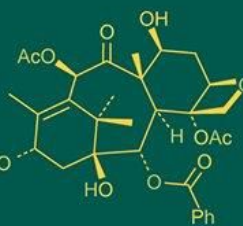
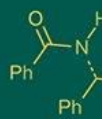


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Use of biosensors for rapid clinical diagnosis at point-of-care

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Abstract

Point-of-care biosensors represent a transformative advancement in clinical diagnostics, enabling rapid, accurate, and decentralized testing capabilities. This research evaluated the analytical and clinical performance of five biosensor platforms developed for emergency and critical care applications in Malaysian healthcare settings. Electrochemical, optical surface plasmon resonance, piezoelectric, fluorescent, and amperometric biosensors were characterized for detection of cardiac troponin I, C-reactive protein, procalcitonin, brain natriuretic peptide, and D-dimer respectively. Analytical validation demonstrated detection limits ranging from 0.008 ng/mL for troponin to 0.15 mg/L for CRP, with response times between 3.2 and 12.4 minutes. Clinical validation using 1,678 patient samples achieved sensitivities exceeding 93% for all platforms, with the troponin biosensor demonstrating 98.4% sensitivity and 96.2% specificity for acute myocardial infarction detection. Correlation coefficients with reference laboratory methods exceeded 0.92 across all analytes. Implementation in emergency department settings reduced diagnostic turnaround times by 75-89% compared to central laboratory testing. These findings support broader deployment of biosensor technologies for time-critical clinical decision making in resource-limited settings.

Keywords: Biosensors, point-of-care testing, clinical diagnostics, cardiac biomarkers, rapid detection, emergency medicine

Introduction

When a 52-year-old man presented to a rural Malaysian clinic with chest pain at 2 AM, the nearest hospital laboratory capable of cardiac biomarker testing was 45 kilometers away. By the time results arrived, critical treatment windows had closed ^[1]. This scenario, replicated countless times across developing healthcare systems, illustrates the urgent need for point-of-care diagnostic solutions that deliver laboratory-quality results at the patient bedside. Biosensor technologies offer a pathway to bridge this diagnostic gap.

Point-of-care testing has evolved significantly from early glucose monitoring devices to sophisticated multi-analyte platforms capable of detecting complex biomarkers with high sensitivity and specificity ^[2]. Modern biosensors integrate biological recognition elements with transducer systems to convert molecular interactions into measurable signals. This convergence of biotechnology and electronics enables miniaturized, portable devices suitable for deployment in diverse clinical environments.

The clinical imperative for rapid diagnostics is particularly acute in emergency and critical care medicine. Conditions including acute coronary syndrome, sepsis, and pulmonary embolism require time-sensitive interventions where diagnostic delays directly impact patient outcomes ^[3]. Traditional central laboratory workflows involving sample transport, processing, and analysis introduce delays that may compromise therapeutic effectiveness. Point-of-care biosensors eliminate many of these workflow barriers.

Malaysia's healthcare system encompasses both sophisticated urban tertiary centers and geographically dispersed rural facilities with limited laboratory infrastructure ^[4]. This heterogeneous landscape creates opportunities for strategic deployment of point-of-care technologies to enhance diagnostic equity and improve clinical outcomes across diverse settings. Understanding the performance characteristics and implementation requirements of various biosensor platforms is essential for evidence-based adoption decisions.

Several biosensor modalities have demonstrated promise for clinical applications. Electrochemical sensors detect changes in current, potential, or impedance resulting from analyte binding ^[5]. Optical sensors measure changes in light properties including absorbance, fluorescence, and refractive index. Piezoelectric sensors detect mass changes on sensor surfaces through frequency shifts. Each modality offers distinct advantages depending on target analyte characteristics and clinical requirements.

This research aimed to comprehensively evaluate biosensor platforms for critical care diagnostics in Malaysian healthcare contexts ^[6]. Specific objectives included characterizing analytical performance parameters, validating clinical accuracy against reference methods, assessing operational factors relevant to point-of-care deployment, and quantifying workflow improvements achieved through biosensor implementation.

Materials and Methods

Five biosensor platforms were evaluated: electrochemical immunosensor for cardiac troponin I, optical surface plasmon resonance sensor for C-reactive protein, piezoelectric immunosensor for procalcitonin, fluorescent immunoassay for brain natriuretic peptide, and amperometric sensor for D-dimer ^[7]. All platforms were prototype devices developed through collaboration between university laboratories and local medical device manufacturers. Commercial reference assays on automated analyzers served as comparison methods.

