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EDITORIAL

Wearable Ultrasound: Are We Ready to Take This Chance for Vascular Ageing Assessment?

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Abstract

Background Wearable ultrasound (US) is an emerging innovative approach with a possibly huge impact on personalized medicine. Recent advancements in transducer material and architecture provide new opportunities in many medical areas. Within this context, assessment of vascular aging can play a crucial role especially related to the early detection of vascular alterations, i.e., before disease-related symptoms occur, reshaping the concept of cardiovascular prevention.

Aim Within this work, we aim to stimulate a multidisciplinary discussion about the possible use of wearable ultrasound in the vascular aging field.

Methods An overview on wearable ultrasound and its potential in the vascular aging field are provided with a view on data processing workflow, preclinical applications, clinical impact, and industrial challenges.

Results and conclusions The concept of wearability opens interesting scenarios for a more effective adoption of the ultrasound technology that is currently underutilized. However, there are still several open issues, both in terms of safety and performance that need to be addressed to translate the innovation into clinical practice. The combination of innovative wearable devices with the holistic and versatile approach typical for US imaging has the potential to revolutionize the vascular field and a multidisciplinary discussion about this challenge can support its advancement.

Keywords Wearable ultrasound, Vascular aging, Translation to practice

1 Introduction

Wearable ultrasound (US) is an emerging disruptive approach with a possibly huge impact on personalized medicine [1]. Recent advancements in transducer material and architecture provide new opportunities in many medical areas, leading to applications that would have been unthinkable and unrealizable years ago. The concepts of portability and wearability are opening interesting scenarios for medical US in new preventive and diagnostic settings for a more effective adoption of a technology that is currently underutilized [2]. However, there are still several open issues, both in terms of safety and performance that need to be addressed in order to translate the innovation into clinical practice [3]. Among different application areas, great interest has been placed on cardiovascular medicine because of the huge social

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impact and incidence of cardiovascular disease, and the longstanding adoption of standard medical US to derive related information [4]. Within this context, assessment of vascular aging, which can provide a picture of mainly asymptomatic changes occurring in the arterial system at the beginning of the disease, can play a crucial role especially related to the early detection of vascular alterations reshaping the concept of cardiovascular prevention [5]. It is worth noting that non-invasive US can provide an extensive characterization of the arterial aging process by providing both structural and functional properties of superficial arteries, such as the carotid, femoral, brachial, or some aortic segments [6]. The combination of innovative wearable devices with the holistic and versatile approach typical for US imaging has the potential to revolutionize the field and a multidisciplinary discussion about this challenge can support its advancement and translation into practice [7].

Within this paper, we provide an overview on wearable ultrasound and on its potential in the vascular aging field with a view on data processing workflow, preclinical applications, clinical impact, and industrial challenges.

2 Overview of Wearable Ultrasound Technology

Medical US is a technique based on the generation of inaudible high-frequency sound waves (higher than 20 kHz), their propagation, and the analysis of their reflection and scattering by the analyzed tissues. The evolution of this technology is remarkable, (i) starting with cumbersome machines, (ii) leading to more compact and portable solutions, and finally (iii) introducing the concept of wearable technology. US is widely adopted in practice because it is non-ionizing, relatively low-cost and providing several non-invasive clinical applications. A scanner is usually composed of a probe, a signal generation unit, a signal-processing pipeline, and a monitor. In dedicated applications requiring accurate and precise measurement of parameters, like for vascular aging assessment, a further step including advance data processing is required (Fig. 1).

This pipeline is quite complex and its evolution and combination with recent advancements in technology leading to the innovative concept of making US theoretically accessible to everyone, is fascinating (Fig. 2). In the next section, we briefly explore how non-invasive US can become wearable.

2.1 Key Concepts

Compact ultrasound systems can be classified according to mobility and ability to wear [8] as portable (i.e., movable solution connecting with a probe, see Fig. 2) or wearable. Wearable solutions can be based on *probe holder* or *wearable transducers,* with the latter being the focus of this paper.

It is worth mentioning that available solutions on the market as wearable probe holder include manual tools for stable fixation or automatic methods able to adjust the posture and the penetration angle of the scanner. The approach improves continuous measurement and data reproducibility. Literature reports mainly applications related to transcranial Doppler (TCD) but also stress that echocardiography, cardiac output monitoring, or vascular dynamic assessment might benefit from the adoption of wearable probe holder [8].

