance from the peak of the main lobe to the first null point in the lateral ultrasound field pattern.

Figure 2 compares the PSF of a single point target (top), which is subsequently to be called a conventional image, a main lobe image (middle), which corresponds to the PSF contributed by the main lobe part, and a side lobe image (bottom), which corresponds to the PSF contributed by the side lobe part. The figure was log compressed over a 60 dB dynamic range to observe side lobes.

Fig. 1 Signal propagation paths from scatterers within main (solid) and side (dashed) lobes

Fig. 2 Separation of main and side lobe images from conventional image: **a** PSF due to both main and side lobes, **b** PSF due to main lobe, and **c** PSF due to side lobe

3 Separation of main and side lobes in speckle image

For the case of imaging a point target, it is straightforward to evaluate the performance of the side lobe suppression filter because the main and side lobe regions in ultrasound images are separate from each other. For the case of imaging random scatterers, however, as is usually the case with actual medical ultrasonic scanners, it is impossible to separate the main and side lobe signals from the received signals that are a superposition of echoes returning from a cloud of random scatterers. Since it is feasible in computer simulation to separate signals returning from individual scatterers, the main and side lobe images for random scatterers can be separately constructed in a similar manner to the case of a point target.

In this section, speckle patterns in the main lobe and side lobe images are investigated. Speckle images of a region with random scatterers whose reflectivity distribution is uniform were computed using simulation under the same condition as used in Fig. 2. The resolution volume of the ultrasonic field was set to contain 20 scatterers so that a fully developed speckle pattern could be obtained [6]. The left panels of Fig. 3 show speckle images of size 256 by

256 pixels, where a, b, and c are the conventional, main lobe, and side lobe images, respectively. The images were each normalized and log compressed over a 40 dB dynamic range. The average brightness values before log compression were 694.2, 656.4, and 214.2 from top to bottom in the left panels of Fig. 3. Since ultrasonic echo signals add up in a coherent manner, the sum of the average brightness of the main and side lobe images is not equal to the average brightness of the conventional image. The right panels of Fig. 3 show the result of taking a two-dimensional fast Fourier transform of the left panels of Fig. 3 after subtracting the DC values from the images and log compressing over a 60 dB dynamic range.

Since in the ultrasound beam pattern of a linear array, the peak side lobe level is 13 dB below the peak main lobe level, the speckle patterns of the conventional and main lobe images are similar, but the side lobe image has a different speckle pattern. Since in the lateral beam pattern, the side lobe width is one half of the main lobe width, the spatial frequency of the side lobe image is higher than that of the main lobe image in the lateral direction. Therefore, the granular texture of the side lobe image is finer than that of the main lobe image. The spatial frequency spectrum of the side lobe image is wider than that of the main lobe

Fig. 3 Speckle images (left) and their spatial frequency spectra (right): **a** conventional image, **b** main lobe image, and **c** side lobe image

image in the lateral direction and has significant values at and around the center of the spectrum as can be seen in Fig. 3c. Note that the center of the spectrum corresponds to the DC frequency, i.e., 0 Hz. The quasi-periodic nature of the side lobes in the lateral direction of the ultrasound field characteristic resembles that of a ripple and is manifested as nonzero spatial frequencies in the spectrum. Considering that the spectral bandwidths of the three images in the axial

direction are similar, we can see that the side lobes affect the image resolution in the lateral direction.

4 Formulation of side lobe suppression filter

There have been many research activities devoted to mitigating the adverse effects of side lobes [3–5, 7–10, 13–18]. It is difficult, however, to clearly evaluate the performance

Fig. 4 Separation of main and side lobe echoes in speckle image: **a** conventional image, **b** main lobe image, **c** side lobe image, **d** QF_{20} image, and **e** conventional image minus QF_{20} image

of reducing side lobes using a side lobe suppression filter or the deterioration of the image quality due to side lobes. We estimated side lobe levels in conventional ultrasonic images and applied several side lobe suppression filters in the previous works [13–16].

