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Recent advances in the application of molecularly imprinted polymers for electrochemical detection of biomedical markers

Fatma BUDAK[a,b], Ensar PISKIN[a,b], Ahmet CETINKAYA[a,c*], Sibel A. OZKAN[a*]

[a]; *Ankara University, Faculty of Pharmacy, Department of Analytical Chemistry, Ankara, Türkiye*
[b], *Ankara University, Graduate School of Health Sciences, Ankara, Türkiye*
[c], *Hacettepe University, Faculty of Pharmacy, Department of Analytical Chemistry, Ankara, Türkiye*

ABSTRACT

Late diagnosis of multifactorial diseases such as cancer, respiratory diseases, and infections continues to be a leading cause of high mortality rates, negatively impacts treatment outcomes, and leads to increased healthcare costs. Biomarkers that indicate the presence of various pathophysiological events, especially cancer, are critical for early diagnosis and monitoring of diseases. However, traditional analytical methods used for biomarker detection, such as chromatographic, spectroscopic, and electrophoretic techniques, have disadvantages such as long analysis times, the need for specialized personnel, and large reagent consumption. Electrochemical methods have emerged as promising alternatives that offer advantages such as faster analysis, cost-effectiveness, sensitivity, and reproducibility. Despite these advantages, electrochemical sensors face selectivity challenges. This problem is addressed by molecularly imprinted polymer (MIP)-based sensors designed to create selective recognition sites that match target molecules. With their high selectivity, specificity, cost-effectiveness, stability, and reusability, MIPs have been rapidly adopted for biomarker detection in various fields, including environmental, food, and biomedical applications. Miniaturized and portable MIP-based sensors further enhance the practicality of biomarker detection. This review covers the recent developments in MIP-based electrochemical sensors, focusing on their applications, sensitivities, and mechanisms for rapid and selective detection of key biomarkers. Additionally, it aims to provide insights and directions for future research in this field.

KEYWORDS
Biomarker, electrochemical analysis, molecularly imprinted polymer, detection, sensor

1. INTRODUCTION

A set of illnesses known as cancer is characterized by aberrant cell proliferation that can infiltrate or spread to other bodily parts [1]. Biomarkers have an important place, especially in the evaluation of cancer cells. Biomedical parameters that indicate many deadly diseases, especially cancer, and various pathophysiological events in the body are called biomarkers. Detecting biomarkers has clinical applications in many diseases affecting oncological, respiratory, and digestive tracts and systemic diseases [2,3]. Therefore, early, rapid, reliable, and sensitive detection of biomarkers in biological samples (blood, urine, etc.) is of vital importance.

In the literature, many methods have been used to detect biomarkers. These methods are chromatographic, spectroscopic, electrophoretic, etc., traditional analytical

*Contact: Sibel A. OZKAN, ozkan@pharmacy.ankara.edu.tr; Ahmet CETINKAYA: ahmet.cetinkya@yahoo.com

methods. However, although these methods have many advantages, they have many disadvantages, such as long analysis time, expert staff support, and the use of large organic solvents [2,3]. Electrochemical methods are widely used as an alternative method to overcome these disadvantages. Moreover, electrochemical methods are frequently preferred in sensor preparation due to their fast analysis time, reliability, cheapness, sensitivity, and repeatability [2]. However, electrochemical sensors still have deficiencies in selectivity. Therefore, the selectivity problem is overcome by integrating molecularly imprinted polymer sensors (MIP) [4].

The purpose of forming MIPs is to produce selective recognition cavities with a shape and functional group composition that directly corresponds to the target compound. The most suitable functional monomer for the target molecule is selected with the help of a cross-linker. In this way, the removal of the target molecule after the polymerization process ensures the formation of specific and selective cavities [2,3,5]. In addition to their excellent selectivity and specificity, MIPs offer stable, cheap, easy-to-prepare, and reusable possibilities [3, 6]. Due to the properties of MIP-based sensors, their areas of use in biomarker detection have grown rapidly, and there are many application areas and rapid and selective detection opportunities in environmental, food, and biological samples [2,3]. Moreover, MIP-based sensors are important in detecting biomarkers when they can be integrated and transformed into miniature and portable devices. When the literature is examined, it is seen that MIP-based sensors are widely used to detect biomarkers, and there is a constantly growing interest in this area [1–3].