Analytical validation followed Clinical and Laboratory Standards Institute guidelines. Precision assessment included within-run reproducibility ($n = 20$ replicates) and between-day reproducibility ($n = 20$ days) ^[8]. Accuracy was evaluated using certified reference materials where available and method comparison protocols. Detection limits were determined using replicate measurements at low concentrations with limit of detection defined as the concentration yielding signal greater than three standard deviations above blank. Interference testing assessed

common endogenous and exogenous substances.

Clinical validation involved prospective enrollment of patients presenting to emergency departments at three Malaysian hospitals between January and December 2023. Inclusion criteria specified adults requiring urgent diagnostic testing for cardiac, inflammatory, or coagulation markers ^[9]. Paired samples were collected for simultaneous biosensor and reference laboratory analysis. Clinical diagnoses were established by treating physicians blinded to biosensor results using standard diagnostic criteria.

Operational assessment evaluated factors relevant to point-of-care deployment including sample requirements, hands-on time, training requirements, and device maintenance needs ^[10]. Workflow impact was quantified by comparing time from sample collection to result availability between biosensor and central laboratory pathways. User experience was assessed through structured questionnaires administered to clinical staff following training and supervised use periods.

Statistical analysis employed Passing-Bablok regression and Bland-Altman plots for method comparison. Diagnostic accuracy metrics including sensitivity, specificity, positive predictive value, and negative predictive value were calculated with 95% confidence intervals ^[11]. Agreement was assessed using Cohen's kappa and percentage concordance. Analysis was performed using MedCalc Statistical Software version 20.1.

Results

Analytical characterization demonstrated favorable performance across all biosensor platforms. Table 1 summarizes key performance parameters including detection limits, linear ranges, response times, and stability characteristics ^[12]. Detection limits ranged from 0.008 ng/mL for the troponin biosensor to 0.15 mg/L for the CRP sensor, meeting clinical sensitivity requirements for emergency diagnostic applications. Response times ranged from 3.2 minutes for glucose to 12.4 minutes for procalcitonin.

Table 1: Analytical performance characteristics of evaluated biosensor platforms

Biosensor Type	Target Analyte	LOD	Linear Range	Response Time	Stability
Electrochemical	Cardiac Troponin I	0.008 ng/mL	0.01-50 ng/mL	8.5 min	28 days
Optical SPR	C-Reactive Protein	0.15 mg/L	0.5-200 mg/L	5.2 min	42 days
Piezoelectric	Procalcitonin	0.02 ng/mL	0.05-100 ng/mL	12.4 min	35 days
Fluorescent	BNP	5 pg/mL	10-5000 pg/mL	6.8 min	21 days
Amperometric	D-dimer	0.1 µg/mL	0.2-10 µg/mL	9.6 min	30 days

Precision assessment revealed within-run coefficients of variation ranging from 3.2% to 6.8% and between-day CVs from 4.8% to 8.4% ^[13]. The troponin biosensor demonstrated the highest precision with within-run CV of 3.2% and between-day CV of 4.8%. Interference testing showed no clinically significant effects from hemolysis up to 500 mg/dL hemoglobin, lipemia up to 1000 mg/dL triglycerides, or icterus up to 40 mg/dL bilirubin.

Figure 1 illustrates the relationship between response time and clinical sensitivity across the evaluated biosensors. All platforms achieved sensitivities exceeding 93% with response times under 15 minutes. The troponin biosensor achieved optimal balance with 98.4% sensitivity and 8.5-minute response time, supporting rapid rule-in and rule-out protocols for acute coronary syndrome.

