Review Article

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Rapid Response at the Nanoscale in Emergency Medicine

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ABSTRACT

This study aimed to highlight the need for advanced scientific approaches, particularly nanotechnology, in clinical settings that require immediate decision-making under emergency conditions. Emergency medicine departments face challenges related to overcrowding, diagnostic delays, and the substantial burden of medical decision-making, highlighting the need for rapid and accurate diagnostic tools. Nanotechnology provides principal benefits in emergency medicine by enabling highly sensitive and rapid detection of crucial conditions, including sepsis, myocardial infarction, pulmonary embolism, severe respiratory infections, and other life-threatening conditions. The application of nanotechnology in biosensors, plasmonic structures, and aptamer-nanomaterial systems can enhance biomarker sensitivity and reduce response times compared with traditional laboratory methods. Similarly, the integration of nanotechnology with artificial intelligence (AI) might improve diagnostic accuracy, risk stratification, and predictive modelling, while the use of nanoparticles (NPs) might enable the combination of diagnostic and targeted therapeutic approaches, as in theranostics. Although challenges related to cost, regulatory requirements, and biocompatibility remain, the convergence of nanotechnology and AI has considerable potential to transform emergency medicine from reactive care toward rapid, precise, and personalized medical management. In this study, we reviewed the applications of nanotechnology in the diagnosis of disorders for which timely diagnosis is critical to initiating appropriate treatment, with particular focus on nanobiosensors that might facilitate rapid and accurate diagnosis in emergency settings.

Keywords: Emergency medicine; Nanotechnology; Nanobiosensor; Personalized medicine; Artificial intelligence

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Introduction

In this review, related studies addressing diagnostic applications or the combination of diagnosis and treatment are highlighted, with a primary focus on nanobiosensors and their application in the field of emergency medicine. Overall, this topic highlighted the challenges faced in emergency medicine and how nanotechnology might provide a new perspective for addressing these challenges in the future. Overcrowding in emergency departments is a common worldwide phenomenon that has been extensively reported, even in non-specialized media outlets. Strategies to address this challenge are urgently required for patients, nurses, physicians, and health center administrators [1]. Emergency physicians continually face a constant flow of complicated and high-risk decisions in a fast-paced and dynamic environment. In this context, the concept of decision fatigue, defined as a decline in decision-making quality following prolonged decision-making, has received growing attention in the healthcare field [2, 3]. To alleviate these challenges in emergency departments, enhancements in both management and technology are essential. From a technological perspective, improving the accuracy and speed of diagnostic tools represents one of the simplest and most accessible strategies. For example, in the context of infection treatment, rapid diagnosis and timely management, particularly in emergency settings, require the use of effective antiseptic and antimicrobial agents [4, 5]. Accordingly, modern techniques aimed at reducing bacterial and viral infections are of critical importance. Nanotechnology is one of the most promising fields in this regard, as it is increasingly applied in scientific research and has demonstrated substantial potential for eliminating or inhibiting a wide variety of pathogens. Owing to their expanded surface-area-to-mass ratio, NPs derived from natural antibacterial substances, including zinc [6] and silver, exhibit stronger antimicrobial properties [7] as their size approaches the nanometer scale. In addition, the specific shape of NPs and their ability to interact with and penetrate bacterial membranes contribute to distinct bactericidal mechanisms for the diagnosis and treatment of these infectious agents [8, 9].

This study aimed to highlight the important role of biosensors in the timely diagnosis and real-time management of diseases encountered in emergency departments. The integration of emerging technologies, such as nanotechnology and artificial intelligence (AI), might help reduce diagnostic time while improving the sensitivity, specificity, and overall performance of biosensors.

Given that early analysis is important for effective disease management and improved patient outcomes in emergency medicine, conventional diagnostic biomarkers frequently show insufficient sensitivity and specificity, susceptibility to external factors, and challenges in detecting disease at early stages [10]. Engineered biomarkers developed through the convergence of bioengineering, chemistry, and nanotechnology [11] can extensively enhance diagnostic signals by exploiting disease-specific features. In Figure 1, the categories of biomarkers [12] are illustrated, along with their use in nanobiosensors compared with conventional diagnostic methods.

Nanotechnology in Emergency Medicine

In various scientific fields, nanomaterials have attracted significant attention because, at the nanometer scale, materials may exhibit new properties or undergo specific physical and chemical changes, making them suitable for a wide range of potential applications [13]. NPs are used in medical applications in three main areas: diagnosis, treatment, and prevention, with their specific roles depending on their unique physicochemical properties. In diagnostics, the use of nano-enabled technologies can be divided into two major categories: sensors and imaging. These applications are particularly important for early-stage diagnosis in emergency settings.