As a result, MIP-based electrochemical sensors have many applications in food, environmental, biomedical, and pharmaceutical fields and are widely used to detect biomarkers. Furthermore, the identification and detection of biomarkers are vital for human health. Therefore, this review will discuss the application areas, sensitivities, and mechanisms of MIP-based sensors developed in recent years for the rapid and sensitive detection of some important biomarkers. In addition, this study is intended to guide future studies.

2. Molecularly imprinted polymers (MIPs)

MIPs, distinguished by the particular recognition sites complementary to the size, shape, and functional groups of the template molecules [7], were first developed by Wulff and Klotz in the 1970s based on the MIT guiding principle [8]. In contrast to natural recognition elements

such as enzymes, antibodies, peptides, proteins, and so on, MIPs are considered artificially synthetic receptors that are superior to the natural ones in terms of physical robustness, chemical and thermal stability, specificity, synthetic cost, ease of storage, and reusability [9]. Therefore, MIPs have been widely used in drug delivery, immunoassay, separation and extraction, and sensing as significant alternatives for natural recognition elements [10–13]. Electrochemical analysis has several advantages over other analytical technologies, including quick reaction times, ease of use, affordability, and the potential for instrument miniaturization [14]. Developing electrochemical sensors with high stability, sensitivity, selectivity, and accuracy is crucial. However, transducers, sensing platforms, and recognition components may limit these capabilities. There has been a lot of interest in combining MIPs with electrochemical sensors since 1990 due to their unique host-guest identification process. The successful creation of MIP-based electrochemical sensors (MIP-ECSs) was made possible by advancements in polymerization techniques and detecting procedures.

To create MIPs, a variety of polymerization techniques are used, namely sol-gel polymerization [15,16], bulk polymerization, suspension and emulsion polymerization [17], and precipitation polymerization [18]. Furthermore, it can be separated into photopolymerization (PP), thermal polymerization (TP), electropolymerization (EP), and radiative polymerization (RP) based on the conditions in which the polymerization reaction is initiated. As illustrated in Figure 1, the preparation procedure is similar, even though the synthesis techniques and strategies for creating MIPs differ.

Functional monomers are usually needed to interact with the template (pre-assembly). The imprinted matrix is then created when monomers polymerize in the presence of templates with the help of an initiator and cross-linker. After producing complimentary cavities with templates, the templates can be extracted. The obtained imprinted sites can rebind and release the template or its structural analogs frequently since they possess selectivity towards them.

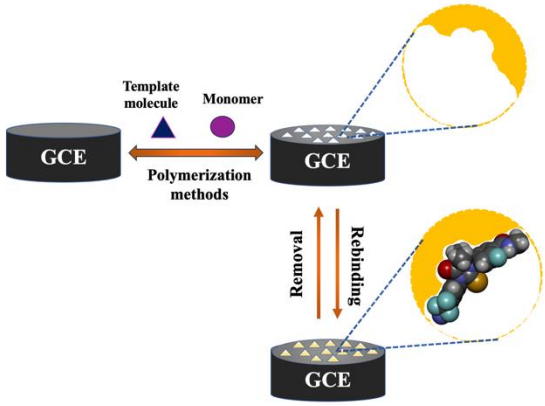

Figure 1. Schematics of the general preparation process of MIPs

3. Biomarkers

- **Lactate (LAC)**

Lactate (LAC), which has a complex and multifaceted structure in the human body, is tightly regulated to maintain the overall metabolic structure [19]. In addition, LAC is an important metabolite that changes during sweating in humans and is generally limited to difficult and intense activities. Therefore, irregular and unbalanced LAC production can indicate abnormal conditions such as respiratory failure, hypoxia, and lactic acidosis [20]. Moreover, LAC concentration is a critical measurement widely used in clinical diagnostics to investigate the health of patients and the diseases it causes[19, 20].

- **Bovine Serum Albumin (BSA)**

Albumin, which plays an important role in maintaining nutritional irregularity, plasma pressure, and the transport of different structures, is of vital importance to human health. Bovine serum albumin (BSA) is a protein found in large amounts in the blood and has a high structural similarity to human serum albumin (HSA). For this reason, BSA has been used as a model protein instead of HSA in different areas. BSA is transmitted to humans through foods obtained from cattle. When there is an excessive intake of BSA, some serious diseases (mad cow disease, insulin-dependent diabetes mellitus, etc.) occur. For this reason, studies are increasing in many areas for the detection of BSA in biological and food [21, 22]

