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Wearable bioelectronics for cancer theranostics

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Abstract
Cancer has emerged as a critical global health concern due to its elevated heterogeneity and mortality rate. Despite the continuous efforts put into medical research, current clinical approaches still face limitations, including dependency on costly facilities, trained operators and suboptimal diagnostic precision. Therefore, innovative strategies for accurate, personalized and patient-friendly cancer theranostic solutions are urgently required. Among all the platforms, wearable bioelectronics stand out for advantages such as non-invasive detection, responsive therapy and long-term monitoring, owing to their functional bioelectronic interfaces. This review summarizes the latest advances in wearable bioelectronics, aiming to provide a new strategy for cancer theranostics. Initially, the clinical status and emerging wearable bioelectronics are briefly described to provide a general overview. The subsequent contents focus on the implementation of wearable bioelectronics across early diagnosis, treatment, prognostic monitoring and rehabilitation with multiple device configurations. Finally, we discuss the current challenges and prospective future development in advanced cancer theranostics.

Introduction

Characterized by unlimited cell proliferation and its ability to form malignant tumors, cancer remains a worldwide leading threat to both public health and society[1–3]. Despite the efforts of people in various fields in recent years, advances have already been made annually to improve patient outcomes[4,5]. Although current cancer theranostic strategies, such as liquid biopsy, chemotherapy and radiotherapy, have gained popularity in the clinic, they still face inevitable restrictions. For example, the limited sensitivity and tumor correlation of liquid biopsy result in misdiagnosis in identifying early-stage cancers[6–8]. Highly toxic intravenous drugs may trigger severe side effects[9,10], whereas radiation can cause damage to both cancer cells and surrounding normal cells[11,12]. Therefore, these limitations appeal the development of advanced technologies that are accurate, continuous, effective and patient-friendly for cancer theranostics.

Wearable bioelectronics have emerged as transformative platforms that can bridge clinical approaches and engineered designs. They normally integrate flexible substrates, electronic components, wireless communication modules and sensors or actuators to interact with the environment[13,14]. As a method of interface communication, wearable bioelectronics work by connecting different functions through energy transformation and propagation, extracting or exporting information from the environment on the basis of passive or active controls. Owing to the inherently flexible, lightweight, biocompatible and financially affordable nature of wearable devices, they have the potential to provide better patient compliance as well as painless and low-burden experiences in whole cancer theranostics. Meanwhile, as wearable bioelectronics serve as high-quality unified frameworks for realizing multidisciplinary integration, advances in multiple subjects, such as molecular imaging[15], machine learning[16] and nanomedicine[17], can also further facilitate the applications of wearable platforms in precision oncology. Moreover, tailored by unique pathophysiological characteristics or clinical requirements, device configurations can be customized to optimize medical resource utilization. Additional technological innovations in the system integration of wearable devices, including self-powered modules[18,19], closed-loop systems[20,21] and

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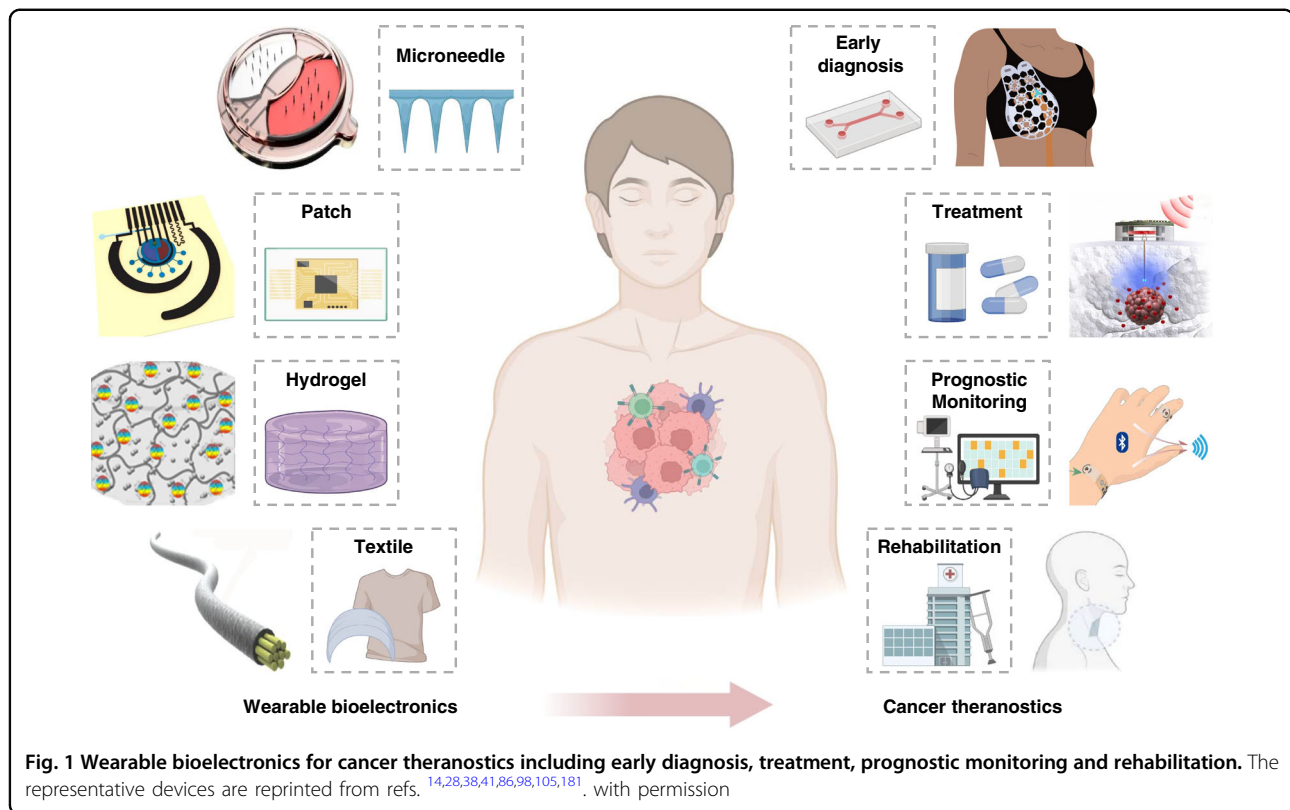Yu Song (yusong@cityu.edu.hk)
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Fig. 1 Wearable bioelectronics for cancer theranostics including early diagnosis, treatment, prognostic monitoring and rehabilitation. The representative devices are reprinted from refs. [14,28,38,41,86,98,105,181]. with permission

artificial intelligence-empowered evaluation[22,23], continue to broaden their design capability, paving the way for autonomous and self-regulating cancer theranostics.

A wide range of wearable bioelectronics, including operational mechanisms: optical[24,25], electrical[26–28], mechanical[29,30], thermal[31] and ultrasonic[32,33] triggered or responsive devices, have been developed for diverse applications. In oncological applications, they can be designed specifically for different types of cancer and different theranostic purposes. Many cancers like breast cancer[34], nasopharyngeal carcinoma[35], melanoma[36], lipomas[37], laryngeal cancer[38] and tongue cancer[39] have already been included in this platform. Meanwhile, diagnostics, therapeutics, prognosis and rehabilitation are also discussed accordingly. Among them, each type of cancer may correspond to different device options. The predictable tumor biomarkers and prognostic indicators required for monitoring of most cancers can be detected in biofluids with wearable sensors. However, limited by the penetration depth owing to certain energy and architecture design, some wearable devices for imaging and treatment focus more on superficial tumors and tumors between superficial and deep tumors, such as melanoma[40] and breast cancer[41]. Furthermore, some cancers, like head and neck cancers, can cause significant damage to bodily functions. Wearable devices targeting these cancers are more focused on functional reconstruction to reduce the impact of cancer treatment on patients' quality of life.

In this review, the potential of wearable bioelectronics in cancer theranostics for diverse malignancies is discussed across diagnostics, therapeutics, prognostic monitoring and rehabilitation (Fig. 1). Initiating detection methodologies, including biomarker sensing and tissue imaging, we then investigate the potential of wearable bioelectronics in cancer therapeutics from transdermal drug delivery and ROS-based therapy to thermal therapy. Consequently, tumor inhibition and drug concentration, as well as specific rehabilitation methods in selected cancer examples, have been explored for the application of wearable bioelectronics in personalized post-therapeutic care. Ultimately, we examine the limitations of the current solution and discuss possible future directions, aiming to bridge wearable breakthroughs with clinical requirements and offering a proposed framework for next-generation cancer theranostics.

Biological overview of wearable bioelectronics in cancer theranostics

The occurrence, development and intervention of cancer involve a series of complex biological mechanisms. According to physiological changes, corresponding wearable bioelectronics can be selected to offer tailored solutions for each stage. This section employs

