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Frequency Compounded Imaging with a High-Frequency Dual Element Transducer

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Abstract

This paper proposes a frequency compounding method to reduce speckle interferences, where a concentric annular type high-frequency dual element transducer is used to broaden the bandwidth of an imaging system. In frequency compounding methods, frequency division is carried out to obtain sub-band images containing uncorrelated speckles, which sacrifices axial resolution. Therefore, frequency compounding often deteriorates the target-detecting capability, quantified by the total signal-to-noise ratio (SNR), when the speckle's SNR (SSNR) is not improved as much as the degraded axial resolution. However, this could be avoided if the effective bandwidth required for frequency compounding is increased. The primary goal of the proposed approach, hence, is to improve SSNR by a factor of two under the condition where axial resolution is degraded by a factor of less than two, which indicates the total SNR improvement to higher than 40% compared to that of an original image. Since the method here employs a dual element transducer operating at 20 and 40 MHz, the effective bandwidth necessary for frequency compounding becomes broadened. By dividing each spectrum of RF samples from both elements into two sub-bands, this method eventually enables four sets of the sub-band samples to contain uncorrelated speckles. This causes the axial resolution to be reduced by a factor of as low as 1.85, which means that this method would improve total SNR by at least 47 %. An *in vitro* experiment on an excised pig eye was performed to validate the proposed approach, and the results showed that the SSNR was improved from 2.081 ± 0.365 in the original image to 4.206 ± 0.635 in the final compounding image.

Keywords

Frequency Compounding; High Frequency Ultrasound Imaging; Dual Element Transducer; High Resolution

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INTRODUCTION

Ultrasound images usually contain speckle patterns attributed to the interaction between ultrasound and scatterers in tissues, i.e., the constructive and destructive interferences within a unit volume defined by a given resolution cell of an imaging system. Despite its frequent use in clinical diagnosis, this speckle pattern is undesirable because it degrades contrast and signal-to-noise ratio (SNR) of images. It can be suppressed by either frequency compounding or spatial compounding [1-6] at the expense of spatial and/or temporal resolutions; both methods involve averaging envelope-detected echoes from the same object under different imaging conditions. By applying these compounding methods, the speckle's SNR (SSNR) can be improved by a factor of $\sqrt{N}$, where N is a number of uncorrelated envelope sets used for averaging [4]. Consequently, the objective of many compounding techniques is to obtain the uncorrelated sets while minimizing the degradation of image resolution.

In the frequency compounding, the bandwidth of a radio-frequency (RF) signal is divided into four or more frequency sub-bands. Signals from those bands are used to form sub-band images. A compounding image is then produced by adding or averaging the sub-band images, either with or without weighting factors. Speckle correlation between the images is mainly determined by the difference of center frequencies, which is normalized by a -6 dB pulse-envelope length of the sub-band signals [2], [7]. Therefore, the speckles become less correlated as the bandwidths of sub-bands are narrower. This inevitably leads to a loss of axial resolution. Although frequency compounding could increase SSNR, the total SNR, a value of target-detecting capability, would even decrease when improvement of SSNR by frequency division is less than degradation of axial resolution [8]. Trahey et al. demonstrated an example that the total SNR reduction by 21% occurred when a bandwidth of 2.36 MHz was divided into four sub-bands whose -6dB pulse-envelope lengths were equally 2 μ s [2].

The spatial compounding can be an alternative, and is performed by acquiring sub-images at different beam orientations or positions. This method, therefore, causes a loss of lateral and temporal resolutions. For the consideration of spatial resolution, the spatial compounding is more favorable since its speckle reduction rate for a given loss of lateral resolution is higher than that by the frequency compounding [2]. However, a loss of temporal resolution remains to be the main disadvantage of spatial compounding over its frequency counterpart, so that it is hardly used for imaging moving tissues, for instance, in cardiac imaging. The disadvantage becomes more pronounced in high frequency ultrasound imaging for which a majority of scanners use single element transducers. This is so because spatial compounding requires the transducer to be mechanically translated several times for different ultrasound propagation directions to obtain uncorrelated RF samples [6].

