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REVIEW

High-Suitcordance Intelligent Fibers for Panvascular Disease Monitoring-Intervention

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Abstract

Panvascular diseases, sharing atherosclerosis as a common pathological basis, pose a significant threat to human health. Flexible fibers combined with sensing elements become implantable and interventional smart fibers with monitoring and intervention capabilities. Due to the prolonged course of panvascular diseases, higher requirements are imposed on the monitoring-intervention closed-loop system of flexible fibers—high suitcordance (a combination of short-term suitability and long-term concordance). Suitcordance implies that novel flexible fibers must meet the traditional concept of compatibility and satisfy the new requirement of long-term co-regulation of fiber-vascular fate. This review introduces emerging flexible fiber electronic devices with exceptional performance related to panvascular diseases. These devices adapt well to the complex panvascular environment and provide ideal technical support for real-time, non-invasive, and continuous health monitoring-treatment. However, existing devices have limitations, and future research should focus on developing novel flexible smart fibers based on the clinical needs of panvascular diseases.

Keywords Panvascular diseases · Flexible fiber electronic devices · High suitcordance · Real time continuous monitoring · Clinical translational application

1 Introduction

Panvascular diseases (PVDs), characterized by atherosclerosis, encompass cardiovascular, cerebrovascular, and peripheral vascular disease [1]. The incidence of PVDs is rising due to aging and lifestyle changes [2, 3], underscoring the critical importance of prevention, early screening, and treatment.

PVDs exhibit vascular damage and hemodynamic alterations, which can be assessed using ultrasound, Computed Tomography (CT), or Magnetic Resonance Imaging (MRI) [4]. However, traditional diagnostic methods have limitations, such as suboptimal biocompatibility, single modality, and difficulty in long-term real-time monitoring, necessitating the development of novel diagnostic and therapeutic systems.

Flexible fiber electronic devices offer innovative solutions and can be classified into mechanical [5], optical [6], acoustic [7], and thermal electronic devices [8] based on their working mechanisms, and into implantable and wearable devices according to their usage. The monitoring requirements vary for different vascular diseases: cardiovascular diseases require real-time dynamic and motion-adaptive monitoring [9]; cerebrovascular diseases demand high sensitivity and rapid response [10]; while peripheral vascular diseases emphasize tissue conformability and motion flexibility [11].

We propose the concept of "suitcordance" to evaluate the applicability of flexible fiber electronic devices.

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Suitcordance encompasses both short-term suitability and long-term concordance. It holds the potential to achieve long-term organic co-regulation and ecological re-balancing between fibers and blood vessels after intervention or wearing. These devices possess advantages such as softness, stretchability, biocompatibility, lightweight, and high sensitivity [12], making them well suited for the aforementioned requirements and providing ideal support for real-time continuous health monitoring. They have the potential to revolutionize PVD monitoring. However, existing devices still face challenges, particularly in addressing the panvascular pathological cascade. For instance, biodegradable sensors often exhibit mismatched degradation kinetics (2–8 weeks) compared to the chronic progression of atherosclerosis (months to years), leading to premature functional failure in long-term monitoring [13]. Optical coherence tomography fibers struggle to differentiate lipid-rich plaques from intraplaque hemorrhage due to similar light scattering coefficients, with diagnostic accuracy dropping in calcified lesions [14]. Furthermore, most wearable devices lack systemic coordination between cardiovascular and cerebrovascular monitoring. A critical gap given that numerous stroke patients exhibit concurrent coronary micro-vascular dysfunction [15]. The limited stretchability of conventional fibers also compromises signal stability during dynamic vascular remodeling. Additionally, existing devices presence insufficient functionality and single modality, leaving ample room for future development and optimization.

In the monitoring and treatment of panvascular diseases, disease management must consider the short-term suitability and long-term concordance between the fiber and the panvascular system—collectively referred to as suitcordance. Panvascular diseases generally progress slowly and involve imbalances in mechanical, cellular, physicochemical, and immune ecologies within and around the blood vessels. Such disorders affect not only vascular function but also pathological changes in extravascular tissues. Under normal conditions, the vascular system is maintained in a state of dynamic equilibrium, in which hemodynamic parameters (e.g., blood pressure and flow), vascular mechanical properties, vascular cell (e.g., endothelial and smooth muscle cells) function, and the physicochemical environment (e.g., pH and ion concentrations), along with immune responses (e.g., inflammation), interact to form a complex vascular ecosystem. However, in diseases such as atherosclerosis, these equilibriums become disrupted, leading to vascular dysfunction, endothelial damage, immune dysregulation, and eventually jeopardizing vascular and perivascular health throughout the body.

In this context, flexible fiber electronic devices can play a critical role by not only supporting the real-time restoration of vascular homeostasis but also facilitating precise therapeutic interventions to counteract the disruption of the vascular ecosystem. Crucially, short-term suitability requires accurate monitoring of physiological signals within and around the blood vessels—such as hemodynamics, cellular activities, and immune responses—to help correct acute or sudden ecological imbalances. Over the long-term concordance, devices must continuously provide monitoring and therapeutic interventions, ensuring the stable coexistence of the panvascular system and fiber materials, preserving long-lasting equilibrium while avoiding rejection, allergic reactions, or maladaptive processes from permanent implants or wearables. By doing so, an enduring co-regulation between the device and the panvascular system can be achieved.

Suitcordance should therefore be regarded as a central design principle for flexible fiber-based electronics. By optimizing material selection and device design, battery size and capacity, biodegradability and stretchability, as well as incorporating intelligent self-responsive systems, we can enhance the suitcordance of flexible fiber electronics, thereby advancing precise health monitoring and personalized therapy for panvascular diseases. Ultimately, this approach aims to realize a stable, long-term co-regulation between fiber devices and the panvascular system.

2 Flexible Fiber Electronic Devices for Cardiovascular Disease Monitoring

Cardiovascular diseases (CVDs), a crucial component of PVDs, are among the leading causes of global mortality [16]. Common CVDs include coronary heart disease, hypertension, myocardial infarction, arrhythmias, and heart failure, primarily characterized by atherosclerosis, often accompanied by vascular stenosis or occlusion, resulting in impaired blood flow and subsequent organ ischemia, hypoxia, and necrosis, severely affecting the function of the heart and other organs. Early screening and monitoring of pulse, blood pressure, heart rate, and electrocardiogram are essential for preventing and treating CVDs [17].

2.1 Pulse and Blood Pressure Monitoring

Hypertension not only increases the burden on the heart but also has a widespread impact on the entire vascular system [18]. Traditional methods for monitoring pulse and blood pressure include palpation, cuff-based sphygmomanometers, arterial catheters, and photoplethysmography (PPG). These methods have limitations in one or more aspects of real-time

capability, continuity, accuracy, and safety [19, 20]. The development of flexible fibers and wearable technology has provided innovative solutions for high-suitcordance pulse and blood pressure monitoring.

Among wearable smart fibers, elements based on optical, pressure, and magnetic principles have advanced rapidly. Optical sensors typically rely on the pressure-induced attenuation of optical power in optical fibers for monitoring [21]. Li et al. achieved precise and rapid pulse monitoring under dynamic conditions in various body parts by embedding small-core fibers (SCFs) in silicone to form a fabric–SCF–silicone sandwich structure (Fig. 1a) [22]. The monitoring principle of pressure sensors is based on changes in charge distribution and electrical signal output

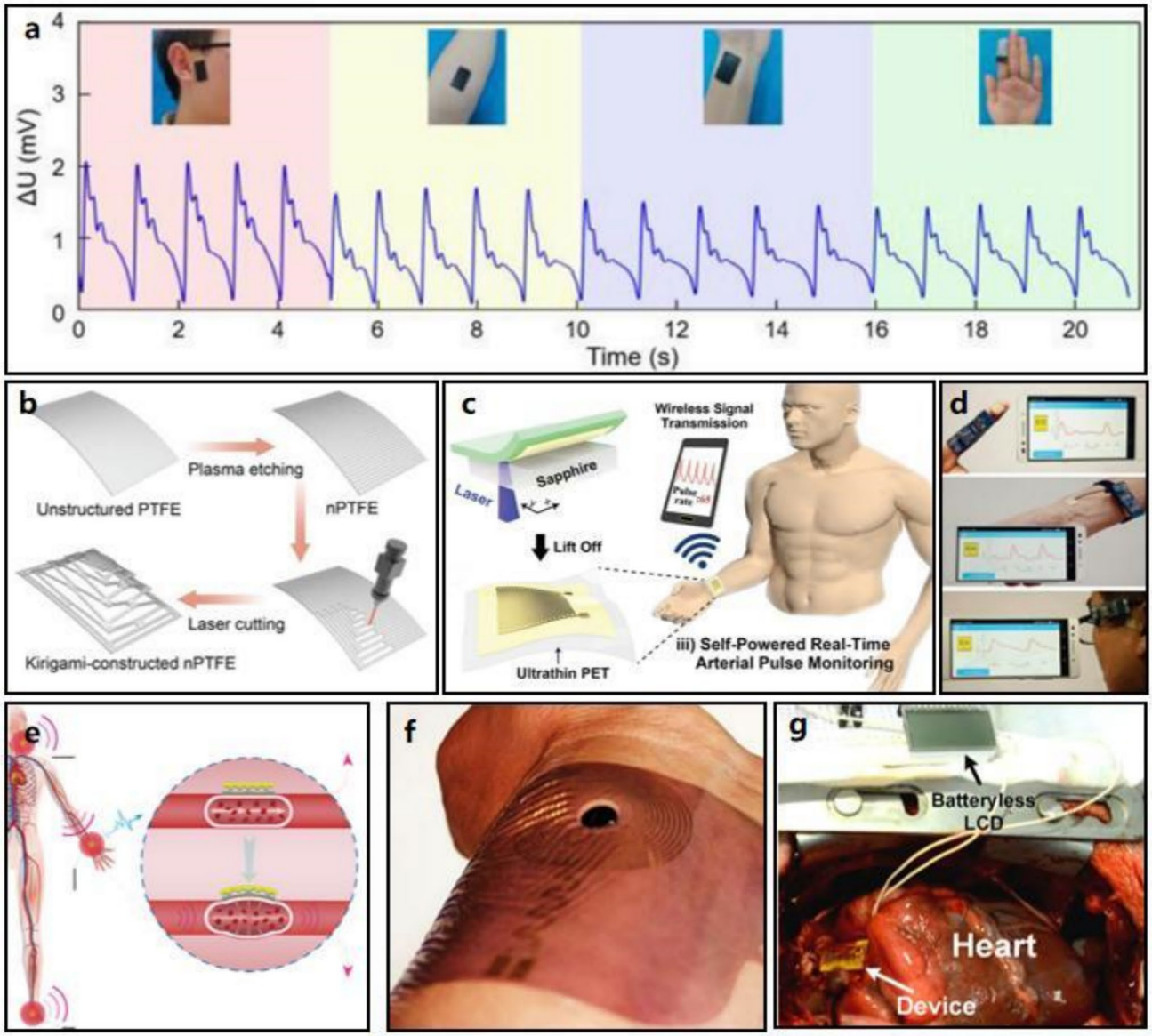


Fig. 1 Flexible fiber-based electronic device sensors for pulse and blood pressure monitoring. **a** Flexible optical sensors for monitoring pulse waves in the temporal, brachial, radial, and fingertip arteries; Reproduced with permission from Ref. [22]; Copyright 2024,Elsevier. **b** Fabrication process of the 3D kirigami-inspired hollow structures of Polytetrafluoroethylene (PTFE) nanowires; Reproduced with permission from Ref. [24]; Copyright 2022, John Wiley and Sons. **c** Self-powered piezoelectric sensors that can wirelessly transmit pulse signals to smartphones; Reproduced with permission from Ref. [27]; Copyright 2017, John Wiley and Sons. **d** Self-powered pressure sensors capable of monitoring pulse waves at human fingers, wrists, and ears, and transmitting real-time data to mobile apps; Reproduced with permission from Ref. [28]; Copyright 2018, John Wiley and Sons. **e** Schematic diagram of the principle for monitoring systolic and diastolic blood pressure in different arteries; Reproduced with permission from Ref. [29]; Copyright 2023, Springer Nature. **f** Schematic illustration of liquid heart sensors; Reproduced with permission from Ref. [30]; Copyright 2024, Springer Nature. **g** Implantable piezoelectric sensors wrapped around the ascending aorta of a pig; Reproduced with permission from Ref. [31]; Copyright 2016, Elsevier

due to material deformation [23]. Meng et al. developed a multi-point pressure sensor with a kirigami-inspired structure (Fig. 1b) where specific 3D vertical kirigami-inspired notches enable adaptation to different body parts and accurate pulse monitoring [24]. To address power supply issues [25, 26], Park, Meng, and Zhang et al., respectively, proposed self-powered sensors that can monitor arterial pulse signals in real time without relying on an external power source (Fig. 1c,d,e) [27].[28] [29] Magnetic sensors measure pulse and blood pressure based on changes in the magnetic field generated by the vibration of a permanently fluidic magnet (PFM) under pressure. Zhao et al. developed a reconfigurable, stable, and shape-preserving liquid heart sensor by integrating PFMs, (Fig. 1f) enabling continuous monitoring of cardiovascular activities such as pulse waves [30]. Compared to wearable elements, implantable fibers can achieve in situ, high-precision monitoring. Cheng et al. fabricated a flexible, implantable, self-powered blood pressure monitoring device based on piezoelectric films that can wrap around the aorta (Fig. 1g) [31]. However, attention should also be paid to the ecological re-balancing after implantation and the long-term harmony between the "fiber" and the "vascular" system.

2.2 Heart Rate Monitoring

Heart rate is the frequency at which the heart beats [32] [33, 34]. Traditional heart rate monitoring often relies on methods such as stethoscopes and pulse estimation, which are prone to human error and difficult to achieve long-term continuous monitoring.

Smart fibers for heart rate monitoring can be divided into two main applicable populations: adults and fetuses during pregnancy. Adult heart rate monitoring primarily uses wearable optical fibers, where heartbeats cause changes in blood flow, resulting in variations in light refraction and attenuation [35]. Leal-Junior et al. proposed a flexible element based on polymer optical fibers with high flexibility and impact resistance (Fig. 2a) [36]. From 2017 to 2022, Presti et al. proposed and improved a Fiber Bragg Grating (FBG) heart rate monitoring system based on optical fibers, gradually achieving multi-point and multi-modal monitoring (Fig. 2b, c) [37–39]. Additionally, optical fiber Mach–Zehnder interferometer (OF-MZI) mattresses can be used for heart rate monitoring. Wang et al. proposed a smart optical fiber mattress suitable for 24-h continuous monitoring, especially for patients with sleep apnea syndrome or those requiring long-term heart rate monitoring [40]. Changes in fetal heart rate can help identify potential fetal distress or other complications, such as placental abruption or umbilical cord entanglement. Skrivanos et al. proposed a high-precision remote monitoring fiber system for fetal heart rate based on photoplethysmography (PPG) technology [41]. Furthermore, as Hamelmann et al. suggested, adaptive ultrasound transducer arrays can also be used for monitoring fetal heart rate during pregnancy (Fig. 2d) [42].

2.3 Electrocardiogram Monitoring

The electrocardiogram (ECG) is one of the essential non-invasive tools for diagnosing cardiovascular diseases, reflecting the heart's rhythm, conduction pathways, and blood supply. It can detect cardiovascular diseases such as arrhythmias, myocardial ischemia, myocardial infarction, and coronary heart disease [43, 44]. For instance, Torsade de Pointes is a specific form of arrhythmia typically characterized by QRS complexes twisting around the isoelectric baseline, frequently accompanied by QT interval prolongation. It tends to recur, often causes syncope, and may progress to life-threatening ventricular fibrillation. Accordingly, real-time continuous ECG monitoring and prompt recognition of this distinctive pattern are crucial for accurate diagnosis and timely intervention. Early detection, coupled with appropriate adjustments to pharmacotherapy or correction of electrolyte imbalances, can significantly decrease the associated mortality risk. Traditional ECGs rely on wet silver/silver chloride (Ag/AgCl) electrodes placed on the patient's chest, arms, or legs, using electrolyte gel to contact the skin and detect cardiac electrical activity. However, this method has poor compatibility, portability, sustainability, and continuity [9], For instance, conventional 24-h Holter monitors are typically large and feature complex wiring, which significantly reduces patient comfort; moreover, during prolonged surveillance, poor lead contact, device misalignment, or incorrect usage can introduce substantial errors and compromise the device's overall suitcordance. To overcome these limitations, smart fibers based on highly compliant conductive fibers or nanomaterials, combined with advanced sensing technologies, can provide more comfortable, portable, continuous, and high-precision ECG monitoring. Compared with conventional ECG devices, miniaturized intelligent fiber-based systems help reduce poor contact between electrodes and the skin, better accommodate diverse wearing scenarios, and deliver more stable monitoring signals. They are particularly beneficial for patients with hypertensive heart disease and atrial fibrillation requiring continuous ECG monitoring, as they enhance both adherence and comfort. Although single-lead ECG yields less comprehensive data than multi-lead systems, it rapidly captures fundamental cardiac electric activity—especially critical in emergent situations such as acute myocardial infarction or arrhythmias. Thus, single-lead ECG has garnered wide interest for mobile monitoring and remote health management, and its integration with flexible fiber electronics stands to further advance clinical utility. [45]

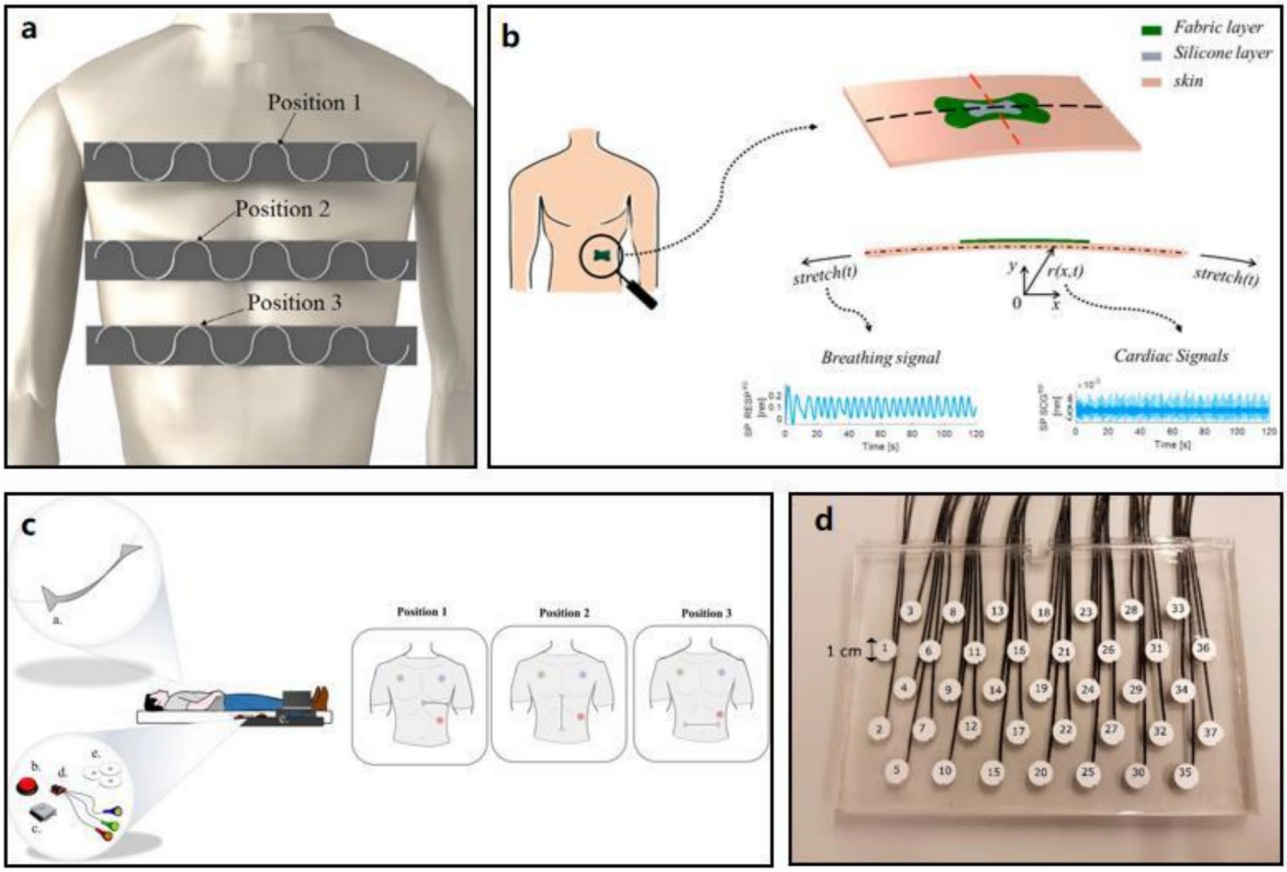


Fig. 2 Flexible fiber-based electronic device sensors for heart rate monitoring. **a** A flexible optical sensor placed on the chest for heart rate monitoring; Reproduced with permission from Ref. [36]; Copyright 2019, Elsevier. **b** A flexible optical sensor capable of multi-point heart rate monitoring; Reproduced with permission from Ref. [38]; Copyright 2021, Springer Nature. **c** A flexible optical sensor for heart rate monitoring and a schematic diagram of the monitoring boundary conditions; Reproduced with permission from Ref. [39]; Copyright 2022, MDPI. **d** A flexible ultrasonic transducer array for monitoring fetal heart rate; Reproduced with permission from Ref. [42]; Copyright 2019, MDPI

Wearable fibers and their textiles often employ dry electrodes and capacitive electrodes. Dry electrode fibers monitor based on direct contact between the electrode material and the skin without requiring electrolyte gel. Capacitive electrodes based on capacitive coupling provide more innovative solutions for developing higher suitcordance elements. Eskandarian et al. proposed 3D woven dry electrodes for long-term, continuous, and high-quality ECG monitoring [46]. Lee et al. introduced carbon nanotube dry electrodes that provide stable signal quality monitoring during exercise and showering [47]. Stauffer et al. developed dry electrodes with high skin conformability and low contact impedance (Fig. 3a) [48]. Rosa et al. proposed dry electrodes for multimodal monitoring needs, including ECG, galvanic skin response (GSR), temperature, and motion parameters [49]. Steffen et al. introduced novel capacitive electrodes based on detecting the biopotentials generated by cardiac polarization and depolarization, reducing skin irritation [50]. Additionally, some implantable fibers with low signal distortion risk can provide high-quality ECG data. Bong et al. proposed an injectable flexible subdermal electrode array (Fig. 3b) that highly matches the needs of patients requiring long-term monitoring [51]. However, it is essential to consider the potential risk of infection from invasive procedures and the stability of long-term implantation.

