FreeBeam Technology

Technical White Paper

Chongchong Guo，Lei Li，Jiaming Li，Weinan Zhao
Ultrasound Imaging System Development Department, Mindray

Contents

FreeBeam Adaptive Beamforming Technology

Introduction

As a safe, non-invasive, real-time and portable medical imaging method, ultrasound imaging plays an important role in the diagnosis of cardiovascular, abdominal, small organs, fetuses and other examinations. Beamforming technology is an important segment of ultrasound imaging process. The technological characteristics of beamforming determines the final quality of ultrasound imaging [1]。

Since the advent of the first B-mode ultrasound in 1950, the main implementation of beamforming has developed from analog to digital beamforming. On this basis, the beamforming algorithm is developed from the conventional Delay and Sum (DAS) algorithm to the full-field focusing algorithm. Now a new third-generation beamforming method, adaptive beamforming algorithm based on software architecture, is developing vigorously. Adaptive beamforming greatly improves the image performance, meanwhile, the computational complexity also increases dramatically. As a result, the method long remained at theoretical stage and could not move to the transition phase. For this purpose, Mindray launched AIT platform, equipped with FreeBeam technology, can achieve the third generation of adaptive beamforming technology.

The Development of Beamforming Technology

As shown in Fig. 1, The ultrasound imaging system mainly includes the following main parts: channel data, beamforming, signal processing, image processing and display. Among them, beamforming is the core process of imaging [2]. Therefore, high-performance beamformer is a focal research point in the field of medical ultrasound.

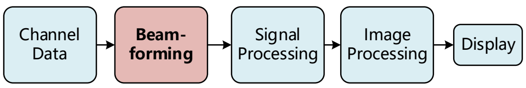


Figure 1. Medical ultrasound system framework

The basic principle of beamformer is to generate a specific acoustic field distribution in the imaging area. A narrower main-lobe and lower side-lobe can improve imaging resolution and contrast. In addition, it can increase the ability to suppress clutter and interference [3]. Prior to this, beamforming algorithms and structures were mainly divided into the following two generations:

The first generation is the DAS algorithm, which initially uses analog circuits to achieve fixed-point focus on the architecture. The representative product is SSL-53H introduced by Aloka in 1976. With the booming development of digital signal processing, digital circuit is used to realize point-by-point receiving focus algorithm, makes the imaging performance far superior to the analog circuit. The representative product is the Sequioa512 from Acuson. Mindray accessed ultrasound field in the digital era and started independent research. However, these methods are implemented through hardware, have many limitations and are easily affected by interference and noise [4].

The second generation is full-field focusing algorithm, which realizes point-by-point focusing of receiving and transmitting. This method achieves a qualitative leap in imaging. Because of its high computational complexity, flexible software beamforming method is adopted to avoid complicated hardware circuit design. And this structure is conducive to the subsequent increasing links and technical iteration. The representative products are Mindray ZST^{+}, GE cSound and Philips nSight.

The Limitation of Conventional Beamforming

The presentation of conventional beamforming is as follows [5]:

$$y = \sum_{m=0}^{M} w^H x_m$$

where M is the element number, x_m is the receiving data, w^H is the weighting coefficient.

The flow of beamforming is shown in Fig. 2. The delay of each channel is calculated and the data is summed with fixed coefficient. This method is difficult to apply to complex imaging conditions, resulting in the inability to display full image information [6].

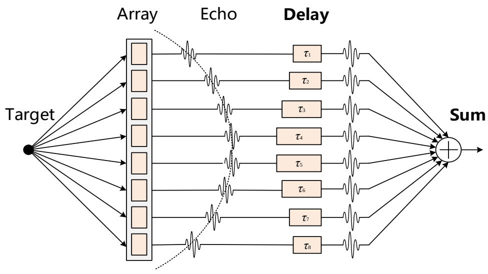


Figure 2. The flow of conventional beamforming

As shown in Fig. 3, the fixed weighting coefficient leads to the inherent contradiction between the main-lobe width and side-lobe level of the beam pattern. In summary, the imaging resolution and contrast of the first two generations of beamforming technology are difficult to further improve [7]. To break through this limitation, the development of beamforming steps into the third generation, adaptive beamforming based on software architecture.