- **Prostate-specific Antigen (PSA)**

One of the most common types of cancer in men is prostate cancer. This type of cancer is the second most common cancer that results in death in older men. Therefore, the most important step in diagnosing this cancer is the detection of the prostate-specific antigen (PSA) protein in the blood. PSA is a protein secreted from the prostate gland and passed into the blood [23]. Therefore, PSA is a very important biomarker in the early diagnosis and prognosis of prostate cancer in the field of oncology [24]

- **Sarcosine (SAR)**

Prostate cancer occurs in the prostate tissue of a malignant tumor in men and is a cancer with a high mortality rate in men. Another biomarker widely used in the diagnosis of prostate cancer is sarcosine (SAR) [25]. SAR levels used to diagnose prostate cancer are detected in urine, tissues, or blood with increasing levels. Therefore, rapid and sensitive detection of SAR biomarkers is of great importance for human health [26]

- **Cardiac Troponin I (cTnI) and T (cTnT)**

Cardiac troponins are regulators of skeletal and cardiac muscle contractions. These troponins consist of cardiac troponin I (cTnI) and cardiac troponin T (cTnT) [27].

cTnI, produced only in the heart muscle, is a biomarker used to detect acute microcardial infarction (AMI). cTnT is another biomarker used to diagnose AMI. Moreover, this biomarker is used as a cardiac biomarker and as a guide in early diagnosis and patient follow-up. AMI is known to be one of the factors that result in the most deaths in the world. Therefore, rapid, sensitive, and reliable detection of cTnI biomarkers is very important for the early diagnosis of AMI [28–30].

- **Carcinoembryonic Antigen (CEA)**

Carcinoembryonic antigen (CEA) is a widely used marker for tumor detection. CEA is a glycoprotein found in excess in malignant tumors, especially in the diagnosis of diseases such as colon, stomach, lung cancer, and breast carcinoma. The CEA level in the blood must be determined for tumor progression. Therefore, biological determination of CEA level is very important for early diagnosis and treatment of tumors [31–33]

- **Amyloid-β Oligomer (AβO)**

Amyloid-β oligomers (AβO) are an important molecular biomarker that plays an important role in Alzheimer's disease (AD). It causes progressive and fatal outcomes for humans, primarily due to the rapid aging of the population. Therefore, reliable and rapid analysis of AβOs is of vital importance in the early diagnosis and prognosis of AD [34, 35]

4. Application of molecularly imprinted polymers for electrochemical detection of biomedical markers

When the studies in the literature are evaluated, it is clear that there is a recent trend toward identifying biomarkers, and numerous studies have been conducted in this field. Table 1 summarizes the recent electrochemical sensor applications to analyze various biomarkers in terms of basic sensor properties, including technique, linear range, LOD, applications, and recovery percentage.

Table 1. MIP-based electrochemical sensors for analysis of various biomarkers

Biomarker	Sensor	Method	Linearity range	LOD	Application	Recovery(%)	References
PSA	GS-AuNP/CS/ GCE	DPV	1 pg mL^{-1}- 100 ng mL^{-1}	0.15 pg mL^{-1}	Women serum sample	92.00-103.50	[36]
PSA	Ab-GO-MWCNTs-Fe_3O_4/SPCE	EIS	0.01-100 ng mL^{-1}	5.4 pg mL^{-1}	Serum Urine	98.17-98.73	[37]
PSA	SPCE/MIP/PEDOT:PSS@Fc	DPV	1.0×10^{-7}–1.0×10^{-4} ng mL^{-1}	$8.3 \pm 1.3\times10^{-8}$ ng mL^{-1}	Human serum sample	89.4 ± 7.4-102.9 ± 6.4	[38]
LAC	3-APBA/Ag-NWs/SPCE/ MIP	DPV	10^{-6} - 0.1 M	0.22 µM	NR	NR	[39]
LAC	4-ABA/LAC/ ZIF-8@ZnQ @MIP-GCE	DPV CV EIS	0.1-1.0 pM	29.9 fM	Human serum sample	99.23- 100.38	[19]
LAC	o-PD/AuNPs/ RGO/GCE	DPV	0.1-1.0 nM	0.09 nM	Sugarcane vinasse sample	99.70-104.80	[40]
BSA	MIP/Pyr/chit/ GCE	DEIS	0.0001-0.01 ng m L^{-1}	$5x10^{-5}$ ng mL^{-1}	Human serum sample	99.40-102.00	[41]
BSA	ACR/DIA/ BisAM/GCE	EIS	$1.5x10^{-16}$ -10^{-12}M	$7.2x10^{-18}$	Serum sample	97.80-103.60	[42]
CEA	FTO/ PPy-MO DMIP	CV EIS	5×10^{4}–10×10^{4} pg mL^{-1}	1.6-3.3 pg mL^{-1}	Human serum sample	96.00–98.80	[43]
SAR	MAA/CPE	DPV	5.0 µM–1.1 mM	0.38 µM	Urine sample	97.4–103.8	[44]
SAR	Fe_3O_4@ZIF-8@MIP	CV	1–100 pM	0.4 pM	Urine sample	96.8–105.8	[45]
cTnT	PANI/PMB/f-MWCNTs/ SPCE	DPV	0.1–8.0 pg mL^{-1}	0.04 pg mL^{-1}	Human plasma sample	91.00-112.00	[46]
cTnI	MB/ ZnONPs/GCE	DPV	0.50-3.3 × 10^5	1.04 pM	Human serum sample	93.40-114.28	[47]
cTnI	PPy/ BNQDs/GCE	DPV	0.01–5.0 ng mL^{-1}	0.0005 ng mL^{-1}	Plasma samples	97.73-101.08	[48]
AβOs	Chit/ SiO_2@ Ag NPs/GCE	DPV	0.5–10 ng mL^{-1}	1.22 pgmL^{-1}	Human serum samples	93.00- 107.70	[49]