2.4 Direct Epicardial Monitoring

Direct epicardial monitoring can track the electrical activity and mechanical deformation on the heart's surface in real-time [52, 53]. Traditional epicardial monitoring devices include electrode patches, cardiac electrogram catheters, and mechanical force sensors. However, long-term monitoring can easily lead to data distortion and biocompatibility issues. In contrast, highly compatible smart fibers can maintain high-resolution, continuous, and stable measurements on the complex curvature of the heart.

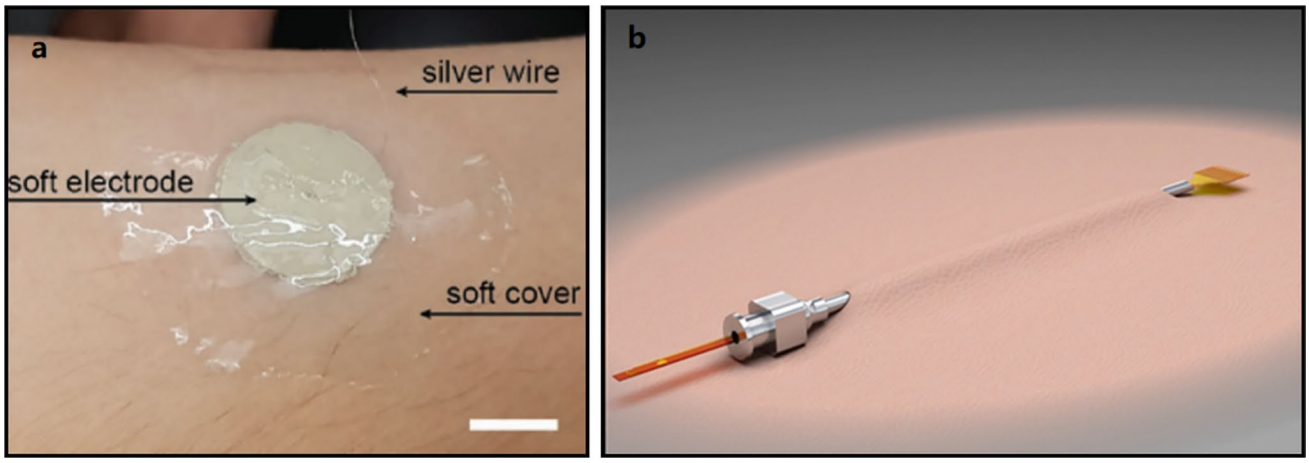


Fig. 3 Flexible fiber electronic device sensors for ECG monitoring. **a** Soft polymer electrodes mounted on the skin; Reproduced with permission from Ref. [48]; Copyright 2018, John Wiley and Sons. **b** ECG monitoring device implanted in the anterior subcutaneous space of the heart; Reproduced with permission from Ref. [51]; Copyright 2020, American Chemical Society

Many smart fibers for epicardial monitoring are mesh structures that directly wrap around the heart's surface, integrating various sensing materials, conforming to the heart's surface, and achieving dynamic self-adjustment for multi-parameter monitoring such as mechanical strain and temperature. Xu et al. proposed a 3D multifunctional integrated membrane, (Fig. 4a) which is a typical example [54]. Choi, Kim, Viventi et al. also proposed mesh fiber for highly compliant monitoring (Fig. 4b,c) [55–57]. Some fiber elements have developed new integrated diagnosis and treatment technologies, gradually becoming a key component in treatment methods. Park et al. proposed an elastic epicardial mesh (Fig. 4d) for electromechanical cardiac shaping surgery, which can stably sense and regulate cardiac electrical activity, terminate arrhythmias, and improve myocardial contraction [58]. Huang et al. proposed a flexible smart array patch (Fig. 4e) that can simultaneously perform precise mechanical force monitoring and electrical stimulation therapy on the heart's surface by constructing electrodes with built-in releasable drugs [59].

2.5 Echocardiographic Monitoring

Echocardiography is a non-invasive imaging technique that clearly displays the heart's structure, function, and blood flow status through high-frequency ultrasound reflection imaging [20, 60]. Traditional echocardiography technology is bulky and cannot achieve real-time, dynamic, and long-term monitoring [61]. In recent years, flexible fibers have achieved long-term, continuous cardiac function monitoring through innovative wireless, Doppler, and bioadhesive ultrasound devices.

Kenny et al. proposed a wireless wearable Doppler ultrasound fiber element (Fig. 5a) that can accurately reflect changes in cardiac output during surgery by monitoring the carotid artery velocity time integral (ccVTI) [62]. Wang et al. introduced a bioadhesive ultrasound (BAUS) fiber element (Fig. 5b) based on a bioadhesive hydrogel–elastomer composite material that can provide continuous imaging for up to 48 h [63]. Hu et al. proposed a wearable ultrasound element (Fig. 5c) composed of a piezoelectric transducer array, liquid metal composite electrodes, and a triblock copolymer, which can achieve high-resolution imaging in deep cardiovascular tissues [64].

2.6 Integration of Flexible Sensors in Cardiovascular Stents

Coronary artery disease (CAD) is one of the leading causes of death, and a common treatment method is percutaneous coronary intervention (PCI) surgery [65]. However, in-stent restenosis (ISR) may occur after stent implantation [66–68]. To monitor CAD and ISR, traditional methods mainly include angiography, intravascular ultrasound (IVUS), optical coherence tomography (OCT), and others. Highly compliant smart fiber stents integrated with various sensors have gradually become an emerging means of monitoring cardiovascular diseases. These devices are mostly based on wirelessly powered LC circuits, using inductors (L) and capacitors (C) to form resonant circuits, which are well suited for long-term, real-time, continuous physiological monitoring after stent implantation.

Oyunbaatar et al. proposed a heat-treated self-rolling polymer stent that facilitates catheter implantation and adapts to complex vascular structures (Fig. 6a) [69]. However, as a non-biodegradable stent, long-term vascular implantation can easily lead to complications, such as chronic inflammatory reactions, tissue hyperplasia, and

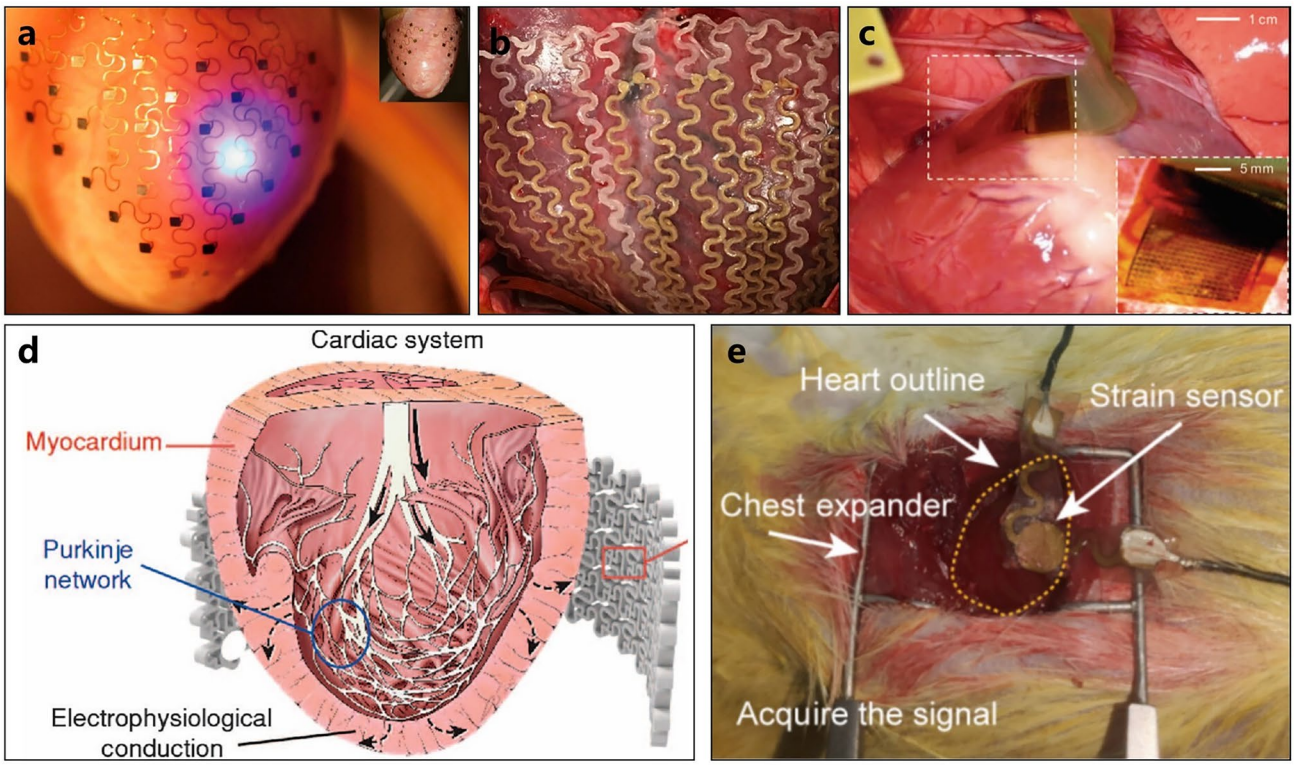


Fig. 4 Flexible fiber electronic device sensors for direct epicardial monitoring. **a** A 3D multifunctional skin integrated onto the heart surface, capable of monitoring multiple parameters; Reproduced with permission from Ref. [54]; Copyright 2014, Springer Nature. **b** A sensor with a silver-gold nanowire composite mesh structure integrated onto the heart surface; Reproduced with permission from Ref. [55]; Copyright 2018, Springer Nature. **c** A flexible device adhering to the heart tissue via surface tension; Reproduced with permission from Ref. [57]; Copyright 2010, The American Association for the Advancement of Science. **d** A schematic illustration of the design strategy for an epicardial mesh for electromechanical cardiac reshaping based on conduction within the cardiac system; Reproduced with permission from Ref. [58]; Copyright 2016, The American Association for the Advancement of Science. **e** An implantable sensor capable of detecting cardiac pulse signals in rats; Reproduced with permission from Ref. [59]; Copyright 2022, Elsevier

thrombosis. Removal also causes secondary trauma and cannot meet the requirements of short-term ecological balance and long-term interface harmony. Park et al. and Sun et al. proposed similar biodegradable polymer stents integrated with wireless pressure sensors that can detect arterial pressure fluctuations and transmit data wirelessly (Fig. 6b, c) [70, 71]. However, the above-mentioned LC pressure sensors are still affected by issues such as stenosis location and pressure changes caused by blood flow. Although capacitive strain sensors are also based on LC circuits, they can directly monitor changes in arterial wall strain and stiffness without relying on pressure changes. Rigo, Herbert et al. proposed a flexible implantable stent system that identifies restenosis by detecting arterial wall strain and hardening (Fig. 6d,e) [72].In addition, electrochemical impedance spectroscopy (EIS) fiber elements can monitor post-operative thrombosis in blood vessels. Hoare et al. proposed a stent that can self-detect and report its status. By integrating multiple EIS sensors, it can identify restenosis cell types, differentiate between blood and thrombus, provide early lesion signals, and wirelessly transmit data (Fig. 6f) [73].

2.7 Other Metrics

In addition to the above indicators, flexible fiber elements can also be used to monitor various other indicators such as endocardial pressure, heart volume, and impedance cardiography, to construct a comprehensive monitoring system for cardiovascular diseases. Endocardial pressure (EP) monitoring can assess the heart's pumping function and the contraction and relaxation of the heart during each cardiac cycle [75, 76]. Minimally invasive flexible fiber electronic devices have brought about a revolution in endocardial pressure monitoring. Liu et al. developed a triboelectric nanogenerator (TENG) based on the principle of periodic voltage changes generated by the contact and separation between layered materials caused by cardiac contraction and relaxation (Fig. 7a) [77]. Heart volume can reflect the heart's pumping ability and is of great

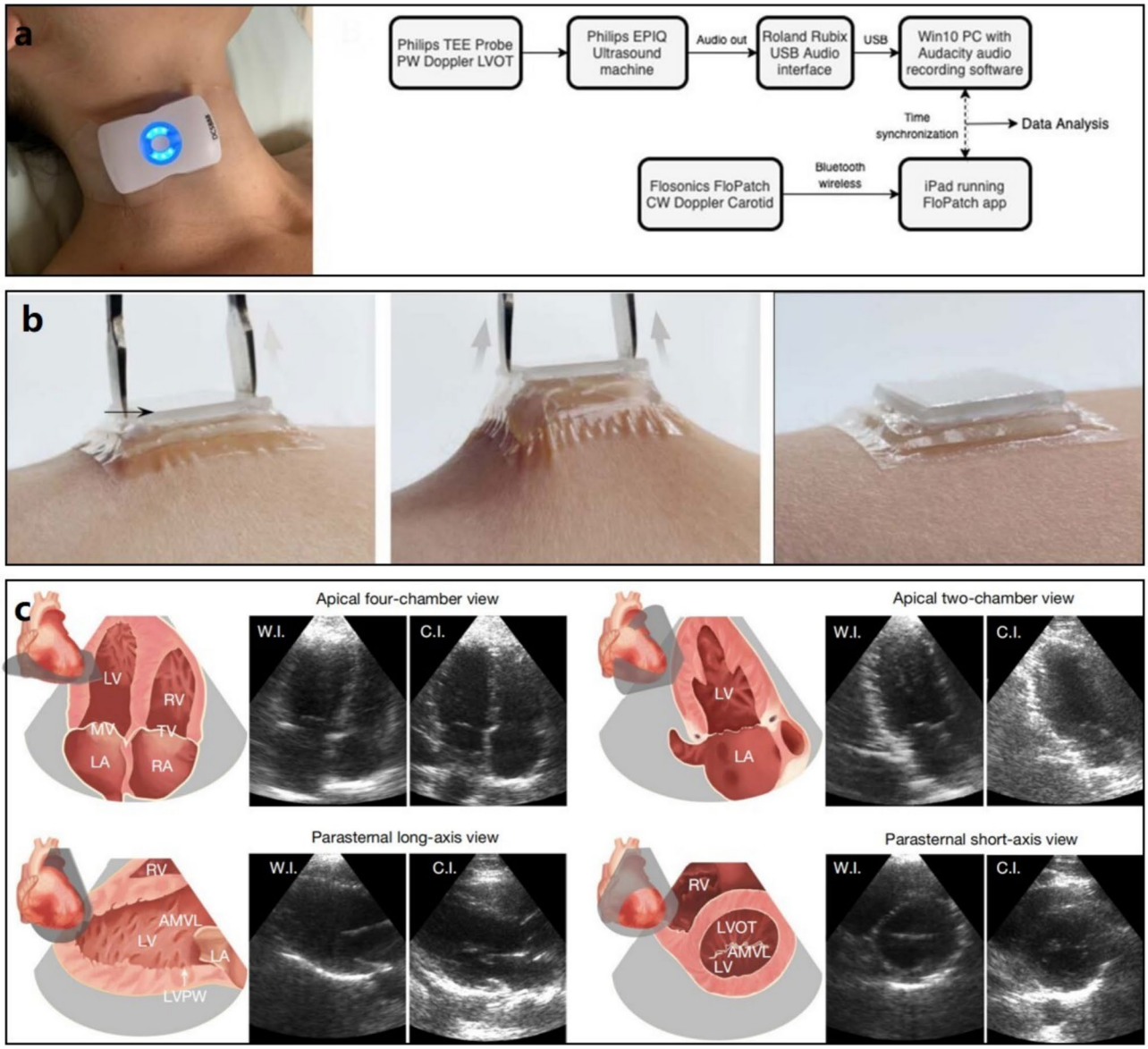


Fig. 5 Flexible fiber electronic device sensors for echocardiographic monitoring. **a** Schematic diagram of a wireless wearable Doppler ultrasound device and monitoring process; Reproduced with permission from Ref.[62]; Copyright 2021, MDPI. **b** BAUS device adhered to the skin, capable of withstanding high tensile forces and maintaining skin adhesion for over 48 h; Reproduced with permission from Ref.[63]; Copyright 2022, The American Association for the Advancement of Science. **c** Echocardiographic imaging from a wearable device; Reproduced with permission from Ref.[64]; Copyright 2023, Springer Nature

significance in monitoring cardiovascular diseases, such as heart failure and valvular heart disease [78]. Traditional monitoring methods can hardly achieve continuous and dynamic monitoring. Dual et al. developed a fiber element implanted on the heart surface that senses myocardial strain caused by changes in heart volume based on the piezoresistive effect (Fig. 7b). Future work should focus on passive implantation to achieve electromagnetic coupling for data transmission and energy supply [79]. Traditional impedance cardiogram (ICG) devices often have monitoring accuracy affected by patient movement or breathing and are difficult to achieve portable monitoring [80, 81]. Pullano et al. developed a flexible ICG device based on the triboelectric charges generated by the friction between red blood cells in blood flow and with the vessel wall (Fig. 7c). The design without a current source makes it suitable for long-term, continuous ICG monitoring, but the interference from environmental and electronic noise needs to be improved [82].