If there is a transducer with a -6dB bandwidth of more than 100%, it is feasible to use frequency compounding for a considerable improvement of the total SNR on an image without any loss of temporal resolution. However, the fabrication of such a transducer is difficult because there are few piezoelectric materials with a Q factor of lower than 1. As a remedy for this problem, this paper proposes a frequency compounding method, utilizing a concentric annular type high-frequency dual element transducer; two elements of this

transducer, producing confocal beams, have different operating frequencies: 20-MHz outer ring and 40-MHz inner circular elements. This feature broadens the total bandwidth, because the four uncorrelated RF sub-bands can be obtained by dividing an original frequency band from each element into two frequency sub-bands. Therefore, this method exploits the frequency compounding to considerably improve the total SNR in spite of the degradation of axial resolution. This paper numerically demonstrates that four RF sets obtained from both elements have a correlation coefficient of less than 0.214 to achieve adequate frequency compounding. From *in vitro* experiments with an excised pig eye, it is verified that the proposed method is capable of improving SSNR by a factor of two, while limiting the degradation of axial resolution to a factor of 1.85 at most. This indicates that the proposed method would improve the total SNR by at least 47 % compared to that of the original image.

METHODS

Recently, a concentric annular type dual element transducer has been built for the purpose of high frequency harmonic imaging [9]; its outer ring element ($a_o = 6$ mm and $a_i = 3$ mm as shown in Fig. 1) was for transmitting 20-MHz ultrasound and its inner circular element ($a_c = 2.5$ mm in Fig. 1) for optimally receiving the attenuated second harmonic component of 20 MHz, i.e., around 40 MHz. Both elements were physically focused at 30 mm to obtain images of the posterior segment of the eye.

Fig. 2 illustrates the pulse-echo responses and frequency spectra of the two elements at the focal depth. These were acquired by exciting the two elements at the same time with an ultrasonic analyzer (5900PR, Panametrics Inc., Waltham, MA, USA), and the echoes from a polished quartz plate through a digital oscilloscope (LC534, LeCroy Corp., Chestnut Ridge, NY, USA) were subsequently recorded. The frequency spectra of the outer and inner elements had center frequencies of 19.7 MHz and 24.5 MHz, respectively. Also, their -6dB pulse-envelope lengths were 90 ns and 55.3 ns. Since the area of the outer element was approximately four times larger than that of the inner one, frequency components in the vicinity of 20 MHz were dominant in the spectrum of the inner element. Due to the receiving characteristic of the inner element, however, frequency components in the range of 30 to 40 MHz were accentuated and were not overlapped with the frequency spectrum of the outer element. Therefore, each bandwidth of two sets of RF samples from both elements could be efficiently divided into two spectral sub-bands so as to obtain four sets of uncorrelated samples. This was achieved with two band-pass filters (BPFs) for each element; their bandwidths were 10 to 18 MHz and 22 to 30 MHz for the outer element, and 14 to 22 MHz and 25 to 33 MHz for the inner element. Note that the lower and upper sub-bands from the inner element are denoted by IL and IH, and the ones corresponding to the outer element by OL and OH, respectively. Once the BPFs were applied to the RF samples, four sub-band signals as shown in Fig. 3 were obtained. Center frequencies and -6dB pulse-envelope lengths of each sub-band were summarized in Table 1.

Given the center frequency f_C and the -6dB pulse-envelope length T of each sub-band, a correlation coefficient of two sub-band signals were calculated from the model developed by Melton and Magnin [7]:

$$\rho_{RF} = \sqrt{\frac{2B_1B_2}{B_1^2+B_2^2}} \cdot \exp\left(-\frac{(f_{C,1}-f_{C,2})^2}{B_1^2+B_2^2}\right) \quad (1)$$

and

$$\rho_{Env} = \frac{2[2\varepsilon(\rho_{RF}^2) - (1-\rho_{RF}^2) \cdot K(\rho_{RF}^2)] - \pi}{4-\pi} \quad (2)$$

where ρ_{RF} and ρ_{Env} are correlation coefficients calculated from RF samples and their envelopes; B_1 and B_2 represent the bandwidths of the -6 dB pulse-envelope length of each sub-band, which are obtained from $1/\pi T_{(1 \text{ or } 2)}$; $f_{C,1}$ and $f_{C,2}$ correspond to their center frequencies. In (2), $\varepsilon(\bullet)$ and $K(\bullet)$ indicate complete elliptic integrals of the first and second kind, respectively. The computation results given in Table 2 demonstrated that all sub-band signals had correlation coefficients less than 0.214.

