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Editorial

Special Issue on Ultrafast Ultrasound Imaging and Its Applications

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1. Introduction

Among medical imaging modalities, such as computed tomography (CT) and magnetic resonance imaging (MRI), ultrasound imaging stands out in terms of temporal resolution. Due to the nature of medical ultrasound imaging, it has been used for observation of the morphology of living organs and, also, functional imaging, such as blood flow imaging and evaluation of the cardiac function. Ultrafast ultrasound imaging, which has become practically available recently, significantly increases the possibilities of medical ultrasounds for functional imaging. Ultrafast ultrasound imaging realizes typical imaging frame-rates up to ten thousand frames per second (fps). Owing to such an extremely high temporal resolution, ultrafast ultrasound imaging enables visualization of rapid dynamic responses of biological tissues which cannot be observed and analyzed by conventional ultrasound imaging. Various studies have been conducted to make ultrafast ultrasound imaging useful in clinical practice and, also, for further improvements in the performance of ultrafast ultrasound imaging itself as well as finding new potential applications.

2. Ultrafast Ultrasound Imaging

The primary factor limiting the temporal resolution in ultrasound imaging is the speed of sound in the body. Ultrasound pulses can be transmitted at pulse repetition frequencies of about 10,000 Hz for superficial organs and about 5000 Hz for deep organs. An ultrasound image is typically composed of 100–250 scan lines and one transmit-receive event is required to create one scan line because a focused transmit beam is used in conventional ultrasound imaging (ultrasonic echoes are coming from only a limited region). As a result, the imaging frame rate is limited to less than 100 fps unless the number or density of scan lines is not reduced.

The concept of ultrafast ultrasound imaging is not new. It was first developed and examined in the 1970s [1–3]. In ultrafast ultrasound imaging, unfocused transmit beams, such as plane and diverging beams, are used. As a result, ultrasonic echoes are coming from a wide region illuminated by an unfocused transmit beam. By creating focused beams in reception, a number of scan lines can be created simultaneously. Therefore, the number of emissions required to create one image frame can be reduced significantly. In an extreme case, an ultrasound image can be created by only one transmit-receive event if we can illuminate a region of interest by a single emission of an unfocused transmit beam.

On the other hand, image quality in ultrafast ultrasound imaging, e.g., lateral spatial resolution and contrast, is inherently worse than that in conventional imaging using focused transmit beams because the directivity is created only in reception and ultrasonic echoes from a wide region produce undesirable echoes. Various attempts have been made for improvement in image quality in ultrafast ultrasound imaging. Spatial coherent compounding is a frequently used method to improve the image quality in ultrafast ultrasound imaging [4–6]. By compounding point spread functions (PSFs) created from multiple steered beams, the compounded PSF is sharpened because only the central parts of the PSFs are coherently summed, and other parts of the PSFs are incoherently summed (canceled). The improvement of the image quality is increased by increasing the number of coherently compounded angles and consequently the imaging frame rate is degraded.

Another approach is to improve the performance of an ultrasound beamformer. One strategy is to use the coherence among ultrasonic echo signals received by individual transducer elements [7,8]. Such methods utilize the characteristics of received signals, e.g., echoes from a focal point are temporally aligned after delay compensation done by a delay-and-sum (DAS) beamformer, while out-of-focus echoes are not aligned. Coherence evaluation metrics, such as coherence factor (CF) and phase coherence factor (PCF), were developed and demonstrated to improve ultrasound image quality. Adaptive beamforming is an alternative strategy for improvement in the performance of an ultrasonic beamformer. The minimum variance beamformer [9] was introduced in medical ultrasound imaging in the late 2000s [10,11]. It minimizes the power of received ultrasonic signals (undesired echoes and noise are suppressed) while keeping the all-pass characteristic with respect to the desired direction (focal point). Significant improvements in image quality can be realized by minimum variance beamforming. On the other hand, the computational complexity of the minimum variance beamformer is very high, and developments of efficient implementations of the minimum variance beamformer are still ongoing [12,13]. In addition, various studies on improvement in the performance of the minimum variance beamformer have been conducted [14,15].

