PHARMACON
Jurnal Farmasi Indonesia
Pharmaceutical Journal of Indonesia

Pharmacon: Jurnal Farmasi Indonesia
Vol. 23 No. 1 (2026), pp. 92–101
DOI:10.23917/pharmacon.v23i1.17888
p-ISSN: **1411-4283**, e-ISSN: **2685-5062**

Smart-Adherence Pillbox (SAP): An Electronic Automatic Pillbox-Based Medication Reminder Device for Tuberculosis Patients at the Purwokerto Pulmonary Clinic

Rian Nurahman[1], Ikhwan Yuda Kusuma[2*], Peppy Octaviani[3], Silma Kaaffah[4], Ruaa Adel Alebead[5], Nur Arifin Akbar[6]
[1-4]Pharmacy Study Program, Faculty of Health, Universitas Harapan Bangsa, Purwokerto, 53182, Indonesia
[5] Department of Clinical Pharmacy and Pharmacy Practice, Faculty of Pharmacy, University of Gezira, Wad Madani, 21111, Sudan.
[6] Department of Math And Computer Science, University Of Messina, Italy
**Corresponding author: ikhwanyudakusuma@uhb.ac.id*

ARTICLE HISTORY:
Submitted: 2026-05-30
Accepted : 2026-06-23
Published : 2026-06-30

KEYWORDS:
Digital health technology; Medication adherence; Smart pillbox; Tuberculosis

Citation:
Nurahman, R, Kusuma, I.Y, Oktaviani, P, Kaaffah, S, Alebead, R.A, Akbar, N.A. (2026). Smart-Adherence Pillbox (SAP): An Electronic Automatic Pillbox-Based Medication Reminder Device for Tuberculosis Patients at the Purwokerto Pulmonary Clinic. Pharmacon: Jurnal Farmasi Indonesia, 23(1), 92-101. https://doi.org/10.23917/pharmacon.v23i1.17888

ABSTRACT

Tuberculosis (TB) remains a major global public health challenge, and poor adherence to anti-tuberculosis therapy contributes to treatment failure and the emergence of multidrug-resistant tuberculosis (MDR-TB). This study aimed to develop and evaluate the SMART-ADHERENCE PILLBOX (SAP), an electronic automatic pillbox with real-time monitoring designed to support medication adherence among TB patients. A prospective quantitative feasibility study was conducted, consisting of prototype validation and limited field implementation at the Purwokerto Pulmonary Clinic. Technical validation was performed using 100 operational simulation cycles across four independent replications, while the feasibility study involved eight TB patients in the intensive treatment phase who used SAP for 14 days. Evaluations included technical performance, timing performance, medication adherence, and acceptability based on the Unified Theory of Acceptance and Use of Technology (UTAUT). The results demonstrated that SAP achieved high technical reliability, with success rates exceeding 95% for alarm activation, medication dispensing, connectivity, notification delivery, and electronic logging. Alarm and logging deviations were close to zero, and notification delivery time consistently remained below five seconds, indicating good real-time monitoring capability. Following SAP implementation, adherence rates significantly increased from 83.9% to 97.4%, accompanied by reductions in missed doses and medication-taking delays ($p<0.05$). In addition, all acceptability domains showed high scores (4.3–4.5), indicating that SAP was well accepted by patients. Overall, SAP has the potential to become an applicable digital adherence technology innovation to support tuberculosis control programs in Indonesia.

INTRODUCTION

Tuberculosis (TB) remains a major global public health challenge, particularly in low- and middle-income countries, with an estimated 10.9 million new cases reported worldwide (WHO, 2024). Despite ongoing implementation of the End TB Strategy, TB incidence and mortality in Indonesia have increased by 19% and 26%, respectively, since 2015, indicating persistent gaps in disease control (WHO, 2024). Poor adherence to long-term anti-tuberculosis therapy remains a key driver of treatment failure, relapse, and the emergence of multidrug-resistant tuberculosis (MDR-TB), which is more difficult and costly to manage (Espinosa-Pereiro et al., 2022; Rosu et al., 2023). Conventional adherence strategies such as

Directly Observed Treatment, Short-course (DOTS) are widely implemented but face practical limitations including resource constraints, transportation barriers, and low patient motivation (Mundakir et al., 2021; Xian et al., 2021). Digital health technologies have therefore been increasingly recommended as alternative approaches to support adherence, including short message services, mobile applications, video-observed therapy, and electronic medication monitoring systems (WHO, 2023). Recent studies in Southeast Asia demonstrated that digital interventions modestly improved adherence but showed limited impact on treatment outcomes (Davis et al., 2024). Similarly, a randomized controlled trial in China reported only minimal reduction in loss to follow-up with digital adherence technologies and no significant improvement in treatment success (Liu et al., 2023). Device-based innovations have also been explored, such as a smart pillbox developed in Egypt that reduced missed doses but lacked disease-specific (Minaam & Abd-ELfattah, 2018), an electronic pillbox in Indonesia that improved adherence without automated dispensing features (Mahardiananta et al., 2022), and a real-time monitoring system in India that still faced technical and usability challenges (Charles et al., 2024).