Recent advancement in technology and material led to the introduction of wearable transducers. According to [1], wearable ultrasound probes can be classified into three main categories: rigid, flexible, and stretchable, with different properties and fabrication strategies [1]. The typical architecture [1] includes a *transducer*, a

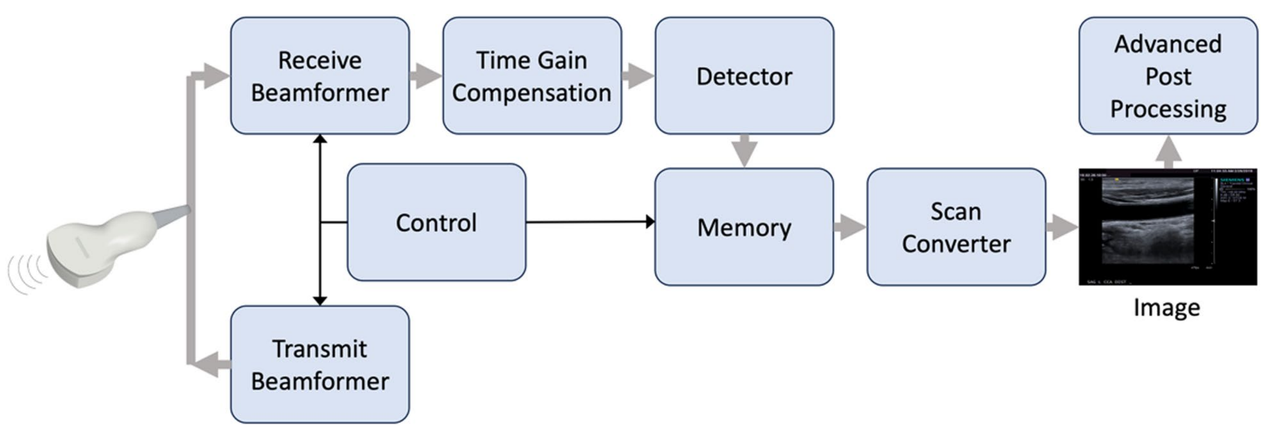

Fig. 1 Typical scheme of an ultrasound scanner composed by a probe, a signal generation unit, signal-processing pipeline, a monitor and, in applications like e.g., vascular parameters assessment, a post-processing component

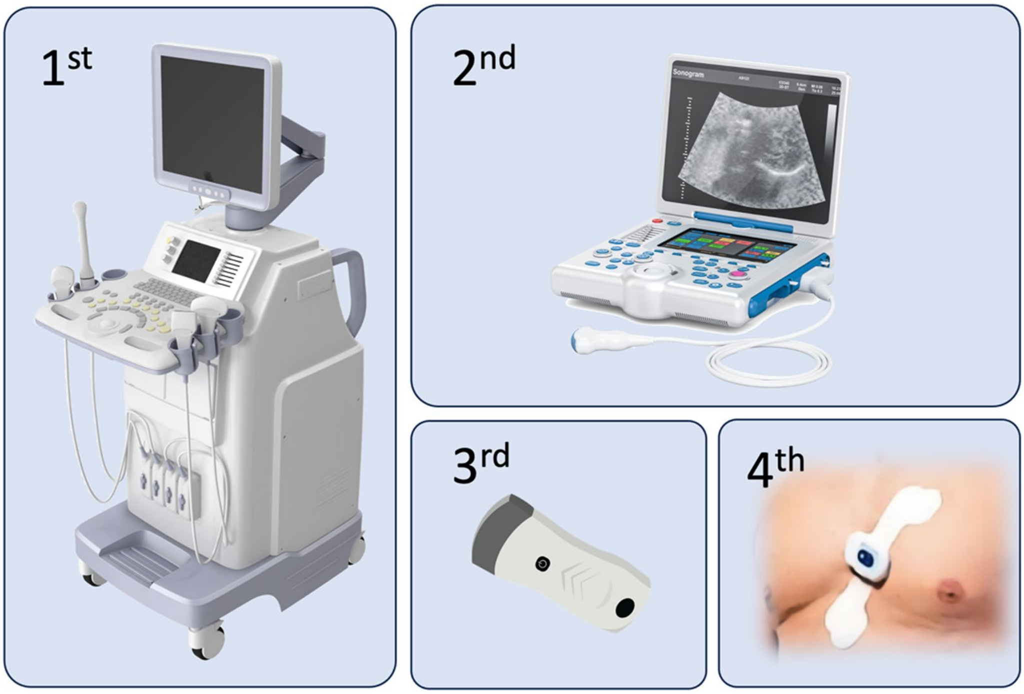

Fig. 2 Evolution of ultrasound scanners. 1st generation: cumbersome, mainly available in dedicated hospital rooms with highly trained operators. 2nd generation: more accessible laptop-based ultrasound solutions, architecture like the first one, where the electronics in a trolley has been replaced with a more portable like laptop platform; expanded adoption to different clinical fields. 3rd generation: integration with mobile, app-based (ultra-)portable ultrasound devices, the probe of the previous generation equipment and part of electronics (up to the beamformer) are generally included in a single object (smart handheld probes); some of the functions previously implemented in the electronics (i.e., the scan converter) are now implemented by a software application that runs in a separated device; more affordable and accessible. 4th generation: concept of wearable device, where all the functions of the smart probe should be implemented in single system; theoretically accessible to everyone

