Random aperture optimization for SRAC in high frame rate volume imaging

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***Abstract*— High frame-rate volume imaging (HFVI) has become a mayor area of research in the last decade. Unfortunately, HFVI usually requires ultrasound systems with a large channel count. Sparse Random Aperture Compounding (SRAC) is a technique that uses random apertures to reduce the number of channels necessary. This approach compounds images from complementary random apertures to balance image quality and frame rate. In the current work we used a Monte Carlo method to optimize random apertures to improve image quality without sacrificing temporal resolution. We also evaluated if complementarity of random apertures plays a significant role in the image quality. A Vantage 256 system equipped with a 1024 MUX UTA and a 3 MHz matrix probe (1024 elements) was used for this study. A series of 1250 groups of complementary random apertures were created (a total of 5000 apertures). A single diverging wave acquisition was used for imaging a phantom with a string at a depth of 53 mm. The apertures were sorted using the Main-lobe to Side-lo Ratio (MLSLR) from best to worst. The optimization process showed an improvement in the image quality of 9.5 dB in MLSLR between the best and worst apertures. SRAC of complementary apertures show an increase in the MLSR from 1 SRAC to 4 SRAC of 2.5 dB, while for non-complementary apertures this value was 1 dB. While previous studies have demonstrated the advantage of using SRAC for HFIV, this work revealed the importance of aperture optimization and complementarity as well as the significance of selecting the proper apertures for a given application.**

Keywords—Ultrafast Volume Imaging, Random apertures, aperture compounding, image quality, high frame rate, aperture optimization

I. INTRODUCTION

In the last few years, high-frame-rate volume imaging (HFVI) has gained considerable interest as a field of research because of its potential for studying complex phenomena in time and space. HFVI allows the translation of 2D applications such as shear wave elastography, super resolution imaging, functional imaging and other, into 3D or even 4D applications. This translation has been possible because of the advancement in scanners and transducers that allow acquisitions of volumetric data at thousands of frame/volumes per second.

Matrix transducer (i.e., 2D arrays) have been employed in the last few years to demonstrate the capability of ultrasound volume imaging without the need of mechanically scanning the volume. In 2014, Provost et al, used a 1024 ultrasound channel system and a 1024 matrix probe (with 32 x 32 elements) to implement multiangle compounding for B-mode, Doppler and elastography applications [1]. A more recent study by Correia et al., implemented vector Doppler applications to evaluate the blood flow in the carotid bifurcation using as similar setup [2]. In 2019, Rabut et al., translated 2D functional imaging into a 4D application [3]. In their study, they were able to track the activation of the rat brain to different stimuli using a matrix probe. Lastly, in 2020, Papadacci et al., demonstrated the possibility to track the natural waves in the heart using HFVI [4]. Despite the importance of all the studies mentioned above, the requirement of an ultrasound system with 1024 channels makes these applications costly and difficult to implement.

One approach to reduce the number of required ultrasound channels for driving matrix probes is the use of multiplexers. In 2019 Yu et al. implemented a sequence using a 4-to-1 multiplexer to control a 1024 element probe with 256 channels system [5]. In their study they were able to produce 3D visualization of an *ex vivo* porcine eye at a volume rate of 30 Hz. Another approach to decrease the number of channels and improve frame rate, is to use random apertures, either with special constructed arrays [6], [7], or by selecting a subset of elements of a matrix array [8]. In 2020 our group published a study demonstrating the advantage of coherently compounding images acquired with different complementary random apertures [9]. This technique is called Sparse Random Aperture Compounding (SRAC) and allows the user to find a balance between image quality and frame rate.

In the current work, we extend the SRAC technique by studying the effect of aperture optimization in image quality and the role that complementarity plays in this process. In this case we used a Monte Carlo approach to optimize random apertures and compared images produced with complementary and non-complementary optimized apertures.

II. METHODS

A. *Ultrasound acquisitions*

A phantom with a single string located at a depth of 120 wavelengths (~ 53 mm) and running parallel to the y axis of the probe was used in this study (Figure 1). A single diverging wave (SDW) acquisition sequence was used to image a phantom and test all the apertures. The sequence was implemented in a Vantage 256 system with a 1024 MUX UTA (Verasonics, Inc) and a 3 MHz matrix probe with 1024 elements (Vermon s.a.).

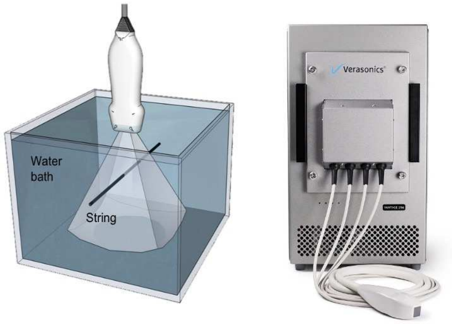

Figure 1. Experimental setup. String phantom and Vantage 256 with 1024 MUX adaptor and 3 MHz matrix probe

B. *Aperture optimization*

Using a Monte Carlo approach 1250 groups of complementary random apertures were created, for a total of 5000 apertures. One single set of complimentary apertures consists of 4 random apertures with 256 active elements each. Complimentary means that if an element e_{ij} is active for aperture A_k then e_{ij} will be inactive for all $A_{l \neq k}$. Figure 2 shows a group of four complementary apertures.