Fig. 2 Biological overview of wearable bioelectronics in cancer theranostics. The representative devices are reprinted from refs. [35,89,180,185]. with permission
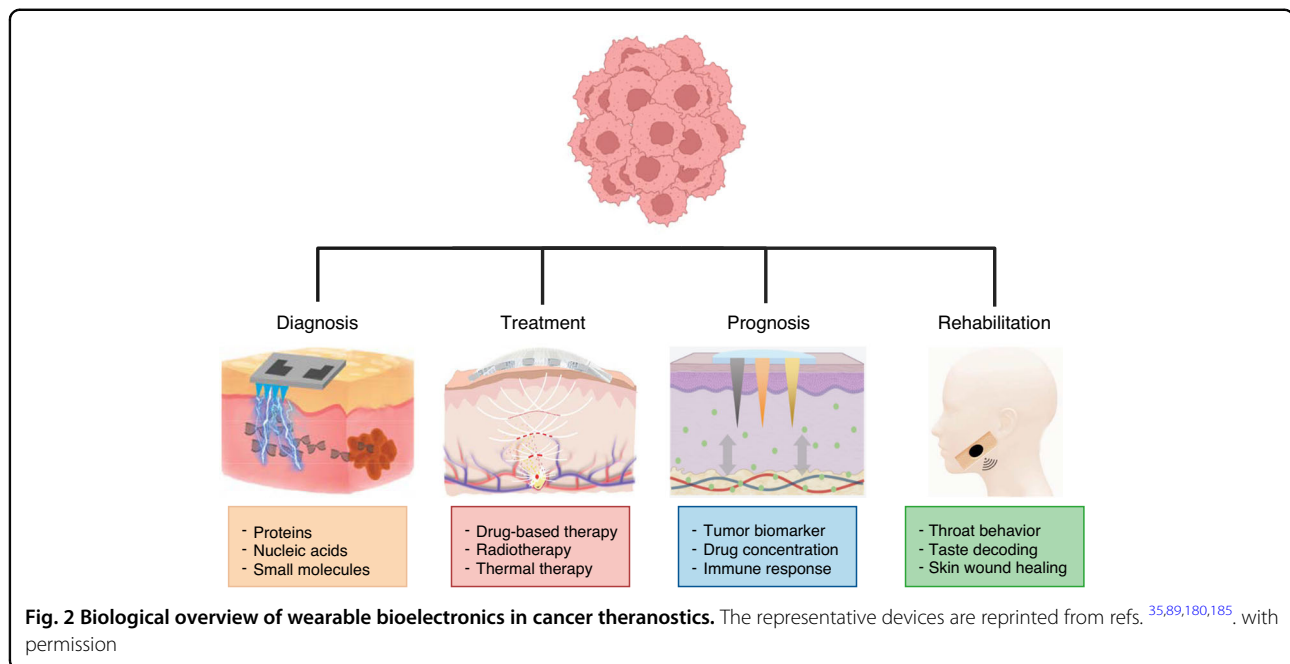
conventional cancer theranostics, spanning early diagnosis, therapeutic intervention, prognostic monitoring and recovery, as a framework to explain the biological principles of oncology and design considerations for wearable bioelectronics (Fig. 2).

The development of cancer is associated with diverse mutagenicity and carcinogenicity. Factors such as gene mutations, epigenetic changes, exposure to carcinogens, radiation, and viruses may all induce cancer. Under the influence of these factors, cancer development begins with the transformation of normal cells, proceeds through uncontrolled proliferation of malignant cells, and culminates in tumor microenvironment formation and metastasis into other tissues. During this process, tumor biomarkers emerge in tissues, biofluids (e.g. blood, interstitial fluid, urine, and saliva) and feces through passive liberation or active secretion from malignant cells or the tumor microenvironment, which indicate the occurrence and progression of cancer[42]. According to biochemical properties, they can be classified into proteins (e.g., alphafetoprotein (AFP) for liver cancer diagnosis[43]), nucleic acids (e.g., *p53* gene sequencing for non-small cell lung cancer[44]) and small molecule metabolites (e.g., pyruvate kinase[45]). Corresponding technologies, including immune histochemistry (IHC)[46], liquid biopsy[47], point-of-care biosensors[48], polymerase chain reaction (PCR)[49] and next generation gene sequencing[50], are developed to achieve rapid and highly specific cancer diagnosis. Recently, microRNA[51], lncRNA[52], extracellular vesicles[53], circulating tumor cells (CTCs)[54] and circulating tumor DNA (ctDNA)[55] have been discussed as novel alternatives to classic tumor biomarkers, as traditional biomarkers

may hold the limitation of low sensitivity[56]. New biomarker detection technologies are also constantly being invented to adapt to new tumor markers. Besides, imaging methods, such as magnetic resonance imaging (MRI) and positron emission tomography (PET), allow the visualization of tumor size and location. Although issues, such as exposure to electromagnetic radiation, contrast agent intake and limited spatial resolution, limit their applicability, their availability for molecular detection and dynamic observation still provides an alternative for cancer detection[15].

The core targets of cancer treatment methods mainly focus on destroying the key survival structures or functional pathways of cancer cells. Therapies targeting cellular nucleic acids, cell replication and direct cell toxicity processes include radiotherapy and chemotherapy[57]. Chemotherapeutic agents predominantly target the cell cycle machinery, with antimetabolites disrupting DNA synthesis and taxanes stabilizing microtubules[58]. Radiotherapy induces DNA double-strand breaks through localized ionization and generates free radicals to kill cancer cells[59]. Immunotherapy modulates immune checkpoint pathways, and therapies that modify immune cells to target cancer cell antigens are also being widely studied (e.g., CAR-T cell therapy)[60]. Emerging modalities now target cancer-specific redox homeostasis and stress response pathways, which exploit distinct biological vulnerabilities of malignant cells. Thermal therapy exploits heat shock protein overexpression in tumors, where localized hyperthermia triggers protein denaturation while sparing normal tissues with functional thermotolerance pathways[61]. ROS-based strategies capitalize

basal oxidative stress in malignant cells, via the use of catalytic nanomaterials along with external stimuli to disrupt redox balance, generating excess reactive oxygen species[62]. In short, cancer treatment uses chemical interventions (drugs) or physical interventions (radiation or heat) to block the progression of cancer in different ways.

Prognostic monitoring plays a pivotal role in evaluating therapeutic efficacy and tumor evolution by tracking dynamic biomarkers that reflect real-time biological changes in cancers. Unlike static diagnostic markers, these evolving indicators capture tumor heterogeneity information and adaptive resistance mechanisms, which place higher demands on the sensitivity of sensors. Circulating biomarkers, such as ctDNA[63,64] and CTC[65], provide a monitoring window into tumor dynamics, revealing shifts in driver mutation dominance or metastatic potential. Furthermore, since most drugs have a clear concentration-effect relationship, they can warn of acquired resistance and organ damage[66]. Moreover, immune markers may also indicate immune escape and immune activation, indicating the therapeutic efficacy of cancer treatment[67]. Therefore, drug concentration and immune responses are also valuable indicators of prognosis.

In cancer rehabilitation, precise monitoring of functional reconstruction markers and long-term biological follow-up constitute the core pillars of survivorship care. The specific mechanisms of functional impairment across different cancer types dictate the variability in recovery focus. For laryngeal cancer patients, the quality of recurrent laryngeal nerve regeneration and mucosal wave dynamics are emphasized[68,69], whereas swallowing function rehabilitation relies on the movement trajectory of the hyoid-laryngeal complex[70]. These biomechanical parameters fundamentally reflect the molecular processes of synaptic remodeling at neuromuscular junctions and extracellular matrix remodeling. Other widely studied examples are taste restoration after tongue cancer therapy[71] and epidermal wound healing[72], which are also of particular interest. Meanwhile, rehabilitation is a long physiological process requiring long-term collaboration between patients and physicians. Therefore, the development of a digital health platform is essential, which reduces communication costs for patients and physicians while enabling longitudinal monitoring and analysis of various indicators.

In conclusion, understanding the biological pathways involved in cancer development is crucial for advancing cancer theranostic strategies. The integration of wearable technology into cancer care represents a significant opportunity for improving patients' quality of life. As research continues to evolve, the synergy between biological insights and technological innovations will pave the way for more effective and personalized cancer management strategies. Here, the sensing/driving modes, application scenarios, and performance metrics of four biomedical platforms (electrical responsive, optical responsive, ultrasonic responsive, and thermal responsive devices) are summarized, demonstrating the key parameter differences between different technologies in cancer theranostics (Table 1)[35,37,40,41,73-94]. In the following sections, more specific applications of wearable bioelectronics will be discussed, with the aim of constructing a more integrated and automated cancer theranostic process.

Early diagnosis

Early cancer diagnosis plays a crucial role, as early detection tends to be correlated with higher cure rates and quality of life in patients[95,96]. This raises the need to build highly accessible platforms for frequent testing to improve the chances of early diagnosis[97,98]. Thus, wearable bioelectronics have been proposed because of their high portability and low manufacturing costs. In this section, the latest advances in wearable bioelectronics, including optical sensing, electrical sensing, ultrasound imaging and thermal imaging, are discussed to provide innovative solutions for early cancer diagnostics.

Optical sensing

Wearable optical sensing is a technology that converts biomarker or tissue information into light differences discernible to the human eyes or detectable by machines. Among them, methods such as colorimetry[99], fluorescence[76,77], and surface-enhanced Raman spectroscopy (SERS)[100] are widely recognized by researchers. Under external light excitation, substances interact with electromagnetic waves through absorption, emission and scattering. By detecting variations in the intensity or frequency of light, optical sensors allow noninvasive, spatially and temporally resolved diagnostics. Compared with the popular solutions, colorimetry offers the advantages of direct observation of color reactions, low cost and low power consumption, but it has the disadvantage of low sensitivity[101]. Fluorescence methods have a lower detection limit, but they face issues such as photobleaching and poor photostability[102]. Among them, surface-enhanced Raman spectroscopy, as a label-free method, offers an alternative for distinguishing structurally similar substances. It amplifies the Raman signals of adsorbed molecules by 10^{10}-10^{11} times through the enhancement of localized electromagnetic fields generated by precious metal nanostructures and chemical adsorption[103]. To conduct the clinical application of wearable sensors, a sensing platform integrating dopamine-modified microneedles (MNs) with ternary metal Au@Ag-Pt nanoparticles was developed for dual-mode detection of

Table 1 Platform comparison with performance metrics

Platform	Sensing/Actuation modality	Intended application	Performance metrics	Ref.
Electrical-responsive	Electrochemical sensing	Biomarker detection	LOD: fM to nM level	[35,73–75]
	Electrical impedance imaging (EIT)	Anatomical imaging	Input current density: 79.58 mA/cm^2 Spatial resolution: 1 mm Conductivity LOD: 0.0075	[37]
Optical- responsive	Colorimetric/ Fluorescence/ SERS	Biomarker detection	LOD: pM Level	[76–78]
	Photodynamic therapy	Tumor treatment	Laser input: 532-660 nm with 100-560 mW/cm^2 for 3-30 min	[41,79–83]
	Photothermal therapy	Tumor treatment	Laser input: 808-971 nm 122.7-500 mW/cm^2 for 15 min Heat output: 40 to 48 °C	[84,85]
Ultrasound- responsive	Ultrasound imaging	Anatomical imaging	Axial/lateral resolution: 0.25 to 1 mm Maximum penetration: tens to hundreds mm	[86,87]
	Sonodynamic therapy	Tumor treatment	Ultrasound input: 1–2 W/cm^2 with 1.2–3 MHz for 3-10 min Penetration depth: 70 to 150 mm	[40,88,89]
Thermal- responsive	Thermal imaging	Anatomical imaging	Precision: ±0.1 to 0.3 °C Spatial resolution: 2.4 mm	[90–92]
	Thermal dynamic therapy/ Hyperthermia	Tumor treatment	Heat input: sustain 42 °C for 45 min or cycle 37 to 45 °C for 5 h	[93,94]

LOD limit of detection

tyrosinase (TYR) activity via SERS and colorimetry, enabling in situ melanoma monitoring (Fig. 3a)[78]. The experimental data revealed that the detection sensitivity of this system reached 0.01 U/mL (SERS mode) and 0.03 U/mL (colorimetric mode), significantly improving the performance indicators of traditional detection methods. Moreover, spectral imaging methods have also been developed for subcutaneous tumor mapping, which has bright prospects for application[104].