backing/matching layer and a number of *substrates/electrodes* (Fig. 3); the combination of these different strata and the related materials have an impact on the final performance of the US device [1].

Commonly used *transducer* materials include piezoelectric ceramics, piezoelectric polymers, and micromachined ultrasound transducers (capacitive and piezoelectric micromachined ultrasound transducers, CMUT and PMUT respectively) [4, 9]. These

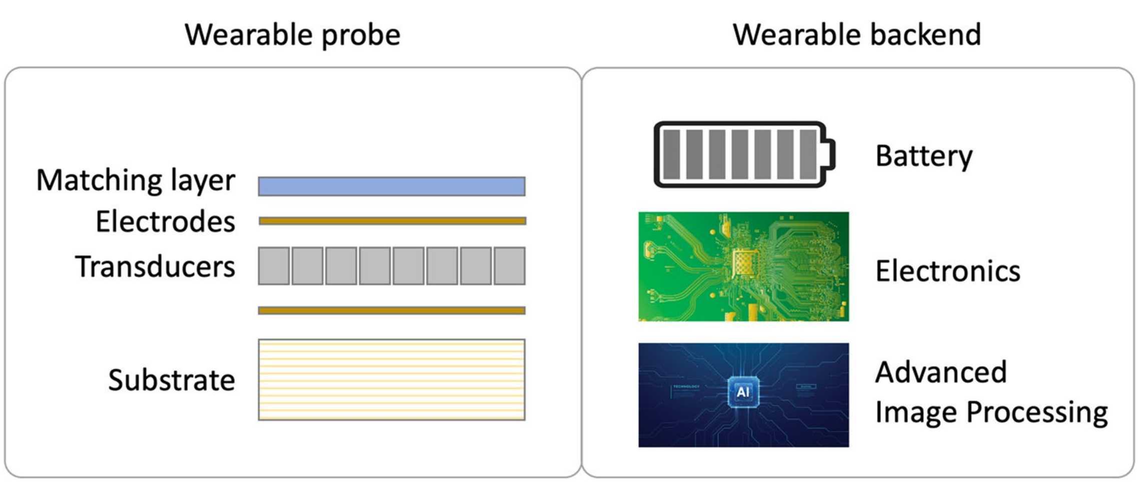

Fig. 3 Key components of wearable US

components present different properties related to transmitting efficiency and acoustic impedance, which are two relevant properties for medical ultrasound related to energy transfer to the tissue under analysis. The most suitable material has to be selected according to the desired application. Another relevant aspect that needs to be managed in the development phase is the US operating frequency to guarantee a trade-off between waves' propagation depth (i.e., the possibility to image deeper vessels) and spatial resolution (i.e., the availability of an accurate signal), which are crucial features and inversely related.

Backing (e.g., metal epoxy resin composite) and *matching* (e.g., composite or metamaterials) materials can improve the performance in terms of back reflection and minimization of the acoustic impedance mismatch, respectively. These can lead to improved quality of signal due to better bandwidth, spatial resolution, and signal-to-noise ratio (SNR).

Finally, the materials adopted for *substrates* are relevant as they lead to different mechanical properties of the probes. In particular, rigid devices are based on rigid substrate (e.g., epoxy, glass fiber epoxy weave, silicon) with well-validated development procedures. Flexible (i.e., polymer substrates) and stretchable (i.e., island bridge structure encapsulated in an elastomer, theoretically suitable for gel-free ultrasound) substrates have the potential for improved usability with respect to the rigid solutions, but the fabrication process requires further development. It is worth noting that this architecture type is dynamic and the unknown position of elements in the array requires a non-standard beamforming approach to reconstruct an image of the analyzed organ. In general, a tradeoff between the performance of the probe and its usability is required.

Finally, a further step to obtain a complete scanner, which is mainly still under development, consists of the integration of the probe with a backend in a compact solution (Fig. 3). A detailed and exhaustive review of the above-mentioned properties can be found in [1].