Flexible fiber electronics have significantly promoted the transformation of cardiovascular disease monitoring. Through flexible designs, minimally invasive implantation,

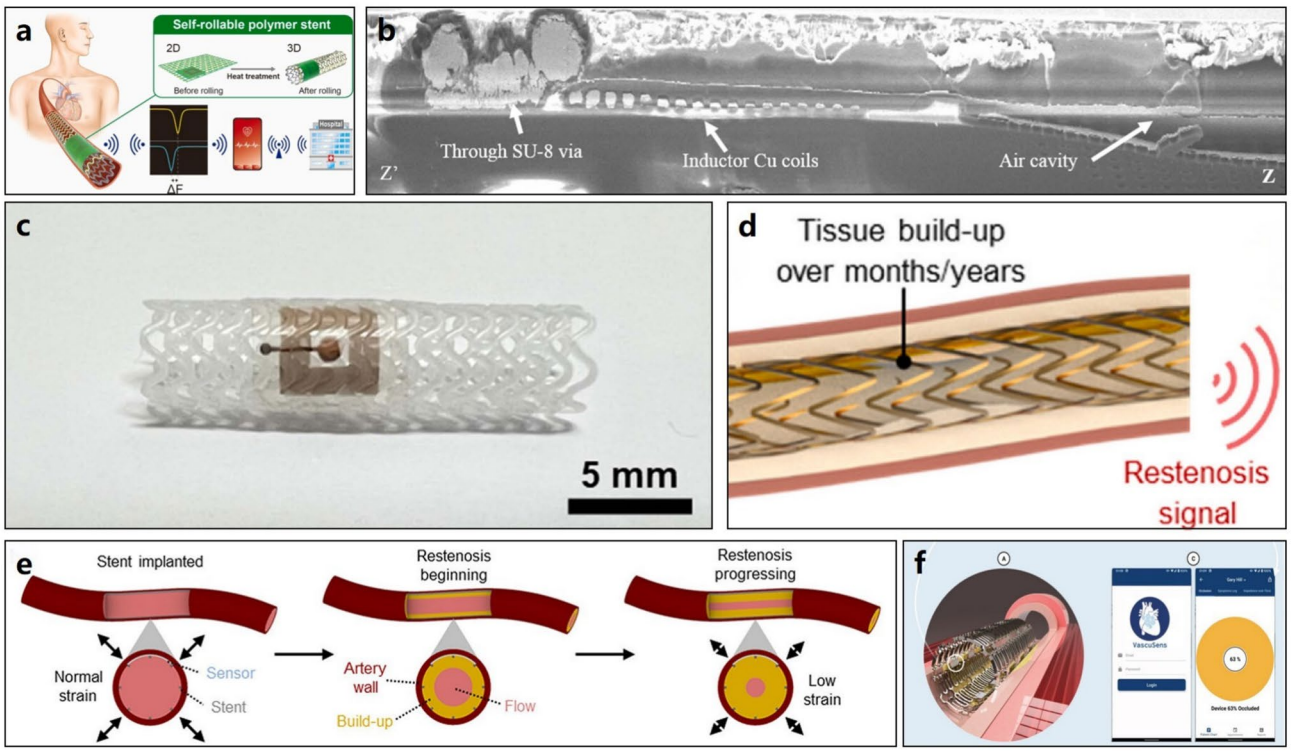


Fig. 6 Sensors integrated on stents. **a** Schematic diagram of a self-rolling polymer stent integrated with an LC pressure sensor; Reproduced with permission from Ref. [69]; Copyright 2022,Elsevier. **b** Wireless pressure sensor integrated on a stent; Reproduced with permission from Ref. [70]; Copyright 2016, MDPI. **c** LC pressure sensor integrated on Polycaprolactone (PCL); Reproduced with permission from Ref. [71]; Copyright 2022,Institute of Physics Publishing. **d** LC circuit consisting of a wireless stent and a capacitive strain sensor; Reproduced with permission from Ref. [72]; Copyright 2023, Elsevier. **e** Schematic diagram of stent restenosis progression and the resulting changes in arterial wall strain; Reproduced with permission from Ref. [74]; Copyright 2022Elsevier. **f** Smart stent with multiple impedance sensors that can wirelessly transmit data; Reproduced with permission from Ref. [73]; Copyright 2022, John Wiley and Sons

self-powering, and wireless transmission, these devices enable prolonged monitoring of cardiac function in heart failure and coronary artery disease, aiding in early diagnosis and treatment. Despite this progress, challenges persist: monitoring accuracy and stability remain major concerns in the complex cardiovascular physiological environment, and signals must overcome drift and external interference to provide accurate data. Long-term implant compatibility also requires further optimization to avoid immune reactions and complications like in-stent restenosis. Additionally, powering such devices, especially under high-load conditions in the cardiovascular system, remains difficult despite emerging self-powering solutions. Future development will involve refining signal processing algorithms, enhancing energy harvesting, and improving wireless communication and data handling. Close collaboration among clinicians, materials scientists, and medical device companies is essential to support further multicenter clinical research and accelerate clinical translation.

3 Flexible Fiber Electronic Devices for Monitoring Cerebrovascular Diseases

Cerebrovascular diseases include stroke, cerebral hemorrhage, and cerebral aneurysms [83]. Vascular damage or aneurysm growth can lead to cerebral tissue compression, inflammation, etc., changing local temperature and pressure. Local oxygenation can reflect the survival status of brain tissue and blood vessels, and ischemic events can be monitored through blood flow. Flexible fiber-based sensors have broad prospects in these fields.

3.1 Intracranial Temperature

Intracranial temperature can reflect cerebral blood flow[84] and arterial blood temperature, which is very important for the diagnosis and treatment of cerebrovascular diseases. Traditional monitoring methods, such as magnetic resonance spectroscopy and near-infrared spectroscopy [85],

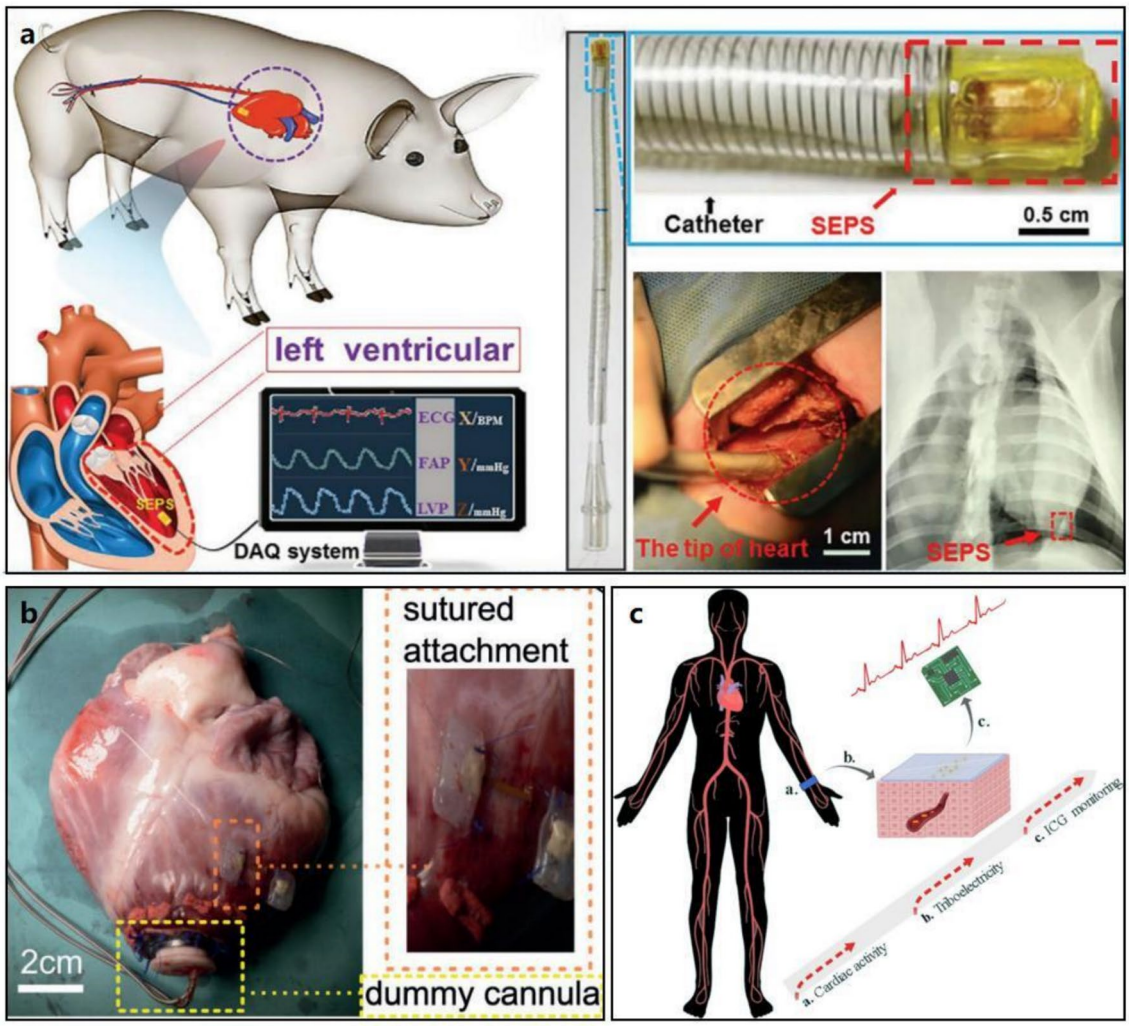


Fig. 7 Flexible fiber electronic device sensors for monitoring other indicators of cardiovascular disease. **a** Schematic diagram of a sensor implanted in a pig heart to monitor endocardial pressure; Reproduced with permission from Ref. [77]; Copyright 2018, John Wiley and Sons. **b** Flexible sensor implanted on the heart surface for monitoring cardiac volume; Reproduced with permission from Ref. [79]; Copyright 2020, John Wiley and Sons. **c)** Schematic diagram of a wearable sensor for monitoring ICG; Reproduced with permission from Ref. [82]; Copyright 2020,Elsevier

are not suitable for continuous monitoring [86], while flexible fiber sensors show good prospects with their real-time and sustainable characteristics.

Intracranial temperature sensors are largely implantable, typically comprising electronic sensors and fiber-optic devices. Electronic sensors rely on electrical signal transduction (resistance/capacitance/piezoresistance), requiring the implantation of electrodes and thus being susceptible to electromagnetic interference. By contrast, fiber-optic devices couple the thermal effects of tissues through optical waveguides, offering chemical inertness and strong interference resistance, making them more suitable for multi-parameter integration and long-term monitoring.

Implantable electronic sensors for intracranial temperature monitoring have been studied for a considerable period. For instance, a polyimide-based thermistor array [87] detects local brain temperature through changes in resistance–temperature coefficients; however, the rigid substrate can easily cause slight tissue damage. Shin et al. [88] developed a millimeter-scale polylactic acid sensor (Fig. 8a) that produces a capacitive signal via a pH-sensitive hydrogel undergoing volumetric phase transitions, with a degradation period of 28 days—still shorter than the typical 6–8 weeks required for monitoring post-traumatic head injuries. Likewise, Kang et al. [89] created a resorbable silicon device using a piezoresistive effect to simultaneously monitor temperature and intracranial pressure, but its signal-to-noise ratio (SNR = 42 dB) falls below the clinical requirement (> 50 dB).

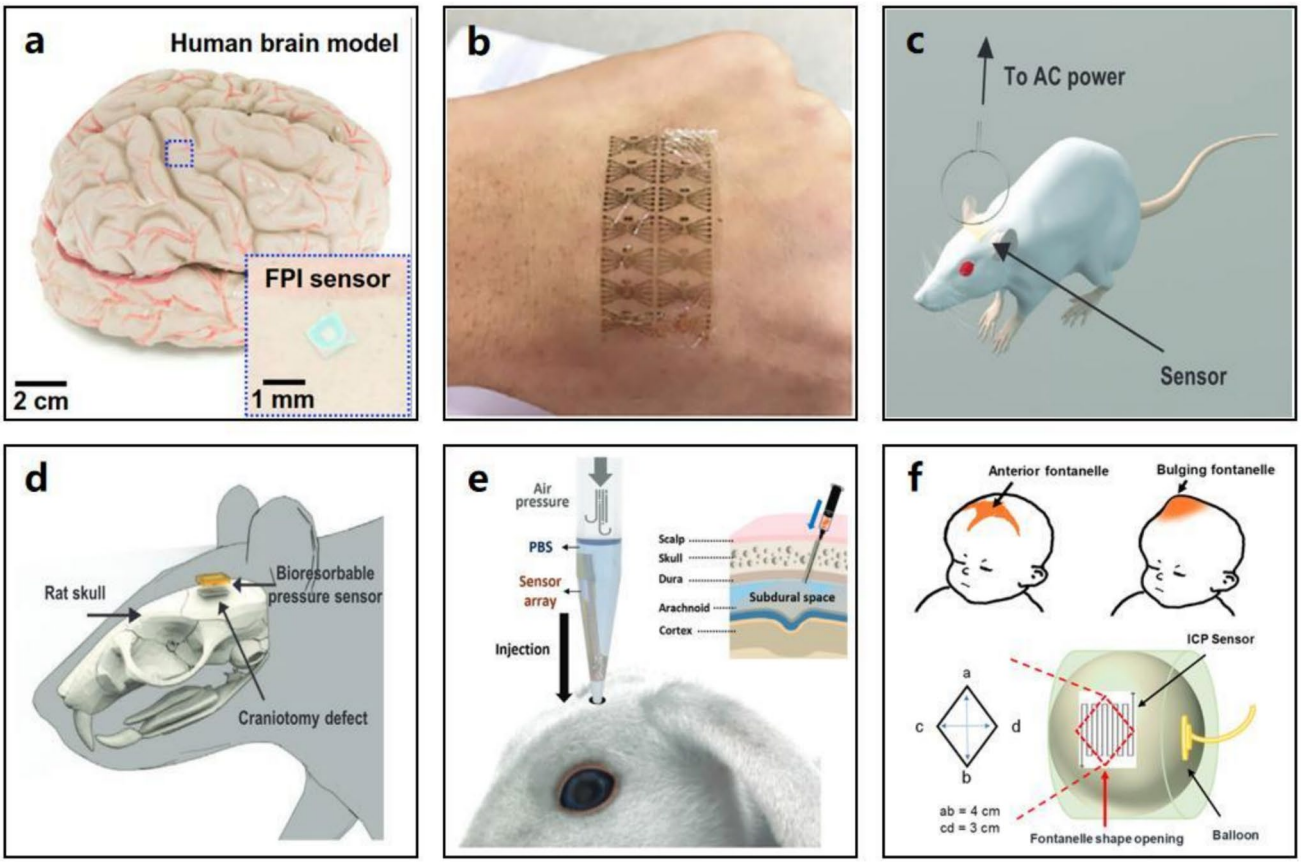


Fig. 8 Flexible fiber electronic devices for intracranial temperature and intracranial pressure monitoring. **a** Millimeter-scale biodegradable flexible sensors capable of precise and continuous monitoring of temperature and pressure; Reproduced with permission from Ref. [88]; Copyright 2019, The American Association for the Advancement of Science. **b** Flexible device arrays with multiple In_2O_3 nanoribbon field-effect transistors fabricated on polyethylene terephthalate substrates for real-time detection of small-molecule neurotransmitters serotonin and dopamine; Reproduced with permission from Ref. [91]; Copyright 2020, Elsevier. **c** A biodegradable wireless pressure sensor based on a passive inductance–capacitance resonant circuit; Reproduced with permission from Ref. [96]; Copyright 2020, John Wiley and Sons. **d** An implantable biodegradable pressure sensor that achieves degradability by encapsulating the device on its top surface and peripheral edge regions using single-crystal silicon membranes and natural wax material mixtures, respectively; Reproduced with permission from Ref. [97]; Copyright 2020, John Wiley and Sons. **e** An implantable multi-modal sensor array that conforms to the cortical surface; Reproduced with permission from Ref. [98]; Copyright 2024, John Wiley and Sons. **f** A wearable, non-invasive ICP fiber-based sensor that can be used like a Band-Aid for infant intracranial pressure monitoring; Reproduced with permission from Ref. [99]; Copyright 2021, Multidisciplinary Digital Publishing Institute

Fiber-optic technology, on the other hand, offers certain advantages for non-invasive/minimally invasive temperature monitoring by interacting with tissues. Tang et al. [90] developed an injectable hydrogel sensor embedding lanthanide-doped nanoparticles, employing an upconversion fluorescence intensity ratio to achieve a 0.1 °C resolution, and it fully degrades after 18 weeks. Meanwhile, Liu et al. [91] introduced a multi-modal fiber (Fig. 8b) that integrates a fiber Bragg grating (FBG) and a pH-sensitive dye onto a polydimethylsiloxane substrate; by combining wavelength and light intensity as dual-parameter calibrations, the device removes interference from cerebrospinal fluid flow.

3.2 Intracranial Pressure

Abnormal intracranial pressure (ICP) is closely related to cerebrovascular diseases such as cerebral edema. Traditional monitoring methods, such as active implantation [92], fluid-based systems [93], and Doppler ultrasound [94], are not suitable for long-term real-time monitoring. Flexible fibers have unique advantages, with their flexibility and biocompatibility suitable for complex brain surfaces and ensuring the "compliance" of the interface between the sensor and tissue.

The flexible pressure sensor developed by Karmakar et al. (Fig. 8c) can monitor pressure during surgery to

avoid brain damage [95]. Implantable sensors require surgical removal, and biodegradable materials can avoid this problem. The biodegradable wireless pressure sensor proposed by Lu et al. (Fig. 8d) can operate stably in the body for 4 days [96]; the biodegradable pressure sensor proposed by Yang et al. (Fig. 8e) has a working life of up to several weeks and a physical life of up to several months [97]. Kim et al. developed an implantable multi-modal sensor array (Fig. 8f) with a mesh structure that conforms to the cortex and simultaneously monitors intracranial temperature and pressure [98]. For infants, invasive ICP measurement can easily lead to infection. The wearable ICP fiber-based sensor developed by Zhang et al. monitors infant ICP through liquid metal deformation, which can reduce potential damage to cerebral blood vessels [99].

3.3 Cerebral Blood Flow

Cerebral blood flow (CBF) is closely related to cerebrovascular diseases. Cerebral ischemia can lead to tissue damage, cerebral edema, etc. [100, 101] Traditional monitoring methods such as transcranial Doppler ultrasound and laser speckle contrast imaging [102] are difficult to continuously monitor, while flexible fiber electronic devices provide a more convenient way.

The chronic cerebral blood flow imaging device developed by Haruta et al. can measure blood flow velocity in real time and obtain images of the brain surface (Fig. 9a) [103]. Hemodynamics is important for post-operative monitoring of cerebral aneurysms. The stretchable nanostructured fiber flow sensing system proposed by Howe et al. can quantify hemodynamics within aneurysms, (Fig. 9b) and the open mesh membrane can be effectively implanted and reduce damage [104].

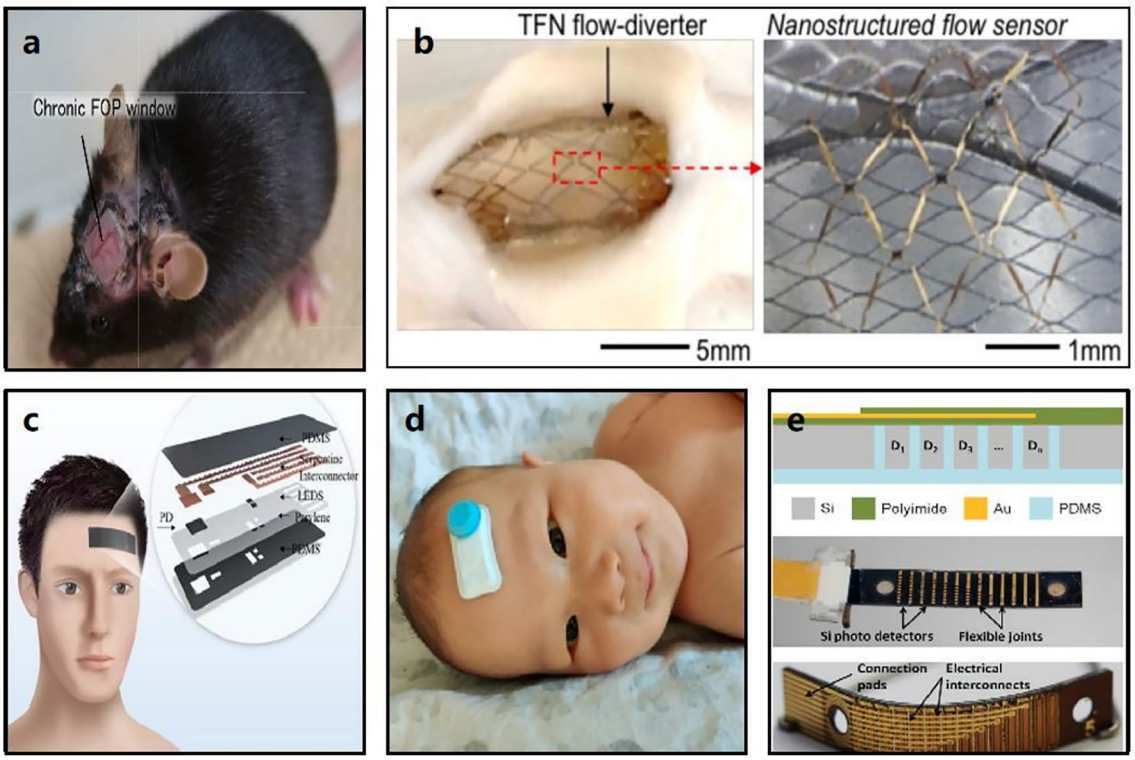


Fig. 9 Flexible fiber electronic devices for monitoring cerebral blood flow and brain tissue oxygenation. **a** A chronic cerebral blood flow imaging device for the treatment of cerebrovascular diseases; Reproduced with permission from Ref. [103]; Copyright 2019, Multidisciplinary Digital Publishing Institute. **b** A stretchable, nanostructured implantable flow sensing system that can quantify hemodynamics within aneurysms; Reproduced with permission from Ref. [104]; Copyright 2018, American Chemical Society. **c** A flexible wearable long-term monitoring system that can accurately measure changes in intracranial hemoglobin concentration; Reproduced with permission from Ref. [114]; Copyright 2022, Multidisciplinary Digital Publishing Institute. **d** A small flexible wireless wearable device that can simultaneously perform whole-body and brain hemodynamic monitoring, with measured indicators including peripheral oxygenation, heart rate, brain oxygenation, and potential cerebral pulse pressure; Reproduced with permission from Ref. [116]; Copyright 2020, National Academy of Sciences. **e** A wearable flexible fiber-based sensor to detect oxygen saturation in brain tissue; Reproduced with permission from Ref. [117]; Copyright 2013, Elsevier

Current non-invasive CBF measurements are limited by penetration depth and motion effects, making accurate measurement difficult. To address this, Huang et al. developed a wearable, fiberless diffuse speckle contrast flowmeter sensor that can detect CBF through the skull [105]. The system developed by Liu et al. can monitor CO_2-induced CBF responses, reflecting changes in local vascular flow, pH, and blood oxygenation [106]. However, these fiberless sensors are difficult to adapt to tissue interfaces in different patients, and fiberized sensors should become a new direction for exploration.