Electrical sensing

Wearable electrochemical sensors, which capture abnormalities before the tumor forms discernible masses or produces clinical symptoms, are of particular interest because of their minute-level responses and high sensitivity[73,105]. With working electrodes modified with biorecognition elements (such as antibodies[106], aptamers[107,108] and enzymes[109]), it can specifically capture target molecules and initiate oxidation-reduction reactions that generate electrical responses. Figure 3b showed a microneedle (MN) array-based electrochemical sensor patch for melanoma screening that targeted tyrosinase (Tyr), an important enzyme in melanin formation[74]. By conducting cyclic voltammetry on the captured electrodes, reversible reduction of the oxidized products could be executed for sensor reusability. To validate its performance under realistic conditions, the device was

tested on a full-thickness human skin model obtained from plastic surgery, which demonstrated excellent prolonged measurement and effective regenerative performance in Tyr-injected skin samples. In addition to melanoma, electrochemical sensors have been developed for the detection of breast cancer[75] and nasopharyngeal carcinoma[35]. These findings support the potential of wearable electrochemical sensors to provide real-time, long-term, noninvasive or minimally invasive cancer diagnosis through highly sensitive biomarker detection.

Electrical signals can also be leveraged to excite different skin responses in wearable imaging devices. Owing to the heterogeneous conductivity of tumor tissues, electrical impedance tomography (EIT) enables abnormal tissue identification by applying weak alternating currents on the skin, measuring boundary voltage changes and constructing an impedance distribution[110]. A wearable impedance tomography (TIT) system based on triboelectric nanogenerators (TENGs) was developed for high-precision, low-power dynamic imaging of biological tissues (Fig. 3c)[37]. By inputting a current density of only 79.58–99.47 mA/m^2, which is much lower than the safe current for humans, this system can achieve a spatial resolution of 1 mm/50 mm, enabling precise localization of lipomas. However, although EIT has high biosafety and dynamic imaging capabilities, its sensitivity can be limited by current penetration[111]. Motion
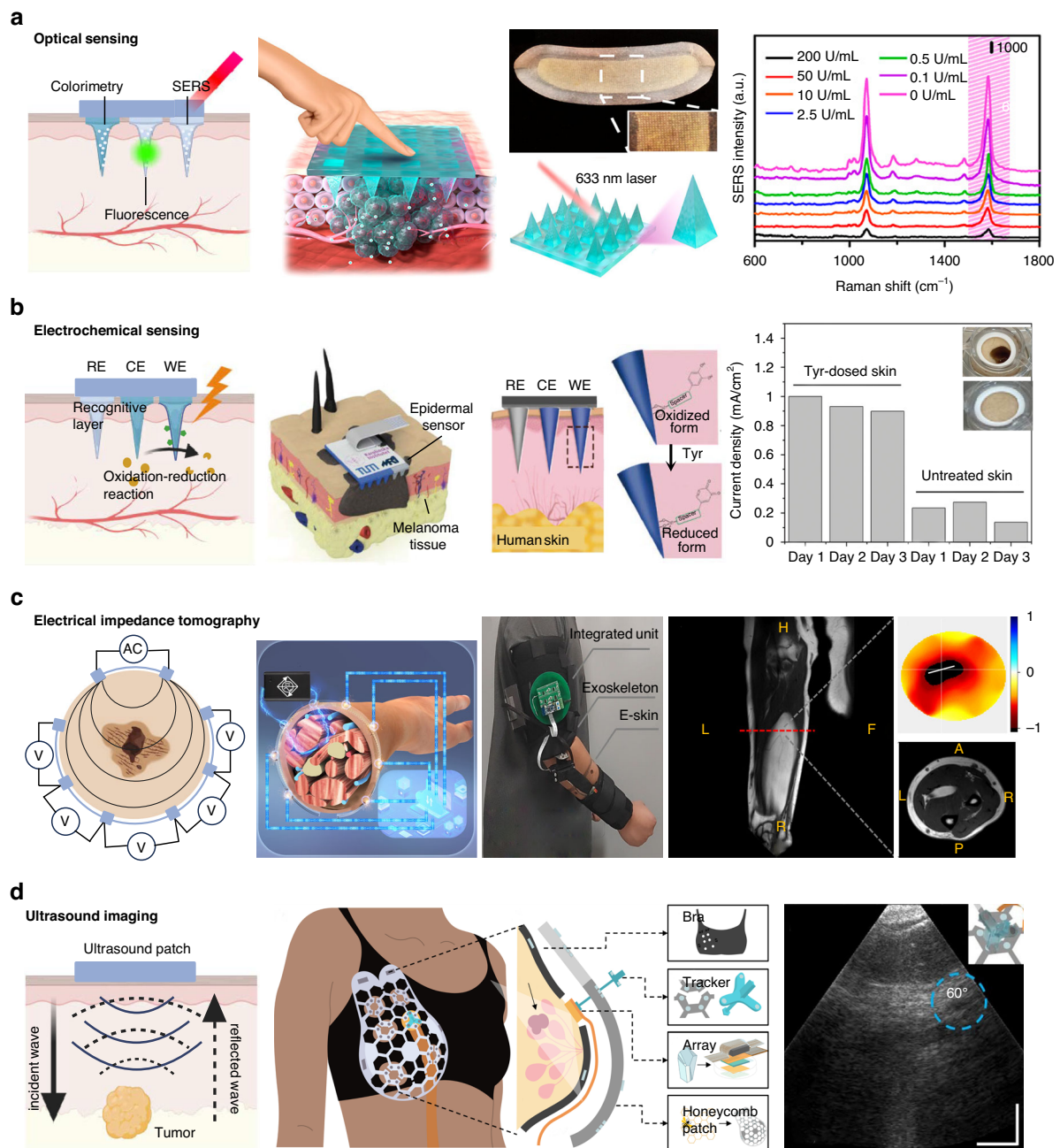
Fig. 3 Wearable bioelectronics for cancer early diagnosis. a Wearable microneedle patch with SERS/colorimetric dual-mode sensing enables in situ tyrosinase monitoring for early melanoma screening and treatment prognosis. Reprinted from ref. [78]. with permission. **b** An electrochemical microneedle patch for the diagnosis of transdermal melanoma. Reprinted from ref. [74]. with permission. **c** A wearable triboelectric impedance tomography (TIT) system for noninvasive, dynamic pathological tissue detection. Reprinted from ref. [37]. with permission. **d** A conformable breast honeycomb patch for the standardized and multi-directional ultrasound imaging. Reprinted from ref. [86]. with permission

artifacts can be caused by dynamic factors, such as electrode movement, human fluids and neural activities, which are not fully considered by algorithms[111,112]. Optimizing electrode array design and advanced algorithms and combining prior information would be an effective solution.

Ultrasound imaging

Medical imaging plays a pivotal role in early cancer detection, which enables estimation of tumor location, size and infiltration depth. However, conventional imaging methods are particularly dependent on bulky, rigid imaging devices, which increase patients' transportation

burdens. Therefore, lightweight portable alternatives are advocated, and wearable bioelectronics have been developed for continuous imaging. In addition to the ionizing radiation utilized or high energy consumption in other imaging devices[113,114], electric-mediated, ultrasound-mediated and thermal-mediated imaging arrays are especially suitable for integration into wearable platforms because of their high biosafety and low power requirements.

Ultrasound imaging has emerged as a promising detection method via the active emission of mechanical waves. By emitting high-frequency sound waves through probes and calculating differences in time delay, frequency shift and echo intensity, the impedance distributions and structural properties can be constructed as possible indicators of tumor formation[115]. Recent advances in microelectromechanical system (MEMS) technology have allowed flexible piezoelectric transducer arrays to realize conformal skin contact and real-time health monitoring[87]. However, achieving an optimal balance between imaging quality, biocompatibility and adhesion remains a key challenge for wearable ultrasound imaging systems[116,117]. To this end, a conformable breast ultrasound patch was constructed, including a honeycomb design for standardized imaging, a monocrystalline probe for superior acoustic properties and an adjustable tracker to expand the field of view, as shown in Fig. 3d[86]. Through simple rotation, the tracker could rotate to change the detection angles, enabling multiangle image reconstruction, while the fixed honeycomb structure minimized image artifacts possibly from misalignment or poor contact. For a patient with breast cancer, the imaging system could detect small residual tumors and predict tumor morphology through multidirectional imaging.