NR: Not reported, PSA: Prostate-specific antigen, LAC: Lactate, BSA: Bovine serum albumin, CEA: Carcinoembryonic antigen, SAR: Sarcosine, cTnT: Cardiac troponin T, cTnI: Cardiac Troponin I, AβOs: Amyloid-β oligomer, GS: Graphene sheets, AuNPs: Gold nanoparticles, CS: Chitosan, Ab: Antibody, GO: graphene oxide, MWCNTs: multi-walled carbon nanotube, PEDOT: poly(3,4-ethylenedioxythiophene), Fc: Ferrocene, 3-APBA: 3-aminophenylboronic acid, AgNWs: Ag Nanowires, 4-ABA: 4 aminobenzoic acid, ZIF-8: Zeolitic imidazolate framework-8, ZnQ: Zinc oxinate, o-PD: o-phenylenediamine, RGO: Reduced graphene oxide, Pyr: Pyrrole, Chit: Chitosan, ACR: Acrylic acid, DIA: Diallylamine, BisAM: N,N-methylenebisacrylamide, PPy: Polymerized polypyrrole, MO: Methyl orange, DMIP: Dual-template molecularly imprinted polymer, MAA: Methacrylic acid, PANI: Polyaniline, PMB: Polymethylene blue, MB: Methylene blue, ZnONPs: Zinc nanoparticles, BNQDs: Boron nitride quantum dots, SiO2@AgNPs: Silver nanoparticles with silica

nanoparticles, FTO: Fluorine-doped tin oxide electrode, SPCE: Screen-printed carbon electrode, GCE: Glassy carbon electrode, CPE: Carbon paste electrode, EIS: Electrochemical impedance spectroscopy, DPV: Differential pulse voltammetry, CV: Cyclic voltammetry, DEIS: Dynamic electrochemical impedance spectroscopy

K. Phonklam et al. [50] introduced a novel electrochemical sensor based on cardiac troponin T (cTnT), an important biomarker for early diagnosing and treating acute myocardial infarction. The sensor used a molecularly imprinted polymer (MIP) technique combined with a screen-printed carbon electrode (SPCE) modified with multi-walled carbon nanotubes (MWCNTs) and an electro-coated polymethylene blue (PMB) redox probe. The sensor sensed the changes in PMB current according to cTnT concentration by differential pulse voltammetry. The sensor showed excellent performance with a linear detection range of 0.10 to 8.0 pg/mL^{-1}, a detection limit of 0.040 pg/mL-1, and high sensitivity, selectivity, and binding affinity. It retained more than 90% of its sensitivity after 6 weeks of storage at room temperature. When applied to human plasma, the sensor results were consistent with the gold standard electrochemiluminescence method. This MIP-based electrochemical sensor shows significant potential for point-of-care (POC) testing applications.