Nano-Based Biosensors

Early detection of diseases can increase the chances of successful treatment and survival, highlighting the need for devices capable of detecting or identifying problems caused by organic and mineral biomolecules in living organisms. In 1956, the American biochemist L.L. Clark invented the biosensor. He used this biosensor to measure the percentage of oxygen in the blood, and the electrode used in this biosensor was called the Clark electrode, or an oxygen electrode. The term biosensor may be defined as an analytical apparatus consisting of a bioreceptor, a transducer which converts the detected signal into a usable output, and an amplifier which enhances and processes the resulting signal. The type of transducer affects the quality and performance of a biosensor. In some studies, specific nano-agents have been selected for particular transducers based on the unique properties and potential of the nanoparticles. Selecting the most appropriate transducer and biorecognition element based on the type of nanoparticle and biomarker is crucial for minimizing response time and optimizing biosensor performance in emergency diagnostic settings. The transducers can be categorized as optical, thermal, electronic, gravimetric, and acoustic. Figure 2 shows the main types of transducers used in biosensors [14]. Biosensors have been applied across various scientific fields, particularly medical science, where rapid performance is an important aspect of their application. These devices can help reduce the time required for detection. The performance of this technology has been improved through the use of nanostructures.

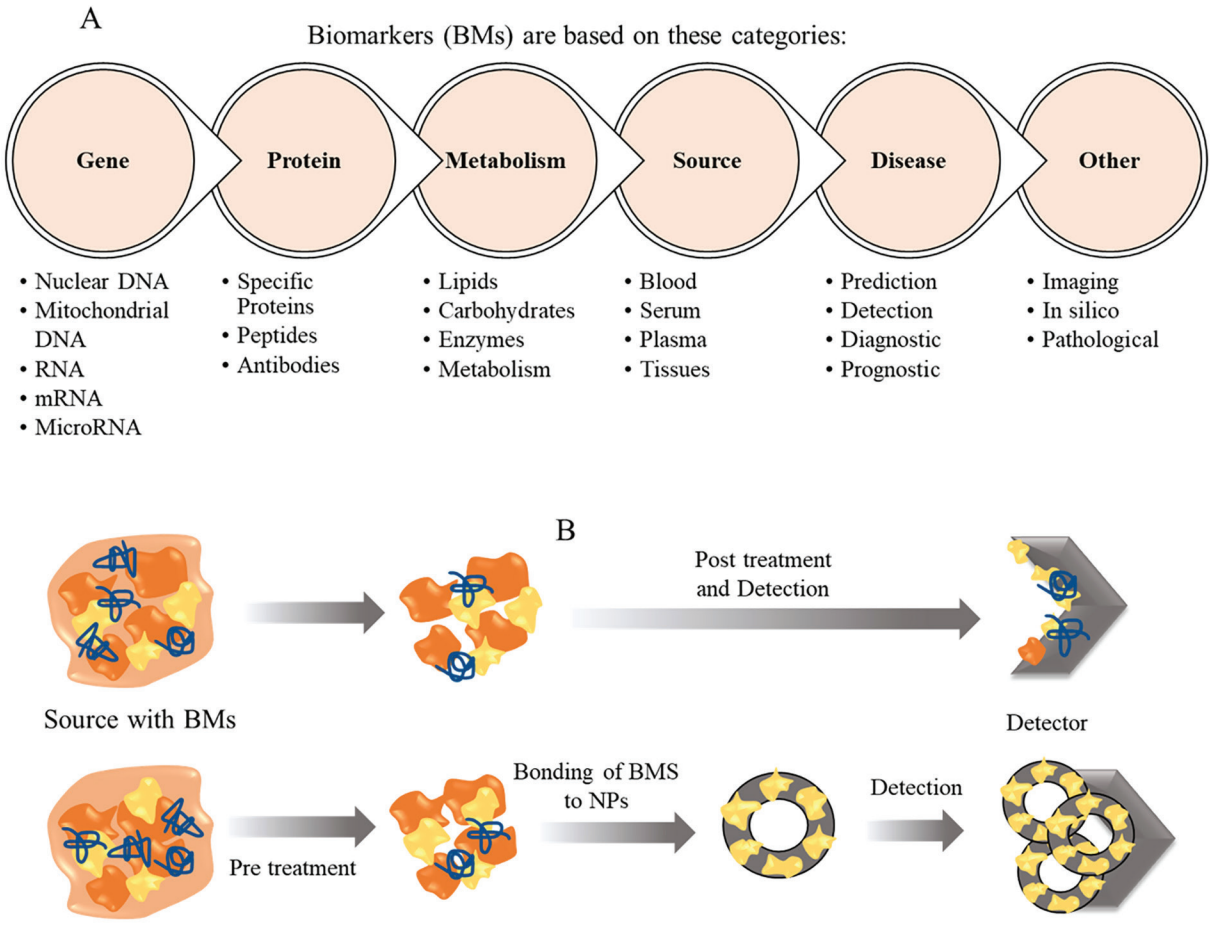


Fig 1. The figure shows the biomarker categories: (A) and a comparison of nanoparticle-based approaches with conventional methods for biomarker detection (B); For further clarification, pre- and post-treatment assessments may occur in one or multiple stages. The figure was created using Microsoft PowerPoint.

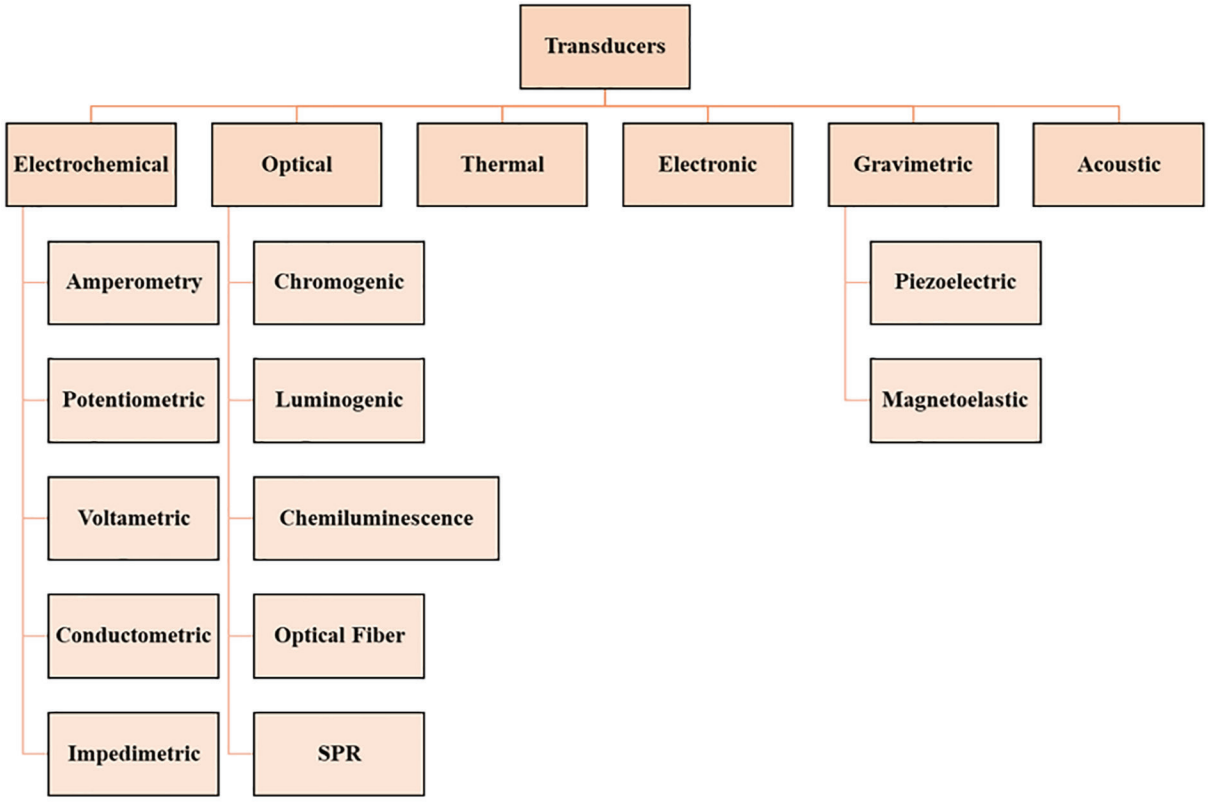


Fig 2. The figure illustrates the main categories of transducers (electrochemical, optical, thermal, electronic, gravimetric, and acoustic) that could be used in nano-based biosensors, and surface plasmon resonance. The figure was created using Microsoft PowerPoint.