Since a given bandwidth was divided into two sub-bands, axial resolution would be inevitably degraded by a factor of 1.63 (147/90) and 1.85 (102.5/55.3) for the outer and inner elements. According to the model to measure the tradeoff between resolution loss and speckle reduction [8], it could be predictable that this compounding method would improve the total SNR by at least 47 %:

$$SNR_T = \frac{C_\psi \cdot d \cdot \sqrt{N}}{\sqrt{S_{cx} \cdot S_{cz}}} \\ SNR_{improve} = SNR_T \cdot \left(\frac{\sqrt{4}}{\sqrt{1.85}} - 1 \right) \quad (3)$$

where C_ψ represents a contrast in circular lesion with diameter d , N is a number of uncorrelated envelope sets, and S_{cx} and S_{cz} are detectable cell sizes in lateral and axial directions, which are proportional to resolution in both directions. The total SNR improvement was about 1.6 times larger than that by spatial compounding with a factor of two in loss of lateral resolution [2].

EXPERIMENTAL RESULTS

To confirm the numerical results, an *in vitro* experiment was undertaken with an excised pig eye and the SSNR improvement after compounding was evaluated. Note that only the posterior segment of the pig eye was immersed into a water tank after removing the anterior segment. Both elements of the transducer were simultaneously excited by the ultrasonic analyzer, and the echo signals from each element were then recorded by the digital oscilloscope at a sampling rate of 500 MHz. A total of 400 scan lines were acquired by repeatedly moving the transducer along the horizontal direction at a 25 μm increment. BPF was used to suppress noises residing outside the bandwidth of the echoes; lower and upper cutoff frequencies of the filter were set to be 5 and 40 MHz.

Each bandwidth of the RF samples from the two elements was divided into two spectral sub-bands by using the BPFs. Four sets of RF samples were then used for the frequency compounded imaging. After Hilbert transformation for envelope detection in each sub-band,

a homogeneous region without any perceptible structure was chosen, where a correlation coefficient between the envelope data sets of two sub-bands was computed to verify whether they had uncorrelated speckle pattern.

Two envelope sets were used for image compounding and thus six compounding images could be obtained. The SSNRs of these images were calculated from 21 scan-line data sets of the selected homogenous region in each image;

$$SSNR = \frac{\mu}{\sigma}, \quad (4)$$

where μ and σ are the mean and standard deviation of the signal magnitude, respectively. Note that no image compression was carried out for these calculations in order to remove nonlinear compression effect on the results.

Fig. 4 shows images of the posterior segment of an excised pig eye; these were formed with the band-limited RF samples from the outer (a) and the inner (b) elements. The selected homogenous region was indicated by a black box in Fig. 4 (a). The mean and standard deviation of the SSNRs computed were 2.115 ± 0.310 and 2.081 ± 0.365 , for the outer and the inner elements, respectively. Since these results were in agreement with those obtained by Burckhardt [4], the region was considered to contain well generated speckles.

Two of four RF sample sets were chosen to perform the frequency compounding, and the mean and standard deviation of the SSNR were computed in the selected homogenous region. Also, a correlation coefficient between two sets of RF samples was calculated. These results were summarized in Table 3. As a result, the compounding image formed with sub-bands of IH and OL had the lowest SSNR, 2.894 ± 0.785 , and one with sub-bands of IL and OL had the highest SSNR, 3.677 ± 0.629 . In Fig. 5, the compounding images with the lowest SSNR (a) and the highest SSNR (b) are presented as representative results. It is theoretically expected that SSNR improvement by compounding with two uncorrelated images would be 2.991 ± 0.438 or 2.943 ± 0.516 , depending on how an original image is selected from either Fig. 4 (a) or (b). The experimental results indicating SSNR improvement agreed fairly well with the theory; an average of differences between experimental and theoretical values was 7.1 % (the maximum of 22.9 % and the minimum of 1.0 %).

Fig. 6 shows an image obtained by the proposed compounding method with four RF sample sets. Because four data sets were used for the compounding, SSNR should be improved by a factor of two, so that the value would be 4.230 ± 0.62 or 4.162 ± 0.73 depending on the selection of the original image. From the experimental data, it was learned that SSNR of the selected area was 4.206 ± 0.635 and had a difference of about 1 % from the theoretical values. Based on the SSNR obtained from two sub-bands, the final compounding image formed with four sub-bands would have SSNR in the range of 4.093 to 5.200, computed by multiply the measured SSNR in Table 3 by $\sqrt{2}$. The average of differences between those values and the measured SSNR of the final compounding image was 6.3 % (the maximum of 19.1 % and the minimum of 0.5 %).