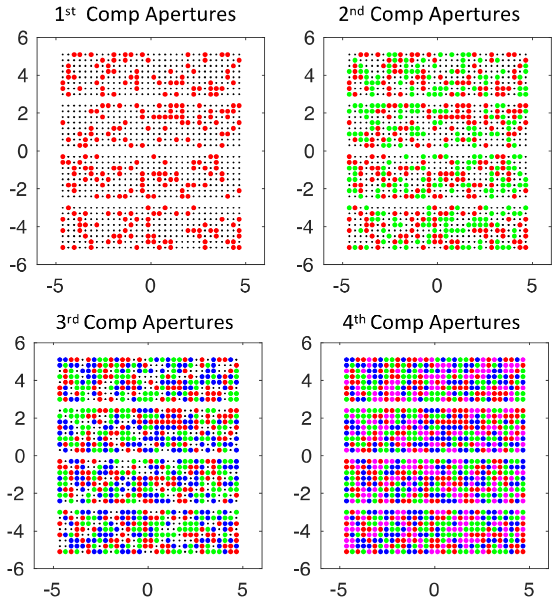

Figure 2. One set of complementary random apertures to be used in SRAC. Each aperture uses 256 elements of the matrix probe. When compounding 4 apertures all the elements are recovered.

To evaluate each aperture, the phantom was imaged using the sequence described above. Only the centered XZ plane at 10 wavelengths (λ) above and below the target was reconstructed to reduce computation time. The log-compressed images of the string were used to calculate the Main-lobe to Side-lobe Ration (MLSLR) as described by Bernal et. al [9]. The MLSLR parameter allows to evaluate the amplitude of the echoes from the target in comparison with those coming from the side lobes. It was calculated by averaging the depth between -10 λ and +10 λ around the string in order to include all sidelobes. A large separation is considered optimal and is expressed as a large negative value (Figure 3).

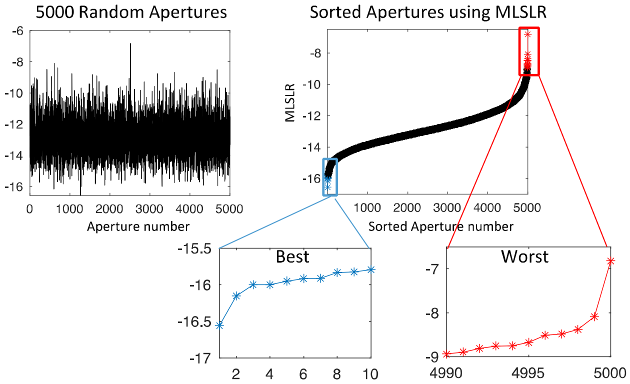

Figure 3. Random aperture optimization using a Monte Carlo method. Five thousand apertures were sorted using the MLSLR metric and the best and works aperture were used for imaging.

The apertures were then sorted based on the MLSLR values and 2 groups of complementary apertures were created. Group A was created using the best overall aperture (i.e., aperture 1 in the blue curve in Figure 3) and its complementary apertures. Group B, was comprised of the four complementary apertures that had the best mean MLSLR. A third group was created to compare the performance of complementary vs non-complementary apertures. Group C included the best 4 apertures out of the 5000 created (i.e., apertures 1 to 4 of the blue curve in Figure 3). It is important to keep in mind that even though these were the best four apertures after the sorting process, being non-complementary means that when using them for SRAC some elements in the probe get used more than once, and others never get used.

Once all the apertures were sorted and the groups created, the phantom was imaged using the best and worst overall apertures (aperture 1 and aperture 5000 from Figure 3). Then using 1 to 4 SRAC the phantom was imaged with the Group A, Group B and Group C; and a full volume reconstruction was performed.

III. RESULTS

Figure 4 shows images of the string with the best (blue) and worst (red) apertures in the XY plane after averaging over 20 λ around the string. This figure also shows the beam profiles for both apertures at the center XZ plane and the calculated MLSLR for each case.