Traditional clinical methods for monitoring cerebral blood flow (CBF) still face fundamental constraints. While transcranial Doppler (TCD) ultrasound is non-invasive, it depends heavily on operator skill and provides limited temporal resolution, often failing to capture instantaneous microembolization signals in ischemic stroke patients [107]. Laser speckle contrast imaging (LSCI) can generate real-time cortical perfusion maps but does not penetrate the superficial cortex and offers virtually no access to deeper structures, such as the basal ganglia which are closely linked to subcortical vascular dementia [108]. Furthermore, both methods lack reliable quantitative correlations with absolute blood flow values, adding complexity to hemodynamic-guided revascularization decisions [109]. Looking ahead, the development of flexible fiber devices should leverage advanced fiber technologies to overcome these obstacles. Integrated, multi-modal fiber probes incorporating diffuse correlation spectroscopy (DCS) and photoacoustic sensing are poised to enable depth-resolved flow quantification with extremely high temporal resolution. As demonstrated in primate models discussed above, biodegradable fiber arrays with nanoscale, antifouling surfaces can facilitate continuous intracranial monitoring for up to 6 months without forming a biofilm. Moreover, machine learning algorithms, trained on panvascular hemodynamic patterns, may reveal imaging-based predictions for specific disease states.

3.4 Brain Tissue Oxygenation

Oxygen partial pressure ($PbtO_2$) is an indicator of brain tissue oxygenation [110] and can substitute for CBF [111] in monitoring patients with acute brain diseases [112]. Current monitoring methods include electrochemical sensing and near-infrared spectroscopy (NIRS) [113], and the rapid development of flexible fiber devices has brought new opportunities for brain oxygenation measurement.

NIRS can indirectly measure brain oxygenation by measuring hemoglobin concentration, but traditional devices are bulky and uncomfortable. The flexible fiber-based wearable system developed by Ji et al. (Fig. 9c) is simple and lightweight, and can monitor brain tissue oxygen supply levels in real-time [114]. The flexible fiber headband designed by Gurel et al. can measure NIRS to quantify prefrontal cortex oxygenation and assess cerebrovascular activity [115]. Adult NIRS devices are large and rigid, making them unsuitable for children. Rwei et al. fabricated a small, flexible, wireless wearable device (Fig. 9d) that can monitor brain oxygenation in children [116]. The wearable flexible fiber-based silicon optoelectronic sensor proposed (Fig. 9e) by Petersen et al. uses NIRS to monitor brain oxygenation in children and has good bending properties [117].

3.5 Other Applications

Some studies have also reported other applications of flexible sensors in monitoring cerebrovascular diseases. The skin interface is crucial for the diagnosis and treatment of cerebrovascular diseases. Tian et al. developed a skin interface compatible with magnetic resonance imaging, suitable for non-invasive brain imaging and long-term Electroencephalogram (EEG) monitoring [118]. Schuhmann et al. proposed a plug-and-play mesh electronics design that can quickly connect and record head potentials [119]. Brain–computer interfaces face the problem of mismatched "device-tissue" interfaces. The flexible, high-density stretchable electrode grid developed by Tybrandt et al. (Fig. 10a) is based on high-performance composite materials and can stably record neural signals [120]. Another challenge for brain–computer interfaces is the limited number of channels. The small flexible electrode array by Musk et al. has promoted the development of scalable brain-computer interfaces [121]. These brain-computer interfaces are expected to build a new "diagnosis-intervention" model for cerebrovascular diseases.

Medical implantable electrocorticography (ECoG) can also be used for the diagnosis of cerebrovascular diseases, but surgical removal is required. The biodegradable ECoG (Fig. 10b) device developed by Xu et al. integrates a cortical pressure sensor and can monitor intraoperative swelling and local vascular pressure changes [122]. The electrophysiology and neurochemical substances of the cerebral cortex can collaboratively reflect the cerebrovascular physiological state. The flexible multifunctional electrode proposed by Yang et al. can record ECoG and extracellular ions, (Fig. 10c) with low impedance and biocompatibility [123].

Flexible fiber electronics demonstrate significant potential for monitoring cerebrovascular diseases but face unique challenges, especially given the systemic and chronic profile of panvascular diseases. First, the central nervous system is highly sensitive to foreign bodies, and long-term implants may provoke chronic inflammation or glial scarring, compromising precision. Second, microdynamic signals such as cerebral blood flow and oxygen partial pressure are often subtle and prone to motion artifacts, particularly in patients with comorbid hypertension or arrhythmias. Third, current devices typically track only single parameters, whereas

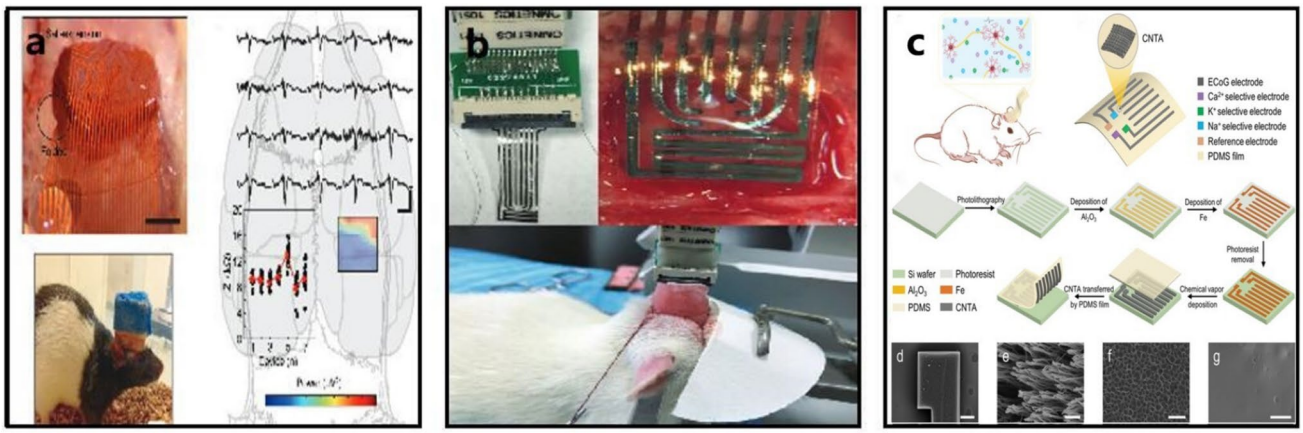


Fig. 10 Other types of flexible fiber electronic devices for monitoring cerebrovascular diseases. **a** A flexible, high-density, stretchable electrode grid that can resolve high spatiotemporal neural signals on the cortical surface of freely moving rats; Reproduced with permission from Ref. [120]; Copyright 2018, John Wiley and Sons. **b** A novel flexible and bioabsorbable ECoG device for monitoring cortical swelling during surgery; Reproduced with permission from Ref. [122]; Copyright 2019, John Wiley and Sons. **c** A flexible multifunctional electrode (FME) based on carbon nanotube arrays to record ECoG and extracellular ions of Ca^{2+}, K^{+}, and Na^{+}; Reproduced with permission from Ref. [123]; Copyright 2022, John Wiley and Sons

cerebrovascular conditions often require measuring multiple factors like flow, oxygen metabolism, and neuroelectric activity simultaneously. Fourth, microcatheter-based interventions must consider the tortuous structure of cerebral vasculature, which can be especially fragile in panvascular patients. Finally, power supply and wireless transmission remain unsolved limitations. Large-scale clinical trials are needed to harmonize device performance across different conditions (e.g., stroke and aneurysm), with standardized evaluation protocols for long-term stability.

Diagnosis and treatment of cerebrovascular diseases require consideration of both local pathological features and the dynamic interplay across the entire vascular system. This review describes significant advances in flexible fiber electronics for intracranial temperature, pressure, blood flow, and cerebral oxygen monitoring: for instance, degradable fiber sensors enabling continuous intracranial pressure measurements over 4 weeks, near-infrared fiber arrays that simultaneously capture cerebral oxygen saturation and hemoglobin concentrations, and liquid–metal Doppler fiber systems exhibiting high sensitivity in detecting microemboli [97]. Nonetheless, multiple challenges remain across different dimensions. Future breakthroughs in flexible fiber devices for cerebrovascular monitoring must adopt a multiangle strategy: for example, constructing biomimetic fiber topologies that mitigate skull-induced heterogeneity; building heart–brain–peripheral sensor networks to integrate intracranial pressure tracking with blood-flow profile reconstruction; and employing reinforcement learning algorithms to interpret systemic blood-flow redistribution. Moreover, the development of self-adjusting fibers that dynamically modulate their elastic modulus can facilitate stable long-term implantation. By fusing multi-scale data on cerebral hemodynamics, intracranial pressure, temperature, and tissue oxygenation, intelligent fiber electronics stand to shift cerebrovascular disease management from treating discrete, isolated events toward upholding the brain's overall functional stability.

4 Flexible Fiber Electronic Devices for Monitoring Peripheral Vascular Diseases

Peripheral artery disease (PAD) is a class of diseases that affect the arteries of the limbs [124] and is closely related to hypertension, diabetes, and its complications such as diabetic foot [125–127]. Blood glucose, arterial stiffness, blood flow, and sweat are important indicators for monitoring PAD, and flexible fiber electronic devices have significant advantages in monitoring these indicators.

4.1 Blood Glucose

Blood glucose can be used to monitor diabetes and hypoglycemia [128, 129] and is associated with vascular diseases such as hypertension [130]. Existing monitoring methods such as glucose meters and glycated hemoglobin detection have problems such as invasiveness, while flexible electronic components provide real-time continuous monitoring solutions.

To adapt to the complex tissue interfaces of the human body, Kudo et al. developed a glucose sensor based on functional polymers, (Fig. 11a) fixing glucose oxidase to flexible

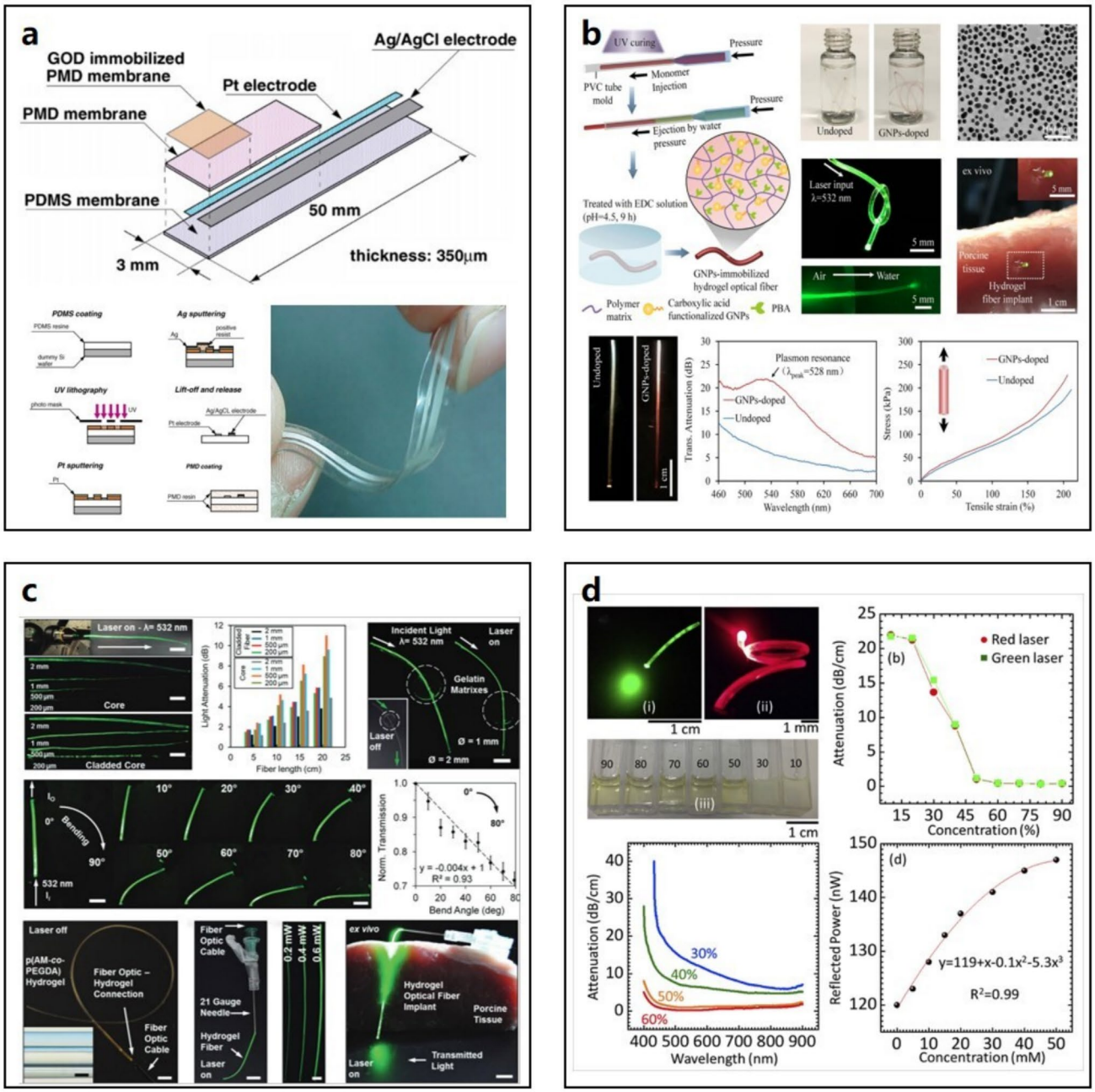


Fig. 11 Flexible fiber electronic devices for monitoring glucose in panvascular diseases. **a** A novel biosensor using functional polymers for measuring glucose; Reproduced with permission from Ref. [131]; Copyright 2006, Elsevier. **b** A soft plasmonic hydrogel optical sensor composed of flexible optical fibers made from gold nanoparticles and glucose-responsive hydrogel composites, enabling real-time and quantitative monitoring of blood glucose; Reproduced with permission from Ref. [132]; Copyright 2021, Walter de Gruyter GmbH. **c** Hydrogel optical fibers for real-time continuous glucose sensing, exhibiting good repeatability, strong continuous sensing capability, and excellent biocompatibility; Reproduced with permission from Ref. [133]; Copyright 2017, John Wiley and sons. **d** Utilizing biocompatible hydrogels made from polyethylene glycol diacrylate for flexible hydrogel fiber fabrication to replace silica fibers in integrated optical fibers, and functionalizing the fiber tips with glucose-sensitive hydrogels during the ultraviolet (UV) curing process, enabling quantitative sensing of glucose under physiological conditions; Reproduced with permission from Ref. [134]; Copyright 2019, Elsevier

electrodes with good flexibility and stretchability [131]. Existing glucose monitors require frequent calibration due to unstable enzyme reactions, while the flexible plasma hydrogel optical sensor (Fig. 11b) created by Guo et al. solves the frequent calibration problem and is suitable for the elderly population [132]. Optical fibers have prospects in continuous glucose monitoring, but traditional solid-state optical fibers have problems such as poor biocompatibility. The hydrogel

fiber proposed by Yetisen et al. can continuously monitor glucose in real time, (Fig. 11c) with good optical properties and biocompatibility [133]. Elsherif et al. also demonstrated an integrated optical fiber (Fig. 11d) using glucose-sensitive hydrogels, with high sensitivity, fast response, and high selectivity [134].

Traditional blood glucose monitoring approaches, including fingertip blood sampling and continuous glucose monitoring systems (CGMs), exhibit several limitations surrounding invasiveness and comfort. For instance, frequent skin pricks can cause pain and raise infection risks [131], while the rigid probes of implantable CGMs may elicit tissue inflammation or fibrotic encapsulation. Second, issues of calibration dependence and signal delay are common. Glucose oxidase-based sensors are often susceptible to variations in temperature, pH, and interfering substances, necessitating daily calibration and exhibiting time-dependent signal lag [26]. Third, traditional methods are typically single mode and constrained by limited functionalities, capturing only blood glucose levels without simultaneously monitoring associated metabolic indices (e.g., lactate and ketones), which hinders a thorough assessment of diabetes-related panvascular complications [6]. To overcome these limitations, future research on flexible electronics may focus on multi-parameter integrated sensing, such as electrochemical–optical dual-mode fibers based on nanomaterials, capable of simultaneously measuring blood glucose, lactate, and pH while using machine learning algorithms to predict the risk of diabetic foot ulcers. Other directions include designing ultra-thin, flexible patches to enable non-invasive monitoring enhanced by biomimetic microneedle arrays for improved skin signal coupling; integrating sensors with micro-drug-release modules to form "monitoring–intervention" closed loops (for example, glucose-responsive hydrogels for controlled insulin release); employing biofuel cells or triboelectric nanogenerators to harvest energy from bodily fluids, thereby extending device longevity, while adding antifouling coatings to limit sensitivity decay; and customizing patient-specific sensor configurations via 3D printing to accommodate diverse vascular anatomies, using big-data analysis to achieve personalized blood glucose fluctuation predictions. By pursuing these innovations, researchers can significantly address current technological shortcomings and develop safer, more effective, and increasingly comfortable solutions for blood glucose monitoring.

4.2 Blood Flow

Blood flow detection involves indicators such as blood velocity and blood flow, which helps understand vascular conditions and predict complications [135]. Traditional monitoring methods, such as Doppler ultrasound and magnetic resonance imaging, are difficult to provide multi-modal data, [136] while flexible fiber electronic devices provide new monitoring solutions.

The Janus flexible perfusion sensor system developed by Huang et al. reduces motion artifacts through Janus structures with different Young's moduli and monitors peripheral blood perfusion in real time [137]. Cannata et al.'s blood flow measurement system based on Doppler ultrasound patches can be used for miniaturized, non-invasive blood flow monitoring [138]. Wired implantation techniques require fixation and removal after use, while Boutry et al.'s biodegradable pressure sensors based on fringe-field capacitance technology reduce the risk of vascular damage through wireless operation [139].

Postoperative monitoring of vascular reconstruction or grafts is important [140, 141]. To address potential interference from implanted sensors on artificial blood vessels, L. Natta et al. proposed an ultra-thin, flexible smart patch integrated on the outer surface of the prosthetic cavity (Fig. 12a) for post-operative vascular monitoring, offering high sensitivity and good biocompatibility [142]. The thin, flexible, and biodegradable arterial sensor developed by Chong et al. can also be wrapped around a graft for long-term monitoring of blood pressure and flow [143]. Meanwhile, the Doppler ultrasound device developed by Wang et al. (Fig. 12b) is thin, lightweight, and conforms to the skin, allowing accurate measurement of blood flow through the dual-beam Doppler method [144].

