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Ultrafast ultrasound imaging beamforming techniques: a review

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Abstract

Ultrasound imaging, commonly known as sonography, is a medical diagnostic procedure that generates images of interior organs and tissues within the body by using high-frequency sound waves. Because of being non-ionizing, inexpensive, reproducible, non-invasive, simple-to-use, and able to display flow data performance characteristics, ultrasonic imaging has gained international interest. As a result, researchers and engineers sought to improve image quality. Image enhancement methods are used to minimize noise in medical image and raise the quality of imaging in term of contrast, speckle homogeneity and resolution and reduce artifacts that produced from proposed algorithms. Several academic papers in the literature use traditional image enhancement approaches. The primary goal of this paper is to highlight the properties and limitations of a number important and commonly used image enhancing techniques that aim to overcome the reduced imaging quality that result from unfocusing of plane wave imaging.

Keywords: *Ultrasound imaging, Ultrasound enhancement, Minimum variance, Eigenspace-based minimum variance, Ultrafast imaging*

1. Introduction

Ultrasound imaging (US) is a type of medical imaging that makes use of high-frequency sound waves beyond the audible frequency to produce images of internal organs and tissues [1]. A piezoelectric effect creates the sound waves and propagation requires matter [1]. The velocity of propagation differs according to the characteristics of matter, and the images result from the interaction of refraction, reflection, scattering, absorption, attenuation, and transmission [1 and 2].
The principle of US is illustrated in Figure 1. First, acoustic waves are produced. The ultrasonic waves emitted are spreading and reacting with the medium. Some reflected and diffused waves will rise due to interaction and inhomogeneities un the medium. These echoes return to the transducer, which converts them into electrical impulses proportionate to the received echoes.
The transducer is the most essential equipment in ultrasonic imaging, which differs according to the number and arrangement of the piezoelectric element's arrays and shapes the way it is used and the application where it is employed [1]. US is one of the most rapidly developing medical imaging techniques, thanks to its non-invasive properties, its fast acquisition methods, and its moderate cost. Some of the applications where it is utilized as a popular diagnostic tool are cardiac, abdominal, fetal, and breast imaging.
B-mode images are the most commonly produced image from Medical US. a B-mode imaging is a two-dimensional image of the scanned area [4]. Other imaging modes Doppler flow images expanded field of view images, and three-dimensional images [1-4]. Currently, many ultrasound probes consist of several elements arranged linearly or sectorally. They allow both the emission of ultrasound waves and reception of echoes reflected from the medium (Figure 1(b)). These echoes, transformed into electrical signals and then digitized, represent the raw data acquired (Figure 1(c)).
Plane wave imaging (PWI) is an US technique that allows for faster image acquisition and higher frame rates [5 and 6]. In traditional US, to send and receive ultrasonic waves, beam focusing is utilized. However, in PWI, to transmit and collect ultrasonic signals, A transducer's accessible elements are all activated at the same moment, to produce an unfocused beam [5 and 6]. PWI can be used in medical diagnosis and non-destructive testing (NDT) in various industries [5 and 7]. In medical diagnosis, PWI can produce high-resolution images through scan conversion and image reconstruction [4]. PWI has various medical applications. Its main benefits are to rise the scan rate and decrease the number of elements required in the transducer array, which allows for ultrafast image collection and is capable of imaging at kHz rates [5 and 6]. Another application of PWI in the medical field is to measure the velocity of blood flow in the body [6]. This technique can also be used to improve doppler by filtering spatiotemporal clutter from ultrafast ultrasound data [6].

