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Perspective

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Some perspectives of continuous arterial blood pressure measurements: from kymograph to tonoarteriographic imaging

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Abstract

The measurement and monitoring of continuous arterial blood pressure (BP) have undergone significant evolution over the past 170 years, transitioning from ancient invasive approaches, like kymograph, to modern non-invasive and unobtrusive technologies such as tonoarteriography (TAG). This progressive shift has revolutionized the way we track BP, providing safer, more accurate, and convenient methods for monitoring BP. This paper aims to provide some historical perspectives on the development of continuous BP technology, highlight key milestones that have shaped the field, discuss the state-of-the-art two-dimensional TAG imaging, and address challenges for future unobtrusive BP measurements. In addition to presenting a concise review of the progression of continuous BP measurement technologies, this article also emphasizes the importance of adopting more precise, convenient and affordable approaches for personalized BP monitoring at home and patient care optimizations at hospitals, thereby empowering healthcare professionals to enhance pervasive hypertension management anywhere.

Keywords: Blood pressure, unobtrusive BP, continuous BP, cuffless BP, two-dimensional tonoarteriographic imaging, hypertension

INTRODUCTION

Hypertension, as the leading preventable risk factor for cardiovascular diseases (CVDs), poses a significant global health challenge. With an estimated 1.3 billion people affected worldwide, it claims the lives of approximately 10 million individuals annually[1]. To effectively prevent and intervene in hypertension and its associated CVDs, reliable and timely measurement, diagnosis, and monitoring of BP are crucial[2]. While conventional office BP measurement is the established gold standard[3], it provides only a single assessment under conditions that can influence the level of BP being measured[4]. Recognizing this limitation, out-of-office BP measurements, including home BP monitoring (HBPM) and ambulatory BP monitoring (ABPM), have gained prominence for their additional diagnostic value in hypertension care interventions[5]. Specifically, patient-initiated HBPM is increasingly preferred due to improved BP control, diagnosis of white-coat hypertension, telemonitoring feasibility, and cardiovascular risk prediction[6]. Moreover, HBPM is also more cost-effective and efficient compared to ABPM, particularly for long-term hypertension screening[7,8]. The significance of personalized long-term BP monitoring at home is widely recognized[9], but commonly used methods, such as auscultatory and oscillometric, have limitations that hinder their effectiveness in this context. Specifically, the use of an inflatable cuff causes discomfort among individuals with hypertension, necessitating frequent readings, and it lacks the ability to perform nocturnal recording, which is critical in preventing sudden deaths[10]. Additionally, these methods only provide intermittent measurements and cannot adequately monitor short- or long-term BP changes, which hold importance in assessing individuals at risk who may not conventionally be considered candidates for treatment benefits[11-14].

Challenges to the implementation of out-of-office BP measurement were patient inertia, poor patient compliance, lack of medical consultation time, limited access to a sphygmomanometer and shortage of related educational materials[5]. Recognizing the indispensability of home-based long-term continuous BP monitoring, a range of strategies are being explored to improve BP control, including individualized treatment, behavioral interventions, user-friend devices, mobile health apps, and online platforms, all of which underscore the essential role of treatment adherence and consistency[15].

In light of these, the purpose of this paper is to provide a concise review of the historical evolutions of continuous BP measurement technology, tracing its evolution from traditional invasive methods to the current advanced TAG techniques[16]. By examining key milestones and advancements in the field, this review offers insights into the challenges faced in BP monitoring and highlights potential opportunities for future developments.

MILESTONES OF CONTINUOUS BP MEASUREMENT TECHNIQUES

This section offers an overview of the progression of continuous BP measurements, categorized into four stages, including the development of invasive methods, non-invasive approaches, the emergence of cuffless technologies, and the current frontiers of TAG imaging, as shown in Figure 1.