2.2 Examples of Applications in Cardiovascular Health

Some applications in the cardiovascular field have been explored by implementing different ultrasound imaging modes (i.e., A mode, M mode, B mode, and Doppler). Proofs of concept for the assessment of blood velocity assessment, heart rate and cardiac parameters, vascular diameter, and blood pressure are described in literature [1, 3, 4]. In general, validation is still fragmented with different in vitro approaches and low sample size for in vivo data [4].

Wearable quantitative carotid Doppler has been developed [10–12], e.g., as surrogate for monitoring rapid changes in left ventricular output and for care of patients after reconstruction surgery. There is a device available on the market: it is based on two continuous-wave 4 MHz ultrasound transducers, includes a wireless communication, and has been tested in terms of usability within a group of volunteer users [10].

Carotid M mode and B mode imaging have also been implemented. In [13], a 128-element flexible polymer array probe with operating center frequency equal to 8.2 MHz has been described. B mode imaging was derived by a commercial programmable ultrasound connected to the transducer. Arterial pressure was derived by measuring diameter in a carotid phantom and in a healthy volunteer. In [14], a rigid ultrasound probe of piezoelectric elements, working with different operating frequency (3, 7, or 10 MHz), was coupled with the skin via bioadhesive hydrogel–elastomer hybrid. The system was used to show carotid diameter and blood flow rate increase after physical exercise. Proof of concept of imaging at other than the carotid artery, such as the radial [15] and ulnar [16] arteries, has been provided as well.

Interestingly, an experience is available in the literature reporting different aspects of the development and application process of new wearable technology [17–19]. A stretchable probe based on orthogonal architecture of 32X32 piezoelectric elements, operating at 3 MHz, to ensure a tradeoff between resolution and depth, was developed for wearable B mode imager. A deep learning model was applied to derive left ventricular parameters, such as stroke volume, cardiac output and ejection fraction [17]. The measurements were validated against data obtained by standard echography. In addition, the same group developed an integrated system with both a US probe and a wireless control in a wearable format, implementing a further step toward the concept of wearable scanner (and not just wearable probe) [18]. An operating frequency of 4 MHz was used for M mode images at the carotid artery and then pulsation waves were automatically derived using a machine learning classification model. Agreement in terms of heart rate and pressure values with respect to tonometry was provided [18]. Moreover, in a further study, a proof of concept integrating acoustic (hemodynamic parameters) and electrochemical (metabolic) sensors was provided in human volunteers: this opens a real window into the medicine of future [19].

3 Wearable US Vascular Aging Assessment: Challenges and Perspectives

Wearable US might be adopted in the vascular aging field: an overview of the related potential and issues is reported in the subsequent paragraphs with a focus on data processing workflow, preclinical applications, clinical impact, and industrial challenges (Fig. 4).

3.1 The View on Biosignal Processing

Wearable devices carry specific challenges in early phases of the received signal reconstruction process. More specifically, considering the acquisition of ultrasound echoes from different directions and analysis of their time delays and attenuated amplitude with respect to the transmitted signal leads to the concept of "beamforming", thus combining information from multiple transducer elements and being crucial for image creation [20, 21]. This is a sophisticated process, important to ensure quality and performance, that becomes particularly complex when dealing with non-rigid wearable probes. In fact, the time delays used for image reconstruction are proportional to the distance between the considered region and the probe elements, and thus a dynamic position of these elements introduces uncertainty. Artificial intelligence (AI) and current advances in biosignal analyses might play an important role and can help improve image reconstruction and quality, which are the bases for the assessment of structural, functional, and dynamic characteristics of the cardiovascular system at various sites (e.g., heart, carotid, femoral, or brachial artery).

In general, well-validated computerized approaches for processing US data (i.e., images and clips) to derive characteristics of vessels are preferable compared to manual measurement by (medical) operators to avoid human bias reducing operator dependency and to increase efficiency [6]. In addition, there are solutions e.g., the measurement of diameter or intima–media thickness or the assessment of structural arterial alterations such as plaques with recent advancements based on artificial intelligence (AI) [6]. Software for advanced US signal processing is either