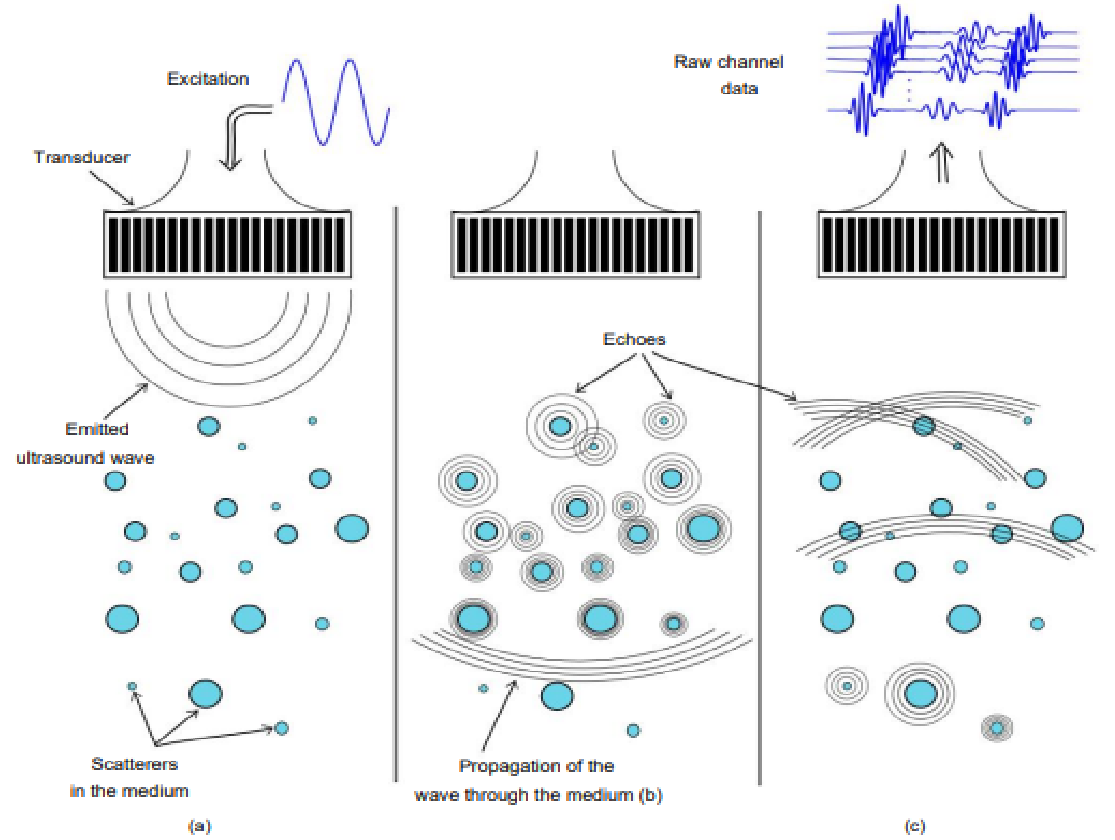

Fig. 1: The US Principle: (a) Transmission phase. (b) Propagation phase. (c) Receive phase.

2. Improved ultrafast ultrasound imaging

2.1. Improvement through system configurations

To generate high-quality images using PWI and overcome weak transmit focusing leads to decreased image quality, in terms of both contrast and resolution, various techniques have been proposed in recent decades, such as sparse arrays and Stolt-migration processing [5 and 6]. Sparse arrays are an array in which many elements have a value of zero, Sparse arrays are used to increase the image quality, using sparse arrays with only a few angles and frames, thus producing high-quality ultrasound images with increased lateral and axial resolution compared to traditional PWI [5 and 6]. In Stolt-migration processing, three commercial arrays are combined to achieve a large imaging aperture to recreate the ultrasound images, where specific interpolation method, are used [5 and 6].

2.2. Improvement through non-adaptive beamforming techniques

A most basic digital beamformer used in medical US is Delay-And-Sum (DAS) [8]. It is a simple and efficient technique that is utilized in ultrafast US [8]. The Delay Multiply and Sum (DMAS) beamforming technique is a nonlinear beamforming algorithm that can be used for medical US [9]. The DMAS algorithm has been proposed to increase the quality of DAS-reconstructed images. Which is a new medical imaging modality that can provide excellent spatial resolution and contrast. It uses the same concept to apply delays to signals received by different elements based on their geometrical position in the probe in order to make signals in phase. The signals are multiplied by each other before being added in the basic version of DMAS, which is mathematically equivalent to an autocorrelation function. That is, the spatial cross correlation of the active transducers' received signals at each time, it is a non-adaptive and blind beamformer that produces low-resolution images with an elevated level of sidelobe.

2.3. Improvement through adaptive beamforming techniques

2.3.1. Minimum variance (Mv) based adaptive beamforming

DAS have limitations in terms of image quality [10]. Advanced data-adaptive reconstruction approaches, just like Minimum Variance (MV) adaptive beamforming, can recover higher image quality versus typical ways [10 and 11]. MV beamforming is a signal processing technique that has been spent years researched in medical US [11-14]. This approach achieves higher spatial resolution than classic (DAS) by lowering overall output power while maintaining the desired

signals [15-18], or by keeping on-axis signals while minimizing off-axis ones [19 and 20]. However, their execution usually imposes a significant computational load [21]. MV beamforming has been used to illustrate how adaptive methods' narrow beamwidth and low sidelobe levels can be used to improve resolution and imaging in a variety of ways [14]. MV beamformer is combined with covariance matrix-based adaptive weighting, it can be utilized to increase penetration depth without sacrificing lateral resolution [22]. The covariance matrix plays a crucial role in adaptive beamforming. It is a matrix that describes the statistical relationship between the array elements' received signals. In adaptive beamforming, the covariance matrix is estimated from the received signals and used to weight the array elements to enhance the desired signal and suppress interference [23 and 24]. The covariance matrix can be estimated using various techniques, such as sample covariance matrix estimation and interference-plus-noise covariance matrix estimation [24 and 25]. The estimation of the covariance matrix's accuracy can impact the performance of the adaptive beamforming process. Overall, the covariance matrix is a key component in adaptive beamforming that enables the enhancement of desired signals and suppression of interference. However, MV beamforming alone does not improve contrast [26]. To address this issue, researchers have proposed combining MV beamforming with other techniques to improve contrast, such as Coherence Factor (CF) weighting [20], Sign Coherence Factor (SCF) [27], and Convolutional Neural Networks (CNN) [26]. Combining MV beamforming with CF weighting enhances in-phase signals while decreases out-of-phase signals to improve contrast and reduce sidelobes [20]. The use of SCF could also modify the beamformer's input vector, which can reduce side lobe noise while requiring nearly no additional calculations [27]. The third proposed method of combining MV beamforming with CNN suppresses off-axis scattering signals while the MV beamforming apodization weights provide improved image resolution performance [26].
Researchers have also proposed combining MV beamforming with Phase Coherence Imaging (PCI) to increase imaging resolution and contrast simultaneously [19]. PCI is a signal processing method that suppresses side and grating lobes by analyzing the phase dispersion in the received signals [19]. In this method, two coherence factors, PCF and SCF, are generated based on the phase variation of the received aperture data and then used to weight the total output of the MV beamformed channel [19]. In (2021) Salari, A., & Asl, B. M. suggested that the parameters that control MV performance balance are adaptively generated, so that this beamformer is fully independent of the user [28]. In the medical field, adaptive beamforming methods can increase image quality while degrading real-time performance. Researchers have devised an adaptive beamforming method based on minimum variance and deep neural network (DNN) to increase image efficiency and speed up the beamforming processing of ultrafast US [22].