Developments in invasive BP measurement approaches

The history of continuous BP measurement dates back to the emergence of invasive BP techniques in 1733, when Stephen Hales observed fluctuating blood levels in a glass tube inserted into a horse's artery, laying the foundation for future developments[17]. A century later, a significant achievement occurred in 1847 with Ludwig's development of the kymograph, which enabled graphical recording of continuous oscillations of human arterial pressure through arterial cannulation, revolutionizing the acquisition of valuable hemodynamic information[18]. In 1949, intra-arterial continuous BP measurement through cannulation was first implemented in clinical settings[19]. Subsequently, technological and medical advancements during the
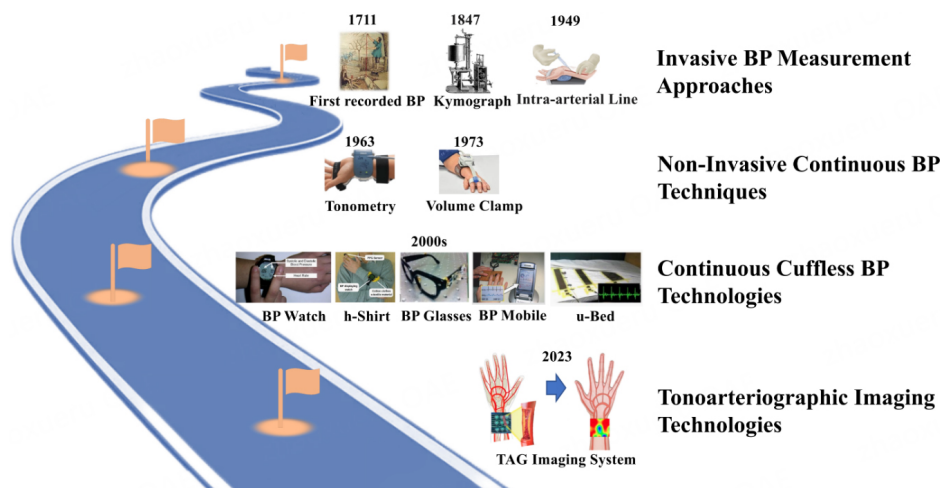
Figure 1. Diagram of four stages in the evolution of continuous blood pressure (BP) measurements.
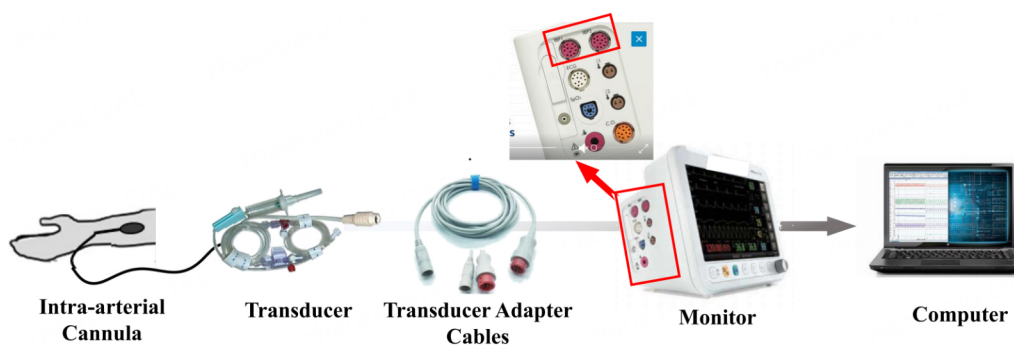

Figure 2. Operational diagram of clinical invasive blood pressure (BP) monitoring device.

20th century propelled the further development of invasive BP measurement techniques, including the refinement of catheterization methods, introduction of electronic amplifiers and transducers, and adoption of disposable catheters, significantly enhancing reliability, real-time monitoring, and availability of invasive BP monitoring. Today, invasive BP (IBP) method is considered the gold standard in ensuring accurate and continuous BP measurement in intensive care units (ICU), operating rooms, and other clinical environments, with the operational diagram depicted in Figure 2[20]. Based on empirical clinical data, this approach demonstrates a commendable reliability and stability, as evidenced by Mean Error (ME) of 3 mmHg and Standard Deviation (SD) of 2 mmHg[21-23]. Nevertheless, it is essential for physicians to be mindful of the potential accuracy limitations of IBP in certain patients due to underdamping/resonance phenomena, as highlighted by a study revealing underdamping/resonance occurrence in 30.7% (92 out of 300 subjects) of arterial signals[24]. Additionally, this approach is not without inherent risks, including symptomatic or asymptomatic arterial thrombosis, infections, accidental injection of intravenous drugs, and other discomforts associated with catheterization, rendering continuous monitoring in daily activities impractical[25]. Consequently, the demand for non-invasive BP measurements has become an ongoing challenge, prompting the necessity for further enhancements in the field.