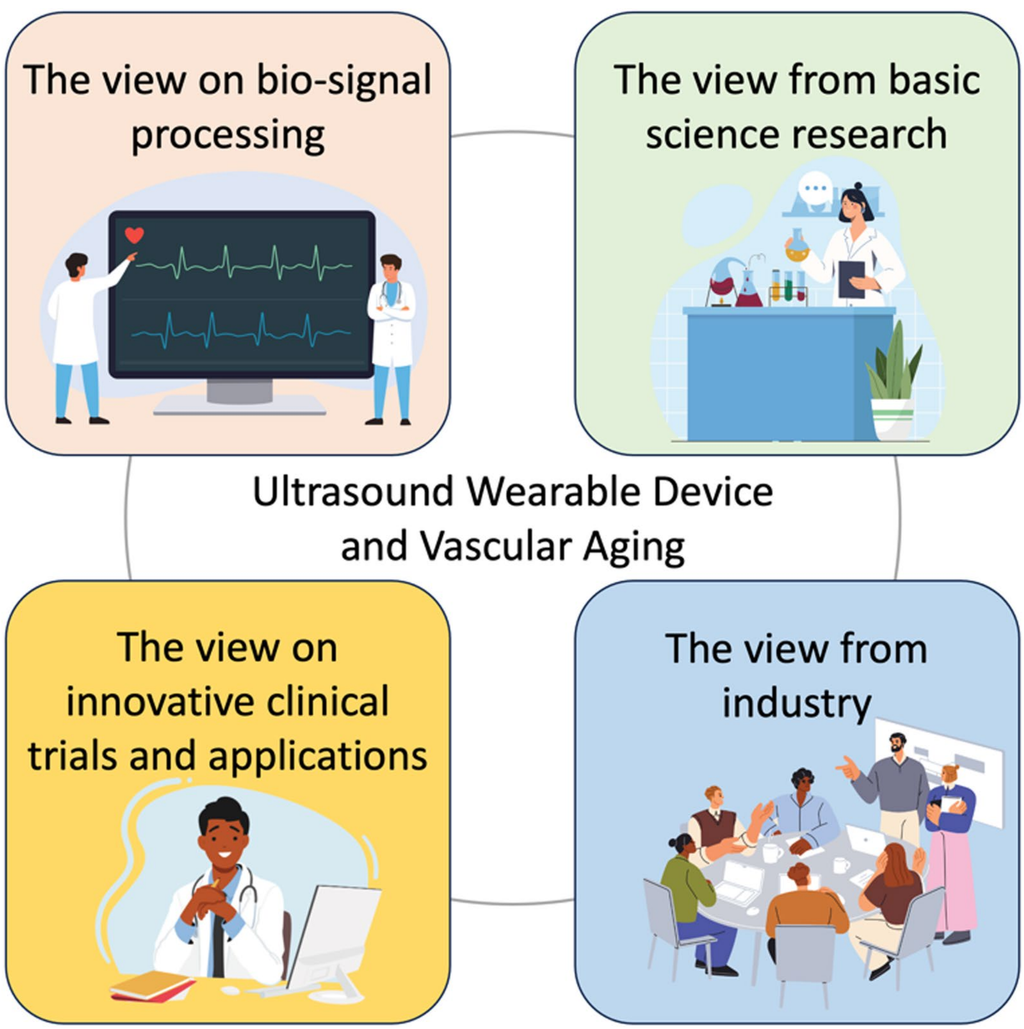

Fig. 4 The reported views around wearable ultrasound application in vascular aging assessment

provided embedded by US equipment manufacturers or as device-independent solutions (i.e., standalone software). Both approaches comprehensively depend on the data quality, whereas former solutions can benefit of deeper knowledge on recording settings, preprocessing, and possibility to directly influence the recording process through real-time feedback during the measurement process. It is worth noting that the integration/connection of US hardware with the related software needed for vascular assessment is a relevant aspect involving several technical requirements that need to be carefully considered for these innovative solutions. Another point to consider is that in “traditional” US acquisition systems using hand-held transducer (probes), data quality highly depends on the operator’s ability to correctly insonate the target structure. This operator influence can be overcome by wearable solutions with the trade-off for possible quality reduction due to loss of skin contact or misplacement related to the site of interest. Thus, wearable solutions are in need for advanced automatic quality assessment, which could as well be used for real-time feedback to the user. Not just quality assurance but as well automatic and real-time analysis of data might benefit from highly sophisticated biosignal processing and AI-based algorithms.

Wearable US solutions offer a unique opportunity by the possibility to easily access US images simultaneously from more than one artery, thus combining time-related parameters from different sites and integrating these with other synchronous biosignals. This can as well be used to synchronously record different US modes, i.e., M, B, and/or Doppler mode, thus combining different information from the different signals. This approach poses additional requirements to the wearable US acquisition system in terms of synchronization of different sites, sources, and modes, especially when real-time assessment is of interest. Furthermore, data storage and possible communication with the host device are important requirements for a smooth realization of signal processing, in real-time and post hoc analysis settings.