4.3 Arterial Stiffness

Arterial stiffness is associated with conditions such as hypertension and stroke [145, 146]. Increased stiffness places additional stress on the heart and facilitates the onset of hypertension [147], serving as a key hallmark of atherosclerosis [148]. The current clinical gold standard is an ultrasound-derived stiffness parameter β ($\beta = \ln(Ps/Pd) / (\Delta D/Dd)$), which quantifies vascular elasticity through simultaneous measurements of systolic pressure (Ps), diastolic pressure (Pd), and arterial diameter changes (ΔD/Dd) [149]. However, traditional methods face notable constraints: the spatial resolution of ultrasound probes is limited, making it challenging to precisely capture the minute diameter fluctuations of peripheral small arteries (e.g., the dorsalis pedis artery) [144]. Moreover, discrepancies in timing between blood pressure cuff measurements and ultrasound imaging introduce errors in calculating β.

In contrast, flexible fiber-based electronic devices excel at collecting the high-precision parameters required by the β formula, rather than directly supplanting ultrasound's stiffness evaluation. For example, distributed fiber pressure sensing utilizes a grating-array patch affixed to the arterial adventitia (spatial resolution of 0.2 mm) to track arterial diameter fluctuations in real time, offering a 20-fold

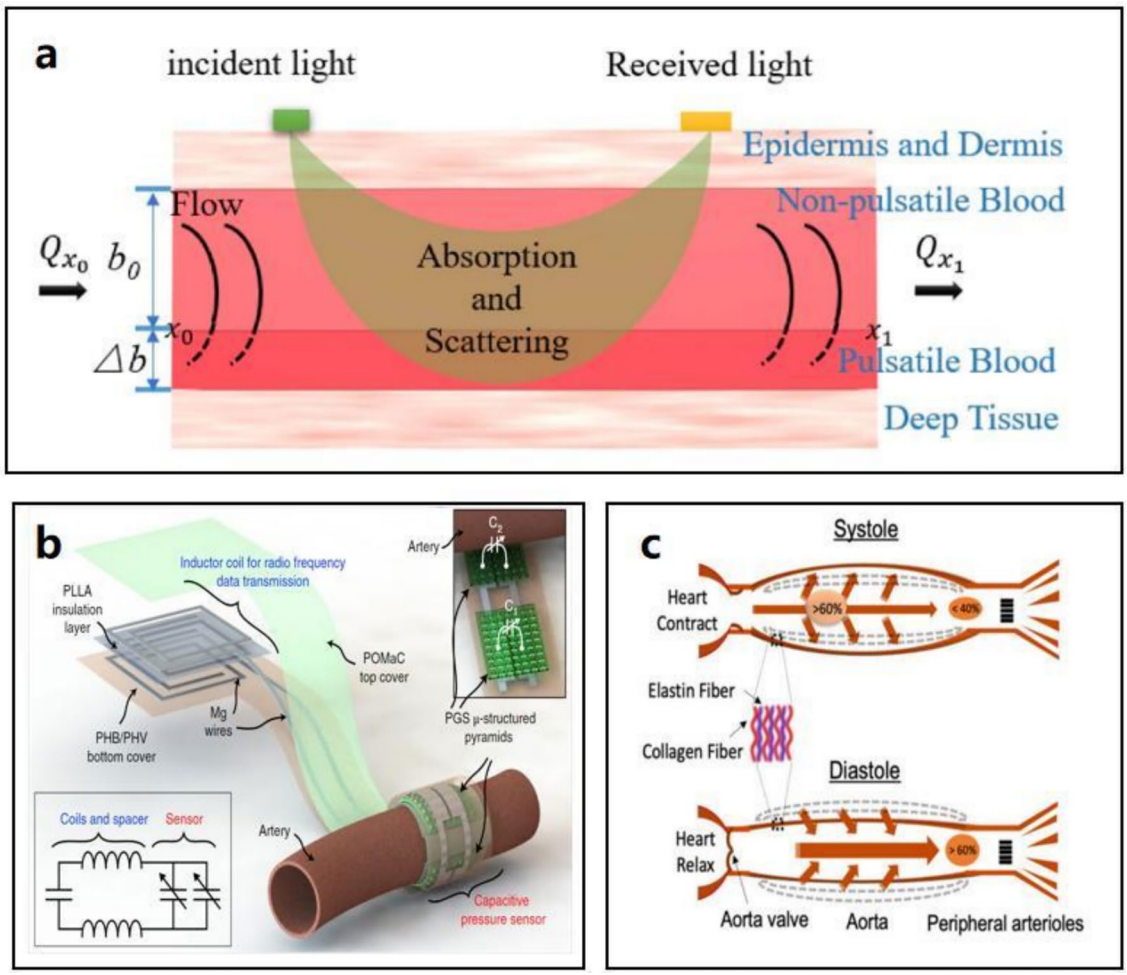


Fig. 12 Flexible fiber electronic devices for blood flow and arterial stiffness monitoring. **a** An ultra-thin, flexible, smart patch based on piezoelectric aluminum nitride (AlN) integrated on the outer surface of a prosthetic cavity that can conformally wrap around the outer surface of the prosthesis; Reproduced with permission from Ref. [142]; Copyright 2019, Springer Nature. **b** A flexible Doppler ultrasound device for continuous monitoring of absolute blood flow velocity in deeply buried arteries, using a dual-beam Doppler method to avoid the influence of Doppler angle on velocity measurements; Reproduced with permission from Ref. [144]; Copyright 2021, The American Association for the Advancement of Science. **c** A stroke volume allocation (SVA) model for quantifying the buffering function of arteries and endowing almost all existing cardiac sensors with new functions, including arterial stiffness assessment, dynamic blood pressure tracking, and classification of CVD-related cardiac damage; Reproduced with permission from Ref. [151]; Copyright 2024, Springer Nature

improvement over ultrasound [150]. Additionally, flexible fibers can achieve non-invasive blood pressure monitoring in conjunction with fiber-optic photoacoustic sensors and machine learning algorithms, enabling cuff-free, continuous Ps/Pd measurements [77].To address the problem of existing devices only being able to measure a single or few vital signs, Qiu et al. reported a stroke volume allocation (SVA) model (Fig. 12c) for quantifying arterial buffering function and adding new functions such as arterial stiffness assessment and dynamic blood pressure tracking to flexible sensors. Through large-scale clinical data testing, the SVA model was closely correlated with gold standard measurements and outperformed single commonly used vital signs in detecting vascular system abnormalities, providing new ideas for solving the problem of single-modal monitoring [151].

Conventional arterial stiffness assessment systems exhibit certain clinical limitations. For example, while the β-parameter method is a vital index for gauging local arterial elasticity, its measurements can be sensitive to patient posture and often target large vessels (e.g., carotid arteries), making it difficult to capture capillary wall sclerosis characteristic of diabetic micro-vascular disease [151]. Although the ankle–brachial index (ABI) can assess arterial calcification indirectly, it cannot distinguish medial calcification from intimal atherosclerosis,

as the two involve distinct pathophysiological mechanisms [139]. Additionally, traditional setups are typically bulky and reliant on professional expertise, ill-suited for real-time stiffness assessments during dynamic movements—precisely the critical scenario for evaluating functional ischemia in patients with peripheral arterial disease [9]. In light of the research above, future flexible electronics could venture into realms, such as multi-modal mechanical sensing integration, biomimetic vascular interface optimization, dynamic closed-loop monitoring, four-dimensional mechanical imaging, and degradable devices for long-term monitoring. Potential examples include capturing circumferential stress and longitudinal elastic moduli concurrently while leveraging deep learning for arterial stiffness grading; reconstructing spatiotemporal distributions of vascular stiffness via topological mapping; and creating intelligent fibers from polylactic-co-glycolic acid (PLGA) with degradation rates aligned to vascular remodeling, equipped with wireless energy-harvesting modules to support monitoring over the entire device lifespan. Through cross-scale mechanical analyses and system-level modeling, the next generation of flexible electronics may profoundly reshape accurate arterial stiffness evaluation.

4.4 Sweat

Sweat monitoring is important for assessing peripheral vascular disease and involves indicators such as electrolyte concentrations and biomarkers [152]. Emerging electrochemical and optical sensors can analyze sweat components, [153] and we pay a special attention to flexible fiber electronic devices.

The measurement of biomarkers in sweat often relies on laboratories, but the wearable microfluidic device developed by Zhao et al. can accurately analyze glucose concentration, pH, and chloride, and calibrate data via smartphones. [154] Metal fracture caused by movement may affect sensor stability, and the flexible wearable sensor proposed by Lin et al. solves this problem (Fig. 13a) and can accurately monitor glucose in sweat. [155] To avoid contamination from traditional sampling, Chen et al. introduced a 3D-printed flexible wearable monitor with self-supporting microfluidic channels that can measure sweat rate and concentrations of glucose, lactate, and uric acid (Fig. 13b) [156] The biocompatible, stretchable, and self-healing hydrogel constructed by Li et al. (Fig. 13c) can monitor human body movements and sweat components. [157] Enzymatic biofuel cells have broad prospects but are limited by rigid platforms, and the nanocomposite inks demonstrated by Veenuttranon et al. for enzyme-based self-powered biosensor design (Fig. 13d) can convert chemical energy into electrical energy and detect glucose in sweat. [158]

4.5 Other Applications

In addition to the above applications, some studies have also made positive explorations for complex vascular diseases.

Vascular transplantation surgery has high risks, and real-time monitoring of blood vessels helps early detection of complications. Li et al. developed an electric field-assisted 3D printing technology to fabricate in situ ferroelectric artificial arteries, (Fig. 14a) enabling battery-free real-time blood pressure and occlusion monitoring to prevent transplant failure. [159] After microsurgery, continuous monitoring of perfusion status is critical for diagnosing thrombosis. Guo et al. proposed a passive implantable, miniaturized, minimally invasive NIRS monitoring system that can continuously monitor tissue oxygenation and heart rate (Fig. 14b) and can be easily removed. [160] D'Ambrogio et al. designed a biocompatible piezoelectric composite material (Fig. 14c) that monitors blood pressure and identifies thrombosis through inductive coil coupling. [161]

Physiological pressure monitoring is often used for early diagnosis of vascular lesions. Farooq et al. proposed a thin-film flexible wireless pressure sensor for interface pressure monitoring in compression therapy for venous insufficiency (Fig. 14d) [162] Biodegradable materials can avoid secondary surgery and meet the concept of "match and harmony". Ouyang et al. reported a triboelectric pressure sensor (Fig. 14e) using antibacterial biodegradable materials that can identify vascular occlusion events and is suitable for post-operative care. [163]

Flexible fiber electronics also show considerable promise in peripheral vascular disease (PVD) monitoring but face challenges. Excessive motion, such as leg movement, can undermine stable attachments in optical fiber devices, while thickening skin in some diabetic patients reduces optical penetration. Moreover, sweat electrolytes can interfere with plasmonic resonance signals, and venous signals can overlap with arterial ones in slow blood flow states. Chronic pathophysiological environments—e.g., diabetic patients with thickened endothelium—elevate implant failure risks. To overcome these obstacles, the next generation of peripheral vascular devices may integrate multi-parameter detection, topologically optimized sensor designs to reduce motion artifacts, and advanced data fusion algorithms to capture synergy among local hemodynamics, micro-vascular remodeling, and systemic cardiac output.

Peripheral arterial disease (PAD), a panvascular disorder affecting vessels in the limbs, requires effective monitoring that accounts for local pathological changes as well as systemic compensatory mechanisms. This review shows that flexible fiber electronics have achieved

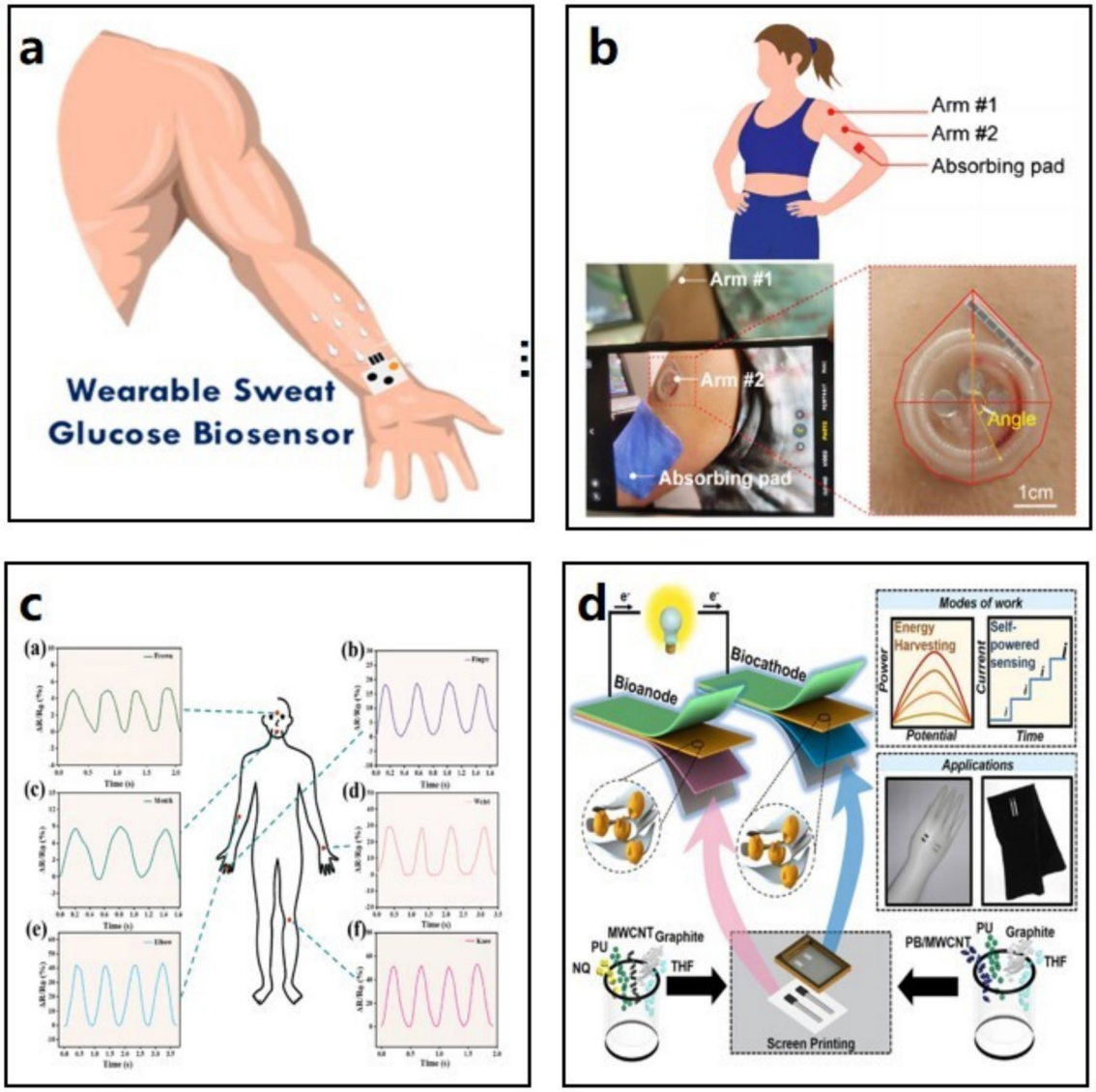


Fig. 13 Flexible fiber electronic devices for sweat monitoring. **a** A Polyaniline (PANI) matrix anchored with Nitrogen-doped Graphene Quantum Dots (N-GQDs), designed as a flexible wearable biosensor with high detection accuracy; Reproduced with permission from Ref. [155]; Copyright 2023, Elsevier. **b** A flexible wearable health monitor based on three-dimensional (3D) printing, with self-supporting microfluidic channels, which can be used to measure sweat rate and concentrations of three biomarkers; Reproduced with permission from Ref. [156]; Copyright 2024, American Chemical Society. **c** A biocompatible, stretchable, and self-healing hydrogel constructed by introducing polydopamine (PDA) and gold nanoparticle (AuNPs) modified Cellulose Nanocrystals (CNCs) into a poly (vinyl alcohol) (PVA) network, used for flexible sensors for human motion monitoring and sweat sensing detection; Reproduced with permission from Ref. [157]; Copyright 2023, Elsevier. **d** A screen-printable nanocomposite ink, combined with a wireless portable system, which can convert chemical energy into electrical energy and detect glucose in artificial sweat; Reproduced with permission from Ref. [158]; Copyright 2023, Springer Nature

prominent progress in glucose, blood flow, arterial stiffness, and sweat monitoring: for example, hydrogel-based optical fibers for continuous glucose tracking, piezoelectric fiber arrays for detecting nanoscale arterial wall vibrations, and plasmonic sensors capable of simultaneously analyzing six metabolic markers in sweat. Nevertheless, current technologies remain challenged by clinical issues spanning multiple scales. Future innovations in intelligent fiber devices for monitoring peripheral vascular diseases should target a three-tiered approach across materials, devices, and integrated systems. Potential directions include designing biomimetic, fatigue-resistant fibers tolerating high shear stress in diabetic foot ulcers; constructing multi-modal closed-loop systems whereby an intelligent sensor network captures glucose–blood-flow–hardness parameters and drives microneedle-based

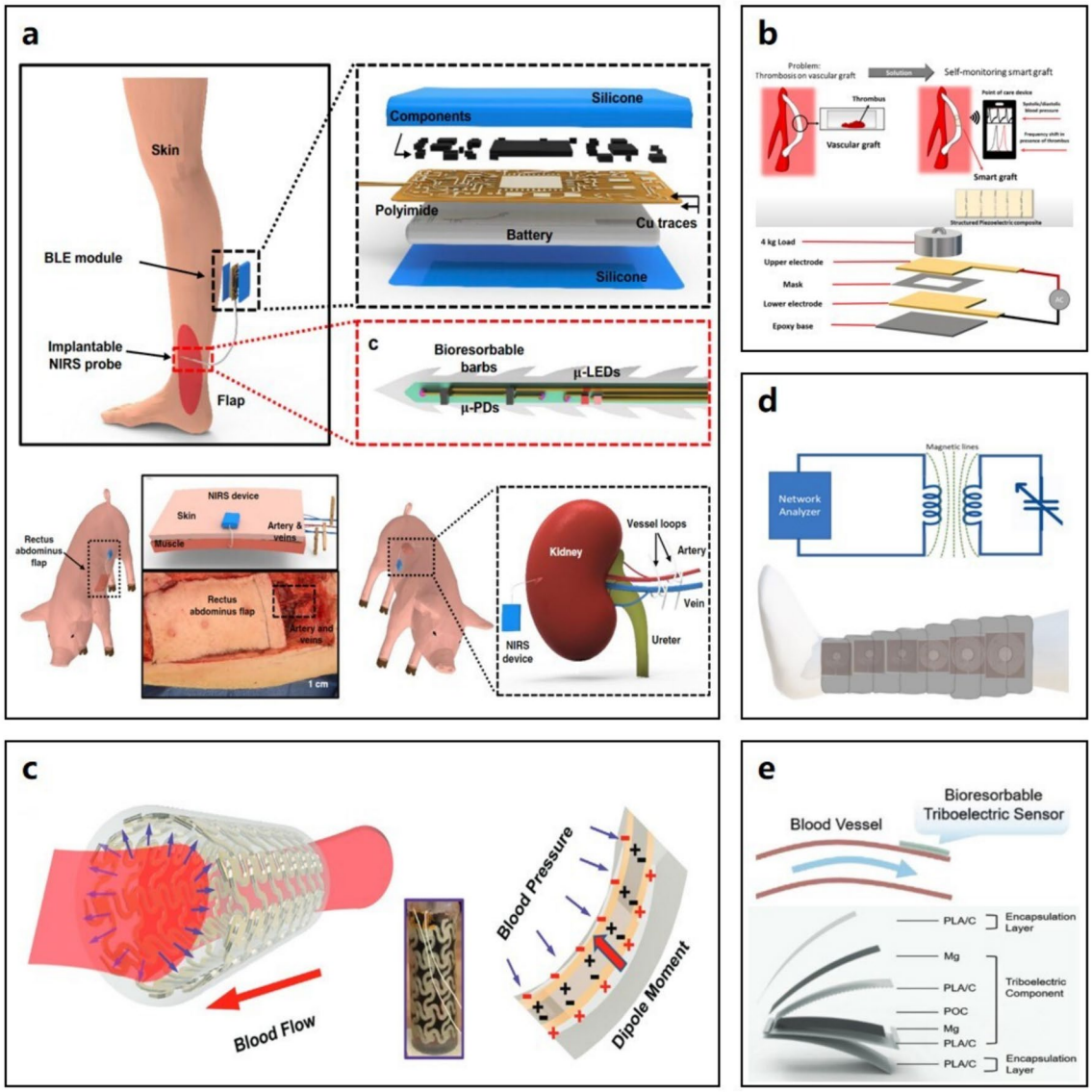


Fig. 14 Other types of flexible fiber electronic devices for peripheral vascular disease monitoring. **a** In situ ferroelectric artificial arteries fabricated based on electric field-assisted 3D printing technology, providing battery-free real-time blood pressure sensing and occlusion monitoring functions; Reproduced with permission from Ref. [159]; Copyright 2020, John Wiley and Sons. **b** A novel passive, implantable, miniaturized, minimally invasive near-infrared spectroscopy monitoring system for continuous monitoring of local tissue oxygenation; Reproduced with permission from Ref. [160]; Copyright 2022, Springer Nature. **c** A novel biocompatible piezoelectric composite made by constructing fibers ($NaNbO_3$ fibers) in an elastomeric matrix via electrophoretic deposition, used for intelligent monitoring of vascular grafts; Reproduced with permission from Ref. [161]; Copyright 2022, Elsevier. **d** A thin-film flexible wireless pressure sensor mainly focusing on interface pressure monitoring during compression therapy for venous insufficiency; Reproduced with permission from Ref. [162]; Copyright 2020, Multidisciplinary Digital Publishing Institute. **e** A pressure sensor based on the triboelectric effect between bioabsorbable materials, which can successfully identify abnormal vascular occlusion events in large animals (dogs); Reproduced with permission from Ref. [163]; Copyright 2021, John Wiley and Sons

drug release on demand; and developing panvascular digital-twin platforms that fuse AI-based hemodynamic simulations with real-time sensor outputs to predict cascading heart–brain–peripheral events. Through cross-scale technical advances, flexible fiber electronics may revolutionize care paradigms from merely assessing localized conditions to orchestrating overall circulatory homeostasis.

