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Review

Recent progress in Nanomaterial based biosensors for the detection of cancer biomarkers in human fluids

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Abstract: Cancer is a global health challenge, and early detection is crucial for effective treatment to improve patient outcomes. In recent years, nanomaterial-based biosensors have emerged as powerful tools for the detection of cancer biomarkers in human fluids. This article highlights the recent progress in biosensor technology for the detection of cancer biomarkers, focusing on advancements in sensitivity, selectivity, multiplexed detection, liquid biopsies, point-of-care testing, wearable biosensors, and integration with artificial intelligence (AI). Recent advancements have significantly improved the sensitivity and selectivity of biosensors, allowing for the detection of low concentrations of cancer biomarkers in complex biological samples. Novel sensing technologies, such as nanomaterial-based sensors and aptamer-based sensors, have played a crucial role in enhancing biosensor performance. Multiplexed biosensors have the ability to simultaneously detect multiple cancer biomarkers, providing comprehensive diagnostic information. This capability is particularly valuable for accurate cancer diagnosis and prognosis. Liquid biopsies, which involve the detection of cancer biomarkers in circulating tumor cells, cell-free DNA, or exosomes present in body fluids, have gained considerable attention. Biosensors have played a pivotal role in the development of liquid biopsy technologies, offering non-invasive and real-time monitoring of cancer progression, treatment response, and the emergence of drug resistance. The integration of biosensors with AI algorithms has shown great potential. AI can analyze and interpret biosensor data, identifying patterns, correlations, and biomarker signatures that may be difficult to detect with traditional methods.

Keywords: biosensor; cancer biomarker; sensitivity; selectivity; multiplexed detection; liquid biopsies; artificial intelligence

1. Introduction

Cancer remains a major global health concern, and timely detection is essential for effective treatment. Recently, nanomaterial-based biosensors have emerged as prevailing tools for the detection of cancer biomarkers in human fluids [1,2]. These biosensors offer numerous advantages, including high sensitivity, selectivity, and the ability to detect multiple biomarkers simultaneously [3,4]. This introduction provides an overview of the recent progress in nanomaterial-based biosensors for the detection of cancer biomarkers in human fluids.

Nanomaterials, due to their unique physicochemical properties such as enhanced surface area and conductivity, have revolutionized biosensing. They can be engineered to possess enhanced surface area, conductivity, catalytic activity, and optical properties, making them ideal candidates for developing highly sensitive and selective biosensors [5,6]. Various types of nanomaterials, such as nanoparticles, nanowires, nanotubes, and nanosheets, have been explored for cancer biomarker detection. The sensitivity of nanomaterial-based biosensors has been significantly improved through the incorporation of functionalized nanomaterials [7–9]. These functionalization strategies involve the attachment of specific ligands, such as antibodies, aptamers, or peptides, onto the nanomaterial surface to selectively capture cancer biomarkers from complex biological samples. The high surface-to-volume ratio of nanomaterials enhances the capture efficiency, allowing for the detection of low concentrations of cancer biomarkers. Additionally, nanomaterials can be utilized to transduce the recognition event into a measurable signal. They can act as labels, catalysts, or signal amplification elements in biosensors. For instance, nanoparticles can be functionalized with fluorophores, enzymes, or electroactive species to generate optical, enzymatic, or electrochemical signals, respectively. These signal transduction mechanisms enable real-time and quantitative detection of cancer biomarkers [10–12].

The development of multiplexed nanomaterial-based biosensors has gained significant attention in recent years. Simultaneous detection of multiple cancer biomarkers provides a comprehensive analysis, improving the accuracy of cancer diagnosis and prognosis. By integrating different types of nanomaterials with distinct recognition properties, multiplexed biosensors offer the ability to detect a panel of biomarkers in a single assay [13–15]. One of the key advantages of nanomaterial-based biosensors is their compatibility with various human fluids, including blood, urine, saliva, and cerebrospinal fluid. This allows for non-invasive or minimally invasive sampling, reducing patient discomfort and enabling frequent monitoring [16,17]. The development of nanomaterial-based biosensors for liquid biopsies has revolutionized cancer diagnostics by providing real-time monitoring of disease progression, treatment response, and the emergence of resistance [18,19].

In brief, nanomaterial-based biosensors have demonstrated significant progress in the detection of cancer biomarkers in human fluids. Their high sensitivity, selectivity, multiplexing capability, and compatibility with different biological samples make them promising tools for early cancer detection, personalized treatment, and improved patient outcomes. Continued research and development in this field hold great potential for advancing cancer diagnostics and improving overall healthcare.