3.2 The View from Preclinical Research

Ultrasound and more specifically Ultra-High-Frequency Ultrasound (UHFUS) imaging are powerful and widespread techniques for preclinical cardiovascular studies [22]. However, it currently requires dedicated devices designed to work, not in normal physiological conditions, but with animals under anesthesia (usually isoflurane), which has a reducing effect on heart rate and blood pressure.

Accordingly, wearable ultrasound could allow in vivo acquisitions in physiological conditions at least after a “training” period to adapt animals to the presence of the device. In addition, the permanent positioning of these devices would allow experimental study designs based on repeated ultrasound analysis over time that are currently not possible because of the limitation on anesthesia duration. Finally, monitoring under special conditions that simulate real-life scenarios (e.g., exercise, cognitive test) would be possible by these systems.

Optimization of weight/size of the devices to allow free movement of animals is a crucial requirement. As regards interspecies differences, this might be more challenging in rodent models (especially mice, which are widely adopted in cardiovascular studies) compared to medium-sized animals, because of the unfavorable weight and volume ratio of the device with respect to the small subject. Other technical difficulties are related to the need, due to the small dimensions of the analyzed organs, of ultrasound transducers working at high frequencies, in the range of 25–70 MHz, whereas, to our knowledge, currently available probes are working at lower frequencies, in the typical range for human studies. In addition, rapid growth of hair (especially in rodents) could interfere with the impedance matching between the ultrasound sensor and the skin. Finally, special attention should be paid to aggressive behavior of animals (self-inflicted or inflicted by cage mates) that can be exacerbated by the presence of the wearable device.

Partial workarounds to the aforementioned problems can be hypothesized. Wearable system could be used under low sedation (working under pseudo-physiological conditions), using hairless animals (when this option is available for a specific cardiovascular pathological model), programming single-cage housing (exposing animals to a nonstandard social condition), and placing the device in not easily self-accessible body areas (reducing the number of scanning views).

Nowadays, the main use of wearable ultrasound in preclinical research is for treatment, with neuromodulation attracting major interest with studies [23, 24] using semi-implantable devices necessitating clipping of the scalp for adhesion; the approach might be useful for vascular preclinical research as well, given the strong evidence supporting the relationship between vascular aging and neurodegenerative diseases [25].

Another prevalent use of wearable ultrasound is for transdermal drug delivery via sonophoresis, [26, 27], an approach might be extended to the study of new drugs aimed at slowing vascular aging.

In the field of medical diagnosis, relatively few applications are available. One of the most significant is the Shear Wave Elastography (SWE) implementation [28] to measure liver stiffness in a rat model of acute liver failure: the measurement of tissue stiffness could be used to analyze vascular aging parameters as well.

With particular reference to the cardiovascular system in [29], a system for the evaluation of the carotid blood flow by continuous Doppler monitoring was tested in a porcine model of cardiac arrest; the same flow velocity information could be used for morpho-functional analysis of the carotid artery. Furthermore, the ultrasound–photoacoustic sensor proposed in [30] provides a valid example of wearable dual imaging modality that could expand the knowledge about vascular wall constituents and their contribution in vascular aging.

As a final consideration, from an ethical point of view, adoption of wearable ultrasound systems would perfectly fit the principle of 3Rs (Replacement, Reduction and Refinement), as a technique with relatively low stress for the animal, allowing acquisition of in vivo images at multiple time-points, thus reducing the number of animals needed for experiments.

3.3 The View on Innovative Clinical Trials and Applications

Quality and applicability of ultrasounds have improved markedly, resulting in its extensive use as a point-of-care tool in medical care [31]. However, to date in the clinical setting, ultrasound is mainly used as a once-in-a-lifetime test or few evaluations over time at best, especially for indications like vascular aging assessment and CV risk stratification [32, 33]. Indeed, a sporadic use seems adequate to improve treatment decisions in chronic, stable conditions. However, wearable US imaging opens novel possible uses related to the opportunity of continuous monitoring in situations that are normally not explored, such as recordings at nights, during dynamic conditions or at home.

Preliminary studies on wearable ultrasound indicate a relevant clinical application for non-invasive, continuous monitoring of hemodynamic conditions in critical situations (surgery, emergency department, intensive care unit, maternity units) [34]. Other studies indicate the feasibility of wearable ultrasound during dynamic conditions such as exercise [17]. This may be useful not only to perform dynamic tests in hospital settings (exercise testing, orthostatic tolerance, etc.), which are extensively used for diagnostic purposes, but make it possible to study hemodynamic adaptation to stress in real-life conditions for a better correlation with symptoms.