Point-of-Care Testing

Point-of-care testing (POCT) is defined as a laboratory test performed at or near the patient's location. POCT refers to a quality-assured pathology service that utilizes analytical instruments for blood gas analysis, critical care testing, glucose measurement, urinalysis, and other metabolite measurement devices [15]. This technique can be used in both portable and wearable modes to measure and analyze body metabolites or biomarkers [16].

Nanotechnology can help overcome the limitations of conventional biomarkers and facilitate early disease detection. When integrated with point-of-care (POC) diagnostic platforms, engineered biomarkers can provide rapid results that support timely clinical decision-making. The integration of nanostructures, including nanoparticles, quantum dots, nanorods, nanofibers, nanopillars, nanowires, nanosheets, nanoplates, nanopores, and three-dimensional nanomaterials such as nanocomposites and hierarchical structures, with prototype biosensors and microelectronic platforms has enhanced the potential of biosensors for the early detection, diagnosis, and prevention of life-threatening diseases. However, the potential of these nanostructures for the design and development of efficient POC sensing platforms has not yet been comprehensively and systematically investigated [17]. Given that POC devices are generally designed in portable formats with small dimensions, and since nanostructures possess a high surface-area-to-volume ratio, their incorporation into these devices does not require additional space for integration with other components. In POC devices, the use of nanostructures could improve their performance, similar to that of other biosensors. Moreover, the portability of POC devices permits their use in various settings, including clinics, emergency rooms, and domestic environments, thereby enhancing accessibility for patients in remote regions or people with limited mobility [18]. In this field, fluorescent, luminescent, or magnetic nanostructures are generally used to measure biomarkers [19]. In addition, the use of noble metal NPs in POCT, with their plasmonic, photothermal, colorimetric, surface-enhanced Raman spectroscopy (SERS), electrochemical, and fluorescent properties, has attracted interest [20].

Traditional colloidal gold-based lateral flow immunoassays (LFI) are frequently afflicted by insufficient sensitivity and an inability to provide quantitative measurements. Through the integration of nanotechnology, however, LFI structures have developed to provide more sensitive and rapid diagnostic capabilities. For example, Wang and colleagues developed an LFI assay utilizing SARS-CoV-2 nucleoprotein conjugated with selenium NPs, achieving high sensitivity and rapid detection. Their assay enabled simultaneous detection of IgG and IgM in human serum, with detection limits of 5 ng/mL and 20 ng/mL, respectively, within simply 10 minutes. The clinical performance of the assay was evaluated using RT-PCR and clinical diagnosis in 90 patients with COVID-19 and 263 non-infected controls, and reported sensitivity and specificity of 93.33% and 97.34%, respectively [21].

Emergency Diagnosis

Imaging modalities such as radiography, CT scans, and ultrasound are routinely used in emergency departments for the initial evaluation of bone fractures, infections, and damage to the lungs and other organs. However, the use of contrast agents or NPs in these applications is currently more limited, largely due to challenges such as high cost, longer preparation times, and concerns regarding the potential toxicity of NP-based contrast agents [22-25]. In contrast, nano-based sensors, particularly *in vitro* diagnostic platforms, offer a more prominent role, as they require minimal direct exposure to the patient while potentially improving the speed and accuracy of diagnostic measurements. For this reason, NPs have gained greater practical relevance in sensor technologies than in imaging within clinical and emergency settings [26, 27].

The common clinical diseases in emergency settings that are being investigated using nano-based sensors include:

- Sepsis and infections (most common and vital application) [28]
- Cardiac ischemia with rapid troponin detection [29]
- Pulmonary embolism (rapid D-dimer detection) [30]
- Severe respiratory infections [31]
- Rapid detection of pathogenic microorganisms [32]

Sepsis and Infections

Despite the urgent need for sepsis monitoring, no sepsis-specific biomarker is currently available for medical diagnosis. Although more than 170 biomarkers have been suggested for sepsis diagnosis [33, 34], only a few of them are relevant to clinical diagnosis, and each biomarker has specific benefits and limitations [35]. Additionally, major scientific challenges are related to patient heterogeneity and variations in the time required for marker levels to increase among individuals [36]. Conventional diagnostic methods, particularly blood culture-based evaluation, as well as specialized molecular diagnostic strategies, including polymerase chain reaction (PCR), isothermal amplification methods, hybridization, and microarray strategies, are usually laboratory-dependent, require skilled personnel, and are multi-step and intensive, with limitations in the limit of detection (LoD) and specificity. Thus, there is an urgent need for developing novel sepsis diagnostic methods that are ideally suited for accessible bedside diagnosis. A small set of

biomarkers has demonstrated utility in the clinical prognosis of sepsis, including C-reactive protein (CRP), procalcitonin (PCT), and Interleukin-6 (IL-6) [37].