Thermal imaging

Additionally, wearable temperature sensor arrays can monitor heat dissipation disorders on the skin, which can be attributed to metabolic activities and vascular anomalies associated with cancer[90]. One type of cancer that widely utilizes this technology is breast cancer. In healthy patients, both breasts exhibit symmetrical temperature distributions, whereas in breast cancer patients, the side with the tumor shows an increase in temperature. Among these methods, infrared thermal imaging (IRT) on the basis of ionizing radiation requires patients to be exposed to an infrared camera for 15 minutes, increasing patient discomfort[118]. Therefore, a contact-based wearable thermal imaging bra system based on the medical Internet of Things (IoMT) was developed, which used 128 high-precision biosensors (± 0.1°C) to monitor breast surface temperature gradients in real time, enabling early screening for breast cancer (2.08°C temperature difference)[91]. Compared with traditional infrared thermal

imaging, the system employed thermal asymmetry analysis and cloud-based algorithm processing to maintain noninvasiveness while enhancing spatial resolution, which demonstrated its potential for detecting small tumors (3 mm). However, despite its noninvasiveness and safety, thermal imaging has limited specificity and low detection depth, restricting its further clinical application in cancer detection.

In conclusion, wearable early diagnostic tools enable precise and rapid identification and localization of tumors via both biomarker detection and imaging methods. However, simple indicators may restrict the precise evaluation of cancer staging, which calls for the construction of multimodal sensing platforms to comprehensively consider more related signals[119,120]. Moreover, parameters within the devices should be considered comprehensively. For example, owing to the flexibility requirements, rigid damping layers are discarded at the expense of shorter pulse lengths in wearable ultrasound arrays[121]. Therefore, innovative technologies still need to be invented to balance the internal subcomponents while integrating as much information as possible to guarantee effective diagnosis.

Cancer treatment

Wearable bioelectronics promise more convenient and personalized cancer treatment. By integrating tailored medicines, engineered configurations and flexible materials, they control processes that are inherently difficult to manage via external interventions, which consequently improves drug delivery efficiency and treatment effects. Therefore, the potential of wearable bioelectronics in cancer treatment has received immense attention.

Transdermal drug delivery

Transdermal drug delivery has emerged as a key approach for localized and systemic cancer treatment, which enables drugs to bypass the biological barriers of the stratum corneum. This method allows for the targeted delivery of drugs to tumor sites and potentially expands the narrow therapeutic window of certain drugs while minimizing invasiveness. Recent advances have been proposed in fabricating methods (e.g., 3D printing microneedles[122,123]), drug types (e.g., responsive drugs[124] and engineered cells[36,125]) and physical enhancement technologies (e.g., electrical[126], acoustic energy[127] and heat energy[128]) to enhance manufacturing processes and delivery efficiency.

For transdermal drug delivery, several methods of different action mechanisms are widely studied (Fig. 4a). Microneedles (MNs) enhance drug permeation by physically bypassing the stratum corneum via micro-sized punctures, enabling direct intradermal delivery of therapeutics[129]. Iontophoresis employs mild electrical
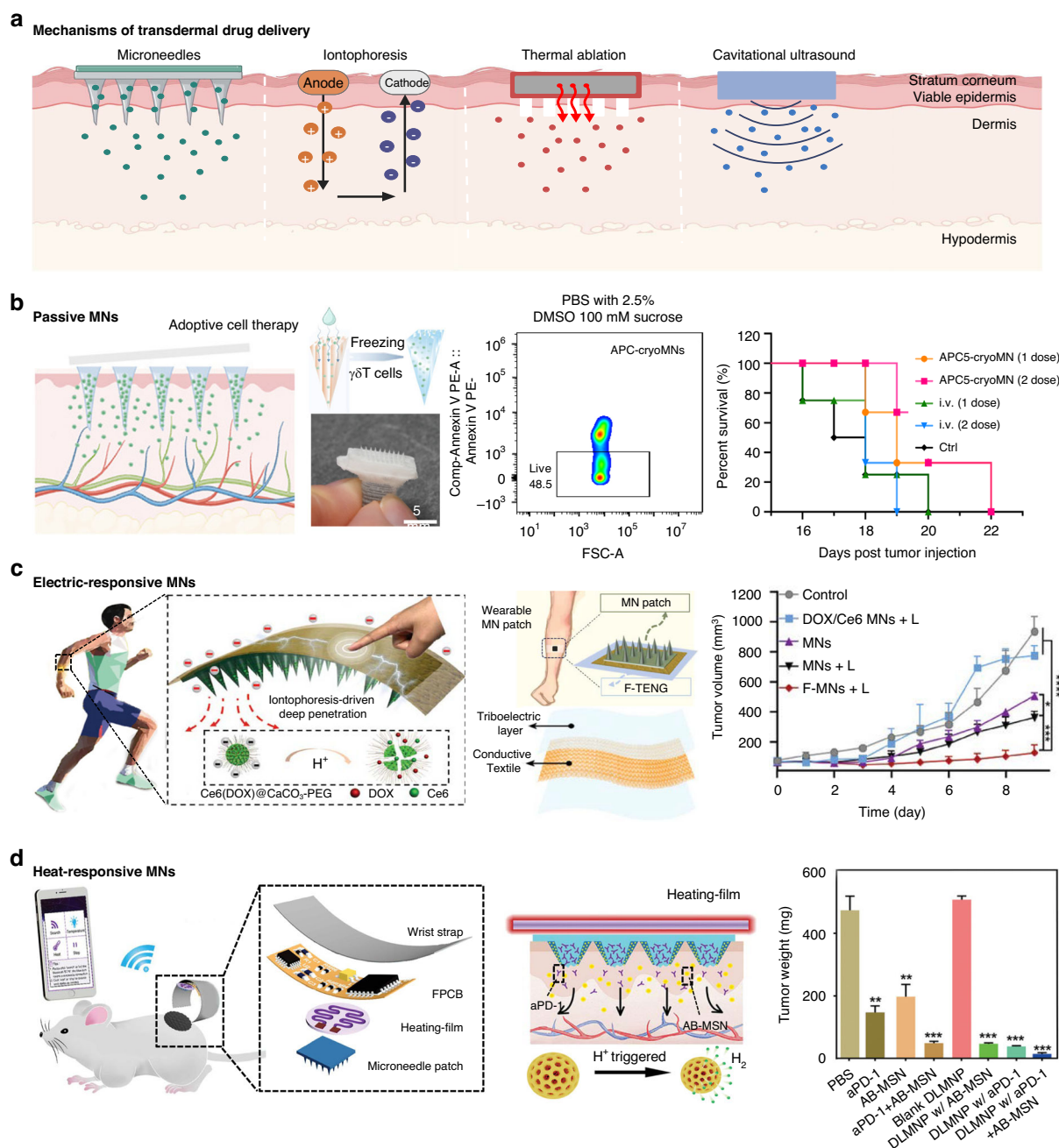
Fig. 4 Wearable bioelectronics for transdermal drug delivery of cancer. a Operational mechanisms of mechanical structure-mediated, electrical mediated, thermal mediated, ultrasonic mediated transdermal drug delivery. **b** Bioinspired microneedles based on anisotropic porous microstructures for Adoptive T cells therapy. Reprinted from ref. [133]. with permission. **c** A self-powered microneedle patch integrated with triboelectric nanogenerators for iontophoresis-driven deep melanoma chemotherapy. Reprinted from ref. [140]. with permission. **d** A silk-based soluble microneedle enabling active smart phone control and synergistic sequential hydrogen/ immunity therapy. Reprinted from ref. [141]. with permission

currents to drive charged molecules across the skin through electrorepulsion and electroosmosis[130]. Thermal ablation temporarily disrupts skin barriers by localized heating[131], increasing permeability, while ultrasound cavitation generates microbubbles that induce microflows for transdermal transportation[132]. Among them, microneedles are ideal for wearable integration due to their miniaturizability, pain-free application, and compatibility with active methods. Their modular design allows hybrid platforms, offering precise spatiotemporal control which

is critical for personalized therapy. Therefore, in the following part, microneedle-based wearable platforms will be mainly discussed.

MNs employ both passive and active release mechanisms. Inspired by the wood xylem vessel structure, a porous cryogen MN system loaded with γδ T cells was developed for cancer immunotherapy, as shown in Fig. 4b[133]. Its unidirectional pore structure enabled the rapid absorption of macromolecular drugs without external assistance and allowed for long-term preservation by freezing. Compared with conventional intravenous injections, γδ T-cell delivery via MNs resulted in improved survival rates in both skin and organ tumor models, highlighting the therapeutic advantages of MN-based systems. Additionally, active pressurization strategies can also be employed for deeper drug penetration. In this strategy, an oxygen pump MN was constructed by integrating chemical oxygen sources and sodium percarbonate in the MN matrix[134]. Upon contact with tissue fluid, the oxygen source could be converted into oxygen to propel the drug preload and relieve tumor hypoxia. In addition to preload diversification, structural design enhancement, such as self-locking[135], has been explored to meet specific therapeutic needs. However, passive methods often lack precise control over release rates, leading to high heterogeneity among different tumor types and patient cohorts.

To address these limitations, external stimuli can be introduced for actively controlled, on-demand drug release with better performance. Electricity and heat are two widely studied energies that can be integrated into microneedle systems to enhance advanced features such as release stability, penetration depth, and control of droplets[136–139]. To achieve deep tumor treatment, a self-powered MN integrated with a flexible triboelectric nanogenerator was developed for combined chemotherapy and photodynamic therapy (Fig. 4c)[140]. By harvesting the biomechanical energy from body movement, the system generated an alternating current that activated pH-responsive nanoparticles, facilitating their delivery into a 750 μm-deep subcutaneous melanoma in mice. Once localized, acid-sensitive drugs decomposed into DOX and Ce6 to induce apoptosis. Moreover, to increase therapeutic sensitivity and actively control the amount of drug delivered, a heat-responsive silk-based MN device was constructed to target cancer stem cells for synergistic immunization and gas therapy (Fig. 4d)[141]. Combined with a heating film for heat generation, flexible electric components for wireless control and a wrist strap for localization, the MN patch allowed real-time temperature monitoring and controlled release via a smartphone. Simultaneously, a coated structure was designed for sequential release. Wrapped around the MNs, the first dissolved AB-MSNs produced hydrogen to

reduce the amount of reactive oxygen species, followed by the central release of aPD-1 for targeted immunosuppression. With these advancements, a closed-loop drug delivery system can be further designed on this basis to realize automatic dynamic treatment adjustments without user intervention[142], and multimodal therapeutic strategies are needed for complex cancer treatment scenarios.