5 Summary and Perspectives

Intelligent flexible fiber devices have shown enormous potential in monitoring and managing panvascular diseases. Numerous innovative approaches have already been developed to enable real-time, continuous monitoring of heart rate, blood pressure, ECG, EEG, intracranial pressure, cerebral blood flow, blood glucose, and arterial stiffness, all of which are important parameters for panvascular health. Owing to the flexibility, comfort, high electrical and thermal conductivity, and biocompatibility of flexible materials, these flexible fibers can be attached to the skin or implanted in the body, thereby enhancing short-term suitability and long-term concordance. They also hold significant potential for multifunctional integration, enabling the detection of potential risks in hypertension, atherosclerosis, diabetes, and other panvascular diseases.

Nonetheless, these devices still encounter certain limitations that restrict their widespread application in clinical settings. Panvascular diseases are characterized by a long-term, chronic progression, affecting populations from young to older adulthood, with high morbidity and mortality. They often involve vascular aging and pathological changes such as atherosclerosis. Accordingly, achieving long-term, real-time, continuous monitoring is paramount. Although existing flexible fiber materials are advantageous in terms of comfort and adaptability, they still show insufficient sensing accuracy and sensitivity in dynamic, complex physiological environments—particularly for detecting subtle physiological changes. Since panvascular diseases progress slowly and entail small, incremental changes, researching high-precision devices capable of real-time tracking is critical. In addition, during prolonged wear, these devices can easily be affected by environmental noise and power supply interruptions, limiting their stability. While flexible materials do offer advantages in biocompatibility, persistent contact with the skin or long-term implantation within the heart, brain, or blood vessels can disrupt the vascular system's cellular, mechanical, physiological, and immunological balance. For instance, implanted stents in long-term contact with the vessel wall may trigger immune responses leading to localized chronic inflammation, which can further induce endothelial cell damage, abnormal smooth muscle cell proliferation, or vascular wall dysfunction. Unstable device fixation may cause mechanical imbalance in blood vessels, uneven contact between the device and the vessel wall, and altered hemodynamics that could raise local stress levels, increasing risks of thrombosis and restenosis while reducing suitcordance. Wearable fibers like conductive polymers could cause skin allergies, eczema, or peeling; in the brain, implanted flexible materials may trigger inflammatory responses in surrounding tissue, affecting device performance and potentially causing neurological symptoms, such as headaches, memory loss, and mood swings. These issues inevitably influence patient comfort and health, emphasizing that safety is critical for long-term management in panvascular diseases. Many devices continue to rely on battery power, restricted by volume and energy density—factors that limit battery capacity for long-term monitoring in clinical settings. Panvascular disease monitoring involves multiple physiological indicators associated with the heart, brain, and peripheral circulation. In diseases like coronary artery disease and stroke, a single indicator may be insufficient to evaluate disease progression comprehensively, and although some devices already track multiple parameters, effectively integrating multi-modal data with synchronous spatial and temporal scales remains a technical challenge. Additionally, acute exacerbations, such as myocardial infarction or stroke, are unpredictable, demanding devices that can quickly capture and transmit critical physiological data at disease onset for timely interventions. Consequently, the reliability and efficiency of data transmission technology remain crucial, and improving transmission capability and energy utilization is an urgent need.

Future investigations should focus on enhancing sensing accuracy by devising more sensitive sensors capable of capturing physiological signals in dynamic real-world environments, improving detection precision and anti-interference performance. Durability and stability of the materials warrant further advancement to ensure stable device operation under complex conditions. As panvascular diseases progress over prolonged periods, long-term wearability and biocompatibility challenges increase. Thus, devices should heighten suitability and reduce rejection or discomfort over time. Simultaneously, new power solutions, such as wearable energy harvesting, wireless power transfer, and high-capacity batteries with extended lifespans, are integral to sustaining long-term monitoring of chronic conditions like diabetes and hypertension. Furthermore, optimizing multi-modal sensor integration and data fusion improves synchronization and accuracy across different monitoring parameters, facilitating robust and real-time cross-modal data analyses through AI algorithms, ultimately promoting more advanced, intelligent panvascular health monitoring. Combined with 5G technology, wireless communication protocols can be enhanced at low power overhead and high throughput, enabling long-term stability in health data transmission for timely and accurate diagnosis and treatment of panvascular diseases.

Addressing these obstacles will have profound implications for the clinical translation and practical application of flexible fiber electronics. Improving sensor accuracy and sensitivity helps detect potential health issues at earlier stages, thereby boosting prevention and individualized

Table 1 High-suitconcordance intelligent fibers for panvascular disease monitoring

System	Central organ	Detection indicator	Related disease	Device classification	Sensing principle	Reference
Panvascular Disease Monitoring System	Cardiovascular	Pulse and blood pressure	Hypertension, arteriosclerosis, myocardial infarction diabetes, arrhythmia, heart failure, etc	Wearable Implantable	Optics, pressure, magnetism Piezoelectricity	[22, 24, 27–30] [31]
		Heart rate	Arrhythmia, coronary heart disease, myocardial infarction, heart failure, etc	Wearable	Optics, acoustics	[36–42]
		Electrocardiogram	Arrhythmia, myocardial ischemia, myocardial infarction heart failure, coronary heart disease, heart failure, etc	Wearable Implantable	Electricity Electricity	[46–50] [51]
		Direct epicardial monitoring	Arrhythmia, heart attack, heart failure, etc	Implantable	Electricity	[55–59]
		Echocardiography	Coronary artery disease, cardiomyopathy, valvular heart disease, hypertension, etc	Wearable	Acoustics	[62–64]
		Integrated stand	Coronary artery disease, etc	Implantable	Piezoelectricity	[69–73]
		Endocardial pressure	Heart failure, valvular disease, endocarditis, heart failure, etc	Implantable	Pressure	[77]
		Cardiac volume	Heart failure, valvular disease, etc	Implantable	Electricity	[79]
		Impedance cardiogram	Heart failure, coronary heart disease, etc	Wearable	Electricity	[82]
	Cerebrovascular	Intracranial temperature	Cerebral hemorrhage, cerebral infarction, etc	Implantable	Photoelectricity, ultrasound, thermal sensing	[87–91]
		Intracranial pressure	Hypertensive cerebral hemorrhage, cerebral infarction rupture of intracranial aneurysm, cerebrovascular malformation, etc	Implantable Wearable	Capacitors, thermal sensing, machinery Piezoresistive	[95–98] [99]
		Cerebral blood flow	Arteriosclerosis, cerebral aneurysm, cerebral vasospasm, stroke, etc	Implantable Wearable	Optics, acoustics Infrared, electrochemistry	[103, 104] [105, 106]
		Oxygenation of brain tissue	Ischemic, hemorrhagic, cerebral apoplexy, etc	Wearable	Infrared, photoelectricity	[114–117]
		Other indicator	Stroke, cerebral aneurysm, cerebral vasculitis, cerebral vasospasm, etc	Wearable& Implantable	Magnetism, optics	[118–123]

Table 1 (continued)

System	Central organ	Detection indicator	Related disease	Device classification	Sensing principle	Reference
	Peripheral vascular	Blood sugar	Hypoglycemia, diabetes, etc	Wearable& Implantable	Electrochemistry, photoelectricity	[131–134]
		Blood flow	Limb ischemia, lower limb arteriosclerosis obliterans, etc	Implantable	Piezoresistive, piezoelectricity	[137–139, 142–144]
		Arterial stiffness	Atherosclerosis, hypertension, diabetic vasculopathy, chronic kidney disease, etc	Implantable	Piezoelectricity	[151]
		Perspiration	Diabetes, limb ischemia, etc	Wearable	Electrochemistry	[154–158]
		Other indicator	Atherosclerosis, thrombosis, restenosis, etc	Wearable& Implantable	Pressure, acoustics	[159–163]

System	Central organ	Detection indicator	Device classification	Sensing principle	Advantage	Disadvantage
Panvascular Disease Monitoring System	Cardiovascular	Pulse and blood pressure	Wearable	Optics	Accurate and rapid monitoring	Demodulation systems are complex and have poor adaptability
				Magnetism	High durability, self-powered monitoring	Susceptible to interference
				Magnetism	Continuous monitoring with good stability	Persistently poor performance
			Implantable	Piezoelectricity	In situ, high-precision monitoring, self-powered	Aggressive invasion
		Heart rate	Wearable	Optics	Resistant to electromagnetic interference, lightweight and portable	Signal error under dynamic conditions
				Acoustics	High precision, real-time alerts	Impact on maternal comfort
		Electrocardiogram	Wearable	Electricity	Dry electrodes: stable signal, suitable for long-term monitoring; Capacitive electrodes: non-contact with skin, reducing irritation	Dry electrode: Humidity or movement affects the signal; Capacitive electrode: Susceptible to noise interference, weak signal
			Implantable	Electricity	Low signal distortion, good stability	Highly invasive, poses infection risk
		Direct epicardial monitoring	Implantable	Electricity	High-resolution, multi-parameter monitoring, integrated diagnosis and treatment	Data distortion, unsuitability, and infection risk
		Echocardiography	Wearable	Acoustics	Wireless design, high resolution	Susceptible to environmental contamination, with poor precision

Table 1 (continued)

System	Central organ	Detection indicator	Device classification	Sensing principle	Advantage	Disadvantage
		Integrated stand	Implantable	Piezoelectricity	Minimize secondary trauma risk, precise in situ monitoring	Susceptible to blood flow interference, with risk of complications
		Endocardial pressure	Implantable	Pressure	Minimally invasive, high sensitivity, self-powered	High environmental interference and poor stability
		Cardiac volume	Implantable	Electricity	Real-time dynamic monitoring	Implant risks, biocompatibility issues
		Impedance cardiogram	Wearable	Electricity	Current source-free design, highly adaptable	Susceptible to interference, with low precision
	Cerebrovascular	Intracranial temperature	Implantable	Photoelectricity	High precision and sensitivity, integrated potential	Localized deep tissue, long-term stability defect issues
				Ultrasound	Deep tissue coverage, multi-parameter synchronous evaluation	Insufficient temperature resolution, cranial heterogeneity interference
				Thermal sensing	High temporal resolution and real-time performance, with mature clinical validation	Invasive risk, electromagnetic interference sensitivity, spatial resolution limitations
		Intracranial pressure	Implantable	Capacitors	High sensitivity and dynamic response, biocompatibility and minimally invasive	Environmental interference sensitivity, long-term stability defects, spatial resolution limitations
				Thermal sensing	Indirect pressure monitoring, non-invasive potential	Low specificity, delayed response
				Machinery	Simple and reliable structure, resistant to electromagnetic interference	Invasive injury, limited low-frequency response
			Wearable	Piezoresistive	High sensitivity, miniaturized integration	Temperature drift, long-term fatigue failure
		Cerebral blood flow	Implantable	Optics	Non-invasive real-time monitoring, multi-modal scalability	Low spatial resolution, deep signal attenuation
				Acoustics	Deep vascular imaging, with low portability and cost	Acoustic window limitations prevent the quantification of absolute blood flow
			Wearable	Infrared	Contactless full-field scanning, vascular structure visualization	Indirect monitoring limitations, insufficient penetration depth, weak dynamic tracking capability
				Electrochemistry	Molecular-level specificity, ultra-high spatiotemporal resolution	Invasive damage, poor long-term stability, sensitive to electromagnetic interference

Table 1 (continued)

System	Central organ	Detection indicator	Device classification	Sensing principle	Advantage	Disadvantage
		Oxygenation of brain tissue	Wearable	Infrared,	High penetration depth, non-invasive, real-time monitoring	Signal interference, limited accuracy
				Photoelectricity	High sensitivity, compact size, multi-parameter monitoring	Surface dependency, motion artifacts
		Other indicator	Wearable& Implantable	Magnetism	Non-invasive monitoring, high-resolution imaging, multi-purpose functionality	High costs, environmentally sensitive
				Optics	Biocompatibility and flexibility, real-time monitoring capabilities, multifunctional integration	Limited penetration depth, signal interference
	Peripheral vascular	Blood sugar	Wearable& Implantable	Electrochemistry	High sensitivity, rapid response, portability	Requires calibration, susceptible to interference, consumable costs
				Photoelectricity	Non-invasive, real-time monitoring capabilities, multi-parameter monitoring	Penetration depth limitations, environmental sensitivity, complex data processing
		Blood flow	Implantable	Piezoresistive	High sensitivity, miniaturization, integration, and low cost	Temperature sensitivity, long-term stability issues, complex signal processing
				Piezoelectricity	Self-powered capability, rapid response, multifunctionality	Signal interference, material limitations
		Arterial stiffness	Implantable	Piezoelectricity	High sensitivity, self-powered, real-time monitoring	Signal interference issues, biocompatibility, and long-term stability
		Perspiration	Wearable	Electrochemistry	Versatility, portability, and comfort, real-time monitoring	Calibration requirements, external interference factors, limited service life, complex data processing
		Other indicator	Wearable& Implantable	Pressure	Real-time monitoring, non-invasive, and portable	Signal interference, service life, stability, and data processing complexity
				Acoustics	Versatility, high sensitivity, self-powered capability	Biocompatibility and safety, manufacturing costs, and technical challenges

therapy for panvascular diseases. Strengthening the durability, biocompatibility, and power systems of fiber-based platforms will, in turn, contribute to superior long-term monitoring in panvascular diseases that manifest extended progression and high mortality and disability. Refining multi-modal monitoring, data transmission, and analytics fosters timely, remote panvascular disease surveillance and warning systems, better matching conditions like acute onset, rapid progression, and multifactorial influence. This is especially beneficial for remote or underserved regions, reducing misdiagnosis rates in complicated cardiovascular issues, such as aortic dissection, pulmonary hypertension, pulmonary embolism, and atrial fibrillation, while advancing telemedicine and customized health management.

We believe that, with the collective efforts of researchers and practitioners across clinical medicine, materials science, physics, chemistry, and other disciplines, high-suitcordance fiber electronics designed for panvascular monitoring will undoubtedly emerge. Once implanted or worn, these fiber–panvascular systems can attain a state of cellular–mechanical–physiological–immunological equilibrium, enabling a long-term, harmonized co-regulation between fibers and the panvascular system.

5.1 Ethical Considerations and Regulatory Challenges

Flexible fiber devices for full-cycle management of panvascular diseases face unique ethical and regulatory challenges, and the complexity of these challenges is closely tied to the specific needs at each disease stage. In the early screening phase, balancing patients' right to be informed against the risks of invasive procedures becomes paramount. Because implantable devices are inserted as foreign objects via invasive operations [164], they may lead to complications including local tissue inflammation, chronic rejection, or secondary infections [165], underscoring the need to establish a three-tiered ethical framework of "monitoring–consultation–decision-making." The biometric data generated during this phase, along with any collected personal information, must be algorithmically cleansed to ensure anonymization occurs locally before uploading to a central analysis system, thereby preventing the disclosure of genetic information or vascular images [166]. Meanwhile, the high costs of intelligent fiber devices can exacerbate disparities in screening accessibility; low-income groups may be relegated to traditional risk assessment methods, perpetuating delays in early intervention.

During acute intervention, disputes over ownership of multi-modal monitoring data may cause overlapping jurisdictions across neurosurgery, hematology, and other disciplines, potentially missing optimal treatment windows. In long-term management, polylactic acid fiber sensors pose a controllability issue regarding their degradation rates; variations could lead to fluctuations in monitoring cycles, violating the principle of consistent clinical trial endpoints. Moving forward, establishing a dedicated panvascular medical ethics committee is recommended—to formulate a phased risk assessment matrix that emphasizes data justice and health equity in the preliminary stage, standardizes emergency authorization pathways in the mid-stage, and strengthens algorithmic transparency and controllable device degradation in the later stages. Finally, regulatory reforms should be pursued to permit innovative devices to undergo risk-stratified validations within a real-world evidence framework. (Table 1).

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Data Availability Data are available upon reasonable request.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

1. Zhou X, Yu L, Zhao Y, Ge J. Panvascular medicine: an emerging discipline focusing on atherosclerotic diseases. *Eur Heart J*. **2022**;*43*:4528.
2. Diseases GBD, Injuries C. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet*. **2020**;*396*:1204.
3. Wong M, Dai Y, Ge J. Pan-vascular disease: what we have done in the past and what we can do in the future? *Cardiol Plus*. **2024**;*9*:1.
4. Desormais I, Vlachopoulos C, Aboyans V. Panvascular disease - Epidemiology and prevention. *Cor Vasa*. **2018**;*60*: e3.
5. Chan AK, Hyde RA, Sweeney EA, Tuckerman DB, inventors; Elwha Llc, assignee. Epidermal electronics system for measuring orientations of body parts, has control circuit to receive first