In another study, Zhang et al. [51] advanced a wearable electrochemical biosensor based on silver nanowires (AgNWs) and molecularly imprinted polymers (MIPs) to noninvasively monitor lactate in human sweat. The biosensor constructed using 3-aminophenyl boronic acid (3-APBA) by electropolymerization showed strong sensitivity and specificity in detecting lactate concentrations ranging from 1×10^{-6} M to 0.1 M, with a detection limit of 0.22 μM. The sensor maintained high stability, maintaining 99.8 ± 1.7% of its sensitivity even after 7 months of storage. Moreover, it showed good flexibility, maintaining reliable performance even after being bent and turned 200 times. When used on human skin, the sensor successfully monitored lactate levels in sweat, demonstrating its potential for application in sports, military, and healthcare.

Finally, Khumngern et al. [52] developed an MIP-based electrochemical sensor to detect prostate-specific antigen (PSA). MIP made of o-phenylenediamine (o-PD) and o-aminophenol (o-AP) was electropolymerized in the presence of PSA and deposited onto a screen-printed carbon electrode (SPCE) modified with a poly(3,4 ethylenedioxythiophene):poly(styrenesulfonate) composite with ferrocene (PEDOT:PSS@Fc). This modification increased the electrode conductivity and aided in the retention of ferrocene, increasing the peak current during PSA detection. The sensor showed a linear response over the PSA

concentration range of 1.0×10^{-7} to 1.0×10^{-4} ng/mL and had a detection limit of $(8.3 \pm 1.3)\times10^{-8}$ ng/mL. Over seven weeks, the sensor demonstrated good selectivity, reproducibility, reusability, and long-term stability. Langmuir adsorption fit showed a high affinity for PSA with a dissociation constant (KD) of 1.91×10^{-6} ng/mL. When tested in blood serum samples, the results were consistent with the electrochemiluminescence immunoassay method (P>0.05), confirming the reliability of the sensor.

5. Conclusions

In recent years, most of the deaths due to multifactorial diseases are due to late diagnosis and high medical care costs. Therefore, selective, reliable, sensitive, and rapid analysis of biomarkers for treating these diseases is of vital importance and is needed. In order to meet this need, many MIP-based electrochemical sensors have been developed by taking advantage of the physical and chemical durability of MIPs and, most importantly, their selective properties. The superior performance of MIP-based electrochemical sensors enables them to be integrated and implemented in miniature devices at an affordable cost to detect biomarkers. Moreover, these sensors are used to detect medical diagnoses without harming human health, without requiring expert knowledge, and in a simple manner, providing significant advantages in the commercial field. The developed MIP-based electrochemical sensors provide reusable, durable, stable, reliable, rapid, and selective results in analyses in both biological and pharmaceutical fields and are expected to have an important place in many future applications.

6. Ethics approval and consent to participate

This study does not need any Ethics report.

7. Consent for publication

The Authors give consent for publication.

8. Availability of data and materials

All data and materials of the paper are available to the public.

9. Authors' contributions

Fatma BUDAK: Writing – original draft, Investigation, Conceptualization. Ensar PISKIN: Writing – original draft, Investigation, Conceptualization. Ahmet CETINKAYA: Writing – original draft, Investigation, Conceptualization. Sibel A. OZKAN: Writing – review & editing, Supervision.

Disclosure statement

No potential conflict of interest was reported by the author(s).