3. Applications and Ongoing Developments

As described above, the basic principle of ultrafast ultrasound imaging was developed in the 1970s. However, practical applications of ultrafast ultrasound imaging only arise from the early 2000s. Ultrafast ultrasound imaging was first used for visualizing the propagation of a shear wave induced by acoustic radiation force applied by an ultrasonic push pulse [16]. The measurement of shear wave propagation speed is useful for evaluation of the elastic properties of biological tissues. Shear wave imaging had a great impact on the field of medical ultrasonics. Owing to the extremely high temporal resolution of ultrafast ultrasound imaging, various applications have been developed for functional imaging, such as blood flow imaging [16–20], evaluation of cardiac function [21–23], and vascular viscoelastic properties [24–26].

Ultrafast ultrasound imaging has not been used practically for very long due to its limited image quality and hardware limitations. However, it attracts significant attention because its extremely high temporal resolution is of great benefit for measurements of tissue dynamic properties. Ultrafast functional ultrasound imaging is now moving to 3D imaging. Various developments are ongoing for transducer fabrication, large-scale acquisition systems, beamforming in 3D space, and estimation of 3D tissue functional properties.

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References

1. Bruneel, C.; Torguet, R.; Rouvaen, K.M.; Bridoux, E.; Nongaillard, B. Ultrafast echotomographic system using optical processing of ultrasonic signals. *Appl. Phys. Lett.* **1977**, *30*, 371–373. [CrossRef]
2. Delannoy, B.; Torguet, R.; Bruneel, C.; Bridoux, E.; Rouaven, J.M.; Lasota, H. Acoustical image reconstruction in parallel-processing analog electronic systems. *J. Appl. Phys.* **1979**, *50*, 3153–3159. [CrossRef]
3. Shattuck, D.P.; Weinshenker, M.D.; Smith, S.W.; von Ramm, O.T. Explososcan: A parallel processing technique for high speed ultrasound imaging with linear phased arrays. *J. Acoust. Soc. Am.* **1984**, *75*, 1273–1282. [CrossRef]