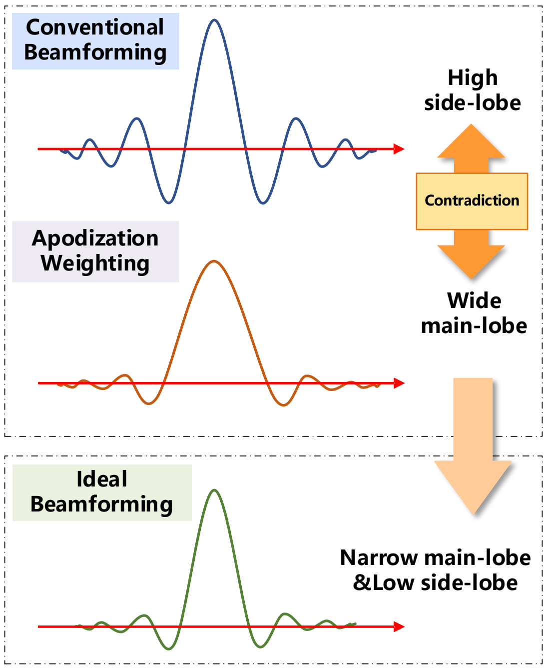


Figure 3. The limitation of conventional beamforming

FreeBeam Beamforming

Because of the inherent contradiction between the main-lobe width and side-lobe level of the beam pattern, high performance adaptive beamforming technology for ultrasound imaging is essential. However, the adaptive beamforming algorithm has extremely high computational complexity and is mainly used in military field [8]. In the field of ultrasound imaging, the technology is still in the theoretical research stage and has not been implemented by products.

In order to solve this problem, Mindray proposes FreeBeam adaptive beamforming technology based on the ultra-high computational performance of the AIT platform to optimize the computational efficiency of the algorithm while ensuring the performance.

The Limitation of Conventional Adaptive Beamforming

As shown in Fig. 4, different from conventional beamforming, adaptive beamforming calculates the adaptive weighting coefficient based on echo information at different sampling times to achieve dynamic channel weighting. This type of methods can fully identify and utilize the valuable information in the acoustic signal, breaking through the limitations of the resolution and contrast of ultrasound imaging.

Compared with conventional method, adaptive beamforming can guarantee a narrower main-lobe and a lower side-lobe at the same time, making the directivity of the beam more controllable. Numerous research papers have shown that the method can suppress clutter and is effective in imaging cysts, the heart, and the abdomen [9,10].

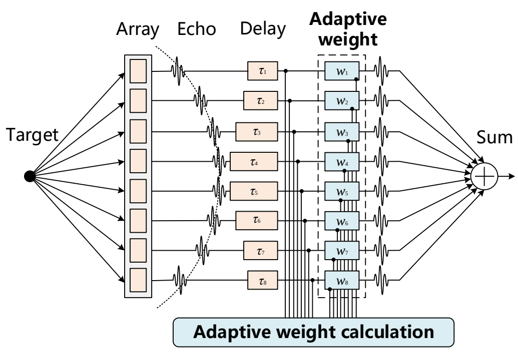


Figure 4. The flow of adaptive beamforming

The formula of adaptive beamforming is shown as follows [11]:

$$y = \frac{1}{M-L+1}\sum_{k=0}^{M-L}\left[\frac{(\boldsymbol{X}_k\boldsymbol{X}_k^H)^{-1}\boldsymbol{a}}{\boldsymbol{a}^H(\boldsymbol{X}_k\boldsymbol{X}_k^H)^{-1}\boldsymbol{a}}\right]^H \boldsymbol{X}_k$$

where L is the subarray length, $\boldsymbol{X}_k$ is the channel data of subarray, $\boldsymbol{a}$ is spatial steering vector, y is the output.

It can be seen from the formula that the calculation process includes a lot of covariance matrix operations and matrix inversion operations. The computational complexity of DAS algorithm is $O(L)$, while that of adaptive beamforming is $O(L^3)$, which requires a very high computational amount. Therefore, the performance of computing platform and the optimization of algorithm are the key points of productization [12,13].