In a study, a nanosensor-stimulated sensor array (NanoSA) was developed, consisting of three sensors that exhibit multiple intermolecular fluorescence resonance energy transfer (FRET) effects. This nanoassembly, comprising six channels for parallel sensing, identified 24 sepsis-associated bacterial species within 30 s, with an accuracy of 96.9%. The nanosensor indicated the ability to discriminate among multiplex bacterial infections, different bacterial concentrations, and samples from different body fluids, including serum and urine. Optimization by the multilayer perceptron (MLP) model achieved a test accuracy of 97.6% in differentiating clinical sepsis samples infected by five distinct bacterial species within 30 s [38]. Rapid, sensitive, simultaneous quantification of multiple biomarkers in POC could enhance the rate and speed of diagnosis, thereby facilitating more effective and rapid measures to control sepsis, a common and potentially life-threatening condition. A plasmonic sensing chip based on NP-spiked gold nanodimple systems fabricated using wafer-scale batch processes was used to detect six cytokines directly from clinical plasma samples and demonstrated high accuracy for sepsis detection [39].

Myocardial Infarction

Cardiac biomarkers are of considerable value in early myocardial infarction (MI) [40]. Myoglobin (Mb) and heart-type fatty acid-binding protein (h-FABP) are among the earliest biomarkers to increase, approximately 1–2 h after the onset of MI. However, they lack specificity [41]. Cardiac troponins (cTns) begin to rise subsequently and are considered the preferred biomarkers for MI diagnosis. Creatine kinase (CK) and creatine kinase isoenzyme (CK-MB) are traditional biomarkers for MI. Additionally, B-Type natriuretic peptide (BNP), glutathione (GSH), lactate dehydrogenase (LDH), CRP, and aspartate transaminase (AST) have been investigated. However, their specificity and sensitivity are unsatisfactory. Antigen-antibody immunoaffinity detection is used to detect these biomarkers, along with enzyme-linked immunosorbent assay (ELISA), electrochemiluminescence (ECL), surface plasmon resonance (SPR), and photoelectrochemical (PEC) methods [42].

Gold NPs with optical properties could be used for the colorimetric detection of cardiac troponins. In one study, an SPR sensor was used for the rapid, sensitive, and precise detection of cardiac troponin T (cTnT) in serum samples using direct and sandwich immunoassay formats. The SPR immunosensor demonstrated reproducible detection of cTnT within concentration ranges of 25–1000 ng/mL and 5–400 ng/mL for the direct and sandwich immunoassay in buffer, respectively. In another study, serum samples were analyzed using a conventional immunosensor in 50% human serum, with a limit of detection (LOD) of 5 ng/mL. The LOD was subsequently improved using AuNP-conjugated antibodies, reaching 0.5 ng/mL with a linear dynamic range of 0.5–40 ng/mL for cTnT. The proposed SPR immunosensor demonstrated promising potential for improving POC testing for the early diagnosis of acute MI [43].

Pulmonary Embolism

D-dimer testing, along with clinical evaluation, has become a standard approach for the diagnosis of venous thromboembolism (VTE). Recently, new POC D-dimer assays have been introduced that require small blood sampling volumes and can expedite VTE testing in a single-step procedure. A study evaluated the analytical validity and ease of use of a series of these new POC D-dimer assays that utilize *ex vivo* detection, by comparing their results with those of a standard laboratory assay [44].

In vivo, the use of NPs for both treatment and diagnosis, known as theranostic NPs, has also been investigated in recent studies for this disease. A kind of poly (lactic-co-glycolic acid) (PLGA)-coated NPs (NPs) containing the first near-infrared (NIR-I) window phototheranostic agent Y8 and urokinase activator (UK) as the NP core, and modified with the fibrin-targeting peptide Gly-Pro-Arg-Pro-Pro (GPRPP), was developed for the detection and treatment of postoperative thromboembolism and was named GPRPP-Y8U@P. The Y8 conjugate molecule provides GPRPP-Y8U@P with NIR-II imaging capability and photothermal/photodynamic therapeutic effects. *In vivo* experiments showed that GPRPP-Y8U@P could rapidly locate thrombi through NIR-II fluorescence imaging. Furthermore, urokinase entrapped in NPs did not cause nonspecific bleeding and significantly improved safety and therapeutic effects by minimizing side effects [45].