Finally, wearable ultrasound may allow home monitoring in severe chronic conditions, once mostly treated in hospital. Recent studies revealed that frequent, day-to-day assessment of vascular hemodynamics allows for the early detection of (clinical) deterioration, and in addition personalized, rapid adjustment of treatment strategies to improve clinical outcomes [35]. This application will also allow setting up decentralized clinical trials with objective hemodynamic variable monitoring in those conditions [36].

Main variables that are useful in those scenarios are cardiac [17] and common carotid [34] motion and flow, but also transcranial Doppler [37]. Besides, arterial diameter assessment has been used to derive cuffless blood pressure [4]. Furthermore, application of multiple sensors may allow assessment of two-point pulse wave velocity and arterial stenosis assessment.

A reflection about clinical and technical validation of ultrasound devices used for continuous monitoring is mandatory. Agreement and reproducibility need to be tested not only in static, but also in dynamic conditions, as suggested in the recommendations for the validation of cuffless blood pressure measuring devices [38].

3.4 The View from Industry

Since the introduction of the first devices, the industry of medical ultrasound has evolved significantly in terms of technology, application, and functionality and one of the most important trend is the miniaturization. The new handheld devices are an important step that brought the industry of medical ultrasound to point-of-care settings, including remote areas, ambulances, and field hospitals. Probably, they cannot totally replace the previous devices because they might not reach the same performances and features, but they can expand the use of ultrasound technology to areas that were not covered previously. The trend is more and more evident in recent advances toward the development of wearable ultrasound devices, that have the potential to transform healthcare and constitute a great and attractive opportunity for the medical ultrasound industry (in Table 1, some business projects' examples are reported). However, the development of this new type of product has also more complex challenges, including technical limitations, measurement reliability, regulatory and user-related issues.

Concerning the technical issues, one of the main challenges is to move from a fixed and rigid to a flexible and stretchable ultrasound transducer. Currently, this results in an increased transducer element pitch, which reduces the focusing capability and lateral resolution, and the use of materials that produce a lower SNR with respect to standard probes. In addition, the geometry of the probe is not known a priori, and this introduces complexity in the generation of an image. Another important challenge is the power management. Ultrasound devices require a significant amount of energy to generate and transmit sound waves deep into tissues, especially for high-resolution imaging or continuous monitoring. Designing a wearable ultrasound

Table 1 Some examples of business projects whose US wearable products might impact on vascular aging assessment; info extracted from the internet

Business project	Type of device	Main application	Link
Pulsify	Flexible 2D array patch of ultrasound transducers	Solution for heart failure acute and chronic management providing key cardiac measurement (i.e., cardiac output, end-systolic/end-diastolic left ventricle volumes, stroke volume, ejection fraction) Planned pivotal trials for MDR and 510 (K)FDA roadmaps	https://pulsify-medical.com
Novosound	Flexible, high-resolution, adaptable and scalable ultrasound sensor	Adoption of latest thin-film deposition technologies to create various products for different industry fields with a unique printed ultrasound sensor. Applied for blood pressure monitoring	https://novosound.net/
Softsonics	Soft stretchable patch. Size of a postage stamp	Wearable ultrasound device to assess cardiac structure and function. It can be worn for up to 24 h and works even during strenuous exercise	https://www.f6s.com/company/softsonics
Flosonics	Wearable Doppler wireless ultrasound	FloPatch device reports carotid arterial pulse metrics in real-time and exploit possible association between carotid Doppler pulse, stroke volume, and arterial hemodynamics. FDA clearance	https://flosonicsmedical.com/
Usono	Wearable probe holder providing lengthy and stable fixation of an ultrasound probe to the body	ProbeFix Cardiac is a tool to attach a phased array to the thorax for continuous cardiac imaging. ProbeFix Dynamic is a CE marked tool to make linear (or convex) transducers wearable. Different applications available and development of customized solutions	https://www.usono.com/

system that operates with minimal power while still providing high-quality imaging is difficult. This is an issue also for handheld devices, and it is more and more challenging for a device where the battery should be of limited weight and size.

Concerning the measurement reliability, besides the ensuring adequate SNR, issues that can arise from the patient movement need to be considered. In fact, a sensor fixed to the skin reduces some limitations of the classical probes like intra-observer variability, but if worn on joints or muscles, the patient's motion can interfere with signal quality, leading to distorted images or inaccurate data. The adoption of artificial intelligence (AI) approaches can certainly help in dealing with signal quality and measurement reliability.