The Theory of FreeBeam

Since the launch of the first generation of ultrasound equipment in 2003, Mindray has been committed to the research and development of advanced ultrasound imaging technology. In 2015, the Mindray R&D team proposed the full-field focus imaging technology based on software beamforming. In 2023, Mindray proposed the unique FreeBeam technology on the new AIT platform, which enabled the third generation of adaptive beamforming imaging algorithms to be productized.

The basic schematic diagram of FreeBeam algorithm is shown in Fig. 5, which is mainly divided into three main parts: compression, optimization, and reconstruction. Firstly, the input data is decomposed into multiple subsignals by multi-scale signal decomposition, and then the subsignals are projected spatially by Improved Proper Orthogonal Projection (IPOP), and the adaptive steering vector of orthogonal space is calculated. This optimization can efficiently obtain the best beamformers. Finally, the data is reconstructed and summed to obtain the output result.

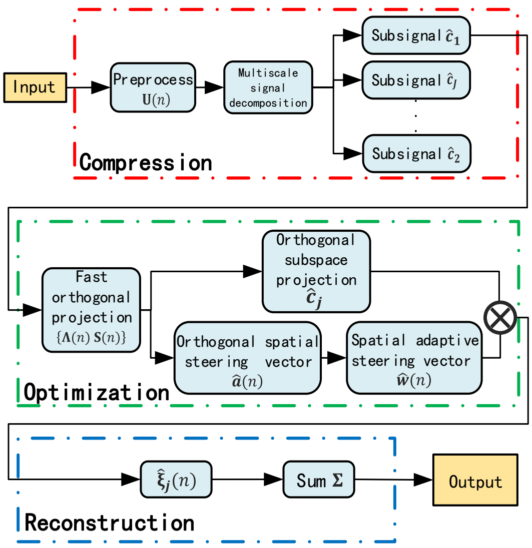


Figure 5. The basic theory of FreeBeam

Compared with the conventional adaptive beamforming, the computational complexity of the improved FreeBeam algorithm is reduced from $O(L^3)$ to $O(L^2)$, and the computation amount is reduced by 20 to 30 times on average. At the same time, FreeBeam improves the performance of the beamformers, and through a large number of measured data verification, the imaging quality can be comprehensively improved.

Fig. 6 illustrates the advantages of FreeBeam over conventional beamforming algorithms. FreeBeam breaks through the limitations of the main-lobe width and side-lobe level in the conventional method, greatly improving the resolution, contrast and robustness of the ultrasound imaging.

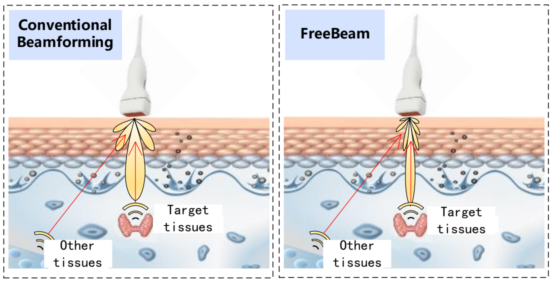


Figure 6. The advantages of FreeBeam

In addition to optimization algorithms, the acoustic intelligent technology (AIT) platform is configured with premium GPU for complex operations, with more than 20TFLOPS, which is more conducive to the realization of imaging algorithms. Profit from FreeBeam technology and high computing power, Mindray has completed the productization of adaptive beamforming for the first time, which can help doctors diagnose and achieve a major breakthrough in the application of advanced technology to the clinic.

Advantages of FreeBeam

Based on the above introduction, adaptive beamforming has been productized. Compared with conventional beamformer, AIT platform has significantly improved the sensitivity and spatial resolution of strong scattering points and cyst edges. While ensuring high performance imaging, high efficiency real-time imaging can be achieved.

As can be seen from Table 1, Full Width at Half-Maximum (FWHM) of FreeBeam is reduced by half, and the lateral resolution can be doubled. The main evaluation of ultrasound imaging, Contrast Ratio (CR), Contrast to Noise Ratio (CNR), Signal to Noise Ratio (SNR) are all significantly improved.

