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Matrix approach of aberration correction in medical ultrasound imaging

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EXTENDED ABSTRACT

1. Introduction

In conventional echography, ultrasonic arrays employ beamforming (applying appropriate time delays in emission and reception) to form images. It is commonly assumed that the insonified medium is homogeneous, with a constant acoustic velocity. However, in heterogeneous media, variations in acoustic impedance causes aberration effects leading to distortion that decrease the image quality. Furthermore, the speed of sound may vary with position, resulting in multiple isoplanatic areas (different aberration effects associated to different areas of the image). Techniques such as adaptive focusing and matched filter methods have been developed to correct for aberration, but most require either iterative focusing, optimization based on image quality, or the presence of dominant scatterers as guidestars, and none can simultaneously correct for multiple isoplanatic areas.

In this study, we present a powerful method of aberration correction based on the distortion matrix concept [1]. This operator compares each wavefront generated from any focal spot with an expected one obtained in the ideal condition of homogeneous medium. Even in speckle, a time-reversal analysis of this operator

enables the estimation of the transmission matrix that links each sensor and image voxel. Phase aberrations can then be unscrambled at any point, thereby providing a full-field image of the medium with diffraction-limited resolution.

2. Methods

In this study, the probe is placed in contact with the calf of a healthy volunteer. The acquisition was performed using a medical ultrafast ultrasound scanner (Aixplorer Mach-30, Supersonic Imaging) driving a 5-18MHz linear transducer array containing 192 transducers with a pitch of 0.2 mm (SL18-5, Supersonic Imagine). The ultrasound sequence consists in transmitting steering angles spanning from -25° to 25° , according to a hypothesis on the tissue speed of sound $c_0 = 1580$ m/s. The acquired reflection matrix is denoted $\mathbf{R}_{\theta,u} \equiv R(\theta_{in}, u_{out})$

3. Matrix imaging and aberration correction

By back-propagating $\mathbf{R}_{\theta,u}$ to any focal plane in transmit and in receive, a focused reflection matrix $\mathbf{R}_{r,r} \equiv R(r_{in}, r_{out})$ is built between virtual transducers at each depth [2]. Spatial Fourier transforms are then performed to analyze the distortion that a wavefront,

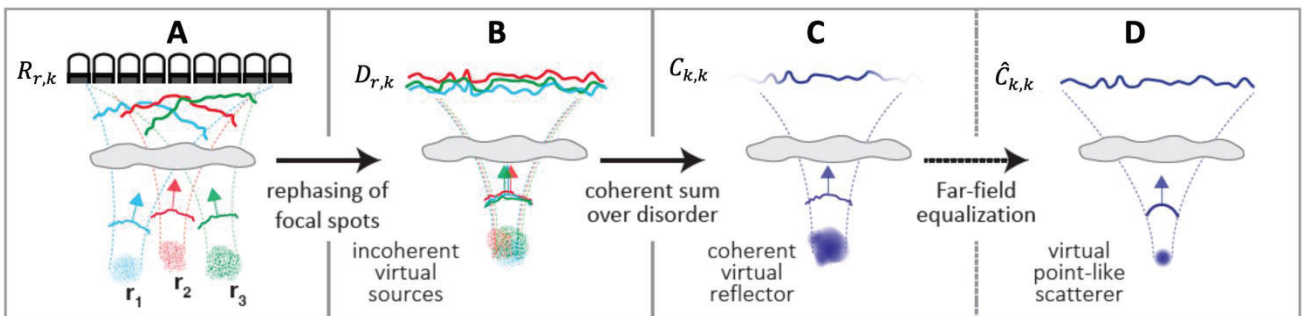


Figure 1. Sketch of the time reversal analysis of the distortion matrix. (A) Each row of the reflection matrix $R_{r,k}$ correspond to the reflected wavefield induced by the associated virtual source r_{in} . (B) The distortion matrix $D_{r,k}$ extracts the aberrated component of those wavefronts. From another point of view, all the wavefronts are realigned as if they were generated by input focal spots that are virtually shifted at the origin. (C) The correlation matrix $C_{k,k}$ of $D_{r,k}$ mimics the time reversal operator applied to a virtual specular reflector that results from the average of all the shifted input focal spots. Its first eigenvector $V_1(k)$ yields the mean aberrated component to focus on this specular reflector. (D) The normalized correlation matrix $\hat{C}_{k,k}$ makes the virtual reflector point like, providing a higher accuracy for large spatial frequencies k .