Advancements in non-invasive continuous BP techniques
In contrast to invasive methods, non-invasive BP (NIBP) measurement techniques offer improved safety, reproducibility, and procedural simplicity[26]. The exploration of NIBP began in 1963 when G.L. Pressman

and P.M. Newgard introduced the first arterial tonometer, accompanied by the development of a discrete, linear mechanical model[27]. Another significant development occurred in 1973 when Peñáz devised the volume clamp method[28], as shown in Figure 3. These techniques continue to be widely used in continuous BP monitoring today and have played an important role in the widespread adoption of home monitoring. There are increasing studies to assess the accuracy of NIBP methods. For example, Saugel *et al.* examined the feasibility of arterial pressure measurement using tonometer technology in 34 ICU patients[29]. They compared TL-200pro (Tensys Medical, Inc., San Diego, CA, USA) radial artery readings to femoral catheter values, revealing bias and limits of agreement for Mean Arterial Pressure (MAP) (+0.72 mmHg, -9.37 to +10.82 mmHg), Systolic Arterial Pressure (SAP) (-1.39 mmHg, -18.74 to +15.96 mmHg), and Diastolic Arterial Pressure (DAP) (+4.36 mmHg, -8.66 to +17.38 mmHg) from 4,502 averaged 10-beat epochs, with errors at 12%, 14%, and 21%[29]. Moreover, Jagadeesh *et al.* found 94.5%, 95.1%, and 99.4% agreement for Systolic Blood Pressure (SBP), Diastolic Blood Pressure (DBP), and MAP, respectively, demonstrating volume clamp technology's reliability comparable to invasive methods[30]. While NIBP methods show promise in terms of accuracy, they are facing challenges including unwieldy design and discomfort caused by cuffs, necessitating external force. At the same time, practical issues on optimal sensor positioning, susceptibility to motion-induced artifacts and complex calibration remain significant considerations[31,32], limiting their suitability for continuous daily use. Thus, substantial efforts are needed to attain ubiquitous, unobtrusive, and continuous BP monitoring.

Achievements in continuous cuffless BP technologies
Recent technological improvements have made notable strides in the field of continuous BP measurement, particularly in the development of cuffless techniques. Different from traditional mechanical-based BP measuring methods such as arterial line and stethoscope, cuffless measurement methods commonly employ techniques such as photoplethysmography (PPG), electrocardiography (ECG), impedance plethysmography (IPG) and innovative camera-based remote PPG[33], which eliminate the need for traditional cuffs, providing more convenient and pervasive methods for measuring BP.

Over the past two decades, significant achievements have been made in the development of wearable cuffless BP/TAG measuring devices, allowing for continuous BP monitoring in daily life. Notably, Li *et al.* have contributed to the early development of various cuffless BP measurement models and platforms[34], as depicted in Figure 4, including BP ring[35], BP watch[36], h-Shirt[37], BP mobile phones[38], u-Chair[39], u-Bed[40], BP glasses[41], BP armband[42], *etc.*, which utilize both physiological mechanism model and data-driven or AI model-based methods for BP estimation. Remarkably, they have introduced multi-wavelength photoplethysmography (MWPPG) technology[43,44], which has been validated by Liu *et al.* in a large-scale study involving 3,077 participants, demonstrating the reasonable performance of the MWPPG-BP method[45]. Overall, these remarkable innovations in wearable continuous cuffless BP measurement devices, coupled with extensive research and validation studies conducted by multiple teams, have offered the possibility of realizing convenient, unobtrusive, continuous monitoring of BP without inflation/deflation cuff for daily uses.