2. Types of nanomaterials used in biosensor

Various types of nanomaterials have been extensively explored for the development of biosensors to detect cancer biomarkers in human fluids. The choice of nanomaterial depends on several factors, including the desired sensing mechanism, target biomarker, and the specific requirements of the biosensing platform.

2.1. Nanoparticles

Nanoparticles offer unique physicochemical properties and can be engineered to

possess specific functionalities. Gold nanoparticles (AuNPs), silver nanoparticles (AgNPs), palladium nanoparticles (PdNPs), and platinum nanoparticles (PtNPs) are widely used due to their excellent optical properties, including surface plasmon resonance, which can be utilized for colorimetric or surface-enhanced Raman scattering (SERS) detection [20–23]. Several types of nanoparticles are demonstrated in **Figure 1**. Semiconductor quantum dots (QDs) are fluorescent nanoparticles with tunable emission wavelengths and high photostability, enabling sensitive and multiplexed detection [24–26].

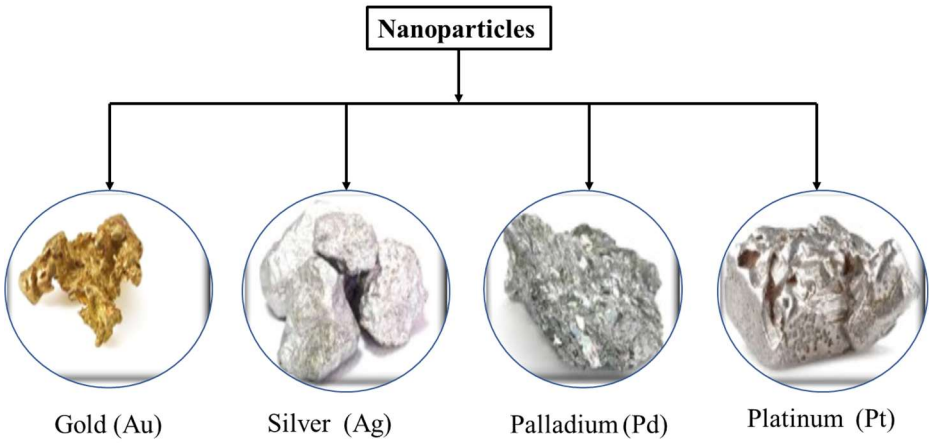

Figure 1. Several types of nanoparticles.

2.2. Carbon-based nanomaterials

Carbon nanotubes (CNTs) and graphene are carbon-based nanomaterials that offer exceptional electrical conductivity and a large surface area. The structures of carbon nanotubes and graphene are shown in **Figure 2**. They can be functionalized with biomolecules to create nanoscale interfaces for the detection of cancer biomarkers through electrical or electrochemical measurements. The high electron transfer properties of these materials make them suitable for label-free, sensitive, and real-time detection [27–29].

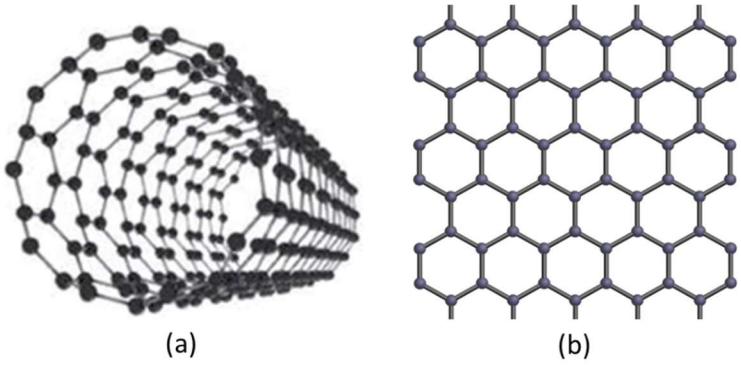

Figure 2. The structure. **(a)** carbon nanotube; **(b)** graphene.

2.3. Magnetic nanoparticles

Magnetic nanoparticles, such as iron oxide nanoparticles, are commonly used for magnetic biosensing applications and also have excellent physical and chemical

properties that are shown in **Figure 3**. They can be functionalized with specific ligands to selectively capture cancer biomarkers from complex biological samples. The captured biomarkers can be quantified using techniques like magnetic relaxation, magnetic resonance imaging (MRI), or magnetic particle detection (MPD) [30–32].