ROS-based therapies

Reactive oxygen species (ROS) are defined as highly reactive oxygen-containing chemical molecules, generally including superoxide radical anions (O_2^-), singlet oxygen ($^1O_2$), hydroxyl free-radicals (OH^-) and hydrogen peroxide (H_2O_2)[143]. Endogenous ROS are produced by mitochondria and peroxisomes as byproducts of cellular reactions, with stable concentrations in normal tissues[144,145]. Low-abundance ROS can act as signaling molecules to promote cancer cell proliferation, whereas excessive ROS may lead to apoptosis and cytotoxicity[146]. Therefore, catalyzing the formation of excessive ROS by exogenous sensitizers is invented as an effective cancer treatment strategy[147]. Recently, the integration of wearable technologies has expanded the application scope of ROS-generating therapies, especially noninvasive or semi-invasive treatments such as photodynamic therapy (PDT), sonodynamic therapy (SDT) and thermodynamic therapy (TDT), which have different performance merits and limitations compared to traditional therapies (Table 2)[57,148–159].

The photosensitizers used in PDT are activated by red, blue or near-infrared light to catalyze the production of ROS from endogenous substances within the tumor. More specifically, after excitation, PS is transferred from the ground state to a singlet state and then spin-converts to a triplet state, where it exchanges electrons or energy with its surroundings to catalyze ROS generation[160]. Here, wearable bioelectronics optimize both the delivery of sensitizers and the excitation process. To integrate the procedure of drug delivery and PDT, a wireless detachable metronomic injector was proposed for battery-free and recyclable breast cancer therapy (Fig. 5a)[41]. By converting mechanical energy from body movement into electrical energy, the device heated a thermal expansion layer, driving drug release from a reservoir into the tumor site. In tumor-bearing mouse models, this device ultimately maintained the tumor volume at a manageable level for 12 days, illustrating its effective and long-term anticancer efficacy. Among the ROS, $^1O_2$ is considered the main cause of phototoxicity via a type II photo process, where energy from the triplet state of photosensitizers is transferred into triplet dioxygen ($^3O_2$)[161]. However, oxygen scarcity in tumor regions limits the effectiveness of this process. Wearable devices can relieve this hypoxic

Table 2 Comparison of ROS-based therapy and traditional therapy with advantages and limitations
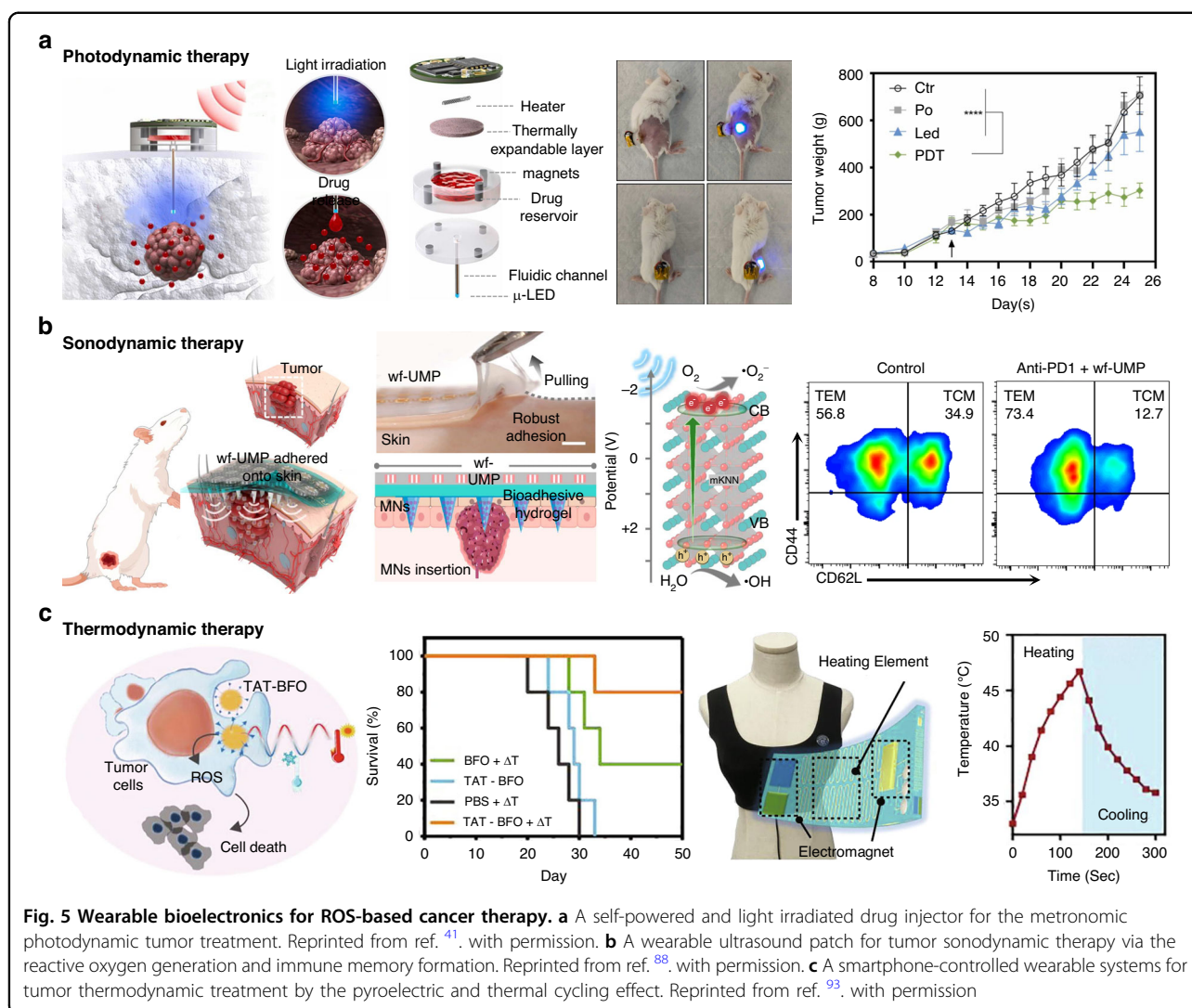
Therapy	Methods	Advantages	Limitations	Ref.
Traditional therapy	Surgery	Rapid tumor reduction, Curative for early-stage cancers	Highly traumatic, Incidence of complications, Risk of residual lesions, Can cause organ functional damage	148
	Chemotherapy	Systemic treatment, Effective against metastatic cancers	Severe systemic side effects, Non-targeted drug delivery, Risk of drug resistance	57,149
	Radiotherapy	Non-invasive, Effective for localized tumor, Valid treatment for palliation	Damage to surrounding tissues, Risk of secondary cancers, Risk of radiation resistance	57,150
	Immunotherapy	Targeted approach, Long-lasting effects, High biosafety	Immune-related side effects, Variable effectiveness among patients	151–153
ROS-based therapy	Photodynamic Therapy (PDT)	Minimally invasive, Minimized systemic toxicity, Minimal damage to surrounding tissues	Limited penetration depth, Rely on surrounding oxygen concentration	154,155
	Sonodynamic Therapy (SDT)	Non-invasive, Deep penetration, Minimal damage to surrounding tissues	Require specific ultrasound parameters, Limited clinical availability	156,157
	Thermodynamic Therapy (TDT)	Not necessarily dependent on oxygen concentration, High compatibility in synergistic therapies	Risk of damage to surrounding healthy tissues, Require precise temperature control	158,159

environment via the simultaneous transport of oxygen or peroxisomes, which facilitate oxygen generation and glutathione (GSH) depletion[79,80,82]. In addition to chemical components, the excitation efficiency can also be optimized by wearable devices through the development of high-power OLEDs[162]. These innovations significantly improve treatment efficacy, allow long-term use, increase patient compliance, and reduce discomfort associated with conventional endoscopic PDT through removable and lightweight structures.

SDT also relies on ROS generation but uses ultrasound as an external stimulus to activate acoustic sensitizers. The principle of ROS generation by SDT can be interpreted as the exploitation of sonoluminescence and the pyrolysis effect caused by the cavitation effect[163,164]. Compared with light-based methods, ultrasound can penetrate deeper into tissue, induce cavitation effects and mediate certain apoptosis pathways, making SDT a highly valuable noninvasive cancer therapy[165,166]. Figure 5b showed a flexible ultrasound MN patch for painless sensitizer delivery, conformal skin adhesion and ultrasound emission[88]. After subcutaneous drug delivery via MNs, embedded piezoelectric nanoparticles accumulated in the tumor via enhanced permeability and retention effects. Upon ultrasound stimulation, the nanoparticles generated separate electrons and holes, which catalyzed the production of ROS from water and oxygen to induce apoptosis. In addition, this device enhanced immunotherapy, which was supported by immune cell-related alterations, demonstrating long-term immune memory and efficient suppression of tumor recurrence in the post-SDT stages.

TDT is an emerging method that utilizes the thermoelectric effect to induce ROS generation. The pyroelectric effect between two pyroelectric terminals results in electron−hole mobility within the internal crystal[167]. Similar to previous therapies, different endogenous substances are catalyzed to generate ROS at the electron end and the hole segments. Here, the wearable device often acts as a controlled heat source to energize the nanomedicine and reduce the effects of hyperthermia on surrounding cells. For example, a joint ferroelectric bismuth ferrite nano effector and smartphone-controlled wearable platform were developed to routinize the cancer treatment process, as shown in Fig. 5c[93]. After treatment, this approach yielded a posttreatment survival rate of approximately 80%, which was twice that of the control groups. For breast cancer recovery, a wearable system is designed later capable of automated temperature cycling on the basis of remote smartphone commands, illustrating the feasibility of practical applications.