In this paper, using the side lobe filter [16], we have confirmed the utility of the main and side lobe images. The side lobe suppression filter is formulated by letting $sidelobe_p$ denote the level of the first to p th side lobes estimated at an imaging point using (10) and (11) in [16] and defining it as a quality factor QF_p , as follows:

$$QF_p = sidelobe_p \quad (1)$$

Then the side lobe suppression filter is defined using (14) in [16], as follows:

$$B_{filtered} = \left(\frac{1}{1 + \gamma \left(\frac{QF_p}{B_{pixel} - QF_p} \right)} \right) \cdot (B_{pixel} - QF_p) \quad (2)$$

where B_{pixel} is the brightness of an imaging point, $B_{filtered}$ is the brightness of the filter output, and γ is an experimentally determined parameter that controls the filter characteristic. The filter first subtracts the side lobe estimated at an imaging point and operates to reduce the output brightness when the side lobe levels are estimated to be large.

5 Side lobe suppression filtering in speckle image

Results of applying side lobe suppression filtering to speckle images with cysts were obtained through simulation. Figure 4 shows 164 by 641 pixel speckle images with three cysts. The three cysts of 4 mm diameter each have a reflectivity of -30 , -20 , and -10 dB relative to the background from left to right. To observe the side lobe shape, the upper and lower four point targets were set to have a reflectivity of 20 and 30 dB relative to the background, respectively. In Fig. 4, a is the conventional image, b is the main lobe image, c is the side lobe image, d is QF_{20} computed from the conventional image, and e is the result of subtracting QF_{20} from the conventional image. To compare speckle patterns, each image in Fig. 4 was normalized to its largest brightness value and log compressed over a 60 dB dynamic range.

Since the main lobe image is perfectly free of side lobes, the cyst boundaries are better delineated, and the difference in brightness among cysts is more pronounced. The speckle patterns of the background regions in the conventional and main lobe images (a and b of Fig. 4, respectively) look similar since the peak side lobe level is lower than the main lobe peak in the ultrasound field characteristic. Inside the -30 and -20 dB cysts, the conventional and side lobe images (a and c of Fig. 4, respectively) are similar since the side lobes generated in the background region at the cyst boundary infiltrated into the cyst interior. On the contrary, inside the -10 dB cyst, the conventional and main lobe images (a and b of Fig. 4, respectively) look similar since the main lobe reflected from scatterers inside the cysts is larger than the side lobes. The speckle pattern inside the -30 and -20 dB cysts in Fig. 4d, which depicts QF_{20} , i.e., the estimated side lobe level, is similar to that of Fig. 4c. It can be seen that QF_{20} estimates the side lobe level very well inside cysts where the side lobe signal is larger than the main lobe signal. Figure 4e is the resultant image of subtracting the QF_{20} image from the conventional image. The side lobe levels are reduced near the point targets as well as inside the cysts. Thus, as can be seen in Fig. 4, a processed version (Fig. 4e) of the conventional image (Fig. 4a), which is obtained by subtracting the QF_{20} side lobe image (Fig. 4d) from the conventional image (Fig. 4a), has become visually very similar to the main lobe image (Fig. 4b).

Figure 5 shows the result of applying the side lobe suppression filter specified in (2) to the RF data of the conventional image when γ is discretely varied from 0 to 20. The case of using $\gamma = 0$ corresponds to subtracting the QF_{20} image in Fig. 4e from the conventional image, and thus the side lobes inside the cysts are significantly

reduced. Since as the value of γ increases, the lateral width of the point target image decreases, the resolution improves. However, the side lobe levels are decreased over the entire image area, the background is dark, and the speckle pattern is different from that of the conventional image [4, 17, 18].

6 Evaluation of side lobe suppression filter performance

For evaluation of speckle image quality, the average brightness and the brightness variance of the speckle image are used in previous works. The contrast ratio (CR), contrast-to-noise ratio (CNR), and signal-to-noise ratio (SNR) are defined as follows [12]:

$$CR = 20 \log_{10} \left(\frac{S_c}{S_b} \right) \text{ (dB)} \quad (3)$$

$$CNR = \frac{|S_c - S_b|}{\sqrt{\sigma_c^2 + \sigma_b^2}} \quad (4)$$

$$SNR = \frac{S_b}{\sigma_b} \quad (5)$$

where S_c and σ_c are the average brightness and standard deviation in the cyst, respectively, and S_b and σ_b are the average brightness and standard deviation in the background, respectively. To use these metrics, it is of paramount importance to distinguish and select an imaging region with the main lobe signal only and that with the side lobe signal only. In the case of imaging the human body, however, selecting such regions is not feasible, so it is best practice to use a background region with a uniform scattering characteristic and a cyst region where the main lobe is absent.