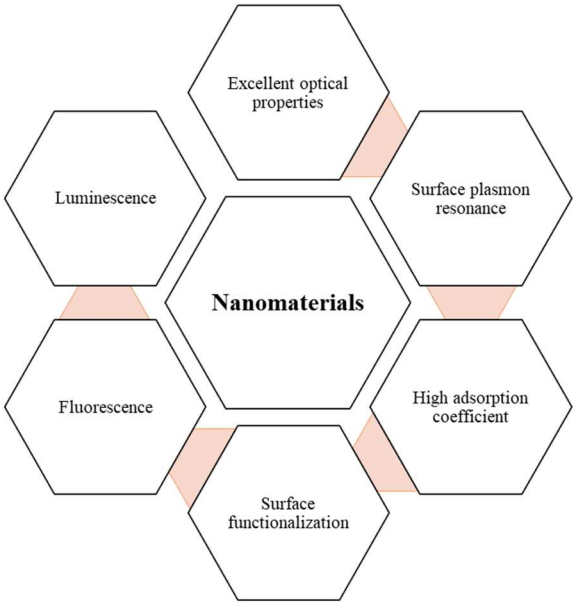

Figure 3. Properties of nanomaterials.

2.4. Nanowires and nanotubes

Semiconductor nanowires and nanotubes offer unique electrical properties and large surface-to-volume ratios, making them suitable for sensitive electrical or electrochemical detection. Silicon nanowires, for example, can be functionalized with recognition elements to create highly sensitive biosensors for the detection of cancer biomarkers [33,34].

2.5. Up-conversion Nanoparticles

Up-conversion nanoparticles (UCNPs) are a type of nanomaterial that can convert low-energy excitation light into higher-energy emission light. They have been used for the detection of cancer biomarkers through near-infrared (NIR) light excitation, enabling deep-tissue imaging and reducing background interference [35,36].

2.6. Metal-organic frameworks (MOFs)

MOFs are porous materials composed of metal ions or clusters coordinated with organic ligands. The structure of the metal-organic framework is illustrated in **Figure 4**. They offer high surface areas and tunable properties, making them suitable for capturing and detecting cancer biomarkers. MOFs can be functionalized with specific receptors or enzymes to create highly sensitive and selective biosensors [37,38].

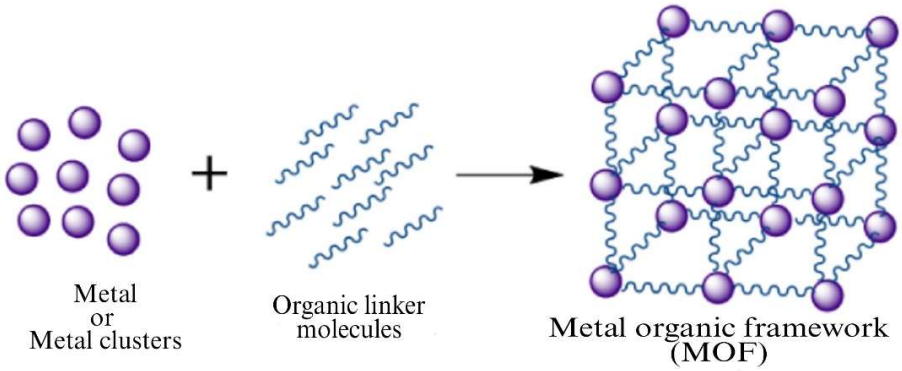

Figure 4. Structure of metal organic framework.

3. Working principle of biosensors

Biosensors for the detection of cancer biomarkers in human fluids operate based on various working principles, depending on the specific design and detection mechanism. However, the general principle involves the recognition of a target biomarker by a biological receptor and the transduction of this recognition event into a measurable signal. A schematic diagram of the working principles of a biosensor is shown in **Figure 5**. Here are some common working principles of biosensors used for cancer biomarker detection:

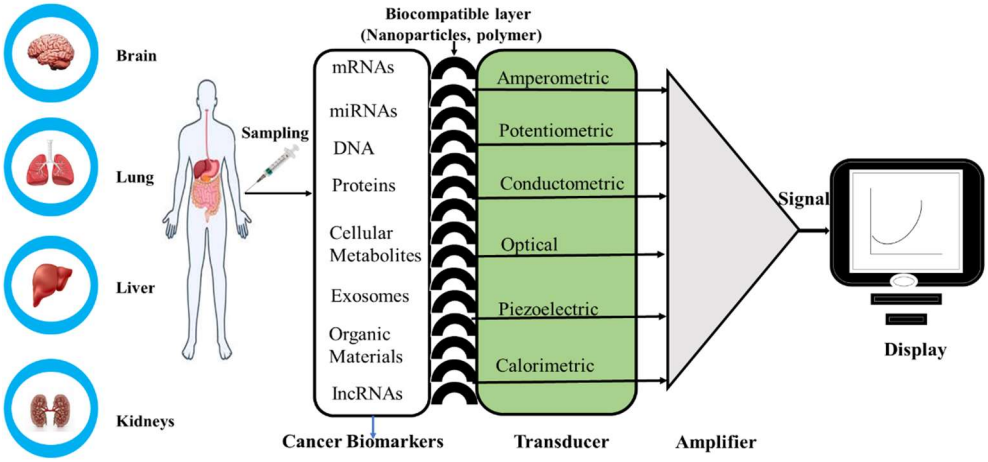

Figure 5. Working principles of biosensor.

3.1. Antibody-antigen interaction

Antibodies are commonly used as recognition elements in biosensors. They specifically bind to their corresponding antigens, which may be cancer biomarkers present in human fluids. The biosensor is typically functionalized with antibodies that selectively capture the target biomarker [39,40]. This recognition event can generate a signal through various transduction mechanisms, such as changes in electrical conductivity, optical properties, or electrochemical reactions.

3.2. Aptamer-target interaction

Aptamers are short, single-stranded DNA or RNA molecules that can bind to target molecules with high affinity and specificity. Biosensors can be designed with

aptamers as recognition elements for cancer biomarkers [41]. When the target biomarker binds to the aptamer, a conformational change occurs, leading to a measurable signal. This signal can be detected using techniques like electrochemical impedance spectroscopy, fluorescence, or surface plasmon resonance [42–44].

3.3. Enzymatic reactions

Some biosensors employ enzymes as recognition elements to detect cancer biomarkers. Enzymes catalyze specific reactions in the presence of the target biomarker, producing a measurable signal [45,46]. For example, the enzymatic reaction can generate an electrochemical current that is proportional to the concentration of the biomarker [47,48]. Glucose oxidase-based biosensors, commonly used in diabetes monitoring, operate on this principle.

3.4. Nucleic acid amplification

Biosensors can utilize nucleic acid amplification techniques, such as polymerase chain reaction (PCR), to detect cancer biomarkers. PCR amplifies the target DNA or RNA sequence to a detectable level. PCR technique illustrated in **Figure 6**. The amplified product can be detected using fluorescence-based methods or electrochemical techniques. This approach offers high sensitivity and specificity for detecting trace amounts of cancer biomarkers [49,50].

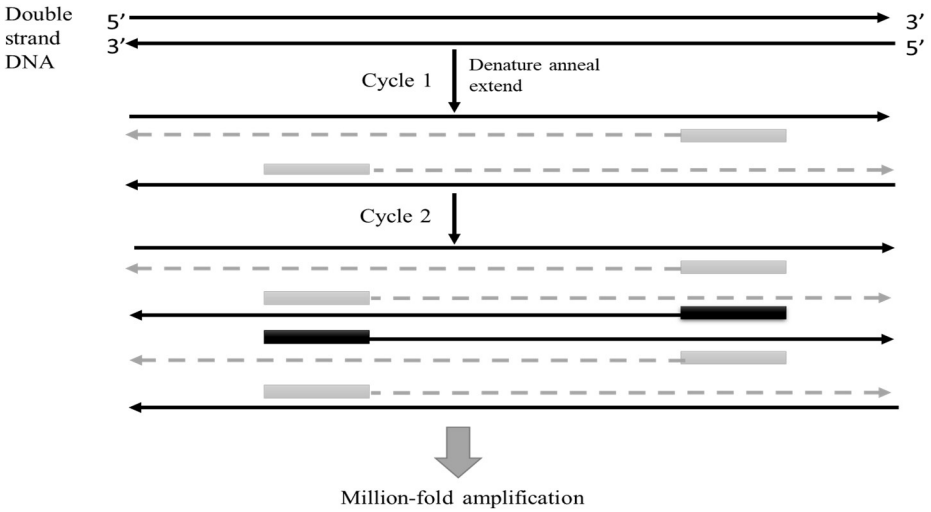

Figure 6. Schematic diagram of PCR technique.