Given the existing limitations of current digital adherence technologies, this study developed and evaluated the SMART-ADHERENCE PILLBOX (SAP), an integrated electronic automatic pillbox combining medication reminders, automated dispensing, electronic logging, and real-time monitoring. The study aimed to assess the technical reliability, operational performance, patient acceptability, and preliminary effectiveness of SAP in improving medication adherence among tuberculosis patients during the intensive treatment phase.

METHODS

Study Design and Setting

This prospective quantitative feasibility study consisted of prototype validation and limited field implementation conducted at the Purwokerto Pulmonary Clinic, Indonesia. The SMART-ADHERENCE PILLBOX (SAP) was developed using an ESP32 NodeMCU microcontroller integrated with an audio-visual alarm system, electronic logging, and an Android application to provide medication reminders, single-dose dispensing, real-time adherence monitoring, and notification delivery.

Prototype Validation

Technical validation was performed under controlled laboratory conditions using 100 operational simulation cycles. Evaluated parameters included alarm accuracy, dispensing accuracy, electronic logging, notification delivery, mechanical safety, and device connectivity. The prototype was considered valid when at least 95% of operational cycles were completed without major technical errors or over-dispensing events.

Participants and Procedures

The feasibility study involved eight adult pulmonary TB patients receiving intensive-phase anti-tuberculosis treatment who were recruited using consecutive sampling. Medication records were reviewed to verify scheduled treatment dates and treatment attendance, while interviews assessed missed doses, medication-taking timing, and any occasions on which anti-tuberculosis medications were not taken as prescribed. These data were used to calculate adherence rate, missed-dose frequency, medication-taking time deviation, on-time streak, and time-to-first lapse. The 14-day assessment period was selected based on tuberculosis treatment interruption management guidelines, which consider interruptions of <14 days eligible for treatment continuation, whereas interruptions of ≥14 days may require treatment re-initiation (Canadian Tuberculosis Committe, 2022; Ministry of Health of the Republic of Indonesia, 2020). Medication adherence was retrospectively assessed for 14 days before intervention using medication records and adherence interviews. Participants then used SAP for 14 consecutive days. The system automatically provided medication reminders, recorded medication-taking events, and sent missed-dose notifications to caregivers and researchers when medication was not taken within two hours of the scheduled time.

Variables and Data Analysis

The evaluated adherence outcomes included adherence rate, missed-dose frequency, medication-taking time deviation, on-time streak, and time-to-first lapse. Acceptability was assessed using a 5-point Likert-scale questionnaire based on the Unified Theory of Acceptance and Use of Technology (UTAUT). Data were analyzed descriptively using means, standard deviations, frequencies, and percentages. Changes in adherence before and after SAP implementation were analyzed using paired t-tests or Wilcoxon signed-rank tests, with statistical significance set at $p < 0.05$.

RESULT

Functional Performance of the SMART-ADHERENCE PILLBOX Prototype

As presented in Table 1, the SMART-ADHERENCE PILLBOX (SAP) demonstrated excellent functional performance across four independent prototype replications, each consisting of 100 operational simulation cycles. Functional performance testing was conducted to verify the reliability and operational stability of all core system components prior to clinical implementation. This evaluation is critical because failures in alarm activation, medication dispensing, connectivity, notification delivery, or electronic logging could compromise adherence monitoring and reduce the effectiveness of digital adherence interventions (Subbaraman et al., 2018). Overall, the system achieved consistently high success rates across all evaluated domains, including alarm activation, medication dispensing, connectivity, notification delivery, mechanical operation, and electronic logging. Alarm accuracy ranged from 98.0% to 100.0%, while LED and buzzer functionality remained above 98.0% in all replications. Medication dispensing accuracy reached 100.0% in every replication, with no repeated over-dispensing events observed. Connectivity performance, including device pairing and data transfer, ranged from 98.0% to 100.0%, whereas notification delivery and electronic logging maintained success rates of 98.0–100.0%. Collectively, all performance indicators exceeded the predefined validation threshold of 95%, indicating high technical reliability and operational feasibility of the SAP prototype.