Table 1. Performance comparison of FreeBeam

Indicators	Conventional beamforming	FreeBeam	Improve
FWHM	0.26mm	0.12mm	54%
CR	31dB	38dB	23%
CNR	1.37dB	1.66dB	21%
SNR	1.61dB	1.86dB	16%

This technology allows full-field focusing, which can highlight the required image features in specific clinical scenario and improve the basis of diagnosis. Depending on the clinical scenario, doctors can select different image features including: noise suppression, edge enhancement, detail enhancement and calcification enhancement. The powerful computing capability of AIT platform provides a foundation for the subsequent research and implementation of more technologies. This endows the product long-term potential.

Clinical Value of AIT

With the support of a large number of case analyses in different clinical scenarios, we have verified the performance improvement of ultrasound imaging by FreeBeam technology. Some imaging results of representative clinical cases are shown below.

Case 1. Breast image

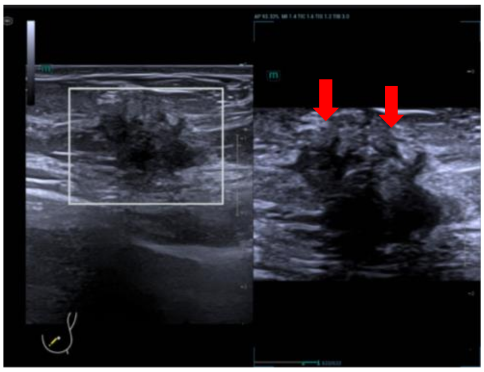


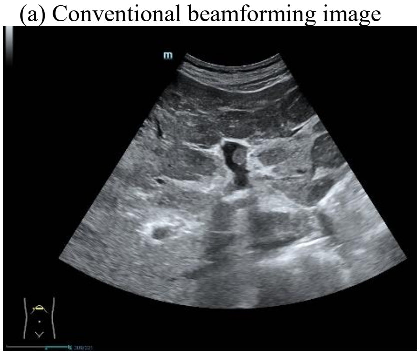
Figure 7. Breast cancer image of FreeBeam

Fig. 7 shows the breast cancer imaging results of Mindray AIT platform using FreeBeam. Compared with the conventional method (left), the image sharpness using FreeBeam is significantly improved (right). The upward invasion of the subcutaneous soft tissue layer of breast cancer is clearly demonstrated.

Case 2. Hepatic portal vein image

Fig. 8 shows the image of hepatocellular carcinoma with portal vein thrombosis of conventional beamforming and FreeBeam technology. FreeBeam provides better overall image penetration and resolution. Thrombus lesions are shown more clearly and noise suppression is better, which helps to diagnose the state.

(a) Conventional beamforming image



(b) FreeBeam image

Figure 8. Comparison of hepatic portal vein

Case 3. Thyroid image

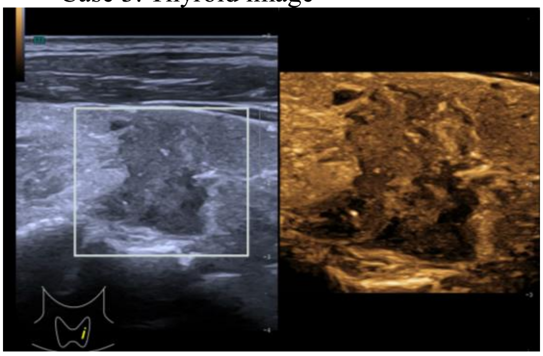


Figure 9. Thyroid cancer image of FreeBeam

Fig. 9 shows the thyroid cancer imaging results of FreeBeam. Compared with the left image, the FreeBeam image shows that the focal boundaries of thyroid cancer are clearer, the internal calcification details are more abundant, and the grey stratum is abundant. It can aid in state analysis and treatment.

Case 4. Hemangioma image

Fig. 10 shows the image of hepatic hemangioma using FreeBeam. FreeBeam technology has obvious performance on overall noise suppression and uniform background. The superficial honeycomb structure is clear. This is conducive to the diagnosis of the tumor.