Concerning the regulatory requirements, gaining approval to enter the market for new medical devices is a lengthy and complex process, especially when introducing innovative technologies or functionalities, where evidence of safety and performance is needed. Wearable ultrasound needs to be tested in terms of safety considering, e.g., potentially harmful effects of a continuous use on tissues. Even though the power of the US cannot be high due to technical restrictions in power consumption, we must deal with potentially thermal and nonthermal effects of a prolonged exposure. In addition, the effectiveness of the vascular aging measurements should be demonstrated in a device that is substantially different from a standard ultrasound scanner.

Nowadays, several steps have been done toward the development of this technology, but several other steps have to be completed. Most of the current wearable ultrasound devices are wired for power supply and data transmission, and, to our knowledge, there have been a few demonstrations of a fully integrated wireless wearable US device [10, 18]. Measurement reliability, usability, and regulatory issues have been not fully addressed so far. Due to complexity and limitations of wearable ultrasound, unlikely this approach might totally replace standard ultrasound devices. However, its huge potential for new and different applications such as dynamic monitoring might provide a new and valid tool for vascular aging assessment.

4 Discussion and Conclusions

The concept of wearable ultrasound for assessing vascular aging is promising, but further research and development is needed to address technical challenges and to show the preclinical and clinical usefulness. In this paper, different and complementary aspects of the translational process into practice, considering the main limitations and underling the remarkable potential of this innovation, are addressed.

In particular, the view on data processing and wearable US is wide, opening many interesting opportunities since this approach could provide, without the need of operator, simultaneously analysis at different sites and combination with other synchronous biosignals. Open issues are related to quality of the data, synchronization, data storage and communication especially for real-time applications as well the integration with software for advanced image processing to derive accurate and precise vascular assessment.

Regarding the preclinical field, the value of wearable US could be the possibility to perform in vivo acquisitions under physiological conditions. It is worth noting that this would be an ethical approach with relatively low stress for the animal, allowing acquisition of in vivo images at multiple time points, thus reducing the number of animals needed for experiments. Technical challenges need to be overcome, especially in terms of size and the needed spatial and temporal resolution for some specific animal models (e.g., rodent models).

The potential of wearable ultrasounds in clinical care and research has been shown in feasibility studies available in the literature. Continuous monitoring of multiple conditions in unprecedented settings, such as during exercise stress testing, sleep monitoring, hemodynamic monitoring in high-risk pregnancies, might open new avenues for assessment of dynamic and functional changes in the cardiovascular system. However, these must be evaluated and validated through trials for their application in routine clinical practice.

According to the above-mentioned points, transition from handheld to wearable devices is an incredible opportunity for the medical ultrasound industry with huge potential of growth. However, the introduction of this new technology also brings some complex technical challenges and sustainability considerations, and, to enter the market, needs to be supported by evidence in terms of safety and performance.

It is worth noting that this translational process implies a new approach for ultrasound's application also from the patient's perspective, with the patient theoretically becoming more active in the adoption's pipeline with potential involvement e.g., in quality checks or cleaning procedures. Thus, further development of the technology demands codesign strategies taking into consideration feasibility also in terms of willingness criteria and training requirements. Future studies focusing on the user experience and perception might be valuable for an integrated context analysis including the view based on the patient's perspective.

In conclusion, wearable ultrasound could represent a significant advancement in the field of preventive cardiovascular health, offering the opportunity for a real paradigm shift based on vascular aging monitoring in new settings through the implementation of a personalized and proactive model. According to the disruptive technology adoption lifecycle by Moore's theories [39], wearable US will have to deal with a crucial difficult phase in order to be translated into practice: the transition from innovators/early adopters to early majority. A crucial step for crossing this chasm in our specific field is the identification of a primary intended use of the technology in vascular aging assessment. A collective intelligence-based approach to this challenge will then provide a solid starting point for a transversal effective roadmap resulting in a huge beneficial impact for the patient.

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EB contributed to conception, design and drafting of the work. RMB, SB, FF and CCM contributed to drafting of the work. VG contributed to drafting of the work and provided the figures. All the authors reviewed and approved the final version of the paper.

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Data Availability
No datasets were generated or analysed during the current study.

Declarations

Conflict of interest
Elisabetta Bianchini, Francesco Faita and Vincenzo Gemignani are co-founder of QUIPU s.r.l., Pisa, Italy a spin-of company of the Italian National Research Council and the University of Pisa developing software medical devices. For the remaining authors, there are no conflicts of interest.

Ethical Approval and Consent to Participate
Not applicable.

Consent for Publication
All the authors reviewed and approved the final version of the paper for publication.

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