Fig. 5 Wearable bioelectronics for ROS-based cancer therapy. a A self-powered and light irradiated drug injector for the metronomic photodynamic tumor treatment. Reprinted from ref. [41]. with permission. **b** A wearable ultrasound patch for tumor sonodynamic therapy via the reactive oxygen generation and immune memory formation. Reprinted from ref. [88]. with permission. **c** A smartphone-controlled wearable systems for tumor thermodynamic treatment by the pyroelectric and thermal cycling effect. Reprinted from ref. [93]. with permission

By utilizing wearable devices, ROS-based therapies are evolving from short-term, hospital-centered interventions to continuous, daily use and patient-friendly solutions. Enabled by smartphone control, wearable bioelectronics support real-time adjustments of treatment parameters for tailored dosing, improved precision and reduced medical waste. With the development of intelligent nanomedicine, more innovative and integrated platforms are expected to emerge to further advance personalized cancer therapeutics. Notably, ROS-based therapies require the assistance of sensitizers, indicating that the body needs to ingest additional drugs to achieve therapeutic effects. Therefore, biosafety assessments, including major organ testing and blood biochemical analysis, are necessary. Moreover, drug metabolism, excretion, and biotoxicity are also key considerations for such therapies and represent major in their transition to clinical application[168].

Thermal therapy

Owing to the difference in heat resistance between cancer and normal cells, thermal therapy has emerged as a promising approach that selectively induces apoptosis in cancer cells without harming surrounding healthy tissues with external heat energy[169]. Among the various temperature-based therapies, hyperthermia is a widely recognized thermal therapy that can be achieved by maintaining a temperature ranging from 42℃ to approximately 48℃[170]. For example, a unidirectional silver nanofiber (AgNF) transparent patch was developed for localized superficial epidermal tumor thermotherapy (Fig. 6a)[94]. The unidirectional AgNF network offered both high transparency and low resistance, allowing safe operation at low voltages while permitting real-time monitoring of the skin condition to prevent burns. Moreover, hyperthermia also has effective synergistic effects with other modalities. It promotes intratumor

Fig. 6 Wearable bioelectronics for cancer thermal therapy. a A unidirectional nanofiber patch for the visible hyperthermia to subcutaneous tumor. Reprinted from ref. [94] with permission. **b** MXene-doped ionic gel for the electrostimulation-augmented photothermal therapy of melanoma. Reprinted from ref. [85] with permission
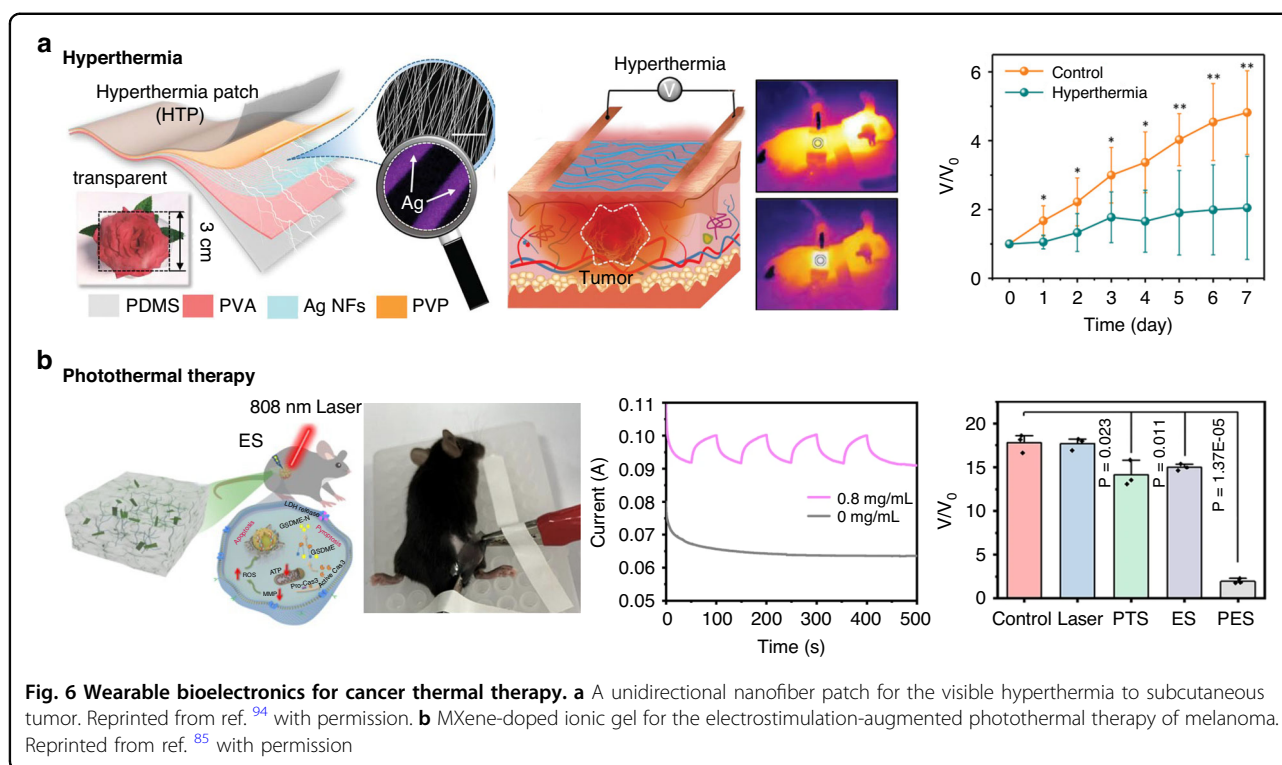
penetration and drug uptake of chemotherapeutic agents by vasodilating tumor blood vessels and increasing metabolism[171]. It can also sensitize cells to radiotherapy and increase the catalytic activity of catalytic therapy[172]. In addition to excitation energy, photothermal therapy (PTT), which converts light energy into heat, represents another promising thermal approach for cancer therapeutics. As shown in Fig. 6b, ionic gels doped with MXene were developed with dual cell death mechanisms for joint electrical stimulation and PTT[85]. The MXene-doped ionic gels possessed highly transparent properties that allowed laser penetration and real-time visualization of the treatment area. It also featured flexibility and conductivity, which enabled uniform electrical stimulation across the entire tumor area and eliminated treatment blind spots. A decrease in tumor volume was observed in the groups that received combined PTT and electrical stimulation, indicating a synergistic therapeutic effect. Therefore, cancer thermotherapy provides a multimechanism treatment approach with enhanced efficacy and relatively low toxicity.

Recent advances highlight the transformative role of wearable bioelectronics in cancer theranostics, significantly improving both therapeutic outcomes and patient experience. For traditional therapies, transdermal drug delivery systems enable painless and precise medication administration, whereas for ROS-based and thermal therapy, wearable bioelectronics miniaturize and simplify the delivery of external stimuli. Furthermore,

they demonstrate the potential of closed-loop drug delivery by combining sensing and treatment components, which enables real-time feedback control to maintain drug homeostasis. By combining different therapies under similar external stimuli, wearable devices are also feasible for synergistic cancer therapies to achieve multifunctional integration.
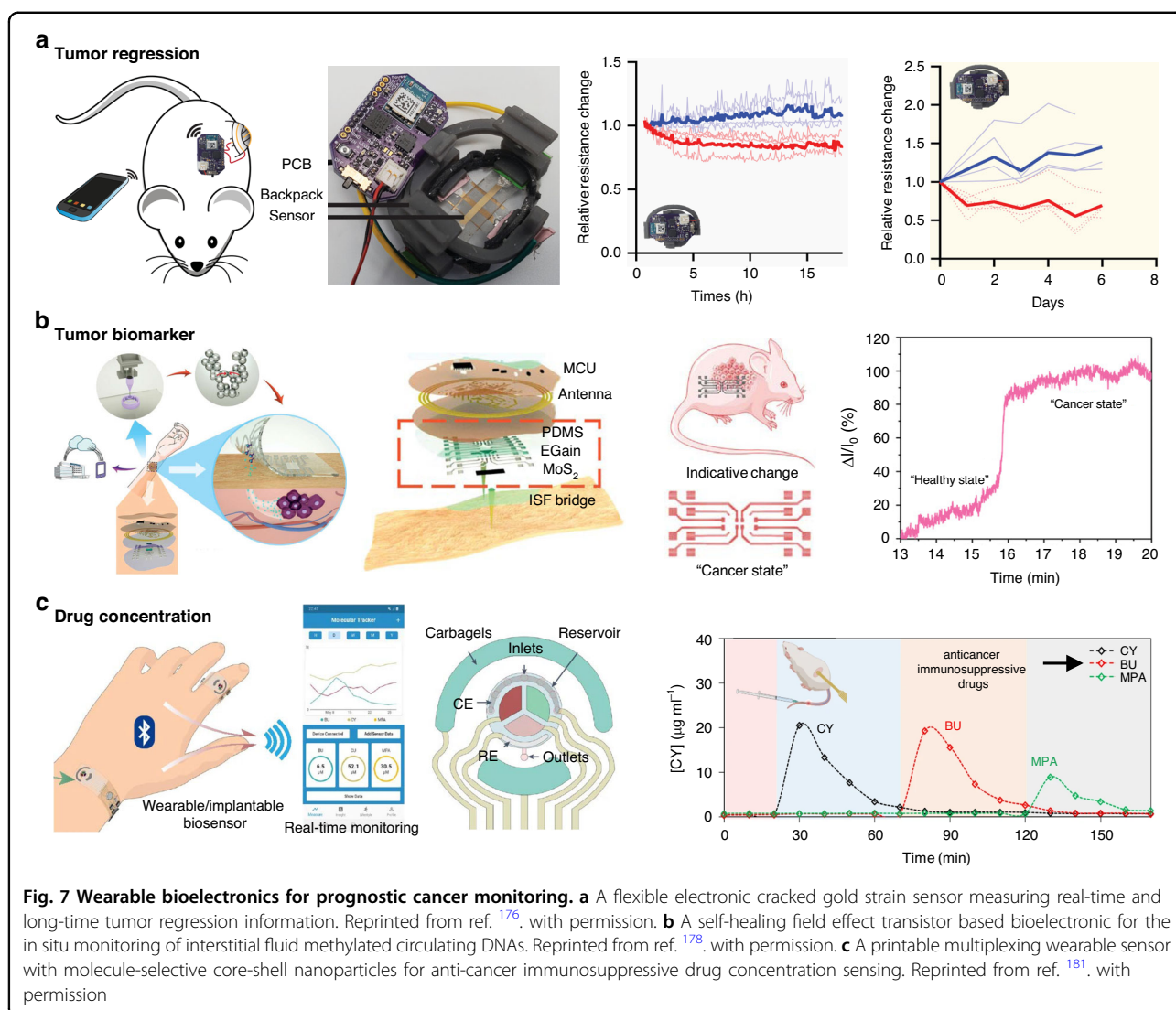
Prognostic monitoring

Cancer prognosis refers to the prediction of disease progression and outcomes following medical intervention on the basis of information from tumor morphology, blood drugs or cells, and clinical manifestations[173–175]. Traditional monitoring tools tend to provide only discrete, point-in-time data; in contrast, wearable bioelectronics enable continuous monitoring, offering valuable insights into disease dynamics. Tumor regression monitoring in animal models, circulating biomarker detection and drug concentration detection in biofluid sensing are discussed in this section to highlight the long-term operation ability of wearable devices.