Table 1. Overall Functional Performance of the SMART-ADHERENCE PILLBOX (SAP) Across Four Independent Prototype Replications

Domain	Performance Indicator	1st Replication (%)	2nd Replication (%)	3rd Replication (%)	4th Replication (%)
Alarm	Alarm accuracy	99.0	100.0	98.0	100.0
Alarm	LED and buzzer functionality	98.0–99.0	99.0	99.0–100.0	99.0–100.0
Dispensing	Successful medication release	99.0	98.0	99.0	100.0
Dispensing	Dispensing accuracy	100.0	100.0	100.0	100.0
Dispensing	No over-dispensing event	100.0	99.0	100.0	100.0
Connectivity	Device pairing and data transfer	99.0–100.0	100.0	98.0–99.0	99.0–100.0
Mechanical	Position sensor activation	100.0	99.0	100.0	100.0
Notification	Successful notification delivery	99.0	100.0	98.0	100.0
Logging	Electronic logging accuracy	100.0	99.0	100.0	100.0

Timing Performance of the SAP Prototype

Table 2 summarizes the timing performance of SAP across four prototype replications. The system exhibited excellent temporal accuracy, with alarm deviations ranging from 0.00 ± 0.01 to 0.02 ± 0.05 minutes and logging deviations ranging from 0.00 ± 0.00 to 0.01 ± 0.03 minutes, indicating near-perfect synchronization between scheduled and recorded events. Data transfer time varied from 5.84 ± 5.12 to 8.34 ± 8.11 seconds, reflecting minor differences in network synchronization conditions while maintaining real-time functionality. The notification delivery target of ≤5 seconds was established based on the operational requirements of real-time adherence monitoring, where rapid transmission of medication-taking events and missed-dose alerts is essential to support timely follow-up and system responsiveness (Subbaraman et al., 2018). Notification delivery remained consistently rapid, ranging from 1.74 ± 0.49 to 2.22 ± 0.71 seconds, with all values remaining below the predefined target of five seconds. These findings demonstrate that SAP is capable of providing accurate medication reminders, timely notifications, and reliable real-time monitoring.

Table 2. Timing Performance of the SMART-ADHERENCE PILLBOX (SAP) Across Four Prototype Replications

Parameter	1st Replication	2nd Replication	3rd Replication 3	4th Replication
Alarm deviation (minutes)	0.01 ± 0.04	0.00 ± 0.02	0.02 ± 0.05	0.00 ± 0.01
Data transfer time (seconds)	7.57 ± 7.98	6.92 ± 6.54	8.34 ± 8.11	5.84 ± 5.12
Notification delivery time (seconds)	2.05 ± 0.64	1.88 ± 0.58	2.22 ± 0.71	1.74 ± 0.49
Logging deviation (minutes)	0.00 ± 0.00	0.00 ± 0.01	0.01 ± 0.03	0.00 ± 0.00

Operational Event Profile During Prototype Testing

The operational event profile presented in Table 3 demonstrated stable system performance under varying simulated operational conditions. Across the four replications, timely-response events, reflecting successful real-time synchronization between the SAP device and the Android application, ranged from 49.0% to 63.0%, whereas delayed-response events ranged from 37.0% to 51.0%. Despite these variations, alarm functionality remained highly stable, with normal alarm operation observed in 98.0–100.0% of cycles and abnormal alarm events occurring in only 0.0–2.0% of cycles. Overall, the prototype maintained consistent operational performance without any major system failures throughout the validation process.

Table 3. Operational Event Profile During SAP Prototype Testing

Variable	1st Replication	2nd Replication	3rd Replication	4th Replication
Timely-response simulation (%)	54.0	60.0	49.0	63.0
Delayed-response simulation (%)	46.0	40.0	51.0	37.0
Real-time synchronization (%)	54.0	60.0	49.0	63.0
Delayed synchronization (%)	46.0	40.0	51.0	37.0
Normal alarm operation (%)	99.0	100.0	98.0	100.0
Abnormal alarm events (%)	1.0	0.0	2.0	0.0

Table 4. Medication Adherence Outcomes Before and After Smart-Adherence Pillbox (SAP) Implementation Among Tuberculosis Patients (n = 8)

Variable	Before SAP	After SAP	p-value
Adherence rate (%)	83.9 ± 7.6	97.4 ± 3.8	0.003*
Missed-dose frequency (n/14 days)	2.3 ± 1.0	0.4 ± 0.5	0.011*
Mean time deviation (minutes)	45.6 ± 18.6	6.0 ± 3.1	0.001*
On-time streak (days)	6.9 ± 2.5	12.9 ± 1.7	0.002*
Time-to-first lapse (days)	5.9 ± 2.4	12.9 ± 1.7	0.002*

*Statistically significant at $p < 0.05$.