However, cuffless BP devices are not recommended for clinical use according to the 2021 European Society of Hypertension Guidelines[46], possibly due to ongoing concerns about their accuracy. These concerns arise from factors such as validation problems, issues with sensor placement, potential motion artifacts, and calibration challenges. While many studies claim to adhere to standards for BP measurement accuracy, such as the AAMI/ESH/ISO Universal Standard (imposing bias and precision errors within 5 and 8 mmHg) or the IEEE Std 1708™ standard for wearable cuffless BP devices [requiring a mean absolute difference (MAD) ≤ 7 mmHg][47], it is important to note that these claims might not fully follow all the essential criteria outlined by these standards[46,48-51]. However, there are some approaches for cuffless BP estimation that have
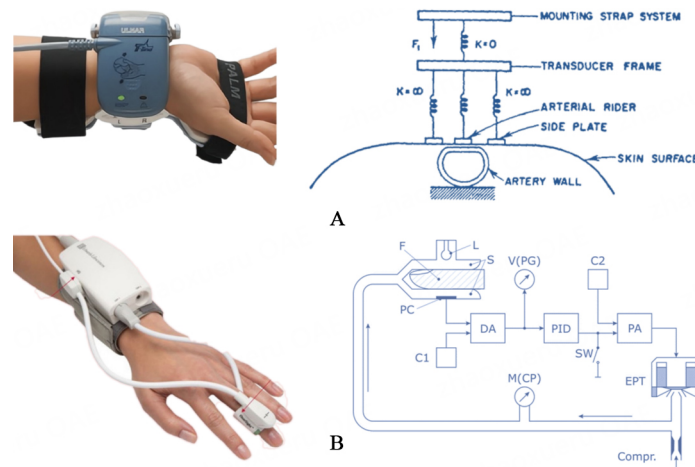
Figure 3. Product forms and block diagrams for (A) arterial tonometer and (B) volume clamp system[11].
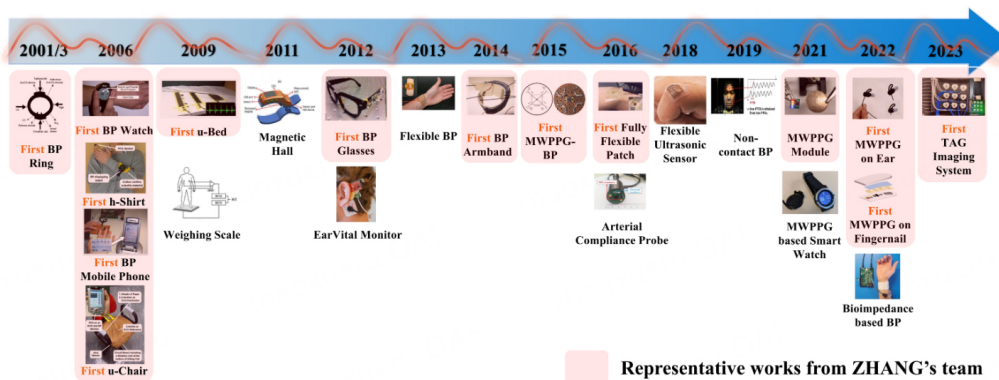

Figure 4. Some major prototype developments of continuous cuffless blood pressure (BP)/tonoarteriography (TAG) measuring devices over the past 20 years.

demonstrated promising outcomes. For instance, a pioneering algorithm integrating PTT and photoplethysmogram intensity ratio (PIR) conducted the validation on a cohort of 27 subjects, resulting in mean ± SD values of -0.37 ± 5.21 mmHg, -0.08 ± 4.06 mmHg and -0.18 ± 4.13 mmHg for systolic, diastolic, and mean BP respectively, with corresponding MAD measuring 4.09 mmHg, 3.18 mmHg and 3.18 mmHg. Remarkably, their findings exceeded the performance of the two most cited PTT algorithms by approximately 2 mmHg in both SD and MAD[52]. This underscores a positive trajectory in the advancement of cuffless BP measurement techniques.

Two-dimensional (2D) TAG imaging technologies
The aforementioned BP measurement techniques primarily focus on single-point or one-dimensional time serial signals, limiting the ability to comprehensively assess BP distribution across different regions[53]. Recognizing the substantial influence of measurement sites on BP evaluation, we have proposed a novel approach known as TAG imaging system, a cost-effective, wearable and non-invasive technique used for continuous 2D BP monitoring based on a homemade electronic-optical sensor array[54].

