Research Highlight

A stretchable cardiac ultrasound imager: a milestone in wearable bioimaging

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Sonography for non-invasive and continuous cardiac function imaging and measurement is essential for the diagnosis and prognosis of cardiovascular diseases [1]. The combination of electronic device miniaturization and flexible manufacturing technology has resulted in great progress in the development of wearable ultrasound patches and probes in recent years and has presented numerous alternative strategies for current clinically available technologies [2,3]. In particular, by utilizing the phased-array technique, wearable probes are capable of monitoring high-resolution ultrasound signals from deeper and wider positions, including the heart [4,5]. Despite all these advances, clinical-grade cardiac ultrasound imaging remains a key challenge in the field of wearable imagers, which still must be operated and evaluated by skilled technicians in medical facilities. This challenge mainly stems from two technical difficulties caused by the complex and fast-moving anatomy of the heart.

First, it is difficult for recently developed wearable ultrasound probes to provide a spatially and temporally comprehensive echocardiogram of the heart [5–8]. In clinical practice, transthoracic echocardiography examinations require the clinician to manually rotate and move a rigid probe to obtain a complete view of the heart for spatially comprehensive investigations [9]. Currently, to achieve this, wearable probes still require repositioning by a trained person for imaging from different perspectives, thereby offering no comparative advantage over traditional probes in practical imaging operations. In addition, although wearable devices can be conformally attached to the chest with negligible motion artefacts, very few wearable ultrasound probes can achieve cardiac imaging for a temporally comprehensive investigation during motion, due to the limitations including element density and stretchability [5]. This temporal comprehensiveness is crucial in the diagnosis of coronary artery diseases and heart failure, which yet is an insurmountable challenge for the conventional medical ultrasound equipment.

Second, high-quality processing and analysis of medical data in image form is complex; in the future, this task will require the assistance of intelligent algorithms, especially for wearable imagers aimed at miniaturization, remote operation, and convenience [10]. However, existing wearable ultrasound devices are still in the exploratory stage of material and structural designs [5–8], and the integration with artificial intelligence algorithms has not yet been realized. Analyzing the massive useful data hidden beneath the continuous image streams obtained by wearable imagers, if done artificially, is a highly arduous and lengthy process for cardiologists or physicians, and it inevitably introduces inter-variability or even personal error [11]. If these difficulties are properly resolved, wearable cardiac imagers will provide new opportunities in clinical practice [12]. Moreover, combined with the inherent strengths of wearable devices, which are related mainly to conformance with the skin, wearable ultrasound imagers can provide more information about organ and tissue changes during body movements than existing bulky equipment [8–10]. Such long-term continuous monitoring plays an important role in disease pathology and diagnosis.

Recently, a milestone in this progress was reported by Xu’s group in Nature for the innovative engineering of a wearable cardiac ultrasound imager that can continuously capture the structure and assess the function of the human heart, even during exercise [13]. As schematically shown in Fig. 1a, the wearable imager is composed of piezoelectric transducer arrays, liquid metal electrodes, and triblock copolymer encapsulation. Unlike existing stretchable ultrasound arrays with serpentine-shaped metal film electrodes, the wearable imager utilizes eutectic gallium–indium liquid metal as the electrode and styrene–ethylene–butylene–styrene (SEBS) as the substrate and insulation. The choice of this combination of stretchable materials provides the entire device with higher processing resolution and better stretchability (Fig. 1b) for conforming with skin deformations. By employing various innovative but reasonable microfabrication techniques (e.g., improved screen printing and laser ablation), the wearable imager with dense elements exhibited good electromagnetic shielding ability to enhance image quality and superior electromechanical performance, including high electromechanical coupling coefficient, low dielectric loss, wide bandwidth, and negligible crosstalk.

More importantly, to provide a comprehensive view of the heart, the wearable imager incorporates two perpendicular transducer arrays (Fig. 1a, right) that can be independently controlled for imaging echocardiograms from two orthogonal perspectives without any manual repositioning of the device. Furthermore, a wide-beam compounding transmission strategy was introduced in the orthogonal array to enhance the acoustic field across the entire insonation area.
By combining it with a center resonant frequency of 3 MHz and a matched receive beamforming strategy, the wearable arrays achieved a range of performance metrics comparable to those of commercial devices, including spatial resolution, signal-to-noise ratio, location accuracy, dynamic range, and contrast-to-noise ratio.

As a result of the material selection, structural design, and imaging strategies, the wearable ultrasound imager exhibits imaging quality similar to that of commercial imagers. Fig. 1d shows the schematics and corresponding brightness mode (B-mode) images of two orthogonal apical views from a single chest position, which were directly and easily captured by the wearable imager. Notably, a 3D scanner was used to collect the contour curvature of the chest to compensate for transducer position shifts and correct phase distortion during the transmit and receive beamforming.

Moreover, wearable imagers can potentially address the limitations of existing echocardiograms, which cannot continuously image cardiac activities before, during, and after exercise for a temporal comprehensiveness in motion. As a demonstration of stress...
Echocardiography, the authors attached the imager to a volunteer subject for continuous recording of heart activities in motion mode (M-mode) from parasternal long-axis views during the rest—exercise process (Fig. 1e). A representative section of the recorded M-mode echocardiograms in each testing stage (1: rest; 2: exercise; 3: recovery) is presented in Fig. 1f. On the basis of these 1D overlay images over time, two cardiac ventricular dimensions, the left ventricular internal diameter end systole and end diastole (LVIDs and LVIDd), were evaluated for each stage. Compared with the rest and recovery stages, the interventricular septum and left ventricular posterior wall of the volunteer’s heart moved closer to the body surface, leading to an obvious decrease in LVIDs and LVIDd during the exercise stage (Fig. 1g).

The aforementioned innovations in device engineering have solved the first technical difficulty in wearable cardiac imaging. For the second, Xu’s group integrated the wearable ultrasound imager with a deep-learning neural network (FCN-32 model) for automatic image processing (Fig. 1h). Deep-learning-based image processing can efficiently derive waveforms of critical cardiac metrics from a continuous stream of images with remarkably high temporal resolution. In brief, after automatic image processing in the apical four-chamber view, the left ventricular volumes were calculated over time (Fig. 1i); from these data, key metrics of heart performance were derived, including end-systolic volume (ESV), end-diastolic volume (EDV), stroke volume, and ejection fraction (Fig. 1j). These cardiac metrics are critical for identifying potential risk factors and changes in the cardiac pumping ability.

In conclusion, a stretchable ultrasound imager was developed that can perform long-term uninterrupted cardiac imaging from various views even during exercise. Additionally, integration with supervised deep-learning models enables the imager to provide objective and actionable quantitative metrics from images continuously and accurately. The implications of this milestone progress extend well beyond cardiac imaging because the technology can be generalized to imaging other deep tissues or organs, thereby providing new and profound insights into the pathology of many organic diseases. In the future, the miniaturization of the backend hardware of this imaging system and its overall integration and wireless enablement will revolutionize the field of wearable ultrasound devices and promote the commercialization process.

**Conflict of interest**

The authors declare that they have no conflict of interest.

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**References**


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