3.5. Mass-sensitive detection

Some biosensors measure changes in mass associated with the binding of the target biomarker to the biosensor surface [51,52]. Quartz crystal microbalance (QCM) and surface acoustic wave (SAW) devices are commonly used in mass-sensitive biosensors. When the target biomarker binds to the biosensor surface, it causes a change in the resonance frequency or propagation velocity of the acoustic wave, which can be measured and correlated with the concentration of the biomarker. The innovative electrochemical biosensors for the detection of cancer biomarkers have been explored in **Table 1**.

Table 1. Summary of innovative electrochemical voltammetric biosensors of cancer biomarkers detection [53].

Biomarker	Cancer Type	Biosensor components	Linear range	Detection Limit
Carcinoembryonic antigen	Multiple	Graphene films/Gr + MB + AB-AuNP + HRP	5–60 ng/mL	5 ng/mL
a-fetoprotein	Multiple	SPCE/Nanogold-Enriched Carbon Nanohorn + AB	0.1 pg/mL–1 ng/ mL	0.07 pg/mL
$p16^{INK4a}$ (p16)	Cervical	SPCE/two capture AB + AuNP + Ag-coated AuNP	15.6–250 ng/mL	0.49 ng/mL
miRNA-34a	Multiple	SPE/Carbon nanofibers + CP + guanine oxidation signal	25–100 ug/mL	10.98 ug/mL
miRNA-24	Multiple	GCE/SWCNT-polyamidoamine dendrimer hybrid + methylene blue	10 fM–1 nM	0.5 fM
Carcinoembryonic antigen	Multiple	GCE/AuNP-thionine-reduced GO nanocomposi-te + AB	10–500 pg/mL	4 pg/mL
p53 Tumor Suppressor Gene	Multiple	AuE/PNA + Indigo carmine	0.01 nM–10.0nM	4.31×10^{-12} M
Carbohydrate antigen 15-3	Breast	GCE/N-doped Gr + AB	0.1–20 U/mL	0.012 U/mL
Epidermal growth factor receptor	Breast	SPE/AP/AB + AuNP + MB	1–40 ng/mL	50 pg/mL
a-Enolase	Lung	SPE/AuNP + AB + PEG + Casein	10–8–10–12 g/mL	2.38 pg/mL
Mucin-1	Breast	AuE/ferrocene-labeled AP-complementary DNA	1 nM–20 nM	0.33 nM
Prostate specific antigen	Prostate	GCE/nanocomposite film of Gr-methylene blue-chitosan + AB	0.05–5.00 ng/mL	13 pg/mL
Platelet-derived growth factor	Multiple	GCE/SWCNT + multi-labeled Gr + platinum NP + AP + AuNP	0.01–35 nM	8 pM
p53 tumor suppressor gene	Multiple	AuE/PNA + methylene blue	0.001–0.010 uM	6.82×10^{-10} M
Epithelial cell adhesion molecule	Multiple	ITO/Gr + quantum dots + AB	100 fg/mL–100 ng/mL	5 fg/mL
Osteopontin	Breast	SPGE/RNA AP + ferro/ferricyanide solution	25 nM–200 nM	3.7 nM
Tissue polypeptide antigen	Multiple	SPCE/Tyramine + prussian blue-gold hybrid nano-structures	1.0 pg/mL–100 ng/mL	0.3 pg/mL
Epithelial ovarian cancer antigen-125	Ovarian	AuE nano/protein molecular imprinted polymer + 3D gold	0.5–400 U/mL	0.5 U/mL

4. Biosensor in cancer diagnoses

Cancer diagnosis using nanomaterial-based biosensors has emerged as a promising approach for early detection, accurate characterization, and personalized treatment of cancer. These biosensors leverage the unique properties of nanomaterials to detect specific cancer biomarkers with high sensitivity and selectivity. Nanomaterial-based biosensors can detect specific cancer biomarkers, such as proteins, nucleic acids, or metabolites, that are indicative of the presence or progression of cancer [54–57]. The nanomaterials used in these biosensors, such as nanoparticles, nanowires, or nanotubes, are functionalized with recognition elements, such as antibodies, aptamers, or peptides, that selectively bind to the target biomarkers discussed above. The binding event generates a signal that is detected and quantified, providing information about the presence and concentration of the biomarkers. Nanomaterial-based biosensors are particularly valuable for liquid biopsies, which involve the analysis of blood, urine, or other bodily fluids to detect cancer biomarkers. Liquid biopsies offer a non-invasive or minimally invasive alternative to traditional tissue biopsies and can provide real-time information about the tumor's molecular characteristics, treatment response, and the emergence of drug resistance. These are

enabling the sensitive and specific detection of circulating tumor cells (CTCs), cell-free DNA, exosomes, or other cancer-related components in liquid biopsies [58–62].