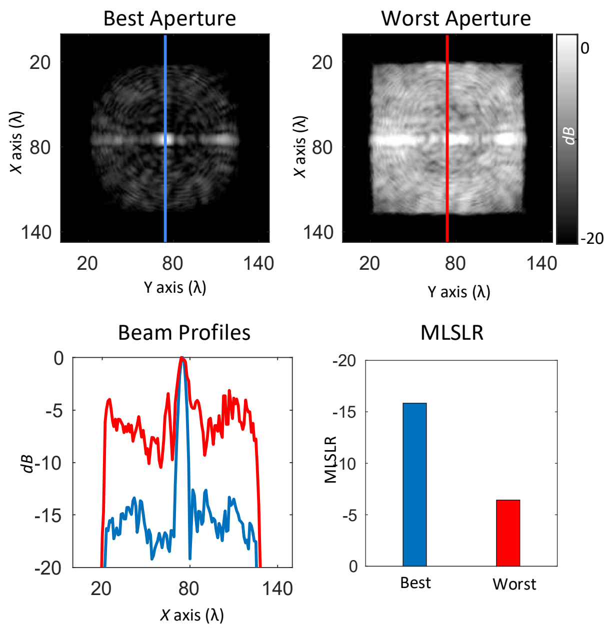

Figure 4. XY plane imaging with best (blue) and worst (red) apertures. Beam profile for both apertures at the center XZ plane, and the MLSLR calculation, respectively

The difference in MLSLR between the best and the worst aperture was over 9.5 dB. Figure 5 shows the effect of SRAC from 1 to 4 apertures. In this figure the blue bars reflect the compounding of the best aperture and its complementary ones Group A), while the green bars show the compounding of the group with the best MLSLR average (Group B). Lastly, the black bars are the compounding of the best four apertures (out of 5000), which are not complementary (Group C). Groups A and B showed comparable improvements when compounding. However, the Group A showed an overall better performance. On the other hand, Group C did not perform as well as the other two categories.

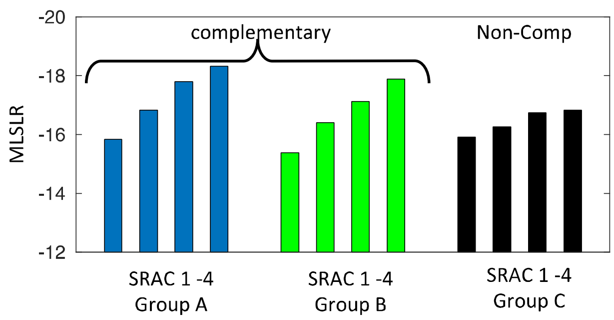

Figure 5. MLSLR using 1 to 4 SRAC method using the Group A (best apertures and its complementary), Group B (group with the best average MLSLR) and Group C (group of the best 4 apertures, non-complementary).

IV. DISCUSSION

The results from this study demonstrate that the choice of the set of random apertures can mean a difference of up to 9.5 dB in contrast resolution given the current results and optimization method. Even the average-performing random apertures (i.e., apertures in the middle of the optimization curve, Figure 3) exhibit a 4-dB difference in the MLSLR with respect to the best aperture, which is significant. These findings highlight the importance of optimizing the random aperture selection.

Comparison of the results for the Group A with those from the study by Bernal et al. in 2020, showed that the optimization process provides a significant increase in image quality. In their paper Bernal et al. reported values of -12.3 dB, -14.6 dB, -15.9 dB and -17.4 dB for 1 to 4 SRAC using a similar string phantom and a SDW acquisition. In comparison the values from this study were -15.8 dB, -16.8 dB, -17.8 dB and 18.3 dB for the same acquisition sequence and the same SRAC. Furthermore, the result of the current work using 4 optimized apertures (4 SRAC) provided comparable image quality results to those in Bernal's study when using a system with 1024 channels, 18.3 dB vs 19.4 dB, respectively.

Comparison of the overall results from this study with that of Bernal et al., showed that SRAC has a significant impact on image quality. However, comparing the values between Group A and Group B showed that starting the compounding process with the best possible apertures plays a significant role. In the SRAC procedure, the first aperture is used during transmission for all subsequent acquisitions with the complementary apertures of a particular set. Therefore, using the best aperture is a key factor since it sets the initial value of MLSRL from which the compounding of more apertures will contribute to the image quality. In the case of the Group B, we also used the best aperture out of the 4 apertures from the set as the first aperture for transmission. However, this aperture does not perform as well as the first aperture in the Group A and the overall performance regardless of the number of apertures used for the SRAC is less when compared to the Group A.

Lastly, the comparison between complementary and non-complementary random apertures showed that complementarity plays a key role in the SRAC approach. The improvement between 1 and 4 SRAC for the complementary apertures was 2.5 dB, while for the non-complementary apertures was 1 dB. It is important to consider that these differences occur even though the apertures used in the non-complementary test were the 4 best apertures out of the 5000 tested.

Future studies should focus on evaluating SRAC and aperture optimization in combination with angle compounding. Moreover, the optimization process needs to be improved to account for multiple targets.

In conclusion, this study showed the importance of aperture optimization to improve image quality without sacrificing frame rate. It was also demonstrated that complementary apertures performed better than simple optimized apertures. Moreover, our findings indicate that better image quality can be achieved by using the best and its corresponding complementary apertures, rather than using the group with the best overall

MLSLR. Lastly, this study further demonstrated that SRAC is a feasible technique to perform HFVI and improve image quality.

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