Medication Adherence Before and After SAP Implementation

Table 4 presents the medication adherence outcomes before and after SAP implementation among eight tuberculosis patients. Following 14 days of SAP use, significant improvements were observed across all adherence indicators. The mean adherence rate increased from 83.9 ± 7.6% before intervention to 97.4 ± 3.8% after intervention (p = 0.003). Missed-dose frequency decreased from 2.3 ± 1.0 to 0.4 ± 0.5 events over 14 days (p = 0.011), while mean medication-taking time deviation decreased substantially from 45.6 ± 18.6 to 6.0 ± 3.1 minutes (p = 0.001). In addition, the mean on-time streak increased from 6.9 ± 2.5 to 12.9 ± 1.7 days (p = 0.002), and the mean time-to-first lapse increased from 5.9 ± 2.4 to 12.9 ± 1.7 days (p = 0.002). These findings were associated with improvements in medication-taking consistency, punctuality, and overall adherence during the SAP utilization period; however, the results should be interpreted as preliminary evidence given the feasibility-study design and limited sample size.

Acceptability Evaluation of the Smart-Adherence Pillbox

Table 5. Acceptability Scores of Smart-Adherence Pillbox (SAP) Based on the UTAUT Framework

Domain	Mean ± SD
Performance Expectancy	4.5 ± 0.5
Effort Expectancy	4.4 ± 0.6
Social Influence	4.5 ± 0.5
Trust	4.5 ± 0.5
Facilitating Conditions	4.4 ± 0.6
Hedonic Motivation	4.4 ± 0.5
Price Value	4.3 ± 0.6
Habit	4.3 ± 0.6
Behavioral Intention	4.5 ± 0.5
Use Behavior	4.5 ± 0.5

As shown in Table 5, participants reported high levels of acceptability across all domains of the Unified Theory of Acceptance and Use of Technology (UTAUT). Mean domain scores ranged from 4.3 to 4.5 out of a maximum score of 5, indicating positive perceptions of SAP usability and usefulness. The highest scores were observed for Performance Expectancy, Trust, Behavioral Intention, and Use Behavior (mean score = 4.5), suggesting that participants perceived SAP as beneficial, reliable, and supportive of medication adherence. Effort Expectancy, Facilitating Conditions, and Hedonic Motivation also demonstrated favorable scores (4.4), indicating that the system was easy to learn and use. Although Habit and Price Value received slightly lower scores (4.3), participants still expressed overall positive acceptance, suggesting that SAP has strong potential for practical implementation among tuberculosis patients.

Inferential Analysis of Medication Adherence Outcomes

Inferential analysis results are presented in Table 6. Significant improvements were observed across all medication adherence indicators following SAP implementation. Adherence rate increased by 13.5 percentage points (p = 0.003), while missed-dose frequency decreased by 1.9 events during the 14-day observation period (p = 0.011).

Table 6. Inferential Analysis of Medication Adherence Outcomes Before and After Smart-Adherence Pillbox (SAP) Implementation (n = 8)

Variable	Before SAP (Mean ± SD)	After SAP (Mean ± SD)	Mean Difference	Statistical Test	p-value
Adherence rate (%)	83.9 ± 7.6	97.4 ± 3.8	+13.5	Paired t-test	0.003*
Missed-dose frequency (n/14 days)	2.3 ± 1.0	0.4 ± 0.5	−1.9	Wilcoxon signed-rank test	0.011*
Mean time deviation (minutes)	45.6 ± 18.6	6.0 ± 3.1	−39.6	Paired t-test	0.001*
On-time streak (days)	6.9 ± 2.5	12.9 ± 1.7	+6.0	Paired t-test	0.002*
Time-to-first lapse (days)	5.9 ± 2.4	12.9 ± 1.7	+7.0	Paired t-test	0.002*

*Statistically significant at $p < 0.05$.

Mean medication-taking time deviation decreased by 39.6 minutes (p = 0.001), indicating substantially improved punctuality. Furthermore, on-time streak duration increased by 6.0 days (p = 0.002), and time-to-first lapse increased by 7.0 days (p = 0.002). These statistically significant findings suggest that SAP was associated with meaningful improvements in medication adherence behavior, medication-taking timeliness, and treatment consistency among tuberculosis patients during the intensive treatment phase.