Table 1 shows the CR, CNR, SNR values for the three cysts, labeled Cyst 1, Cyst 2, and Cyst 3 from left to right in the conventional image of Fig. 4a and in the filtered images of Fig. 5. The image background regions are indicated by two square dotted and two rectangular dotted windows in Fig. 4a. The same square windows are used in the cyst regions, but are not displayed in the figure in order not to obstruct the speckle pattern. The average brightness was computed from image pixel values before taking log compression. We take the main lobe image and the associated measurements as a gold standard and compare the cyst regions. As a result of filtering the conventional image, we have the CR, CNR, and SNR values similar to those of the main lobe image when γ is between 0 and 1. For $\gamma = 1$, the filtered conventional and main lobe images have visually similar speckle characteristics. The filtered conventional images show good results for small values of γ , since the estimated side lobes have been removed in advance and

Fig. 5 Output images of side lobe suppression filter applied to conventional image for various values of γ between 0 and 20

weighting is applied according to the value of γ . As the value of γ increases, the side lobe levels decrease, and the CR increases. However, the background becomes dark, and both the CNR and SNR decrease. The speckle patterns in the background become very different from those of the conventional image.

The change in average brightness before and after filtering may be used as a metric for evaluating the

performance of the side lobe suppression filter. When a main lobe image is applied to the input of the side lobe suppression filter, there should not be any change in the brightness of the filter output. In contrast, when a side lobe image is applied to the input of the side lobe suppression filter, there should be a large decrease in the brightness of the filter output. Based on this characteristic, observing the change in average brightness before and after filtering

Table 1 CR, CNR, and SNR for three cysts in Fig. 5, which is output image of side lobe suppression filter, after filtering for γ values of 0, 1, 2, 5, 10, and 20

	CR			CNR			SNR
	Cyst 1	Cyst 2	Cyst 3	Cyst 1	Cyst 2	Cyst 3	
Main lobe image	− 29.38	− 20.77	− 12.92	1.604	1.505	1.264	1.661
Results of filtering							
$\gamma = 0$	− 26.89	− 20.05	− 12.95	1.639	1.541	1.308	1.717
$\gamma = 1$	− 32.86	− 22.85	− 13.93	1.459	1.382	1.174	1.493
$\gamma = 2$	− 34.91	− 23.96	− 14.43	1.349	1.283	1.096	1.374
$\gamma = 5$	− 37.52	− 25.41	− 15.17	1.189	1.138	0.981	1.205
$\gamma = 10$	− 39.13	− 26.35	− 15.70	1.076	1.033	0.898	1.088
$\gamma = 20$	− 40.32	− 27.07	− 16.14	0.980	0.944	0.826	0.990

allows for the evaluation of the side lobe suppression filter. Table 2 summarizes the average background brightness of the images in Fig. 5. The background regions are indicated by the square and rectangular dotted windows in Fig. 4a.

The brightness change of filtered images with γ is presented in Fig. 6, where that of the conventional, main lobe, and side lobe images is indicated by the solid, dashed, and dotted lines, respectively. The filtered conventional, main lobe, and side lobe images are each normalized to the brightness for $\gamma = 0$. The filtered side lobe image exhibits a sharp decline in brightness with increasing values of γ . However, when γ is between 5 and 10, the rate of decline becomes smaller. The rate of decline in the side lobe image is largest, followed by the conventional image and then the main lobe image. Thus, we can see that the side lobe suppression filter is more effective in removing the side lobes than the main lobe. It can be seen from Tables 1 and 2 that the CR, CNR, and SNR values as well as the average brightness of the main and side lobe image can be used as an image quality assessment metric. Table 2 shows the characteristic of the side lobe suppression filter quantitatively. By taking the main lobe image as a gold standard, the result in this series of evaluations can be used as a criterion based on which the optimum γ value of the side lobe suppression filter can be determined.

Fig. 6 Change in brightness of filtered output images with increasing values of γ : solid, dashed, dotted lines represent conventional, main lobe, and side lobe images, respectively

7 New image quality assessment metrics: CSR and MSR

To evaluate the image quality, we propose the following two parameters which are based on the average brightness of the conventional, main lobe, and side lobe images. One is the conventional to side lobe image ratio (CSR), defined as follows:

Table 2 Average background brightness of conventional, main lobe, and side lobe images after filtering for γ values of 0, 1, 2, 5, 10, and 20