The architecture of the TAG imaging system is graphically depicted in Figure 5. Comprising a wearable multichannel signal acquisition configuration, this apparatus features an arrangement of 9 PPG sensors. These sensors are strategically positioned to encompass the radial and ulnar arteries, as well as the adjacent
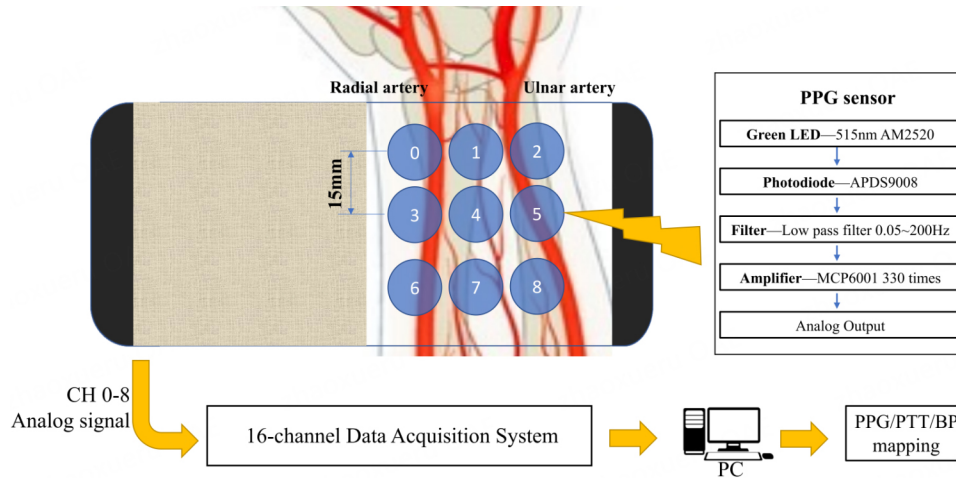
Figure 5. Architecture of the tonoarteriography (TAG) imaging visualization system.

regions, optimizing spatial coverage. Imbedded within a designed wristband, these sensors wrapped by the elastic band hold a close and conforming interface with the skin. Additionally, we employed a 16-channel data collection module (manufactured by Biopac Systems Inc., USA) to gather data simultaneously and continuously for the analysis and mapping of PPG, PTT, and BP.

This system visualizes the distribution of PPG/BP at the wrist using a multi-channel PPG array and one-lead ECG. BP is derived based on the PIR-PTT equations (1-2), as introduced by Ding *et al*.[52,55]:

$$DBP = DBP_0 \cdot \frac{PIR_0}{PIR} \tag{1}$$

$$SBP = DBP_0 \cdot \frac{PIR_0}{PIR} + PP_0 \cdot (\frac{PTT_0}{PTT})^2 \tag{2}$$

where PTT is derived from calculations on ECG and localized PPG signals, DBP_0, PIR_0, PP_0 and PTT_0 are calibrated from continuous BP from Biopac. Distinct variations in local peripheral BP can be identified, providing valuable insights into BP distribution across different regions. The estimated differences in SBP and DBP from different channels are calculated using the equation (3):

$$Difference = BP_{Reference} - BP_{ChX} \tag{3}$$

where $BP_{Reference}$ are continuous BPs obtained from Biopac, and BP_{Chx} are estimated BPs from Channel X (X = 1, 2, 3…9). Subsequently, these variations are graphically represented through heatmap and color fill, as illustrated in Figure 6. The study presents a two-dimensional framework for regional BP measurement, offering potential applications in evaluating peripheral vascular conditions and improving central or brachial BP estimation accuracy for effective hypertension management.