2.3.2. Eigen space based minimum variance (ESBMV) adaptive beamforming

The Eigenspace-Based Minimum Variance Beamformer (ESBMV) is a method utilized in ultrasonic imaging in medicine to improve the resolution and contrast of images [29 and 30]. It was developed to highly improve the contrast of MV beamformer. ESBMV was first introduced by Van Veen in (1988) [31]. However, it may introduce dark region artifacts alongside the hyperechoic scatterers when obtaining obvious contrast.
Lately, several research groups have investigated and developed several ways to improve ESBMV beamforming. In (2010) and by Using a simulated cyst phantom, Mahloojifar & Asl proposed using iterative ESBMV to determine appropriate imaging parameter choices to improve imaging quality [32]. Nonetheless, the impact of changed parameters on BBR artifacts was not taken into account for the proposed iterative approach [33 and 34]. Zeng et al. in 2012 suggested combining Wiener postfiltering with ESBMV to improve ESBMV resolution and contrast [35]. This proposed combination, however, did not eradicate the black spots and BBR artifacts in the background speckle. Aliabadi et al. (2015) developed a method for improving contrast in ESBMV by modifying the focus point value based on the qualities of the echo signals received by the surrounding sites [36]. This approach was effective in reducing dark-spot artifacts but not at eliminating BBR artifacts. In 2016 Zhao et al. suggested an original technique that combines a coherence factor based on subarrays with ESBMV. This technique aids in the enhancement of imaging quality in terms of resolution, speckle homogeneity, and contrast [37], However, the use of subarray smoothing reduces computing efficiency, and BBR artifacts were not eliminated. In 2017, The Partial-ESBMV (PESBMV) approach was proposed. to address the ESBMV limitation. According to this method, ESBMV is applied or stopped based on the amount of eigenvector’s in the signal subspace. As a result, this strategy was able to decrease BBR artifacts [38], However, the contrast is lower in comparison to ESBMV. Following that, several techniques for improving ESBMV's performance were proposed. Short-lag spatial coherence together with ESBMV has been proposed to remove BBR artifacts when eigenvalues are high [39]. ESBMV was also linked with DMAS beamformer to reduce sidelobes and raise the signal-to-noise ratio. However, this did not reduce the ESBMV artifacts [40]. It was also advised to use ESBMV be used with the SCF to improve the signal-to-noise ratio, however dark areas and BBRs were not removed [41]. In 2021, Lan et al. suggested the use of an adaptive eigenvalue threshold for subspace development to improve contrast and reduce dark region artifacts [42]. Image quality can be improved by adaptively altering the subarray length of the covariance matrix, this also helps to decrease the size of the covariance matrix and, to some extent, increase computational efficiency. However, this suggestion produced lower hyperechoic target`s brightness compered to classical ESBMV and according to that the borders of hyperechoic targets suffers from lack of clarity [42].

3. Conclusion

Image improvement techniques modify images to produce more accurate representation of the information in the image. This paper provides an overview of many forms of beamforming techniques suggested in the literature for image enhancement. all developments technique in MV able to increase contrast and resolution to some extent. This improvement in contrast is very little compared to contrast improvement achieved using ESBMV. All techniques combined with ESBMV are able to increase contrast but with artifacts introduced, until PESBMV and Adaptive Threshold for Eigenspace-Based Minimum Variance Beamformer were introduced, as the two methods were able to reduce the BBR artifact, but the limitation for PESBMV is to reduced contrast compared to ESBMV. Also, Adaptive Threshold for Eigenspace-Based Minimum Variance is not able to remove dark spots completely. Many techniques and algorithms proved to be suitable for improving Ultrasound imaging quality. There is, however, no universal imaging techniques that provides an ultimate form of improved images in Ultrasound without having any limitation or drawback, yet.

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