orientation data and second orientation data from first sensor and second sensor patent US2018132761-A1.
6. Gao W, Emaminejad S, Nyein HYY, Challa S, Chen K, Peck A, Fahad HM, Ota H, Shiraki H, Kiriya D, Lien DH, Brooks GA, Davis RW, Javey A. Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis. *Nature*. **2016**;*529*:509.
7. Jiang S, Zhang T, Zhou Y, Lai P, Huang Y. Wearable ultrasound bioelectronics for healthcare monitoring. *Innovation (Camb)*. **2023**;*4*: 100447.
8. Sargolzaeiaval Y, Padmanabhan Ramesh V, Neumann TV, Misra V, Vashaee D, Dickey MD, Öztürk MC. Flexible thermoelectric generators for body heat harvesting – Enhanced device performance using high thermal conductivity elastomer encapsulation on liquid metal interconnects. *Applied Energy*. **2020**, *262*.
9. Hong YJ, Jeong H, Cho KW, Lu N, Kim DH. Wearable and Implantable Devices for Cardiovascular Healthcare: from Monitoring to Therapy Based on Flexible and Stretchable Electronics. *Advanced Functional Materials*. **2019**, *29*.
10. Sheng KK, Lu YF, Fan WT, Liu YL. Flexible and stretchable electrodes for in vivo electrophysiological and electrochemical monitoring†. *Chin J Chem*. **2024**;*42*:1523.
11. Rogers JA, Someya T, Huang Y. Materials and mechanics for stretchable electronics. *Science*. **2010**;*327*:1603.
12. Dang C, Wang Z, Hughes-Riley T, Dias T, Qian S, Wang Z, Wang X, Liu M, Yu S, Liu R, Xu D, Wei L, Yan W, Zhu M. Fibres-threads of intelligence-enable a new generation of wearable systems. *Chem Soc Rev*. **2024**;*53*:8790.
13. Wang X, Zhang Y, Shen P, Cheng Z, Chu C, Xue F, Bai J. Preparation of 4D printed peripheral vascular stent and its degradation behavior under fluid shear stress after deployment. *Biomater Sci*. **2022**;*10*:2302.
14. Kume T, Akasaka T, Kawamoto T, Watanabe N, Toyota E, Neishi Y, Sukmawan R, Sadahira Y, Yoshida K. Assessment of coronary arterial plaque by optical coherence tomography. *Am J Cardiol*. **2006**;*97*:1172.
15. Bao CH, Zhang C, Wang XM, Pan YB. Concurrent acute myocardial infarction and acute ischemic stroke: case reports and literature review. *Front Cardiovasc Med*. **2022**;*9*:1012345.
16. Perel P, Scarlatescu O, Avezum A, Chazal RA, Creager MA, Narula J, Pineiro D, Prabhakaran D, Wyss F, Yong H, Zuhlke L, Eisele J-L, Pinto F. The World Heart Observatory: Harnessing the Power of Data for Cardiovascular Health. *Global Heart*. **2022**, *17*.
17. Firooz A, Hallaji Z, Khatami A, Lajevardi V, Mansouri P, Mozafari Z, Nassiri-Kashani M, Robati RM, Seirafi H, editors. clinical practice guideline2015.
18. Fuchs FD, Whelton PK. High blood pressure and cardiovascular disease. *Hypertension*. **2020**;*75*:285.
19. Ghasemzadeh N, Zafari AM. A brief journey into the history of the arterial pulse. *Cardiol Res Pract*. **2011**;*2011*: 164832.
20. Zhang T, Liu N, Xu J, Liu Z, Zhou Y, Yang Y, Li S, Huang Y, Jiang S. Flexible electronics for cardiovascular healthcare monitoring. *Innovation (Camb)*. **2023**;*4*: 100485.
21. Wang W, Yiu HHP, Li WJ, Roy VAL. The Principle and Architectures of Optical Stress Sensors and the Progress on the Development of Microbend Optical Sensors. *Advanced Optical Materials*. **2021**, *9*.
22. Li Z, Tang X, Zhao T, Chen K, Zhang T. Highly sensitive skin-like wearable optical sensor for human physiological signals monitoring. *Optical Fiber Technology*. **2024**, *82*.
23. Connor C, Deng W, Ortega R. Use of pressure transducers reply. *N Engl J Med*. **2017**;*377*:401.
24. Meng K, Xiao X, Liu Z, Shen S, Tat T, Wang Z, Lu C, Ding W, He X, Yang J, Chen J. Kirigami-Inspired Pressure Sensors for Wearable Dynamic Cardiovascular Monitoring. *Advanced Materials*. **2022**, *34*.
25. Sawane M, Prasad M. MEMS piezoelectric sensor for self-powered devices: A review. *Materials Science in Semiconductor Processing*. **2023**, *158*.
26. Xu S. Barbosa PHdS, Wu W. *Biopolymers-based skin-interfaced triboelectric sensors Nano Research*. **2023**;*16*:11753.
27. Park DY, Joe DJ, Kim DH, Park H, Han JH, Jeong CK, Park H, Park JG, Joung B, Lee KJ. Self-Powered Real-Time Arterial Pulse Monitoring Using Ultrathin Epidermal Piezoelectric Sensors. *Adv Mater*. **2017**, *29*.
28. Meng K, Chen J, Li X, Wu Y, Fan W, Zhou Z, He Q, Wang X, Fan X, Zhang Y, Yang J, Wang ZL. Flexible Weaving Constructed Self-Powered Pressure Sensor Enabling Continuous Diagnosis of Cardiovascular Disease and Measurement of Cuffless Blood Pressure. *Advanced Functional Materials*. **2018**, *29*.
29. Zhang Y, Lu Q, He J, Huo Z, Zhou R, Han X, Jia M, Pan C, Wang ZL, Zhai J. Localizing strain via micro-cage structure for stretchable pressure sensor arrays with ultralow spatial crosstalk. *Nature Communications*. **2023**, *14*.
30. Zhao X, Zhou Y, Kwak W, Li A, Wang S, Dallenger M, Chen S, Zhang Y, Lium A, Chen J. A reconfigurable and conformal liquid sensor for ambulatory cardiac monitoring. *Nat Commun*. **2024**;*15*:8492.
31. Cheng X, Xue X, Ma Y, Han M, Zhang W, Xu Z, Zhang H, Zhang H. Implantable and self-powered blood pressure monitoring based on a piezoelectric thinfilm: Simulated, in vitro and in vivo studies. *Nano Energy*. **2016**;*22*:453.
32. Perret-Guillaume C, Joly L, Benetos A. Heart rate as a risk factor for cardiovascular disease. *Prog Cardiovasc Dis*. **2009**;*52*:6.
33. Böhm M, Reil JC, Deedwania P, Kim JB, Borer JS. Resting heart rate: risk indicator and emerging risk factor in cardiovascular disease. *Am J Med*. **2015**;*128*:219.
34. Zhao Y, Yu H, Gong A, Zhang S, Xiao B. Heart rate variability and cardiovascular diseases: a Mendelian randomization study. *Eur J Clin Invest*. **2024**;*54*: e14085.
35. Kassal P, Horak E, Sigurnjak M, Steinberg MD, Steinberg IM. Wireless and mobile optical chemical sensors and biosensors. *Reviews in Analytical Chemistry*. **2018**, *37*.
36. Leal-Junior AG, Díaz CR, Leitão C, Pontes MJ, Marques C, Frizera A. Polymer optical fiber-based sensor for simultaneous measurement of breath and heart rate under dynamic movements. *Opt Laser Technol*. **2019**;*109*:429.
37. Presti DL, Massaroni C, Formica D, Saccomandi P, Giurazza F, Caponero MA, Schena E. Smart textile based on 12 fiber bragg gratings array for vital signs monitoring. *IEEE Sens J*. **2017**;*17*:6037.
38. Lo Presti D, Santucci F, Massaroni C, Formica D, Setola R, Schena E. A multi-point heart rate monitoring using a soft wearable system based on fiber optic technology. *Sci Rep*. **2021**;*11*:21162.
39. Lo Presti D, Bianchi D, Massaroni C, Gizzi A, Schena E. A Soft and skin-interfaced smart patch based on fiber optics for cardiorespiratory monitoring. *Biosensors (Basel)*. **2022**;*12*(6):363.
40. Wang S, Ni X, Li L, Wang J, Liu Q, Yan Z, Zhang L, Sun Q. Noninvasive monitoring of vital signs based on highly sensitive fiber optic mattress. *IEEE Sens J*. **2020**;*20*:6182.
41. Skrivanos AG, Kosma EI, Chronopoulos SK, Kouretas I, Dimopoulos D, Petrakos G, Alhazidou E, Christofilakis V, Ziavra N, Peppas KP, Toki EI. Fetus heart rate monitoring: a preliminary research study with remote sensing. *IEEE Consumer Electronics Magazine*. **2022**;*11*:32.
42. Hamelmann P, Mischi M, Kolen AF, van Laar J, Vullings R, Bergmans JWM. Fetal Heart Rate Monitoring Implemented by Dynamic Adaptation of Transmission Power of a Flexible Ultrasound Transducer Array. *Sensors (Basel)*. **2019**, *19*.

43. Bhatia RS, Dorian P. Screening for Cardiovascular Disease Risk With Electrocardiography. *JAMA Intern Med*. **2018**;*178*:1163.
44. Dehkordi P, Bauer EP, Tavakolian K, Xiao ZG, Blaber AP, Khosrow-Khavar F. Detecting Coronary Artery Disease Using Rest Seismocardiography and Gyrocardiography. *Frontiers in Physiology*. **2021**, *12*.
45. Hall A, Mitchell ARJ, Wood L, Holland C. Effectiveness of a single lead AliveCor electrocardiogram application for the screening of atrial fibrillation: a systematic review. *Medicine (Baltimore)*. **2020**;*99*: e21388.
46. Eskandarian L, Toossi A, Nassif F, Golmohammadi Rostami S, Ni S, Mahnam A, Alizadeh Meghrazi M, Takarada W, Kikutani T, Naguib HE. 3D-Knit Dry Electrodes using Conductive Elastomeric Fibers for Long-Term Continuous Electrophysiological Monitoring. *Advanced Materials Technologies*. **2022**, *7*.
47. Lee SM, Byeon HJ, Lee JH, Baek DH, Lee KH, Hong JS, Lee S-H. Self-adhesive epidermal carbon nanotube electronics for tether-free long-term continuous recording of biosignals. *Scientific Reports*. **2014**, *4*.
48. Stauffer F, Thielen M, Sauter C, Chardonnens S, Bachmann S, Tybrandt K, Peters C, Hierold C, Vörös J. Skin Conformal Polymer Electrodes for Clinical ECG and EEG Recordings. *Advanced Healthcare Materials*. **2018**, *7*.
49. Rosa BMG, Yang GZ. A flexible wearable device for measurement of cardiac, electrodermal, and motion parameters in mental healthcare applications. *IEEE J Biomed Health Inform*. **2019**;*23*:2276.
50. Steffen M, Aleksandrowicz A, Leonhardt S. Mobile noncontact monitoring of heart and lung activity. *IEEE Trans Biomed Circuits Syst*. **2007**;*1*:250.
51. Bong J, Yasin O, Vaidya VR, Park J, Attia ZI, Padmanabhan D, Cho SJ, Asirvatham R, Schneider N, Lee J, Kim EM, Friedman PA, Ma Z. Injectable flexible subcutaneous electrode array technology for electrocardiogram monitoring device. *ACS Biomater Sci Eng*. **2020**;*6*:2652.
52. Guglielmo M, Lin A, Dey D, Baggiano A, Fusini L, Muscogiuri G, Pontone G. Epicardial fat and coronary artery disease: Role of cardiac imaging. *Atherosclerosis*. **2021**;*321*:30.
53. Streef TJJ, Smits AMM. Epicardial Contribution to the Developing and Injured Heart: Exploring the Cellular Composition of the Epicardium. *Frontiers in Cardiovascular Medicine*. **2021**, *8*.
54. Xu L, Gutbrod SR, Bonifas AP, Su Y, Sulkin MS, Lu N, Chung HJ, Jang KI, Liu Z, Ying M, Lu C, Webb RC, Kim JS, Laughner JI, Cheng H, Liu Y, Ameen A, Jeong JW, Kim GT, Huang Y, Efimov IR, Rogers JA. 3D multifunctional integumentary membranes for spatiotemporal cardiac measurements and stimulation across the entire epicardium. *Nat Commun*. **2014**;*5*:3329.
55. Choi S, Han SI, Jung D, Hwang HJ, Lim C, Bae S, Park OK, Tschabrunn CM, Lee M, Bae SY, Yu JW, Ryu JH, Lee SW, Park K, Kang PM, Lee WB, Nezafat R, Hyeon T, Kim DH. Highly conductive, stretchable and biocompatible Ag-Au core-sheath nanowire composite for wearable and implantable bioelectronics. *Nat Nanotechnol*. **2018**;*13*:1048.
56. Kim DH, Ghaffari R, Lu N, Wang S, Lee SP, Keum H, D'Angelo R, Klinker L, Su Y, Lu C, Kim YS, Ameen A, Li Y, Zhang Y, de Graff B, Hsu YY, Liu Z, Ruskin J, Xu L, Lu C, Omenetto FG, Huang Y, Mansour M, Slepian MJ, Rogers JA. Electronic sensor and actuator webs for large-area complex geometry cardiac mapping and therapy. *Proc Natl Acad Sci U S A*. **2012**;*109*:19910.
57. Viventi J, Kim DH, Moss JD, Kim YS, Blanco JA, Annetta N, Hicks A, Xiao J, Huang Y, Callans DJ, Rogers JA, Litt B. A conformal, bio-interfaced class of silicon electronics for mapping cardiac electrophysiology. *Sci Transl Med*. **2010**, *2*, 24ra22.
58. Park J, Choi S, Janardhan AH, Lee SY, Raut S, Soares J, Shin K, Yang S, Lee C, Kang KW, Cho HR, Kim SJ, Seo P, Hyun W, Jung S, Lee HJ, Lee N, Choi SH, Sacks M, Lu N, Josephson ME, Hyeon T, Kim DH, Hwang HJ. Electromechanical cardioplasty using a wrapped elasto-conductive epicardial mesh. *Sci Transl Med*. **2016**, *8*, 344ra86.
59. Huang K, Li X, Chen W, Pan L, Kong L, Shao J, Lin Z, Miao H, Zhang W, Ma F, Zou M, Min G, Liu X-Y, Lin N. Flexible intelligent array patch based on synergy of polyurethane and nanofiber for sensitive monitor and smart treatment. *Chemical Engineering Journal*. **2022**, *443*.
60. Chen Y, Du J, Sun X, Li Q, Qin M, Xiao Q, Bryan M. Treatment of left ventricular circulation disorder: application of echocardiography information data monitoring. *JMIR Med Inform*. **2020**;*8*: e19110.
61. Luis SA, Chan J, Pellikka PA. Echocardiographic assessment of left ventricular systolic function: an overview of contemporary techniques. *Including Speckle-Tracking Echocardiography Mayo Clin Proc*. **2019**;*94*:125.
62. Kenny JS, Clarke G, Myers M, Elfarnawany M, Eibl AM, Eibl JK, Nalla B, Atoui R. A Wireless Wearable Doppler Ultrasound Detects Changing Stroke Volume: Proof-of-Principle Comparison with Trans-Esophageal Echocardiography during Coronary Bypass Surgery. *Bioengineering (Basel)*. **2021**, *8*.
63. Chonghe Wang XC, Liu Wang,Mitsutoshi Makihata,Hsiao-Chuan Liu,Tao Zhou,Xuanhe Zhao. Bioadhesive ultrasound for long-term continuous imaging of diverse organs. *Science*. **2022**, *277*, 517.
64. Hu H, Huang H, Li M, Gao X, Yin L, Qi R, Wu RS, Chen X, Ma Y, Shi K, Li C, Maus TM, Huang B, Lu C, Lin M, Zhou S, Lou Z, Gu Y, Chen Y, Lei Y, Wang X, Wang R, Yue W, Yang X, Bian Y, Mu J, Park G, Xiang S, Cai S, Corey PW, Wang J, Xu S. A wearable cardiac ultrasound imager. *Nature*. **2023**;*613*:667.
65. Doenst T, Thiele H, Haasenritter J, Wahlers T, Massberg S, Haverich A. The treatment of coronary artery disease. *Dtsch Arztebl Int*. **2022**;*119*:716.
66. Kim MS, Dean LS. In-stent restenosis. *Cardiovasc Ther*. **2011**;*29*:190.
67. Shlofmitz E, Khalid N, Waksman R. In-Stent Restenosis: a Second Chance to Get It Right. *J Am Coll Cardiol*. **2020**;*76*:1389.
68. Ekmejian A, Allahwala U, Ward M, Bhindi R. Impact of coronary disease patterns, anatomical factors, micro-vascular disease and non-coronary cardiac factors on invasive coronary physiology. *Am Heart J*. **2023**;*257*:51.
69. Oyunbaatar N-E, Kim D-S, Prasad G, Jeong Y-J, Lee D-W. Self-rollable Polymer Stent Integrated with Wireless Pressure Sensor for Real-time Monitoring of Cardiovascular Pressure. *Sensors and Actuators A: Physical*. **2022**, *346*.
70. Park J, Kim JK, Patil SJ, Park JK, Park S, Lee DW. A Wireless pressure sensor integrated with a biodegradable polymer stent for biomedical applications. *Sensors (Basel)*. **2016**;*16*(6):809.
71. Sun G-h, Kim D-S, Shanmugasundaram A, Lee D-W. Additive manufactured cardiovascular scaffold integrated with SU-8 based wireless pressure sensor. *Journal of Micromechanics and Microengineering*. **2022**, *32*.
72. Rigo B, Bateman A, Lee J, Kim H, Lee Y, Romero L, Jang YC, Herbert R, Yeo WH. Soft implantable printed bioelectronic system for wireless continuous monitoring of restenosis. *Biosens Bioelectron*. **2023**;*241*: 115650.
73. Hoare D, Tsiamis A, Marland JRK, Czyzewski J, Kirimi MT, Holsgrove M, Russell E, Neale SL, Mirzai N, Mitra S, Mercer JR. Predicting cardiovascular stent complications using self-reporting biosensors for noninvasive detection of disease. *Adv Sci (Weinh)*. **2022**;*9*: e2105285.
74. Herbert R, Elsisy M, Rigo B, Lim HR, Kim H, Choi C, Kim S, Ye SH, Wagner WR, Chun Y, Yeo WH. Fully implantable batteryless soft platforms with printed nanomaterial-based arterial