Nanomaterial-based biosensors can simultaneously detect multiple cancer biomarkers, allowing for a comprehensive assessment of the disease. By functionalizing different nanomaterials with specific recognition elements, biosensors can detect panels of biomarkers associated with different cancer types or specific molecular signatures [63–66]. Multiplexed detection enhances the specificity and reliability of cancer diagnosis, enabling more accurate characterization and classification of tumors. Nanomaterials, such as quantum dots, magnetic nanoparticles, or carbon nanotubes, can be used as contrast agents for cancer imaging and localization [67–69]. These nanomaterials can be functionalized with targeting ligands to specifically bind to cancer cells or tissues, allowing for precise imaging and localization of tumors. Nanomaterial-based imaging techniques, such as fluorescence imaging, magnetic resonance imaging (MRI), or surface-enhanced Raman scattering (SERS), enhance the accuracy and sensitivity of cancer diagnosis by providing detailed spatial and molecular information [70–72].

The integration of nanomaterial-based biosensors with portable and handheld devices enables point-of-care testing for cancer diagnosis. These devices allow for rapid and on-site analysis, providing immediate results and reducing the need for sample transportation and centralized laboratory testing. Point-of-care testing using nanomaterial-based biosensors improves access to cancer diagnosis, particularly in resource-limited settings or remote areas where timely diagnosis is crucial [73–75]. Besides this, nanomaterial-based biosensors play a vital role in personalized medicine by providing information about a patient's specific cancer biomarkers. This information can guide treatment decisions, such as targeted therapies or the selection of appropriate chemotherapeutic agents [76,77]. In addition, nanomaterial-based biosensors enable real-time monitoring of treatment response, allowing for timely adjustments in therapy and personalized treatment strategies [78,79]. Therefore, the use of nanomaterial-based biosensors in cancer diagnosis holds great promise for improving early detection, accurate characterization, and personalized treatment approaches. Continued research, development, and validation of these biosensors will further enhance their sensitivity, specificity, and clinical translation, ultimately benefiting patients through improved outcomes and more tailored cancer management.

5. Progress of nanomaterial-based biosensors

Nanomaterial-based biosensors for the detection of cancer biomarkers in human fluids have made significant progress in recent years. The unique properties of nanomaterials, such as high surface area, enhanced sensitivity, and versatile functionalization, have contributed to the development of highly sensitive and selective biosensing platforms.

5.1. Enhanced sensitivity

Nanomaterials, such as nanoparticles, nanowires, or nanotubes, have enabled the detection of cancer biomarkers at extremely low concentrations. Their high surface-to-volume ratio facilitates efficient biomarker capture and signal amplification,

leading to enhanced sensitivity [80–82]. Functionalization of nanomaterials with recognition elements, such as antibodies, aptamers, or peptides, further improves the sensitivity and specificity of biosensors.

5.2. Signal amplification

Nanomaterials have been utilized for signal amplification in biosensors, enabling the detection of low-abundance cancer biomarkers. For example, gold nanoparticles (AuNPs) can be functionalized with multiple antibodies or aptamers, allowing for the simultaneous binding of multiple biomarkers and enhancing the signal. Additionally, nanomaterials like quantum dots (QDs) exhibit bright and stable fluorescence, enabling highly sensitive and multiplexed detection [83,84].

5.3. Multiplexed detection

Nanomaterials have facilitated the development of multiplexed biosensors, allowing for the simultaneous detection of multiple cancer biomarkers. By functionalizing different nanomaterials with specific recognition elements, researchers have created biosensors capable of detecting multiple biomarkers in a single assay. Multiplexed detection provides a comprehensive assessment of the disease state and improves diagnostic accuracy [85,86].

5.4. Integration with other technologies

Nanomaterials have been integrated with other technologies, such as microfluidics or lab-on-a-chip systems, to create integrated biosensing platforms. These platforms enable automated sample handling, rapid analysis, and portable detection. Integration with microfluidics also allows for precise control of sample flow, enhancing the sensitivity and reproducibility of biosensors [87,88].

5.5. Non-invasive sampling

Nanomaterials have facilitated the development of biosensors for non-invasive or minimally invasive sampling of cancer biomarkers. For instance, nanomaterial-based biosensors integrated into wearable devices or patches can collect biomarkers from sweat, saliva, or other bodily fluids. This non-invasive approach offers convenience, patient comfort, and the potential for continuous monitoring [89,90].