CONCLUSIONS

A frequency compounding method, using a concentric annular type high-frequency dual element transducer, was proposed in the paper. It was shown that both elements operated at different frequencies, 20-MHz for outer ring and 40-MHz for outer circular elements, and effectively created sufficiently broad bandwidth for the frequency compounded imaging. Four uncorrelated RF sample sets only reduced the axial resolution by a factor of 1.85, and this method was thus shown to be capable of performing frequency compounding with a total SNR improvement of at least 47 %. Results from an *in vitro* experiment on an excised pig eye demonstrated that the proposed method could improve the SSNR by a factor of two, which agreed well with the theoretical prediction. Since the results showed that the total SNR could be improved without losing temporal resolution, cardiac imaging of small animals such as mice or zebrafish may be a potential application of this method.

Acknowledgments

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Fig. 1.

Dual element transducer with outer ring and inner circular elements. The outer ring element ($a_o = 6$ mm, $a_i = 3$ mm) transmits 20-MHz ultrasound and the inner circular element ($a_c = 2.5$ mm) optimally receives the attenuated second harmonic component of 20 MHz, i.e., around 40 MHz.

Fig. 2.

Pulse-echo responses (top and middle panels) and frequency spectra (bottom panel) of outer ring and inner circular elements at a focal depth of 30 mm. These were obtained by exciting the two elements at the same time and recording echoes received by each element. The spectra of the outer (dashed line) and the inner (solid line) elements had the center frequencies of 19.7 MHz and 24.5 MHz, respectively.

Fig. 3.

Four sub-band signals and their frequency spectra. The sub-band signals were obtained by using two BPFs for each element; their bandwidths were 10 to 18 MHz and 22 to 30 MHz for the outer ring element and 14 to 22 MHz and 25 to 33 MHz for the inner circular element. Lower and upper sub-bands from the inner circular element are denoted by IL and IH, respectively, and the ones from the outer ring element by OL and OH.

(a)

(b)

Fig. 4. Images of the posterior segment of the excised pig eye obtained by the dual element transducer. These were formed with the band-limited RF samples from the outer ring (a) and the inner circular (b) elements and logarithmically compressed with a dynamic range of 48 dB. The black box represents the selected homogenous region.

(a)

(b)

Fig. 5. Representative compounding images formed with two sub-band signals: the lowest SSNR image formed with sub-bands of IH and OL (a) and the highest SSNR image formed with sub-bands of IL and OL (b). Logarithmic compression with a dynamic range of 48 dB was performed.

Fig. 6. Image formed with four sub-band signals. Logarithmic compression with a dynamic range of 48 dB was performed.

TABLE 1

Center frequency and -6dB pulse-envelope length of each sub-band. Lower and upper sub-bands from the inner circular element are denoted by IL and IH, respectively, and the ones from the outer ring element by OL and OH.

	OL	OH	IL	IH
Center Frequency	19.7 MHz	23.9 MHz	24.5 MHz	27.8 MHz
-6dB Pulse Envelope Length	147 ns	119.1 ns	102.5 ns	100.6 ns

TABLE 2

Correlation coefficients calculated with RF sample sets ρ_{RF} and their envelope versions ρ_{Env} with the model developed by Melton and Magnin [7].

	IL+OL	IL+OH	IH+OL	IH+OH	IL+IH	OL+OH
ρ_{RF}	0.480	0.447	0	0.408	0.054	0.187
ρ_{Env}	0.214	0.185	0	0.154	0.003	0.032

Correlation coefficients of each combination and speckle's signal-to-noise ratio (SSNR) values of compounding images obtained from the combination. Theoretically, SSNR improves by a factor of $\sqrt{2}$ after compounding with two images, so that the value becomes 2.991 ± 0.438 or 2.943 ± 0.516 depending on selection of an original image from Fig. 4 (a) or (b).

TABLE 3

	IL+OL	IL+OH	IH+OL	IH+OH	IL+IH	OL+OH
Correlation Coefficient	0.345	0.035	0.163	0.032	0.094	0.144
SSNR	3.677 ± 0.629	3.292 ± 0.903	2.892 ± 0.785	3.064 ± 0.562	2.960 ± 0.497	2.898 ± 0.651