stiffness sensors for wireless continuous monitoring of restenosis in real time. *Nano Today*. **2022**;*46*:101557.
75. Bridgeman A, Benedetto U. Invasiveness of left- and right-sided infective endocarditis: does pressure explain pathology? *J Thorac Cardiovasc Surg*. **2018**;*155*:62.
76. Boulate D, Arthur Ataam J, Connolly AJ, Giraldeau G, Amsallem M, Decante B, Lamrani L, Fadel E, Dorfmuller P, Perros F, Haddad F, Mercier O. Early development of right ventricular ischemic lesions in a novel large animal model of acute right heart failure in chronic thromboembolic pulmonary hypertension. *J Card Fail*. **2017**;*23*:876.
77. Liu Z, Ma Y, Ouyang H, Shi B, Li N, Jiang D, Xie F, Qu D, Zou Y, Huang Y, Li H, Zhao C, Tan P, Yu M, Fan Y, Zhang H, Wang ZL, Li Z. Transcatheter Self-Powered Ultrasensitive Endocardial Pressure Sensor. *Advanced Functional Materials*. **2018**, *29*.
78. Aslam MI, Gruslova AB, Almomani A, Nolen D, Elliott JJ, Jani VP, Kottam A, Porterfield J, Heighten C, Anderson AS, Valvano JW, Feldman MD. Modification of a transvalvular microaxial flow pump for instantaneous determination of native cardiac output and volume. *J Card Fail*. **2023**;*29*:1369.
79. Dual SA, Llerena Zambrano B, Sundermann S, Cesarovic N, Kron M, Magkoutas K, Hengsteler J, Falk V, Starck C, Meboldt M, Voros J, Schmid DM. Continuous heart volume monitoring by fully implantable soft strain sensor. *Adv Healthc Mater*. **2020**;*9*: e2000855.
80. Panagiotou M, Vogiatzis I, Jayasekera G, Louvaris Z, Mackenzie A, McGlinchey N, Baker JS, Church AC, Peacock AJ, Johnson MK. Validation of impedance cardiography in pulmonary arterial hypertension. *Clin Physiol Funct Imaging*. **2018**;*38*:254.
81. Wan L, Tang J, Xiao Y, Li H, Peng Z, Xu DY, Shen L. Improvement of hemodynamic parameters in aortic stenosis patients with transcatheter valve replacement by using impedance cardiography. *Front Cardiovasc Med*. **2022**;*9*: 950437.
82. Pullano SA, Critello DC, Fiorillo AS. Triboelectric-induced Pseudo-ICG for cardiovascular risk assessment on flexible electronics. *Nano Energy*. **2020**, *67*.
83. Katan M, Luft A. Global burden of stroke. *Semin Neurol*. **2018**;*38*:208.
84. Bain AR, Nybo L, Ainslie PN. Cerebral vascular control and metabolism in heat stress. *Compr Physiol*. **2015**;*5*:1345.
85. Izhar U, Piyathilaka L, Preethichandra DMG. Sensors for brain temperature measurement and monitoring – a review. *Neuroscience Informatics*. **2022**, *2*.
86. Dittmar A, Gehin C, Delhomme G, Boivin D, Dumont G, Mott C. A non invasive wearable sensor for the measurement of brain temperature. *Conf Proc IEEE Eng Med Biol Soc*. **2006**;*2006*:900.
87. Liu T, Yao P, Li Z, Feng H, Zhuang C, Sun X, Liu C, Xue N. Implantable Sufficiently Integrated Multimodal Flexible Sensor for Intracranial Monitoring. 2021 IEEE Sensors**2021**. p. 1.
88. Shin J, Liu Z, Bai W, Liu Y, Yan Y, Xue Y, Kandela I, Pezhouh M, MacEwan MR, Huang Y, Ray WZ, Zhou W, Rogers JA. Bioresorbable optical sensor systems for monitoring of intracranial pressure and temperature. *Sci Adv*. **2019**, *5*, eaaw1899.
89. Kang SK, Murphy RK, Hwang SW, Lee SM, Harburg DV, Krueger NA, Shin J, Gamble P, Cheng H, Yu S, Liu Z, McCall JG, Stephen M, Ying H, Kim J, Park G, Webb RC, Lee CH, Chung S, Wie DS, Gujar AD, Vemulapalli B, Kim AH, Lee KM, Cheng J, Huang Y, Lee SH, Braun PV, Ray WZ, Rogers JA. Bioresorbable silicon electronic sensors for the brain. *Nature*. **2016**;*530*:71.
90. Tang H, Yang Y, Liu Z, Li W, Zhang Y, Huang Y, Kang T, Yu Y, Li N, Tian Y, Liu X, Cheng Y, Yin Z, Jiang X, Chen X, Zang J. Injectable ultrasonic sensor for wireless monitoring of intracranial signals. *Nature*. **2024**;*630*:84.
91. Liu Q, Zhao C, Chen M, Liu Y, Zhao Z, Wu F, Li Z, Weiss PS, Andrews AM, Zhou C. Flexible Multiplexed In(2)O(3) Nanoribbon Aptamer-Field-Effect Transistors for Biosensing. *iScience*. **2020**, *23*:101469.
92. Zhong J, Dujovny M, Park HK, Perez E, Perlin AR, Diaz FG. Advances in ICP monitoring techniques. *Neurol Res*. **2003**;*25*:339.
93. Evensen KB, Eide PK. Measuring intracranial pressure by invasive, less invasive or non-invasive means: limitations and avenues for improvement. *Fluids Barriers CNS*. **2020**;*17*:34.
94. Blanco P, Abdo-Cuza A. Transcranial Doppler ultrasound in neurocritical care. *J Ultrasound*. **2018**;*21*:1.
95. Karmakar RS, Wang JC, Huang YT, Lin KJ, Wei KC, Hsu YH, Huang YC, Lu YJ. Real-time intraoperative pressure monitoring to avoid surgically induced localized brain injury using a miniaturized piezoresistive pressure sensor. *ACS Omega*. **2020**;*5*:29342.
96. Lu D, Yan Y, Deng Y, Yang Q, Zhao J, Seo MH, Bai W, MacEwan MR, Huang Y, Ray WZ, Rogers JA. Bioresorbable Wireless Sensors as Temporary Implants for In Vivo Measurements of Pressure. *Advanced Functional Materials*. **2020**, *30*.
97. Yang Q, Lee S, Xue Y, Yan Y, Liu TL, Kang SK, Lee YJ, Lee SH, Seo MH, Lu D, Koo J, MacEwan MR, Yin RT, Ray WZ, Huang Y, Rogers JA. Materials, Mechanics Designs, and Bioresorbable Multisensor Platforms for Pressure Monitoring in the Intracranial Space. *Advanced Functional Materials*. **2020**, *30*.
98. Kim J, Hong J, Park K, Lee S, Hoang AT, Pak S, Zhao H, Ji S, Yang S, Chung CK, Yang S, Ahn JH. Injectable 2D material-based sensor array for minimally invasive neural implants. *Adv Mater*. **2024**;*36*: e2400261.
99. Zhang B, Huang Z, Song H, Kim HS, Park J. Wearable Intracranial Pressure Monitoring Sensor for Infants. *Biosensors (Basel)*. **2021**, *11*.
100. Astrup J, Siesjö BK, Symon L. Thresholds in cerebral ischemia - the ischemic penumbra. *Stroke*. **1981**;*12*:723.
101. Friess SH, Kilbaugh TJ, Huh JW. Advanced neuromonitoring and imaging in pediatric traumatic brain injury. *Crit Care Res Pract*. **2012**;*2012*: 361310.
102. Kazmi SM, Richards LM, Schrandt CJ, Davis MA, Dunn AK. Expanding applications, accuracy, and interpretation of laser speckle contrast imaging of cerebral blood flow. *J Cereb Blood Flow Metab*. **2015**;*35*:1076.
103. Haruta M, Kurauchi Y, Ohsawa M, Inami C, Tanaka R, Sugie K, Kimura A, Ohta Y, Noda T, Sasagawa K, Tokuda T, Katsuki H, Ohta J. Chronic brain blood-flow imaging device for a behavioral experiment using mice. *Biomed Opt Express*. **2019**;*10*:1557.
104. Howe C, Mishra S, Kim YS, Chen Y, Ye SH, Wagner WR, Jeong JW, Byun HS, Kim JH, Chun Y, Yeo WH. Stretchable, implantable, nanostructured flow-diverter system for quantification of intra-aneurysmal hemodynamics. *ACS Nano*. **2018**;*12*:8706.
105. Huang C, Gu Y, Chen J, Bahrani AA, Abu Jawdeh EG, Bada HS, Saatman K, Yu G, Chen L. A wearable fiberless optical sensor for continuous monitoring of cerebral blood flow in mice. *IEEE J Sel Top Quantum Electron*. **2019**;*25*(1):1–8.
106. Liu X, Irwin DA, Huang C, Gu Y, Chen L, Donohue KD, Chen L, Yu G. A wearable fiber-free optical sensor for continuous monitoring of cerebral blood flow in freely behaving mice. *IEEE Trans Biomed Eng*. **1838**;*2023*:70.
107. Samaei S, Sawosz P, Kacprzak M, Pastuszak Z, Borycki D, Liebert A. Time-domain diffuse correlation spectroscopy (TD-DCS) for noninvasive, depth-dependent blood flow quantification in human tissue in vivo. *Sci Rep*. **1817**;*2021*:11.
108. Li DY, Xia Q, Yu TT, Zhu JT, Zhu D. Transmissive-detected laser speckle contrast imaging for blood flow monitoring in thick tissue: from Monte Carlo simulation to experimental demonstration. *Light Sci Appl*. **2021**;*10*:241.
109. Knutsson L, van Westen D, Petersen ET, Markenroth Bloch K, Holtas S, Stahlberg F, Wirestam R. Absolute quantification of

cerebral blood flow: correlation between dynamic susceptibility contrast MRI and model-free arterial spin labeling. *Magn Reson Imaging*. **2010**;*28*:1.
110. Roh D, Park S. Brain multimodality monitoring: updated perspectives. *Curr Neurol Neurosci Rep*. **2016**;*16*:56.
111. Akbik OS, Carlson AP, Krasberg M, Yonas H. The utility of cerebral blood flow assessment in TBI. *Curr Neurol Neurosci Rep*. **2016**;*16*:72.
112. Scheeren TWL, Kuizenga MH, Maurer H, Struys M, Heringlake M. Electroencephalography and brain oxygenation monitoring in the perioperative period. *Anesth Analg*. **2019**;*128*:265.
113. Ledo A, Fernandes E, Quintero JE, Gerhardt GA, Barbosa RM. Electrochemical evaluation of a multi-site clinical depth recording electrode for monitoring cerebral tissue oxygen. *Micromachines (Basel)*. **2020**;*11*(7):632.
114. Ji H, Xu Z, Wang M, Zou H, Chen Y, Ai J. A flexible optoelectronic device for continuous cerebral blood flow monitoring. *Biosensors (Basel)*. **2022**;*12*(11):944.
115. Gurel NZ, Jung H, Hersek S, Inan OT. Fusing near-infrared spectroscopy with wearable hemodynamic measurements improves classification of mental stress. *IEEE Sens J*. **2019**;*19*:8522.
116. Rwei AY, Lu W, Wu C, Human K, Suen E, Franklin D, Fabiani M, Gratton G, Xie Z, Deng Y, Kwak SS, Li L, Gu C, Liu A, Rand CM, Stewart TM, Huang Y, Weese-Mayer DE, Rogers JA. A wireless, skin-interfaced biosensor for cerebral hemodynamic monitoring in pediatric care. *Proc Natl Acad Sci U S A*. **2020**;*117*:31674.
117. Petersen SD, Thyssen A, Engholm M, Thomsen EV. A flexible infrared sensor for tissue oximetry. *Microelectron Eng*. **2013**;*111*:130.
118. Tian L, Zimmerman B, Akhtar A, Yu KJ, Moore M, Wu J, Larsen RJ, Lee JW, Li J, Liu Y, Metzger B, Qu S, Guo X, Mathewson KE, Fan JA, Cornman J, Fatina M, Xie Z, Ma Y, Zhang J, Zhang Y, Dolcos F, Fabiani M, Gratton G, Bretl T, Hargrove LJ, Braun PV, Huang Y, Rogers JA. Large-area MRI-compatible epidermal electronic interfaces for prosthetic control and cognitive monitoring. *Nat Biomed Eng*. **2019**;*3*:194.
119. Schuhmann TG Jr, Yao J, Hong G, Fu TM, Lieber CM. Syringe-injectable electronics with a plug-and-play input/output interface. *Nano Lett*. **2017**;*17*:5836.
120. Tybrandt K, Khodagholy D, Dielacher B, Stauffer F, Renz AF, Buzsaki G, Voros J. High-density stretchable electrode grids for chronic neural recording. *Adv Mater*. **2018**;*30*: e1706520.
121. Musk E, Neuralink. An Integrated Brain-Machine Interface Platform With Thousands of Channels. *J Med Internet Res*. **2019**, *21*, e16194
122. Xu K, Li S, Dong S, Zhang S, Pan G, Wang G, Shi L, Guo W, Yu C, Luo J. Bioresorbable electrode array for electrophysiological and pressure signal recording in the brain. *Adv Healthc Mater*. **2019**;*8*: e1801649.
123. Yang H, Qian Z, Wang J, Feng J, Tang C, Wang L, Guo Y, Liu Z, Yang Y, Zhang K, Chen P, Sun X, Peng H. Carbon Nanotube Array-Based Flexible Multifunctional Electrodes to Record Electrophysiology and Ions on the Cerebral Cortex in Real Time. *Advanced Functional Materials*. **2022**, *32*.
124. Selvin E, Erlinger TP. Prevalence of and risk factors for peripheral arterial disease in the United States: results from the national health and nutrition examination survey, 1999–2000. *Circulation*. **2004**;*110*:738.
125. American DA. Standards of medical care in diabetes-2021 abridged for primary care providers. *Clin Diabetes*. **2021**;*39*:14.
126. Lavery LA, Armstrong DG, Wunderlich RP, Mohler MJ, Wendel CS, Lipsky BA. Risk factors for foot infections in individuals with diabetes. *Diabetes Care*. **2006**;*29*:1288.
127. Libby P. Inflammation in atherosclerosis. *Arterioscler Thromb Vasc Biol*. **2012**;*32*:2045.
128. Brownlee M. The pathobiology of diabetic complications: a unifying mechanism. *Diabetes*. **2005**;*54*:1615.
129. Stamler J, Vaccaro O, Neaton JD, Wentworth D. Diabetes, other risk factors, and 12-yr cardiovascular mortality for men screened in the multiple risk factor intervention trial. *Diabetes Care*. **1993**;*16*:434.
130. Singh N, Armstrong DG, Lipsky BA. Preventing foot ulcers in patients with diabetes. *JAMA*. **2005**;*293*:217.
131. Kudo H, Sawada T, Kazawa E, Yoshida H, Iwasaki Y, Mitsubayashi K. A flexible and wearable glucose sensor based on functional polymers with soft-MEMS techniques. *Biosens Bioelectron*. **2006**;*22*:558.
132. Guo J, Zhou B, Du Z, Yang C, Kong L, Xu L. Soft and plasmonic hydrogel optical probe for glucose monitoring. *Nanophotonics*. **2021**;*10*:3549.
133. Yetisen AK, Jiang N, Fallahi A, Montelongo Y, Ruiz-Esparza GU, Tamayol A, Zhang YS, Mahmood I, Yang SA, Kim KS, Butt H, Khademhosseini A, Yun SH. Glucose-Sensitive Hydrogel Optical Fibers Functionalized with Phenylboronic Acid. *Advanced Materials*. **2017**, *29*.
134. Elsherif M, Hassan MU, Yetisen AK, Butt H. Hydrogel optical fibers for continuous glucose monitoring. *Biosens Bioelectron*. **2019**;*137*:25.
135. Cosgrove D, Eckersley R, Blomley M, Harvey C. Quantification of blood flow. *European Radiology*. **2001**;*11*:1338.
136. Sibley RC 3rd, Reis SP, MacFarlane JJ, Reddick MA, Kalva SP, Sutphin PD. Noninvasive physiologic vascular studies: a guide to diagnosing peripheral arterial disease. *Radiographics*. **2017**;*37*:346.
137. Huang C, He O, Lao Z, Liu H, Leng Y, Xu X, Tian S, Wang Y, Wu G, Li R, Fan Y. Dynamic Peripheral Hemoperfusion Distribution Monitoring Based on Janus Flexible Sensor System. *IEEE Trans Biomed Eng*. **2024**;*71*:2580.
138. Cannata JM, Vilkomerson D, Chilipka T, Yang H-C, Han S, Rowe VL, Weaver FA. A flexible implantable sensor for postoperative monitoring of blood flow. *The Journal of the Acoustical Society of America*. **2010**;*128*:2304.
139. Boutry CM, Beker L, Kaizawa Y, Vassos C, Tran H, Hinckley AC, Pfattner R, Niu S, Li J, Claverie J, Wang Z, Chang J, Fox PM, Bao Z. Biodegradable and flexible arterial-pulse sensor for the wireless monitoring of blood flow. *Nat Biomed Eng*. **2019**;*3*:47.
140. Stone GW, Ellis SG, Cox DA, Hermiller J, O'Shaughnessy C, Mann JT, Turco M, Caputo R, Bergin P, Greenberg J, Popma JJ, Russell ME. A polymer-based, paclitaxel-eluting stent in patients with coronary artery disease. *N Engl J Med*. **2004**;*350*:221.
141. Lane TR, Metcalfe MJ, Narayanan S, Davies AH. Post-operative surveillance after open peripheral arterial surgery. *Eur J Vasc Endovasc Surg*. **2011**;*42*:59.
142. Natta L, Mastronardi VM, Guido F, Algieri L, Puce S, Pisano F, Rizzi F, Pulli R, Qualtieri A, De Vittorio M. Soft and flexible piezoelectric smart patch for vascular graft monitoring based on aluminum nitride thin film. *Sci Rep*. **2019**;*9*:8392.
143. Chong H, Lou J, Bogie KM, Zorman CA, Majerus SJA. Vascular pressure-flow measurement using cb-pdms flexible strain sensor. *IEEE Trans Biomed Circuits Syst*. **2019**;*13*:1451.
144. Wang F, Jin P, Feng Y, Fu J, Wang P, Liu X, Zhang Y, Ma Y, Yang Y, Yang A, Feng X. Flexible Doppler ultrasound device for the monitoring of blood flow velocity. *Sci Adv*. **2021**, *7*:eabi9283.
145. Laurent S, Boutouyrie P, Asmar R, Gautier I, Laloux B, Guize L, Ducimetiere P, Benetos A. Aortic stiffness is an independent predictor of all-cause and cardiovascular mortality in hypertensive patients. *Hypertension*. **2001**;*37*:1236.
146. Lewis JE, Williams P, Davies JH. Non-invasive assessment of peripheral arterial disease: automated ankle brachial index

measurement and pulse volume analysis compared to duplex scan. *SAGE Open Med*. **2016**;*4*:2050312116659088.
147. Vlachopoulos C, Aznaouridis K, Stefanadis C. Prediction of cardiovascular events and all-cause mortality with arterial stiffness: a systematic review and meta-analysis. *J Am Coll Cardiol*. **2010**;*55*:1318.
148. Cecelja M, Chowienczyk P. Role of arterial stiffness in cardiovascular disease. *JRSM Cardiovasc Dis*. **2012**;*1*(4):1–10.
149. Beneto SPLBAGLGD. Aortic Stiffness Is an Independent Predictor of All-Cause and Cardiovascular Mortality in Hypertensive Patients. *Hypertension*. **2001**.
150. Zhang Y, Lu Q, He J, Huo Z, Zhou R, Han X, Jia M, Pan C, Wang ZL, Zhai J. Localizing strain via micro-cage structure for stretchable pressure sensor arrays with ultralow spatial crosstalk. *Nat Commun*. **2023**;*14*:1252.
151. Qiu S, Yan BPY, Zhao N. Stroke-volume-allocation model enabling wearable sensors for vascular age and cardiovascular disease assessment. *npj Flexible Electronics*. **2024**, *8*.
152. Sonner Z, Wilder E, Heikenfeld J, Kasting G, Beyette F, Swaile D, Sherman F, Joyce J, Hagen J, Kelley-Loughnane N, Naik R. The microfluidics of the eccrine sweat gland, including biomarker partitioning, transport, and biosensing implications. *Biomicrofluidics*. **2015**;*9*: 031301.
153. Heikenfeld J, Jajack A, Rogers J, Gutruf P, Tian L, Pan T, Li R, Khine M, Kim J, Wang J, Kim J. Wearable sensors: modalities, challenges, and prospects. *Lab Chip*. **2018**;*18*:217.
154. Zhao Z, Li Q, Chen L, Zhao Y, Gong J, Li Z, Zhang J. A thread/fabric-based band as a flexible and wearable microfluidic device for sweat sensing and monitoring. *Lab Chip*. **2021**;*21*:916.
155. Lin Y-C, Rinawati M, Chang L-Y, Wang Y-X, Wu Y-T, Yen Y-H, Chen K-J, Ho K-C, Yeh M-H. A non-invasive wearable sweat biosensor with a flexible N-GQDs/PANI nanocomposite layer for glucose monitoring. *Sensors and Actuators B: Chemical*. **2023**, *383*.
156. Chen C, Fu Y, Sparks SS, Lyu Z, Pradhan A, Ding S, Boddeti N, Liu Y, Lin Y, Du D, Qiu K. 3D-printed flexible microfluidic health monitor for in situ sweat analysis and biomarker detection. *ACS Sens*. **2024**;*9*:3212.
157. Li P, Ling Z, Liu X, Bai L, Wang W, Chen H, Yang H, Yang L, Wei D. Nanocomposite hydrogels flexible sensors with functional cellulose nanocrystals for monitoring human motion and lactate in sweat. *Chemical Engineering Journal*. **2023**, *466*.
158. Veenuttranon K, Kaewpradub K, Jeerapan I. Screen-printable functional nanomaterials for flexible and wearable single-enzyme-based energy-harvesting and self-powered biosensing devices. *Nanomicro Lett*. **2023**;*15*:85.
159. Li J, Long Y, Yang F, Wei H, Zhang Z, Wang Y, Wang J, Li C, Carlos C, Dong Y, Wu Y, Cai W, Wang X. Multifunctional Artificial Artery from Direct 3D Printing with Built-In Ferroelectricity and Tissue-Matching Modulus for Real-Time Sensing and Occlusion Monitoring. *Adv Funct Mater*. **2020**, *30*.
160. Guo H, Bai W, Ouyang W, Liu Y, Wu C, Xu Y, Weng Y, Zang H, Liu Y, Jacobson L, Hu Z, Wang Y, Arafa HM, Yang Q, Lu D, Li S, Zhang L, Xiao X, Vazquez-Guardado A, Ciatti J, Dempsey E, Ghoreishi-Haack N, Waters EA, Haney CR, Westman AM, MacEwan MR, Pet MA, Rogers JA. Wireless implantable optical probe for continuous monitoring of oxygen saturation in flaps and organ grafts. *Nat Commun*. **2022**;*13*:3009.
161. D'Ambrogio G, Zahhaf O, Le M-Q, Bordet M, Lermusiaux P, Della Schiava N, Liang R, Cottinet P-J, Capsal J-F. Piezoelectric biosensor for smart cardiovascular grafts based on NaNbO3 fibers/PDMS structured composite. *Materials & Design*. **2022**, *223*.
162. Farooq M, Iqbal T, Vazquez P, Farid N, Thampi S, Wijns W, Shahzad A. Thin-Film Flexible Wireless Pressure Sensor for Continuous Pressure Monitoring in Medical Applications. *Sensors (Basel)*. **2020**, *20*.
163. Ouyang H, Li Z, Gu M, Hu Y, Xu L, Jiang D, Cheng S, Zou Y, Deng Y, Shi B, Hua W, Fan Y, Li Z, Wang Z. A bioresorbable dynamic pressure sensor for cardiovascular postoperative care. *Adv Mater*. **2021**;*33*: e2102302.
164. Capuani S, Malgir G, Chua CYX, Grattoni A. Advanced strategies to thwart foreign body response to implantable devices. *Bioeng Transl Med*. **2022**;*7*: e10300.
165. Barone DG, Carnicer-Lombarte A, Tourlomousis P, Hamilton RS, Prater M, Rutz AL, Dimov IB, Malliaras GG, Lacour SP, Robertson AAB, Franze K, Fawcett JW, Bryant CE. Prevention of the foreign body response to implantable medical devices by inflammasome inhibition. *Proc Natl Acad Sci U S A*. **2022**;*119*: e2115857119.
166. Rehman AU, Tariq N, Jan MA, Khan F, Song H, Ibrahim M. A blockchain-based hybrid model for iomt-enabled intelligent healthcare system. *IEEE Transactions on Network Science and Engineering*. **2024**;*11*:3512.

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