REFERENCES

1. Liu X, Cui B, Wang Q, et al (2021) Biomarkers for respiratory diseases: Present applications and future discoveries. Clinical and Translational Discovery 1
2. Alahmad W, Cetinkaya A, Kaya SI, et al (2024) Molecularly imprinted polymer paper-based analytical devices for biomarkers detection. TrAC - Trends in Analytical Chemistry 170
3. Wasilewski T, Orbay S, Brito NF, et al (2024) Molecularly imprinted polymers for the detection of volatile biomarkers. TrAC - Trends in Analytical Chemistry 177
4. Cetinkaya A, Kaya SI, Budak F, Ozkan SA (2024) Current Analytical Methods for the Sensitive Assay of New-Generation Ovarian Cancer Drugs in Pharmaceutical and Biological Samples. Crit Rev Anal Chem
5. Cetinkaya A, Bilge S, Karadurmus L, et al (2022) The role and the place of ionic liquids in molecularly imprinted polymer-based electrochemical sensors development for sensitive drug assay. TrAC - Trends in Analytical Chemistry 147
6. Belbruno JJ (2019) Molecularly Imprinted Polymers. Chem Rev 119:94–119
7. Belbruno JJ (2019) Molecularly Imprinted Polymers. Chem Rev 119:94–119
8. Wulff G (1995) Molecular Imprinting in Cross-Linked Materials with the Aid of Molecular Templates— A Way towards Artificial Antibodies. Angewandte Chemie International Edition in English 34:1812–1832
9. Lowdon JW, Diliën H, Singla P, et al (2020) MIPs for commercial application in low-cost sensors and assays – An overview of the current status quo. Sens Actuators B Chem 325:. https://doi.org/10.1016/j.snb.2020.128973
10. Jian P, Muhammad T, Wei A, et al (2022) A membrane-protected micro-solid-phase extraction method based on molecular imprinting and its application to the determination of local anesthetics in cosmetics. J Sep Sci 45:2675–2686. https://doi.org/10.1002/jssc.202200012
11. Piletska E, Magumba K, Joseph L, et al (2022) Molecular imprinting as a tool for determining molecular markers: a lung cancer case. RSC Adv 12:17747–17754. https://doi.org/10.1039/d2ra01830f
12. Zhou H, Qiu H, Zhang J, et al (2024) Design, preparation, and application of molecularly imprinted nanomaterials for food safety analysis with electrochemistry. Coord Chem Rev 500
13. Faysal A Al, Kaya SI, Cetinkaya A, et al (2024) The Effect of Polymerization Techniques on the Creation of Molecularly Imprinted Polymer Sensors and Their Application on Pharmaceutical Compounds. Crit Rev Anal Chem
14. Liang XH, Yu AX, Bo XJ, et al (2023) Metal/covalent-organic frameworks-based electrochemical sensors for the detection of ascorbic acid, dopamine and uric acid. Coord Chem Rev 497
15. Herrera-Chacon A, Gonzalez-Calabuig A, Del Valle M (2021) Dummy molecularly imprinted polymers using dnp as a template molecule for explosive sensing and nitroaromatic compound discrimination. Chemosensors 9:. https://doi.org/10.3390/chemosensors9090255
16. Herrera-Chacon A, González-Calabuig A, Campos I, del Valle M (2018) Bioelectronic tongue using MIP sensors for the resolution of volatile phenolic compounds. Sens Actuators B Chem 258:665–671. https://doi.org/10.1016/j.snb.2017.11.136
17. Motaharian A, Hosseini MRM, Naseri K (2019) Determination of psychotropic drug chlorpromazine using screen printed carbon electrodes modified with novel MIP-MWCNTs nano-composite prepared by suspension polymerization method. Sens Actuators B Chem 288:356–362. https://doi.org/10.1016/j.snb.2019.03.007
18. Liu Z, Jin M, Lu H, et al (2019) Molecularly imprinted polymer decorated 3D-framework of functionalized multi-walled carbon nanotubes for ultrasensitive electrochemical sensing of Norfloxacin in pharmaceutical formulations and rat plasma. Sens Actuators B Chem 288:363–372. https://doi.org/10.1016/j.snb.2019.02.097