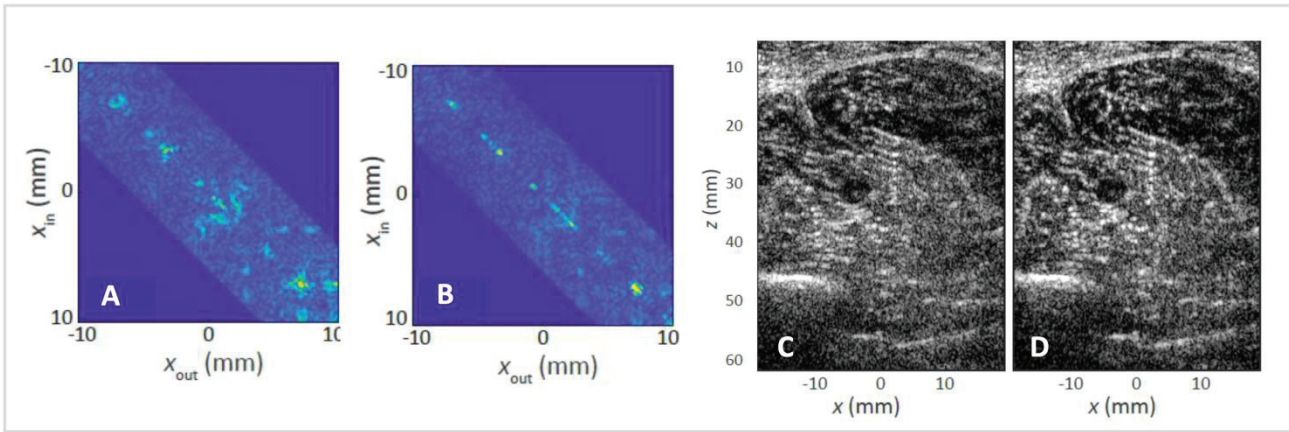


Figure 2. Results of the aberration correction process applied to the in-vivo case of the human calf. Focused reflection matrix (A, B) and corresponding conventional ultrasound image (C, D) before and after matrix aberration correction, respectively.

emitted from any point of the medium, experiences due to heterogeneities. These wavefronts $\mathbf{R}_{r,k} \equiv R(r_{in}, k_{out})$ (Figure. 1A) can be decomposed as the sum of 2 components: (i) An ideal geometric wavefront linked to diffraction and related to the input focusing point; (ii) A distorted component due to the mismatch between the propagation model and reality. A key idea is to isolate the latter contribution by subtracting, from the experimentally measured wavefront, its ideal counterpart $G(r_{in}, k_{out})$. This is done by means of a Hadamard product:

$$D(r_{in}, k_{out}) = G(r_{in}, k_{out})^* \circ R(r_{in}, k_{out}) \quad (1)$$

where the symbols * stands for phase conjugate and \circ for the Hadamard product. This constitutes the distortion matrix $\mathbf{D}_{r,k} \equiv D(r_{in}, k_{out})$ (Figure. 1B) whose singular value decomposition gives access to an optimized focusing law for any point in the medium. Finally, this matrix formalism allows to invert the role of the virtual transducers r_{in} and r_{out} so that the same correction can be applied in receive with $R(r_{in}, k_{out})$.

4. Results

This matrix approach is applied to the in-vivo imaging of the human calf that is heterogeneous and composed of different kind of tissues. While the main diagonal of the focused reflection matrix $R_{r,r}$ (Figure. 2A) yields the conventional ultrasound image (Figure. 2C), its off diagonal elements display the spatial extension of the point spread function and prove to be valuable for aberration correction. In such a complicated case where speed-of-sound fluctuations over the entire field-of-view induce multiple isoplanatic patches, the field of view is divided into overlapping sectors so that an aberration law for each sector is retrieved. After correction, $R_{r,r}$ is close to be diagonal and reaches the diffraction limit (Figure. 2B) leading to a large enhancement of the image contrast and resolution (Figure. 2D).

5. Discussion and Conclusion

The distortion matrix provides a powerful tool for imaging inside a heterogeneous medium with *a priori* unknown characteristics. Aberrations can be corrected without any guide stars or exact knowledge of the speed of sound distribution in the medium. Current investigations are extending this proof-of-concept to 3D-imaging. Because of a higher number of degrees of freedom in 3D-imaging, a coherent control of the incident and reflected wavefronts are achieved and therefore lead to a better evaluation of the aberration law.

Last but not least, the distortion matrix concept can be extended to any field of wave physics for which multi-element technology is available such as optical microscopy, radar and seismology.

REFERENCES

- [1] W. Lambert, L. A. Cobus, T. Frappart, M. Fink and A. Aubry: "Distortion matrix approach for ultrasound imaging of random scattering media," *Proc. of the National Academy of Sciences*, 2020.
- [2] W. Lambert, L.A. Cobus, M. Couade, M. Fink and A. Aubry: "Reflection matrix approach for quantitative imaging of scattering media," *Physical Review X*, vol. 10, no. 2, p. 021048, 2020.