4. Montaldo, G.; Tanter, M.; Bercoff, J.; Benech, N.; Fink, M. Coherent plane-wave compounding for very high frame rate ultrasonography and transient elastography. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control.* **2009**, *56*, 489–506. [CrossRef] [PubMed]
5. Couade, M.; Pernot, M.; Tanter, M.; Messas, E.; Bel, A.; Ba, M.; Hagege, A.-A.; Fink, M. Ultrafast imaging of the heart using circular wave synthetic imaging with phased arrays. In Proceedings of the IEEE International Ultrasonics Symposium, Rome, Italy, 20–23 Septembar 2009; pp. 515–518.
6. Hasegawa, H.; Kanai, H. High-frame-rate echocardiography using diverging transmit beams and parallel receive beamforming. *J. Med. Ultrason.* **2011**, *38*, 129–140. [CrossRef] [PubMed]
7. Li, P.-C.; Li, M.-L. Adaptive imaging using the generalized coherence factor. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2003**, *50*, 128–141. [PubMed]
8. Camacho, J.; Parrilla, M.; Fritsch, C. Phase coherence imaging. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2009**, *56*, 958–974. [CrossRef] [PubMed]
9. Capon, J. High-resolution frequency-wavenumber spectrum analysis. *Proc. IEEE* **1969**, *57*, 1408–1418. [CrossRef]
10. Synnevåg, J.F.; Austeng, A.; Holm, S. Adaptive beamforming applied to medical ultrasound imaging. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2007**, *54*, 1606–1613. [CrossRef] [PubMed]
11. Holfort, I.K.; Gran, F.; Jensen, J.A. Broadband minimum variance beamforming for ultrasound imaging. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2009**, *56*, 314–325. [CrossRef] [PubMed]
12. Synnevåg, J.F.; Austeng, A.; Holm, S. A low-complexity data dependent beamformer. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2011**, *58*, 281–289. [CrossRef] [PubMed]
13. Asl, B.M.; Mahloojifar, A. A low-complexity adaptive beamformer for ultrasound imaging using structured covariance matrix. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2012**, *59*, 660–667. [CrossRef] [PubMed]
14. Asl, B.M.; Mahloojifar, A. Minimum variance beamforming combined with adaptive coherence weighting applied to medical ultrasound imaging. *IEEE Trans. Ultrasonics. Ferroelectr. Freq. Control* **2009**, *56*, 1923–1931. [CrossRef] [PubMed]
15. Kim, K.; Park, S.; Kim, J.; Park, S.-B.; Bae, M. A fast minimum variance beamforming method using principal component analysis. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2014**, *61*, 930–945. [CrossRef] [PubMed]
16. Udesen, J.; Gran, F.; Lindskov Hansen, K.; Jensen, J.A.; Thomsen, C.; Nielsen, M.B. High frame-rate blood vector velocity imaging using plane waves: Simulations and preliminary experiments. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2008**, *55*, 1729–1743. [CrossRef] [PubMed]
17. Hasegawa, H.; Kanai, H. Simultaneous imaging of artery-wall strain and blood flow by high frame rate acquisition of RF signals. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2008**, *55*, 2626–2639. [CrossRef] [PubMed]
18. Bercoff, J.; Montaldo, G.; Loupas, T.; Savery, D.; Mézière, F.; Fink, M.; Tanter, M. Ultrafast compound Doppler imaging: Providing full blood flow characterization. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2011**, *58*, 134–147. [CrossRef] [PubMed]
19. Yiu, B.Y.; Yu, A.C. High-frame-rate ultrasound color-encoded speckle imaging of complex flow dynamics. *Ultrasound Med. Biol.* **2013**, *39*, 1015–1025. [CrossRef] [PubMed]
20. Takahashi, H.; Hasegawa, H.; Kanai, H. Echo speckle imaging of blood particles with high-frame-rate echocardiography. *Jpn. J. Appl. Phys.* **2014**, *53*, 07KF08. [CrossRef]
21. Honjo, Y.; Hasegawa, H.; Kanai, H. Two-dimensional tracking of heart wall for detailed analysis of heart function at high temporal and spatial resolutions. *Jpn. J. Appl. Phys.* **2010**, *49*, 07HF14. [CrossRef]
22. Provost, J.; Nguyen, V.T.-H.; Legrand, D.; Okrasinski, S.; Costet, A.; Gambhir, A.; Garan, H.; Konofagou, E.E. Electromechanical wave imaging for arrhythmias. *Phys. Med. Biol.* **2011**, *56*, L1. [CrossRef] [PubMed]
23. Cikes, M.; Tong, L.; Sutherland, G.R.; D'hooge, J. Ultrafast cardiac ultrasound imaging: Technical principles, applications, and clinical benefits. *JACC Cardiovasc. Imaging* **2014**, *7*, 812–823. [CrossRef] [PubMed]
24. Shahmirzadi, D.; Li, R.X.; Konofagou, E.E. Pulse-wave propagation in straight-geometry vessels for stiffness estimation: Theory, simulations, phantoms and in vitro findings. *J. Biomech. Eng.* **2012**, *134*, 114502. [CrossRef] [PubMed]

25. Hasegawa, H.; Hongo, K.; Kanai, H. Measurement of regional pulse wave velocity using very high frame rate ultrasound. *J. Med. Ultrason.* **2013**, *40*, 91–98. [CrossRef] [PubMed]
26. Saris, A.E.C.M.; Hansen, H.H.G.; Fekkes, S.; Nillesen, M.M.; Rutten, M.C.M.; de Korte, C.L. A comparison between compounding techniques using large beam-steered plane wave imaging for blood vector velocity imaging in a carotid artery model. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2016**, *63*, 1758–1771. [CrossRef] [PubMed]