5.6. Point-of-care applications

Nanomaterial-based biosensors have shown promise for point-of-care testing, bringing cancer biomarker detection closer to the patient. The small size, portability, and rapid response of nanomaterial-based biosensors make them suitable for use in resource-limited settings or remote locations. Point-of-care biosensors allow for immediate diagnosis, timely treatment decisions, and improved patient outcomes [91,92].

5.7. Integration with nanotechnology

Nanomaterials have been integrated with other nanotechnologies, such as nanoelectronics or nanofabrication techniques, to create advanced biosensing

platforms. For example, nanowire-based field-effect transistors (FETs) offer ultrasensitive detection and real-time monitoring of cancer biomarkers [93,94]. The integration of nanomaterials with nanotechnology enables the development of highly sensitive, miniaturized, and label-free biosensors [95].

The progress in nanomaterials-based biosensors has paved the way for improved detection, monitoring, and personalized treatment of cancer. Continued research and development in this field hold the potential to enhance the sensitivity, specificity, and clinical translation of biosensors for cancer biomarker detection.

6. Cancer biomarker detection with Artificial Intelligence (AI)

Cancer biomarker detection integrated with artificial intelligence (AI) techniques has shown great promise in improving cancer diagnosis and treatment [96,97]. By combining the power of AI algorithms with biomarker analysis, it becomes possible to extract valuable insights from complex data and make more accurate predictions [98,99]. AI algorithms can process and analyze large volumes of biomarker data, including genetic, proteomic, and imaging data. By leveraging machine learning and deep learning techniques, AI models can identify patterns, correlations, and anomalies within the data that may not be apparent to human analysts [100]. This can lead to more accurate and efficient cancer biomarker detection. AI can aid in the early detection of cancer by analyzing biomarker profiles. By training on large datasets that include biomarker data from both healthy individuals and cancer patients, AI models can learn to identify subtle biomarker changes associated with early-stage cancer [101,102]. Early detection improves the chances of successful treatment and better patient outcomes. AI algorithms can assist in personalized cancer diagnosis and treatment. A block diagram of a biosensor integrated with AI is represented in **Figure 7**. By considering a patient's biomarker data, medical history, and other relevant information, AI models can generate individualized risk assessments and treatment recommendations [103,104]. This can help clinicians tailor treatment plans to each patient's specific needs, resulting in more targeted and effective therapies.

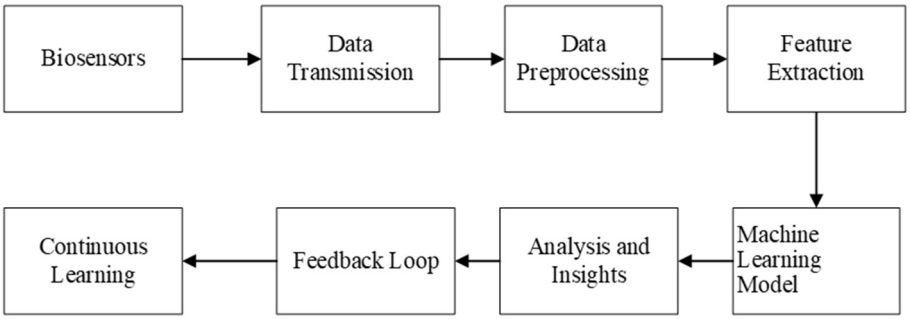

Figure 7. Enhanced biosensor operation with AI.

AI can analyze biomarker data to provide accurate prognostic assessments for cancer patients. By considering multiple biomarkers and integrating them with clinical and demographic information, AI models can predict disease progression, recurrence, and overall patient outcomes. This information can assist clinicians in making informed decisions about treatment options and patient management [105]. AI can help monitor treatment response and guide therapeutic decisions. By analyzing

changes in biomarker levels over time, AI algorithms can provide real-time feedback on treatment effectiveness. This can enable clinicians to make timely adjustments to treatment regimens and optimize patient care. AI can integrate biomarker data from various sources, such as electronic health records, medical imaging, and genomic databases. By combining and analyzing these diverse datasets, AI models can generate a more comprehensive view of a patient's cancer profile. This integration can lead to a better understanding of the disease and facilitate more accurate diagnosis and treatment planning. AI can contribute to cancer research and drug development by analyzing biomarker data. By identifying novel biomarkers associated with specific cancer types or drug responses, AI models can provide insights that help researchers develop targeted therapies and improve treatment outcomes [106,107].