Tumor regression

Prognostic monitoring via wearable bioelectronics plays a crucial role in animal models, where tumor volume is an important indicator to assess drug efficacy. Wearable sensors enable fast and convenient data collection, thereby reducing the labor burden. Compared with other detection methods, strain sensors ensure noninvasive detection with

Fig. 7 Wearable bioelectronics for prognostic cancer monitoring. a A flexible electronic cracked gold strain sensor measuring real-time and long-time tumor regression information. Reprinted from ref. [176]. with permission. **b** A self-healing field effect transistor based bioelectronic for the in situ monitoring of interstitial fluid methylated circulating DNAs. Reprinted from ref. [178]. with permission. **c** A printable multiplexing wearable sensor with molecule-selective core-shell nanoparticles for anti-cancer immunosuppressive drug concentration sensing. Reprinted from ref. [181]. with permission

satisfactory diagnostic accuracy. As shown in Fig. 7a, a strain sensor based on microcrack extension of a gold film was developed for automated tracking of dynamic changes in tumor size[176]. As the tumor grew or shrunk, changes in the circumference stretched the surrounding sensor, modulating the resistance of the gold film. In both the subcutaneous and internal tumor-bearing mouse models, the device demonstrated stable and continuous monitoring over several days. This method detected differences in tumor regression between the treatment and control groups much earlier than conventional methods did. Integrating such tumor regression monitoring tools with therapy development efforts may enhance comprehensive cancer management[40].

Circulating biomarkers

Another effective prognostic indicator is the continuous monitoring of tumor-associated circulating biomarkers[177].

Unlike early cancer diagnosis, prognosis requires long-term tracking of biomarker levels. To support this, sensors should be both durable and resilient to the mechanical stresses of daily wear. Figure 7b showed a field-effect transistor platform with self-healing circuitry developed for real-time and transdermal monitoring of methylated circulating tumor DNA (ctDNA)[178]. The functionalized antibodies on the gate could specifically bind to methylated ctDNA, modulating the channel current. Notably, the system incorporated liquid metal components capable of forming an oxide layer for self-healing. Although this study highlighted a promising direction for long-term use, wearable prognostic monitoring, antibody degradation and liquid metal biosafety remained challenging. Future advancements should focus on biosensors that are robust under long-term monitoring and capable of maintaining stable performance in complex living environments, thus supporting treatment effectiveness analysis and adaptive cancer treatment.

Drug concentration

Apart from direct measurement of the tumor, evaluating drug concentration levels is essential for predicting cancer recurrence, assessing drug resistance and determining the optimal dosage[179]. Owing to the extremely narrow therapeutic window of cancer drugs, it is assumed that the effective and toxic doses of cancer drugs are very close to each other, resulting in a greater risk of ineffective treatment or severe toxic side effects[180]. Moreover, individual differences in drug metabolism make standardized dosing ineffective for many patients. To address these issues, a reproducible inkjet-printed core−shell nanoparticle microfluidic sensing platform was developed for real-time monitoring of multiple drugs (Fig. 7c)[181]. Designed for bedridden patients, this platform enabled sweat-based drug monitoring by using iontophoresis to stimulate sweat induction and microfluidics to guide the fluid into the sensor reservoir. The system incorporated selective cavities that binded target drugs, reducing the exposure of the magnetic nanoparticle core, hindering electron transfer, and decreasing the redox current. Because of its excellent long-term operational stability in a mouse model, this device represented an innovative approach in wearable bioelectronics for pharmacokinetic monitoring.

Wearable bioelectronics offer promise for cancer prognosis through continuous, real-time monitoring of tumor status, circulating biomarkers, and therapeutic drug levels. Their utility in preclinical animal models can streamline drug development by reducing costs and manual labor. Furthermore, these systems address the limitations of traditional tools by reducing time delays in prognostic evaluation and supporting data-driven medicine in cancer management.

Rehabilitation

Cancer rehabilitation marks the final yet essential stage in comprehensive cancer theranostics, requiring not only medical support but also social and psychological care. To automate the evaluation of recovery states, diverse sensor inputs and machine learning data processing methods are widely utilized in wearable bioelectronics[182]. Furthermore, devices can be customized with cancer-specific assistive functionalities to improve patients' quality of life during recovery. Here, laryngeal and tongue cancer recovery environments are specifically described below to demonstrate the significance of wearable bioelectronics in scenario-customized healthcare.
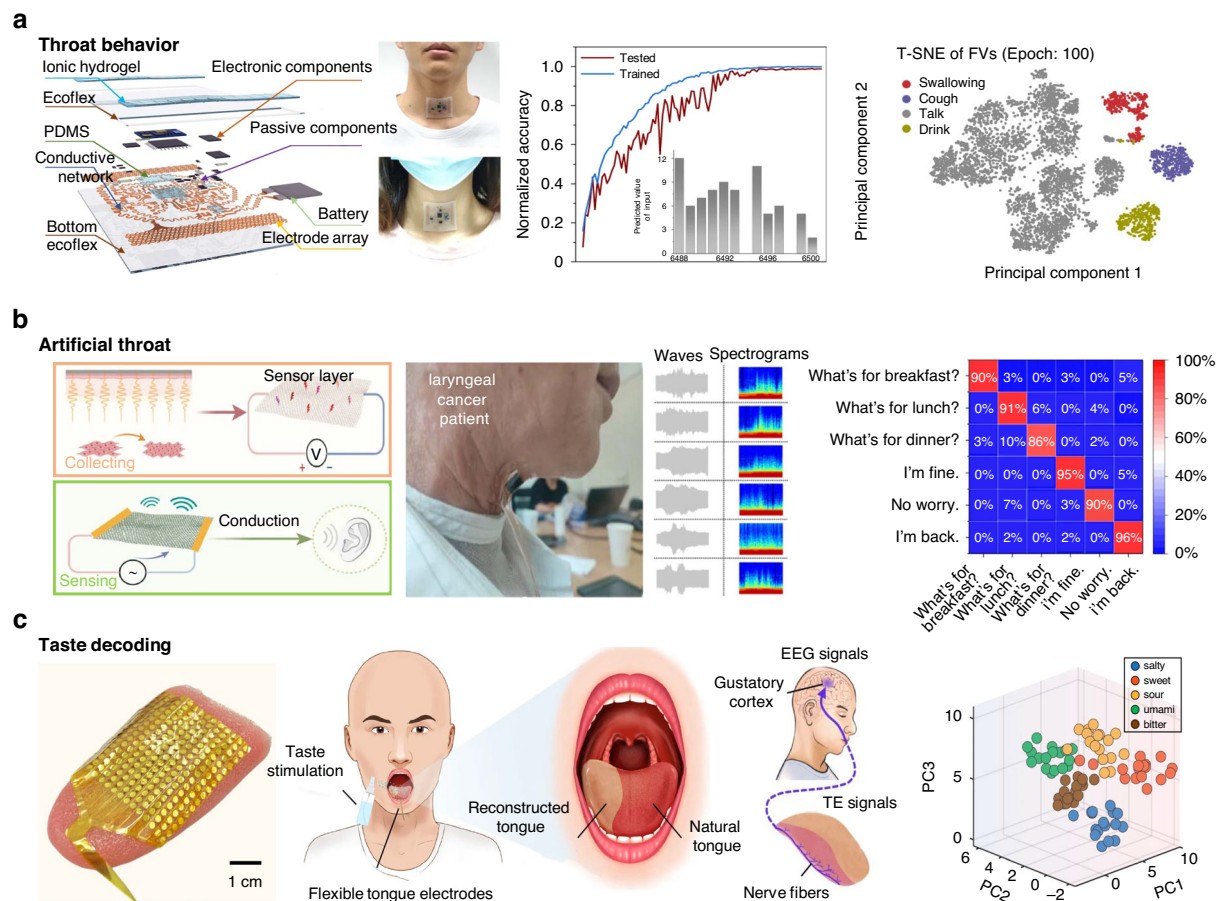
Throat behavior evaluation

Head and neck cancer is one of the most specific cancer sites, as therapeutic treatment may result in difficulty swallowing or even vocalization disorders, greatly reducing the well-being of the patient[183–185]. As postoperative rehabilitation of assisted patients requires equipment for long-term monitoring of vocal cord movement and swallowing, wearable bioelectronics offer flexible alternatives for daily sensing. As shown in Fig. 8a, a lightweight and stretchable hydrogel platform was proposed, which integrated a built-in triaxial accelerometer, a surface electromyography (sEMG) sensor, and a convolutional neural network data analysis module for laryngeal rehabilitation management[186]. This platform captured both gross body movements and subtle laryngeal physiological vibrations, along with muscle electrical activity, enabling precise evaluation of swallowing behavior. The trained CNN model achieved an accuracy of 98.2% in classifying key laryngeal motions and demonstrated adaptability with new subjects, making it an ideal and accurate solution for postsurgical laryngeal cancer patients with personalized rehabilitation management. Moreover, mechanoacoustic sensors[187], strain sensors[188], vibration sensors[189] and multimodal systems[190] diversify the sensor choices for the precise monitoring of throats.