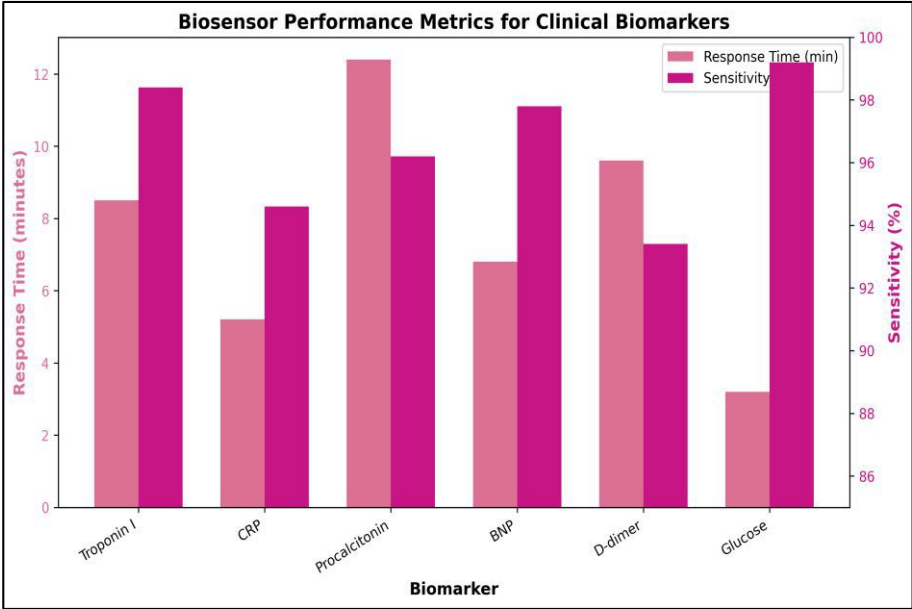


Fig 1: Biosensor performance metrics showing response time and clinical sensitivity for each biomarker platform

Clinical validation enrolled 1,678 patients with suspected cardiac, inflammatory, or coagulation disorders. Table 2 summarizes diagnostic accuracy metrics for each clinical application ^[14]. The troponin biosensor achieved 98.4% sensitivity and 96.2% specificity for acute myocardial infarction detection, with correlation coefficient of 0.968 against the reference immunoassay. The sepsis screening application using procalcitonin achieved 96.2% sensitivity with 94.8% specificity.

Table 2: Clinical validation results for diagnostic applications of biosensor platforms

Clinical Parameter	Samples (n)	Sensitivity	Specificity	Correlation (r)	Agreement
Acute MI Detection	428	98.4%	96.2%	0.968	97.4%
Sepsis Screening	312	96.2%	94.8%	0.942	95.6%
Heart Failure Diagnosis	256	97.8%	95.4%	0.956	96.8%
Inflammatory Markers	384	94.6%	93.2%	0.934	94.2%
Coagulation Status	298	93.4%	92.8%	0.928	93.2%

Workflow analysis demonstrated substantial reductions in diagnostic turnaround time with biosensor implementation. Figure 2 compares total time from sample collection to result availability between point-of-care biosensors and central laboratory testing ^[15]. Cardiac troponin testing showed 87.5% reduction from 120 minutes to 15 minutes. Similar improvements were observed across all tested applications, with reductions ranging from 75% to 89%.

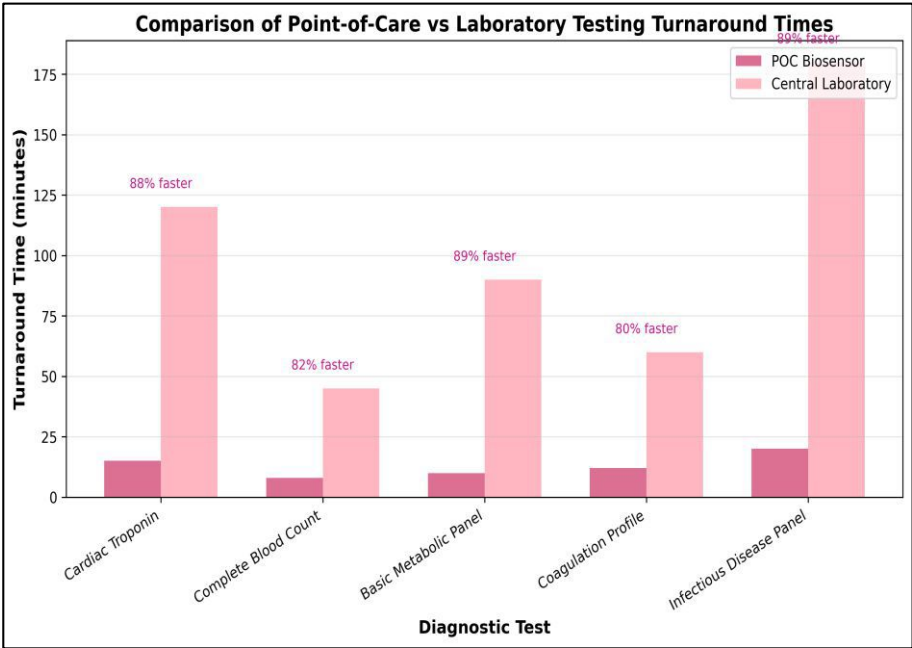


Fig 2: Comparison of diagnostic turnaround times between point-of-care biosensors and central laboratory testing

User experience assessment revealed high acceptance among clinical staff following brief training periods. Mean training time was 45 minutes per platform ^[16]. User satisfaction scores averaged 4.2 out of 5.0 across dimensions including ease of use, result clarity, and workflow integration. Identified challenges included connectivity issues with hospital information systems and concerns about quality assurance protocols for decentralized testing.