However, *in vivo*, fluorescence imaging methods are limited to intraoperative and endoscopic applications. Therefore, most optical imaging methods developed in mice do not apply to humans. Autofluorescence of endogenous tissue components and degradation in the gastrointestinal tract are limitations of fluorescence imaging, as they reduce the signal-to-background ratio. However, bioluminescence and Raman spectroscopy do not have these limitations. Currently, the availability of Raman spectroscopy as an *in vivo* imaging method is also limited to specialized laboratories [46].

Severe Respiratory Infections

Reverse transcription-polymerase chain reaction (RT-PCR) is the main green technique for the detection of SARS-CoV-2 [47]. The disadvantages of PCR, including detection time, the need for expert operators, expensive instruments, and laboratory equipment, restrict its application [48].

Nano-biosensors based on SERS, SPR, field-effect transistor (FET), fluorescence techniques, and electrochemical strategies are used in this field [49]. Specific biological molecular systems (BMSs), including ACE2, S protein-antibody, IgG antibody, IgM antibody, and SARS-CoV-2 DNA probes, are considered for these sensors [49].

In some studies, the detection of SARS-CoV-2 as a causative agent of severe respiratory infections has been performed using nanobiosensors based on the measurement of SARS-CoV-2 oligonucleotides as BMS [50, 51]. For example, one study investigated the detection of respiratory infection using composites of several metal oxide NPs, vanadium oxide (V_3O_5), antimony oxide (Sb_2O_3), selenium oxide (SeO_2), zirconium oxide (ZrO_2), cerium oxide (CeO_2), manganese dioxide (MnO_2), Lanthanum oxide (La_2O_3), titanium oxide (TiO_2), tungsten oxide (WO_3), and germanium oxide (GeO_2), and gold NPs for SARS-CoV-2 RNA. For immobilizing the surface of the biosensor detector, 4-aminothiophenol (4-ATP) was selected as a cross-linker and connected to the surface of the nano-metallic composite (by EDC/NHS coupling agents). Furthermore, diphenylamine acts as an activator of the surface probe to improve immobilization of the coated probe with the cross-linker. The electrochemical performance was evaluated using electrochemical impedance spectroscopy. Compared with the standard method, the nano metallic composite increased the sensor performance and improved its conductivity and electrocatalytic properties [51]. A schematic representation of this nanobiosensor is shown in Figure 3.

Rapid Detection of Pathogens

Traditional methods for identifying differences between normal and abnormal cells or between host and pathogenic cells rely on the long-standing observation of cellular phenotypes or PCR-based molecular detection [52]. Currently, simple methods have been developed to target abnormal cells using sensor molecules such as monoclonal antibodies, smaller antibody fragments, peptides, and low molecular mass ligands [53].

Aptamers are short single-stranded oligonucleotides, such as ssDNA or RNA, that, in addition to their chemical stability, cost-effectiveness, and large-scale production, are intermediate in size between antibodies and small peptides and have comparable or higher affinity for their targets [54]. These targets, ranging from small molecules to whole cells, can be selected through an *in vitro* selection process known as systematic evolution of ligands by exponential enrichment (SELEX). This approach allows for reliable identification of target cells at the molecular level in combination with various analytical tools, such as fluorescence-activated cell sorting or enzyme-linked immunosorbent assay [52, 55]. To further exploit the potential of aptamer-based cell targeting, aptamers can be combined with nanomaterials such as gold NPs (AuNPs) [56-58], silica NPs (SiNPs) [59], graphene [60], magnetic NPs (MNPs) [61], and quantum dots (QDs) [62]. This aptamer-nanomaterial hybridization process can be readily performed due to the simple chemical modification and well-defined structures of aptamers. These hybrid materials can improve target detection and therapy, with higher sensitivity and selectivity compared to aptamer-based targeting strategies. Most importantly, due to the large surface area, multivalent structure, and physicochemical properties of nanomaterials, aptamer-nanomaterial hybrids can provide signal amplification and increased affinity for targets through multivalent interactions. In general, DNA-based aptamers have been used to detect Mycobacterium tuberculosis, Staphylococcus aureus, Shigella dysenteriae, Escherichia coli O157:H7, E. coli, Campylobacter jejuni, Listeria monocytogenes, Pseudomonas aeruginosa, Salmonella O8, and DNA/RNA-based aptamers for Salmonella Enteritidis by bacterium-SELEX [52].