Artificial Throat

Although laryngeal monitoring is a good approach to support rehabilitation, some patients face permanent or prolonged vocal impairments after laryngeal cancer surgery. Moreover, the conventional electronic larynx can only produce mechanical and unnatural sounds that limit effective communication. To address this gap, a wearable artificial larynx system has been developed by integrating machine learning algorithms and vocalization modules according to the structure of laryngeal monitoring for electromyographic signals. For example, a graphene strain sensor-based artificial larynx was developed to cope with signal perception and speech output in noisy environments (Fig. 8b)[38]. Graphene sensors affixed to the neck synchronized residual muscle contractions with skin-conducted vocal fold vibrations. By converting the signals into spectrograms and using them for AlexNet model-based deep learning classification, the device showed 91% classification accuracy for laryngeal cancer resection patients, demonstrating the device's excellent immunity to interference and adaptive learning capability. Simultaneously, machine learning-integrated artificial larynxes have emerged based on different skin signal detection principles. By responding to sensing signals in real time, the artificial larynx, as a wearable device specifically targeting laryngeal cancer, provides inspiration for broader functional recovery applications tailored to specific cancer types. In addition to strain sensors, electromyograms[191], piezoelectric transducers[192] and soft magnetoelastic sensors[193] are also promising alternatives for input formation to achieve more precise corresponding device responses.

Fig. 8 Wearable bioelectronics for the post-therapeutic cancer rehabilitation. a A fully integrated stretchable platform with machine learning-based throat behavior and body motion classification for laryngeal cancer rehabilitation monitoring. Reprinted from ref. [186]. with permission. **b** An artificial throat enabling multiplexed speech recognition and voice reproduction for the post-laryngectomy aphonic patient. Reprinted from ref. [38]. with permission. **c** A high-density electrode arrays for the taste restoration of tongue cancer patients. Reprinted from ref. [39]. with permission

Taste decoding

In tongue cancer, postoperative complications often include partial sensory loss, particularly in taste perception, which impacts quality of life. Patients with sensory loss acquire specific sensations or generate alternative sensation signals, which are important and relevant. Therefore, a flexible tongue electrode for postoperative recovery monitoring of tongue cancer and reconstruction of taste function was developed to achieve high-resolution whole tongue electrical signal recording, as depicted in Fig. 8c[39]. The device monitored electrophysiological differences between the reconstructed and natural tongues under gustatory stimulation, allowing visualization of recovery. Additionally, the simultaneously recorded electroencephalography (EEG) signals were compared by using a bimodal fusion algorithm to predict taste information. Although there was limited research on tongue signal decoding, this study highlighted the potential of wearable bioelectronics in restoring sensory functions.

Moreover, as a growing area of interest, salivary biosensing could be leveraged to enhance recovery monitoring and rehabilitation in tongue cancer patients.

In summary, the complexity and diversity of cancer-related impairments necessitate tailored wearable solutions. Current advances in wearable bioelectronics for laryngeal and tongue cancer rehabilitation demonstrate how multimodal sensing and machine learning can support partial restoration of lost functions. The development of cancer-specific wearable interventions could play a key role in personalized and high-quality postoperative care, bridging wearable healthcare closer to the ideal of individualized medicine.

Conclusion and perspective

Wearable bioelectronics facilitate development in the whole loop of cancer theranostics, including early diagnosis, on-patient treatment, and recovery support. They have demonstrated notable advantages in the

Fig. 9 Future perspective of wearable bioelectronics in advanced cancer theranostics. Reprinted from ref. [27]. with permission
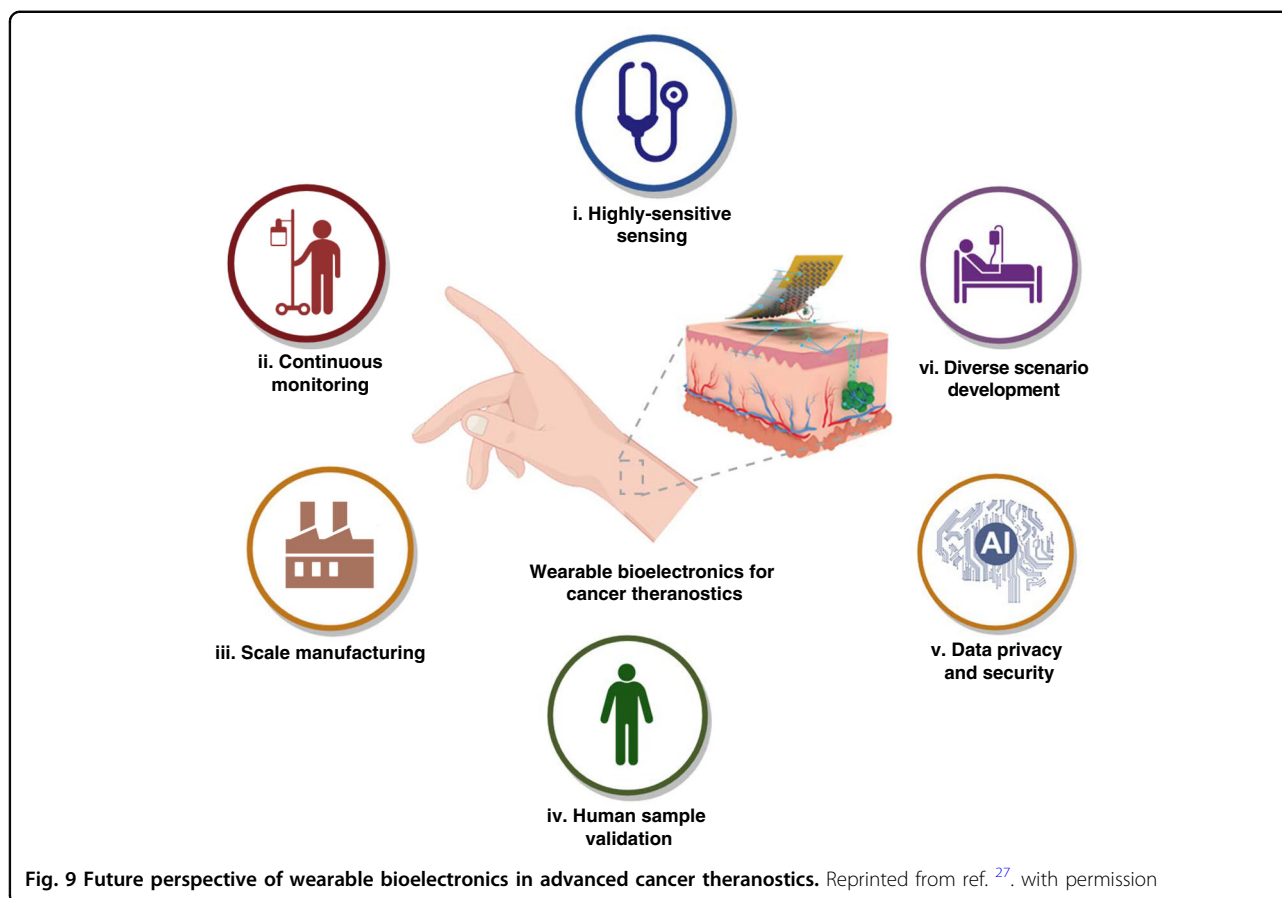
combination of molecular, cellular and anatomical information for monitoring the cancer progression. However, several challenges should be addressed before their successful translation to the clinical market (Fig. 9).

Device sensitivity and continuity

The development of highly sensitive detection systems remains paramount for improving diagnostic reliability. Sensitive materials and novel recognition elements are promising signal enhancement techniques for improving the detection limit of the sensor. Continuous monitoring is also essential because of the high spatial and temporal heterogeneity of tumors during the treatment cycle. This requires the implementation of stable sensing platforms with extended operational lifetimes, achieved through optimized interfacial contact mechanics and biocompatible material to reduce inflammatory reactions in long-term wear. Power management represents another key consideration for long-term monitoring. The development of lower energy consumption devices, higher energy density batteries and active energy harvesting methods are recommended. Ultimately, multimodal sensors are crucial methods to enhance both sensitivity and continuity. By integrating sensors targeting multiple tumor biomarkers, they can improve diagnostic accuracy and precision, while they can perform timely calibration to reduce the impact of environmental factors by combining both physical and chemical sensors.

Standardized fabrication

Cost-effective manufacturing methods are key elements for making multifunctional wearable bioelectronics accessible for economically disadvantaged patients. For manufacturers, to reduce the process complexity and manufacturing difficulty, all-in-one fabrication solutions, including roll-to-roll processing[194], printing methods[122] and laser patterning[195], are also advocated, which facilitates the commercialization of wearable bioelectronics.

Clinical validation

Successful clinical translation requires rigorous validation of device performance in human populations. Comprehensive biocompatibility assessments must address both material components and energy delivery parameters. For instance, while traditional metallic microneedle arrays may present toxicity concerns, polymeric alternatives offer improved safety profiles without compromising mechanical integrity[196]. Similarly, stimulation parameters must be carefully optimized to prevent tissue damage. The implementation of robust data governance frameworks is

equally important to ensure patient privacy and ethical data handling throughout continuous monitoring processes. Furthermore, device functionality should be tailored to specific clinical contexts, such as incorporating respiratory and swallowing function assessment in laryngeal cancer rehabilitation. The development of disease types is important. Current research mainly focuses on superficial cancers, while the development of deep cancers places higher demands on the penetration capabilities of devices. Although advanced actuators have been developed, devices that combine penetration depth, targeting ability and biosafety are still scarce.

Overall, wearable bioelectronics show great promise for advancing cancer theranostics. By overcoming key challenges in sensor sensitivity and continuous monitoring as well as the limitation in scenario consideration, these devices can enable real-time, precise and personalized health care in diverse cancer types. With further development of multimodal sensing, biocompatible materials, and standardized manufacturing, wearable bioelectronics may ultimately transform cancer theranostics through decentralized, data-driven approaches that improve the intervention outcomes.

Conflict of interest
The authors declare no competing interests.

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