19. Piskin E, Cetinkaya A, Eryaman Z, et al (2024) Development of ultra-sensitive and selective molecularly imprinted polymer-based electrochemical sensor for L-lactate detection. Microchemical Journal 204:. https://doi.org/10.1016/j.microc.2024.111163
20. Kanokpaka P, Chang LY, Wang BC, et al (2022) Self-powered molecular imprinted polymers-based triboelectric sensor for noninvasive monitoring lactate levels in human sweat. Nano Energy 100:. https://doi.org/10.1016/j.nanoen.2022.107464
21. Wang L, Zhao L (2022) A novel nanocomposite optosensing sensor based on porous molecularly imprinted polymer and dual emission quantum dots for visual and high selective detection of bovine serum albumin. Colloids Surf A Physicochem Eng Asp 632:. https://doi.org/10.1016/j.colsurfa.2021.127843
22. Guoning C, Pengqi G, Yan W, et al (2019) Preparation of molecularly imprinted polymers and application in a biomimetic biotin-avidin-ELISA for the detection of bovine serum albumin. Talanta 198:55–62. https://doi.org/10.1016/j.talanta.2019.01.088
23. Turan E, Zengin A, Suludere Z, et al (2022) Construction of a sensitive and selective plasmonic biosensor for prostate specific antigen by combining magnetic molecularly-imprinted polymer and surface-enhanced Raman spectroscopy. Talanta 237:. https://doi.org/10.1016/j.talanta.2021.122926
24. Karami P, Bagheri H, Johari-Ahar M, et al (2019) Dual-modality impedimetric immunosensor for early detection of prostate-specific antigen and myoglobin markers based on antibody-molecularly imprinted polymer. Talanta 202:111–122. https://doi.org/10.1016/j.talanta.2019.04.061
25. Tang P, Wang Y, He F (2020) Electrochemical sensor based on super-magnetic metal–organic framework@molecularly imprinted polymer for Sarcosine detection in urine. Journal of Saudi Chemical Society 24:620–630. https://doi.org/10.1016/j.jscs.2020.06.004
26. Hamdi F, Roushani M, Hoseini SJ (2025) Novel biosensor for sarcosine detection in prostate cancer: Combining molecular imprinted polymer and aptamer strategies. Microchemical Journal 208:. https://doi.org/10.1016/j.microc.2024.112429
27. Mokhtari Z, Khajehsharifi H, Hashemnia S, et al (2020) Evaluation of molecular imprinted polymerized methylene blue/aptamer as a novel hybrid receptor for Cardiac Troponin I (cTnI) detection at glassy carbon electrodes modified with new biosynthesized ZnONPs. Sens Actuators B Chem 320:. https://doi.org/10.1016/j.snb.2020.128316
28. Silva BVM, Rodríguez BAG, Sales GF, et al (2016) An ultrasensitive human cardiac troponin T graphene screen-printed electrode based on electropolymerized-molecularly imprinted conducting polymer. Biosens Bioelectron 77:978–985. https://doi.org/10.1016/j.bios.2015.10.068
29. Wang S, Qin J, Liang Y, et al (2024) A magnetic SERS-imprinted sensor for the determination of cardiac troponin I based on proteolytic peptide technology. Anal Chim Acta 1332:343316. https://doi.org/10.1016/j.aca.2024.343316
30. Phonklam K, Wannapob R, Sriwimol W, et al (2020) A novel molecularly imprinted polymer PMB/MWCNTs sensor for highly-sensitive cardiac troponin T detection. Sens Actuators B Chem 308:. https://doi.org/10.1016/j.snb.2019.127630
31. Bounoua N, Cetinkaya A, Piskin E, et al (2024) The sensor applications for prostate and lung cancer biomarkers in terms of electrochemical analysis. Anal Bioanal Chem 416:2277–2300
32. Xu Y, Zhang Y, Zhang H, et al (2025) Enrichment of carcinoembryonic antigen by epitope molecularly imprinted polymer based on cucurbituril host-guest interaction. J Chromatogr A 1740:. https://doi.org/10.1016/j.chroma.2024.465584
33. Carneiro MCCG, Sousa-Castillo A, Correa-Duarte MA, Sales MGF (2019) Dual biorecognition by combining molecularly-imprinted polymer and antibody in SERS detection. Application to carcinoembryonic antigen. Biosens Bioelectron 146:. https://doi.org/10.1016/j.bios.2019.111761
34. You M, Yang S, An Y, et al (2020) A novel electrochemical biosensor with molecularly imprinted polymers and aptamer-based sandwich assay for determining amyloid-β oligomer. Journal of Electroanalytical Chemistry 862:. https://doi.org/10.1016/j.jelechem.2020.114017
35. Carneiro MCCG, Sousa-Castillo A, Correa-Duarte MA, Sales MGF (2019) Dual biorecognition by combining molecularly-imprinted polymer and antibody in SERS detection.