Compared with the current commercial BP measurement products, the proposed system offers a potential solution to addressing issues related to inconsistent device placement, which is the limitation inherent in single-point cuffless BP measurements. It holds promise for delving into the complex relationship between signal accuracy and spatial positioning, leading to improved precision and a wider range of physiological
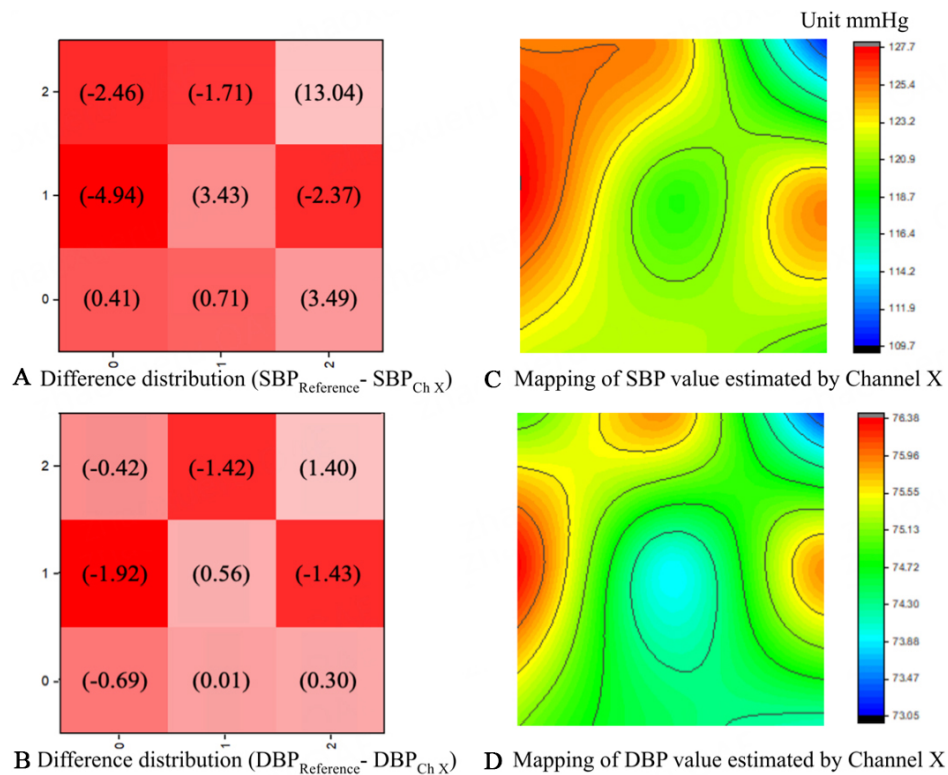
Figure 6. Mapping of estimated difference distribution ofblood pressure (BP) values from different channels[54].

parameter estimations within confined measurement locations. Moreover, the system demonstrates the capability to improve the accuracy of central or brachial BP estimations, thereby providing substantial support for clinical decision-making. Beyond this, the novel non-invasive and cuffless imaging approach overcomes the constraints posed by traditional inflatable cuff-based methods, not only enhancing patients' comfort, compliance and continuous BP monitoring but also proving additional local geographic-dependent BP information useful for studying clinical micro-circulation.

Furthermore, given the ongoing concerns regarding accuracy, the validation methodology for the proposed BP monitoring system is designed to closely adhere to the scenario-based validation test protocols stipulated by the European Society of Hypertension (ESH) for the Validation of Cuffless Blood Pressure Measuring Devices[56]. The initial phase involves static tests for quantifying the absolute precision of BP measurements. Additionally, compliance with the IEEE Std 1708™ standard, which is a landmark contribution in the era of cuffless BP devices[47], serves to reinforce the assurance of precision and reliability in real-world clinical scenarios, thereby contributing to the effective control and treatment of hypertension.

CONCLUSION

The historical evolution of continuous BP measurements has demonstrated a remarkable progression, spanning from the development of invasive techniques to state-of-the-art obtrusive 2D BP/TAG imaging devices, and culminating in the diverse ranges of modern unobtrusive methods, which highlights the growing significance of continuous BP measurement methods in monitoring hypertension[53]. As technology continues to advance, the shift of BP measurement techniques has emphasized the importance of high-dimensional approaches in enhancing accuracy and overcoming the limitations of single-point or snapshot measurements. The assessment of regional BP distribution and evaluation of vascular conditions have

emerged as crucial factors for future BP monitoring devices. Notably, the recent emergence of TAG imaging technology holds substantial potential in enriching the evaluation of vascular conditions through visualizing BP distribution at different locations, thereby enhancing the capabilities of early monitoring for peripheral vascular conditions. Looking ahead, we anticipate that further progress in BP measurement techniques will be characterized by multi-modal, multi-parameter, and multi-dimensional approaches. This trajectory will lead to the development of more unobtrusive, intelligent and multifunctional connected wearable devices, resulting in improved accuracy, enhanced usability, and elevated standards of personalized patient care at both home and hospital, ultimately revolutionizing hypertension management in the future.

DECLARATIONS

Authors' contributions

Made a substantial contribution to the conception and writing of the manuscript: Liu ZJ, Zhang YT
Contributed to the original idea of blood pressure imaging: Zhang YT
Contributed to the manuscript's editing: Liu ZJ, Xiang T, Ji N, Zhang YT

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Not applicable.

Financial support and sponsorship

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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