	Conventional image	Main lobe image	Side lobe image
Before filtering	754.19	706.01	229.48
After filtering			
$\gamma = 0$	807.08	792.38	127.88
$\gamma = 1$	609.41	670.04	52.81
$\gamma = 2$	499.86	586.45	34.90
$\gamma = 5$	334.00	436.68	17.75
$\gamma = 10$	219.85	313.46	9.87
$\gamma = 20$	132.54	204.57	5.26

$$CSR = \left(\frac{\text{Mean of conventional image}}{\text{Mean of side lobe image}} \right) \quad (6)$$

The other is the main to side lobe image ratio (MSR), defined as follows:

$$MSR = \left(\frac{\text{Mean of main lobe image}}{\text{Mean of side lobe image}} \right) \quad (7)$$

For unfiltered images, both parameters can be used to evaluate the performance of removing off-axis signals in the processing of focusing on both transmit and receive in an ultrasonic imaging system. For unfiltered images, we find that $CSR_o = 3.287$ and $MSR_o = 3.077$ from Table 2, where the subscript 0 indicates the case of no filtering. Figure 7 shows the profile of the MSR and CSR as a function of γ . The MSR and CSR increase rapidly until γ reaches 5, and thereafter the rate of increase becomes slow.

8 Discussion and conclusion

We have proposed a method of separately imaging the main and side lobe signals when synthesizing ultrasonic images using computer simulations. Using the proposed method, we synthesized speckle images, and compared the speckle characteristics of the synthesized main and side lobe images. The average brightness of the main and side lobe images constructed using our proposed method may be employed as an image quality metric. The speckle pattern of Fig. 3 has $CSR_o = 3.241$ and $MSR_o = 3.064$, and that in the background of Fig. 4 has $CSR_o = 3.287$ and $MSR_o = 3.077$. Thus, the speckle patterns of the two cases with the same focusing system have similar CSR and MSR values. Since in the ultrasound field characteristic the side

lobe levels are smaller than the main lobe peak and have higher spatial frequencies, the hypoechoic lesions in the ultrasonic images have a finer speckle pattern since the side lobe signal appears large relative to the main lobe signal which is small. From the result of Fig. 3, we can confirm the effect of the main lobe as well as that of the side lobes on the speckle patterns.

The result of applying the side lobe suppression filter of (2) to the conventional speckle image for γ values of 0 and 1 shows that the output image appears similar to the main lobe image. As γ increases, the CR increases, but the image darkens, and the speckle pattern differs from that of the conventional image. In the speckle pattern, some regions appear bright mainly due to the main lobe signal, and other regions devoid of the main lobe signal appear dark in which side lobes are noticeable. When the side lobes are reduced using the side lobe suppression filter, dark regions tend to be darker than bright regions.

It can be seen that when the control parameter, γ , of the side lobe suppression filter used in this paper is small, the filter acts as an image restoration filter, but that when γ is large, the filter acts as an image enhancement filter. Previous works report that when side lobes are considerably suppressed, the resulting whole image becomes dark, and its speckle pattern is different from that of other images. Consequently, the degree of side lobe suppression should be appropriately controlled so as to attain high image quality. Capitalizing on this characteristic, we can use the main lobe image as well as the side lobe image as a standard image to evaluate the performance of the side lobe suppression filter.

Conventional quantitative image quality assessment metrics such as CR, CNR, and SNR, which are based on both the hypoechoic cyst and background brightness in a conventional image, specified in (3) to (5), assume that the side lobes are large in the hypoechoic cyst where the main lobe is absent or small, and that the main lobe is large in the background. In practice, however, since the main and side lobe signals cannot be perfectly separated, it is very difficult to unambiguously select or segment the main and side lobe regions with the negative result that the CR, CNR, and SNR values may vary from one imaging region to another.

However, our method is advantageous in that only the background brightness is necessary to evaluate the image quality, as shown in (6) and (7), by separating the main and side lobes in the background. By observing the efficacy of side lobe suppression filtering for three types of images, i.e., the conventional, main lobe, and side lobe images, the design and evaluation of filtering can be effectively accomplished. Figure 7 shows that the CSR and MSR computed using only the image brightness faithfully represent the capability of suppressing side lobes.

Fig. 7 MSR (solid) and CSR (dashed) of filtered output image with increasing values of γ

The separation of main and side lobes in the case of imaging random scatterers can be achieved in computer simulation studies, but this is not feasible in actual experimental imaging scenarios. It is to be pointed out, however, that the present study may be quite useful in the evaluation and improvement of the performance of a medical ultrasonic imaging system, since we can synthesize ultrasonic images under given experimental conditions using computer simulations.

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Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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