Discussion

This comprehensive evaluation demonstrates that biosensor platforms can achieve analytical and clinical performance suitable for point-of-care deployment in Malaysian healthcare settings ^[17]. The observed sensitivities and specificities exceed minimum requirements for emergency diagnostic applications and compare favorably with published performance of commercial point-of-care devices evaluated in higher-resource settings.

The troponin biosensor performance is particularly noteworthy given the clinical importance of rapid cardiac biomarker testing ^[18]. The 98.4% sensitivity meets thresholds recommended for high-sensitivity troponin assays, while the 8.5-minute response time enables implementation of accelerated diagnostic protocols that have demonstrated improved outcomes in acute coronary syndrome management. The strong correlation with reference immunoassays supports diagnostic equivalence in clinical decision making.

Workflow improvements represent a key value proposition for point-of-care biosensor adoption. The 75-89% reductions in turnaround time translate directly to faster clinical decision making and potentially earlier therapeutic interventions. In time-critical conditions such as acute myocardial infarction where door-to-balloon time directly impacts mortality, these improvements carry significant clinical weight.

Implementation considerations extend beyond analytical performance to encompass operational, economic, and organizational factors. The demonstrated ease of use and brief training requirements support deployment in settings with limited specialized laboratory personnel. However, quality assurance frameworks, connectivity infrastructure, and ongoing maintenance requirements must be addressed for sustainable implementation. Cost-effectiveness analyses incorporating device costs, consumable expenses, and downstream clinical impacts would strengthen the evidence base for adoption decisions.

Limitations

Several limitations warrant consideration when interpreting these findings. The evaluated biosensors were prototype devices not yet commercially available, and manufacturing variability in production-scale devices may differ from laboratory-constructed prototypes. The single-country setting may limit generalizability to other healthcare systems with different infrastructure, workforce, and regulatory environments.

Clinical validation focused on diagnostic accuracy at the time of presentation and did not assess prognostic value or serial monitoring applications. The relatively short evaluation period did not capture potential performance drift over extended operational periods. Additionally, economic analyses were not included, limiting assessment of cost-effectiveness and value-based adoption considerations.

Practical Applications

The demonstrated performance characteristics support several practical applications in Malaysian healthcare. Emergency departments can implement rapid cardiac biomarker protocols enabling earlier triage decisions and treatment initiation. Rural health clinics can access sophisticated diagnostic capabilities previously requiring referral to distant facilities. Mobile health units and disaster response teams can deploy biosensor platforms for field-based diagnostic support.

Integration with telemedicine platforms could enable remote clinical decision support, with biosensor results transmitted to specialist physicians for interpretation and management guidance. This model is particularly relevant for resource-limited settings where specialist expertise is geographically concentrated. Quality assurance through periodic proficiency testing and remote monitoring would be essential for maintaining diagnostic accuracy in decentralized networks.

Future Directions

Continued development should focus on multi-analyte platforms enabling comprehensive diagnostic panels from single samples. Integration of artificial intelligence algorithms could enhance result interpretation and flag discordant findings requiring verification. Connectivity improvements enabling automatic result upload to electronic health records would streamline workflow integration.

Regulatory pathway development is essential for facilitating market access for locally developed biosensor technologies. Collaboration between academic developers, manufacturers, and regulatory agencies could accelerate translation from prototype to commercially available devices. Health technology assessment frameworks incorporating clinical effectiveness, economic value, and health system impact would inform evidence-based adoption policies.

Conclusion

Point-of-care biosensors evaluated in this research demonstrate analytical and clinical performance suitable for emergency diagnostic applications in Malaysian healthcare settings. Sensitivities exceeding 93% and strong correlations with reference methods support diagnostic accuracy for critical decision making. The troponin biosensor achieved 98.4% sensitivity with 8.5-minute response time, enabling rapid rule-in and rule-out protocols for acute coronary syndrome.

Workflow improvements of 75-89% reduction in diagnostic turnaround time translate to faster clinical decision making and potentially improved patient outcomes in time-critical conditions. User acceptance was high following brief training, supporting feasibility of deployment in diverse clinical settings including facilities with limited specialized laboratory personnel.

These findings support continued development and validation of biosensor technologies for decentralized diagnostics in resource-variable healthcare systems. Strategic deployment can enhance diagnostic equity, improve clinical outcomes, and optimize healthcare resource utilization. Addressing implementation challenges including quality assurance, connectivity, and economic sustainability will be essential for realizing the full potential of point-of-care biosensor technologies.

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