In one study, Methicillin-resistant Staphylococcus aureus (MRSA) was selected and treated using DNA aptamer-conjugated magnetic graphene oxide (Apt@MGO) as a multifunctional and biocompatible nanoplatform. Magnetic graphene oxide (MGO) acts as a nanoplatform for aptamer conjugation and

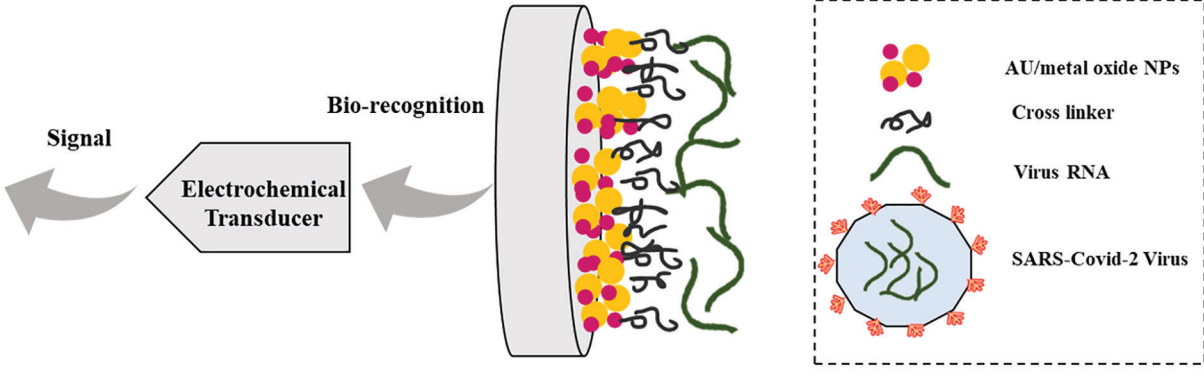


Fig 3. Schematic representation of an electrochemical nanobiosensor for SARS-CoV-2 virus detection is illustrated. The RNA is extracted from the clinical sample and subsequently attached to an appropriate cross-linker conjugated to NPs. Finally, the signal from a change in the electrochemical properties of the nanoparticles is detected, resulting in biorecognition. The figure was created using Microsoft PowerPoint.

as a photothermal agent by converting NIR light to heat. Iron oxide NPs (Fe_3O_4 NPs) were used for their magnetic properties, allowing the collection of MRSA cells using an external magnet. An *in vitro* study found that Apt@MGO functioned as a targeted, biocompatible, and light-activated photothermal agent for the efficient and rapid killing of MRSA in the aggregated state under NIR light [63]. In another study, quick separation of Gram-negative bacteria, such as Escherichia coli *(E. coli)*, from water sources (for example, urinary tract infections) was investigated. The results demonstrated that aptamer-conjugated core-shell magnetic NPs (MNPs) could rapidly capture E. coli DH5α from water. The core-shell MNP, composed of an iron (Fe_3O_4) core and a silica (SiO_2) shell, was bioconjugated with aptamers using glutaraldehyde as a cross-linker [64].

The Integration of Nano to AI Assistance for Emergency Diagnosis

With the increasing need for accurate and precise disease diagnosis, the application of mathematical models and AI concepts in healthcare can be highly beneficial. AI technology uses various models and algorithms to identify patterns and specific findings for diagnosing disease severity in triage and patient management with maximum accuracy [65]. A study incorporating 17 other studies analyzed the use of AI in terms of sensitivity, accuracy, positive predictive value, specificity, and negative predictive value in the diagnosis of Barrett's neoplasia, cardiac arrest, esophageal adenocarcinoma, sepsis, and gastrointestinal stromal tumors. The available evidence showed that AI could be extremely useful in diagnosis by providing maximum accuracy and enabling early detection. This might help prevent disease progression and allow treatment to be delivered as soon as possible [66].

Given that nanotechnology offers unique advantages in the field of emergency medicine, including early molecular diagnosis, targeted drug delivery, and advanced therapeutic systems, engineered nanocarriers, biosensors, and responsive nanodevices can be designed to target specific disease characteristics. When combined with AI, these technologies can enhance biomarker sensitivity, improve patient stratification, and enable predictive disease modeling (Figure 4). From AI-guided NP design to nanodrug delivery systems, the integration of these technologies might work synergistically to support improved real-time and personalized healthcare [67].