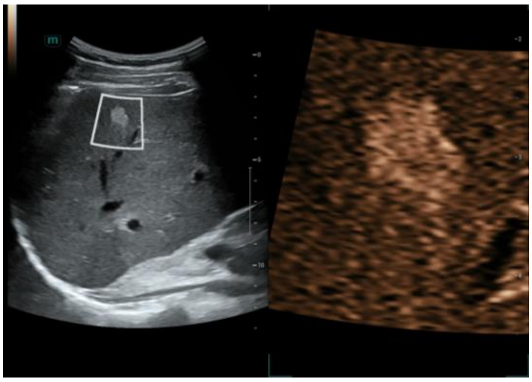


Figure 10. Hemangioma image of FreeBeam

Conclusion

The concept of AIT platform is to create a premium ultrasound imaging product. FreeBeam technology breaks through the resolution and contrast performance bottlenecks of conventional beamforming methods. AIT platform realizes real-time imaging of FreeBeam based on GPU parallel processing technology with super computing power. Compared with the conventional method, the spatial resolution of FreeBeam is increased by 2 times. The imaging contrast, signal-to-noise ratio and other aspects are significantly improved, which is conducive to displaying more details.

Preliminary clinical tests have shown that FreeBeam technology can clearly display venous thrombosis, significantly enhance the lumen outline and glandular boundaries, and provide more detailed imaging of the honeycomb structure of hemangiomas. Thanks to the increase of lateral resolution, the accuracy of ultrasound equipment for contour detection is also improved. Furthermore, the technology enables more accurate positioning of human bones and interventional devices such as medical probe.

With more comprehensive and in-depth clinical research in the future, more application value of FreeBeam will be explored. We expect that the launch of this new technology can provide more accessible, more comprehensive and more valuable guidance information for the early diagnosis and treatment of diseases.

References

[1] F. S. Jnhan, A. Andreas, H. Sverre, Adaptive beamforming applied to medical ultrasound imaging, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2007; 54 (8):1606–1613

[2] J. Park, S. M. Wi, J. S. Lee. Computationally efficient adaptive beamformer for ultrasound imaging based on QR decomposition. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2016; 63(2):256-265.

[3] O. L. Frost III. An algorithm for linearly constrained adaptive array processing. Proceedings of the IEEE, 1972; 60(8):926–935.

[4] M. O’Donnell, W. E. Engeler, J. T. Pedicone. Real-time phased array imaging using digital beamforming and autonomous channel control. Honolulu: IEEE Ultrasonics Symposium, 1990; 3:1499-1502.

[5] S.W. Flax, M. O’Donnell. Phase-aberration correction using signals from point reflectors and diffuse scatterers: basic principles. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 1988; 35(6):758-767.

[6] J. F. Synnevag, A. Austeng, S. Holm. Benefits of minimum-variance beamforming in medical ultrasound imaging. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 2009; 56(9):1868-1879.

[7] T. Mickael, F. Mathias. Ultrafast imaging in biomedical ultrasound, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2014; 61 (1):102–119.

[8] G. Krieger, N. Gebert and A. Moreira, Multidimensional Waveform Encoding: A New Digital Beamforming Technique for Synthetic Aperture Radar Remote Sensing, IEEE Transactions on Geoscience and Remote Sensing, 2008; 46(1): 31-46.

[9] J. Mann, W. Walker. A constrained adaptive beamformer for medical ultrasound: Initial results. Proceedings in Ultrasonics Symposium IEEE, 2002: 1807-1810.

[10] F. Vignon, M. R. Burcher, Capon beamforming in medical ultrasound imaging with focused beams. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 2008; 55(3):619-628.

[11] J. Capon. High-resolution frequency-wavenumber spectrum analysis. Proceedings of the IEEE, 1969; 57(8):1408–1418.

[12] M. D. Ali, M. Babak. Low complex subspace minimum variance beamformer for medical ultrasound imaging. Ultrasonics, 2016; 66:43-53.
[13] F. Akopyan, R. Manohar, A. B. Apsel. A level-crossing flash asynchronous analog-to digital converter. Proceedings of the 12th IEEE International Symposium on Asynchronous Circuits and Systems. Grenoble，2006:12－22.

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