Thus, the integration of cancer biomarker detection with AI has the potential to revolutionize cancer care by enabling early detection, personalized diagnosis and treatment, and improved patient outcomes. However, it is important to ensure the quality and reliability of the data used to train AI models and to address ethical and regulatory considerations associated with the use of AI in healthcare.

7. Challenges of nanomaterial-based biosensor for cancer biomarker detection

While nanomaterial-based biosensors have shown great promise for cancer biomarker detection, several challenges need to be addressed for their successful implementation. Here are some key challenges associated with nanomaterial-based biosensors for cancer biomarker detection:

7.1. Standardization

Establishing standardized protocols and methodologies for nanomaterial-based biosensors is crucial to ensure reproducibility and comparability of results across different research groups and clinical settings. Consistency in sample preparation, assay conditions, and data analysis is essential for reliable and accurate biomarker detection.

7.2. Sensitivity and specificity

Achieving high sensitivity and specificity is crucial for accurate cancer biomarker detection. Nanomaterial-based biosensors need to be optimized to minimize false-positive and false-negative results. Factors such as non-specific binding, interference from complex biological matrices, and variability in target biomarker levels pose challenges that need to be addressed to improve the overall performance of biosensors.

7.3. Biomarker validation

Validating the clinical relevance and accuracy of biomarkers detected by nanomaterial-based biosensors is essential. Large-scale studies involving diverse patient populations are needed to establish the clinical utility and predictive value of the biomarkers identified. Additionally, correlation with gold standard diagnostic methods is necessary to verify the accuracy and reliability of the biosensor-based detection.

7.4. Biocompatibility and safety

Nanomaterials used in biosensors should be thoroughly evaluated for their biocompatibility and potential toxicity. Understanding the interactions between nanomaterials and biological systems is critical to ensure the biosensors' safety for use in humans. This includes assessing the long-term effects, potential accumulation, and biodegradability of the nanomaterials.

7.5. Regulatory and ethical considerations

Regulatory frameworks need to be developed to govern the use of nanomaterial-based biosensors in clinical practice. It is essential to ensure compliance with ethical guidelines, patient privacy, and informed consent. Addressing these considerations will facilitate the translation of nanomaterial-based biosensors from research to clinical applications.

7.6. Scalability and cost-effectiveness

For widespread adoption, nanomaterial-based biosensors should be scalable and cost-effective. Manufacturing processes should be optimized to produce biosensors at a large scale without compromising their performance. Additionally, the overall costs associated with biosensor development, production, and maintenance need to be considered to make them accessible and affordable for clinical use.

7.7. Long-term stability and reliability

Nanomaterial-based biosensors should demonstrate long-term stability and reliability to maintain their performance over extended periods. Ensuring the stability and reproducibility of the biosensors is crucial for their successful integration into routine clinical practice.

Addressing these challenges will require interdisciplinary collaborations between researchers, clinicians, engineers, and regulatory bodies. Continued research and development efforts, along with robust validation studies and adherence to regulatory guidelines, are essential to overcoming these challenges and unlocking the full potential of nanomaterial-based biosensors for cancer biomarker detection.

8. Conclusion

Finally, nanomaterial-based biosensors for cancer biomarker detection in human fluids seem promising. They are intriguing for cancer diagnostics because of their improved sensitivity, multiplexed detection, label-free operation, and point-of-care potential. Nanomaterials improve performance and analysis when combined with microfluidics and AI. Nanomaterial-based biosensors can detect cancer biomarkers at low concentrations with great specificity, enabling early cancer diagnosis, tailored medication, and treatment response monitoring. Rapid, on-site analysis using these biosensors reduces time and expense compared to laboratory approaches. Clinical translation of nanomaterial-based biosensors remains difficult. Standardizing test procedures, validating them with large and varied patient groups, and resolving regulatory and ethical issues are necessary for clinical use. To improve nanomaterial-based biosensor performance, reliability, and repeatability, research and development

must continue. Researchers, physicians, and regulators must work together to deploy biosensors safely and effectively in cancer diagnosis. Nanomaterial-based biosensors might transform cancer diagnosis, patient outcomes, and tailored therapy with further development and translation. AI-biosensor integration has great promise, but it needs overcoming various obstacles and pursuing new research avenues. Biosensor sensitivity and specificity, data processing and interpretation, real-time and remote monitoring, customized healthcare, and regulatory and ethical challenges should be the focus of future advances.

Conflict of interest: The authors declare no conflict of interest.

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