Barriers and Future Perspectives

The application of nanobiosensors to provide rapid and sensitive diagnostic information in emergency settings still faces several barriers to clinical translation. Many reported examples remain at the proof-of-concept or early validation stage, and their analytical performance does not necessarily translate into clinical validity or applicability in heterogeneous patient populations. As a result, the application of nanoparticle-based assays requires rigorous validation of analytical accuracy, reproducibility, safety, and manufacturing quality before their integration into clinical diagnostics and care [27]. The use of complex biological materials in their structure can introduce nonspecific interactions and interferences that may reduce assay selectivity, reproducibility, and accuracy [27, 68]. Furthermore, variability in nanomaterial synthesis, physicochemical properties, nanoparticle surface functionalization, and device fabrication can pose challenges in standardization and reproducibility [27]. Importantly, analytical sensitivity alone is not sufficient for clinical acceptance. Nanobiosensors must demonstrate clinical validity and utility through well-designed clinical studies, comparison with established reference methods, and validation in independent patient cohorts [68, 69]. Therefore, future research must move beyond laboratory-scale proof-of-concept studies toward multicenter clinical validation and standard real-world performance evaluation before nanobiosensors can be routinely incorporated into emergency care.

In the future, nanotechnology-based diagnostic technology will revolutionize emergency medicine by enabling ultrafast, highly sensitive, and POC diagnostics. In addition, nanobiosensors and patient-side nanosensors in both wearable and portable forms can offer early detection of sepsis, myocardial infarction, stroke, trauma-related hemorrhage, and infectious pathogens within minutes, allowing faster, more cost-effective, and much less risky decisions to guide targeted interventions. Furthermore, the combination of nanotechnology with AI may enhance predictive monitoring and automated risk stratification

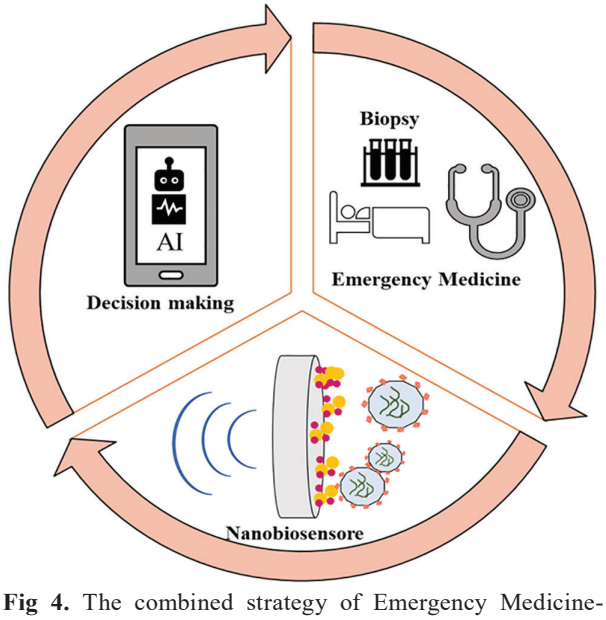


Fig 4. The combined strategy of Emergency Medicine-Nano-artificial intelligence is shown. In disease diagnosis, nanobiosensors could generate signals that are processed by AI algorithms to produce biomarker-specific diagnostic outputs, supporting real-time decision-making in emergency settings. The figure was created using Microsoft PowerPoint.

for prognosis and treatment, while theranostic nanoplatforms may integrate bedside diagnosis and treatment with real-time drug delivery for improved outcomes. Despite these advances, challenges remain regarding regulatory approval, additional costs associated with these technologies, the biocompatibility of substances used in clinical settings, and the safety of data within emergency workflows. Nevertheless, the long-term vision is a shift from reactive emergency care toward predictive and precise emergency care.

Considering the application of nanotechnology to improve the performance of various scientific fields, including medicine, emergency medicine, which requires rapid diagnosis and therapeutic interventions within a short period, may particularly benefit from nanoscience because of its potential to increase the speed and accuracy of diagnostic and treatment systems. The POC, as one of the most efficient aspects in this field, has considerable interaction with this subject. Recent studies have clearly shown that wearable nanobiosensors using nanotechnology could demonstrate improved performance compared with expensive methods and lengthy conventional laboratory protocols. AI, alongside nanotechnology, can further enhance the performance of diagnostic and therapeutic devices and potentially create synergistic effects. Ultimately, the future integration of diagnostic and therapeutic interventions in emergency medicine with these technologies might provide substantial opportunities for the field.

Declaration

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Consent for Publication: Not applicable.

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Data Availability: The Datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Declaration of Generative AI in Scientific Writing: Generative AI or AI-assisted technologies were not used to generate the scientific content, analysis, interpretation, or conclusions of this manuscript. An AI-assisted tool was used solely for limited language editing and improvement of the wording and readability of some parts of the manuscript. The authors reviewed and approved all edited content and take full responsibility for the final content of the manuscript.

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