Application to carcinoembryonic antigen. Biosens Bioelectron 146:. https://doi.org/10.1016/j.bios.2019.111761
36. Ma Y, Shen XL, Zeng Q, Wang LS (2017) A glassy carbon electrode modified with graphene nanoplatelets, gold nanoparticles and chitosan, and coated with a molecularly imprinted polymer for highly sensitive determination of prostate specific antigen. Microchimica Acta 184:4469–4476. https://doi.org/10.1007/s00604-017-2458-y
37. Karami P, Bagheri H, Johari-Ahar M, et al (2019) Dual-modality impedimetric immunosensor for early detection of prostate-specific antigen and myoglobin markers based on antibody-molecularly imprinted polymer. Talanta 202:111–122. https://doi.org/10.1016/j.talanta.2019.04.061
38. Khumngern S, Thavarungkul P, Kanatharana P, et al (2022) Molecularly imprinted electrochemical sensor based on poly(o-phenylenediamine-co-o-aminophenol) incorporated with poly(styrenesulfonate) doped poly(3,4-ethylenedioxythiophene) ferrocene composite modified screen-printed carbon electrode for highly sensitive and selective detection of prostate cancer biomarker. Microchemical Journal 177:. https://doi.org/10.1016/j.microc.2022.107311
39. Zhang Q, Jiang D, Xu C, et al (2020) Wearable electrochemical biosensor based on molecularly imprinted Ag nanowires for noninvasive monitoring lactate in human sweat. Sens Actuators B Chem 320:. https://doi.org/10.1016/j.snb.2020.128325
40. Pereira TC, Stradiotto NR (2019) Electrochemical sensing of lactate by using an electrode modified with molecularly imprinted polymers, reduced graphene oxide and gold nanoparticles. Microchimica Acta 186:. https://doi.org/10.1007/s00604-019-3898-3
41. Ma Y, Liu C, Zeng Q, Wang LS (2020) An Impedance Molecularly Imprinted Sensor for the Detection of Bovine Serum Albumin (BSA) Using the Dynamic Electrochemical Impedance Spectroscopy. Electroanalysis 32:923–930. https://doi.org/10.1002/elan.201900570
42. Yang C, Ji XF, Cao WQ, et al (2019) Molecularly imprinted polymer based sensor directly responsive to attomole bovine serum albumin. Talanta 196:402–407. https://doi.org/10.1016/j.talanta.2018.12.097
43. Taheri N, Khoshsafar H, Ghanei M, et al (2022) Dual-template rectangular nanotube molecularly imprinted polypyrrole for label-free impedimetric sensing of AFP and CEA as lung cancer biomarkers. Talanta 239:. https://doi.org/10.1016/j.talanta.2021.123146
44. Sheydaei O, Khajehsharifi H, Rajabi HR (2020) Rapid and selective diagnose of Sarcosine in urine samples as prostate cancer biomarker by mesoporous imprinted polymeric nanobeads modified electrode. Sens Actuators B Chem 309:. https://doi.org/10.1016/j.snb.2019.127559
45. Tang P, Wang Y, He F (2020) Electrochemical sensor based on super-magnetic metal–organic framework@molecularly imprinted polymer for Sarcosine detection in urine. Journal of Saudi Chemical Society 24:620–630. https://doi.org/10.1016/j.jscs.2020.06.004
46. Phonklam K, Wannapob R, Sriwimol W, et al (2020) A novel molecularly imprinted polymer PMB/MWCNTs sensor for highly-sensitive cardiac troponin T detection. Sens Actuators B Chem 308:. https://doi.org/10.1016/j.snb.2019.127630
47. Mokhtari Z, Khajehsharifi H, Hashemnia S, et al (2020) Evaluation of molecular imprinted polymerized methylene blue/aptamer as a novel hybrid receptor for Cardiac Troponin I (cTnI) detection at glassy carbon electrodes modified with new biosynthesized ZnONPs. Sens Actuators B Chem 320:. https://doi.org/10.1016/j.snb.2020.128316
48. Yola ML, Atar N (2019) Development of cardiac troponin-I biosensor based on boron nitride quantum dots including molecularly imprinted polymer. Biosens Bioelectron 126:418–424. https://doi.org/10.1016/j.bios.2018.11.016
49. You M, Yang S, An Y, et al (2020) A novel electrochemical biosensor with molecularly imprinted polymers and aptamer-based sandwich assay for determining amyloid-β oligomer. Journal of Electroanalytical Chemistry 862:. https://doi.org/10.1016/j.jelechem.2020.114017
50. Phonklam K, Wannapob R, Sriwimol W, et al (2020) A novel molecularly imprinted polymer PMB/MWCNTs sensor for highly-sensitive cardiac troponin T detection. Sens Actuators B Chem 308:. https://doi.org/10.1016/j.snb.2019.127630
51. Zhang Q, Jiang D, Xu C, et al (2020) Wearable electrochemical biosensor based on molecularly imprinted Ag nanowires for noninvasive monitoring lactate in human sweat. Sens Actuators B Chem 320:. https://doi.org/10.1016/j.snb.2020.128325

52. Khumngern S, Thavarungkul P, Kanatharana P, et al (2022) Molecularly imprinted electrochemical sensor based on poly(o-phenylenediamine-co-o-aminophenol) incorporated with poly(styrenesulfonate) doped poly(3,4-ethylenedioxythiophene) ferrocene composite modified screen-printed carbon electrode for highly sensitive and selective detection of prostate cancer biomarker. Microchemical Journal 177:. https://doi.org/10.1016/j.microc.2022.107311