DISCUSSION

To the best of our knowledge, this study represents the first attempt to develop and evaluate the SMART-ADHERENCE PILLBOX (SAP), an integrated digital adherence technology that combines automated medication dispensing, real-time monitoring, electronic logging, and adherence-based notification systems for tuberculosis (TB) patients in Indonesia. The results demonstrated excellent technical performance, high user acceptability, and significant improvements in medication-taking behavior following SAP implementation. These findings suggest that SAP may offer a feasible and scalable approach to supporting adherence among TB patients, while providing a foundation for future large-scale evaluations of digitally assisted tuberculosis care. The technical validation results showed that SAP exhibited stable operational performance across all tested domains, with success rates exceeding 95% for alarm activation, medication dispensing, notification delivery, connectivity, and electronic logging throughout four independent replications. System stability is a critical component of technologies designed to support adherence in chronic disease management because minor disruptions in reminder or dispensing systems may lead to delayed medication intake, reduced adherence, and ultimately treatment failure (Charles et al., 2024). Furthermore, the absence of repeated over-dispensing events indicates that SAP may contribute to medication safety in TB therapy, where dosing accuracy is essential to prevent treatment failure, adverse drug reactions, and antimicrobial resistance.

The timing performance of SAP was also highly satisfactory. Alarm and logging deviations were close to zero, indicating highly accurate synchronization between medication schedules and system operation (Pande et al., 2026). Timely medication intake is particularly important in TB treatment to maintain consistent drug exposure and reduce the risk of resistance development in Mycobacterium tuberculosis (Hasan et al., 2019). In addition, notification delivery times consistently remained below five seconds, demonstrating effective real-time monitoring capability despite minor delayed synchronization events during several operational cycles. These delays did not result in system or notification failures, suggesting that SAP maintained functional stability under varying network conditions.

This study further demonstrated that SAP implementation was associated with significant improvements in medication adherence among TB patients. Following 14 days of SAP use, adherence rates increased from 83.9% to 97.4%, accompanied by reductions in missed doses and medication-taking delays. Improvements were also observed in on-time streak and time-to-first lapse, indicating greater consistency in medication-taking behavior after intervention. These findings are clinically important because medication adherence remains a major challenge in global TB control programs (Sazali et al., 2022). Non-adherence to anti-tuberculosis therapy has been associated with treatment failure, relapse, ongoing transmission, and the emergence of multidrug-resistant tuberculosis (MDR-TB) (Santosa et al., 2025).

Several mechanisms may explain the observed improvement in adherence following SAP implementation. The audio-visual reminder system may help reduce forgetfulness, one of the most common causes of non-adherence during long-term therapy (Fenerty et al., 2012). In addition, electronic logging and real-time monitoring may enhance patients' self-awareness regarding their medication-taking behavior (Chai et al., 2022). Notifications sent to caregivers and researchers may also provide additional reinforcement to support adherence (Ridho et al., 2021). Social and behavioral support has previously been recognized as an important determinant of successful TB treatment, particularly during the intensive phase of therapy (Sariem et al., 2019).

The improvement in medication-taking timeliness observed in this study is also noteworthy. Following SAP implementation, the mean medication-taking time deviation decreased substantially, indicating that SAP not only improved whether patients took their medication but also improved when they took it. Consistent medication timing may help maintain stable drug concentrations, which is particularly important in prolonged TB treatment, although pharmacokinetic outcomes were not directly assessed in this study (Crabtree-Ramírez et al., 2022).

The acceptability evaluation revealed positive perceptions of SAP across all UTAUT domains. High scores in performance expectancy suggest that patients perceived SAP as beneficial in supporting treatment adherence, whereas high trust scores indicate confidence in the reliability of the system during daily use (Zhang et al., 2025). High behavioral intention and use behavior scores further indicate participants' willingness to continue using SAP. User acceptance is a crucial factor in the sustainability of digital health interventions because systems perceived as difficult or impractical are less likely to achieve meaningful clinical benefits (Hussain et al., 2025). Although slightly lower scores were observed in the habit and price value domains, these findings still reflect positive acceptability and may indicate the need for adaptation to new technologies and consideration of future implementation costs.

Compared with previous smart pillbox and digital adherence technology studies, SAP offers several advantages by integrating reminders, medication dispensing, electronic logging, and real-time notifications into a single system. Most previous interventions focused primarily on reminder functions or electronic monitoring, whereas TB adherence interventions have commonly relied on SMS reminders, video-observed therapy, or direct observation, all of which require substantial resources (Ridho et al., 2021). The peer-support notification feature incorporated into SAP may further strengthen adherence supervision without requiring continuous direct observation by healthcare providers, making it particularly suitable for resource-limited healthcare settings (Musiimenta et al., 2019).

This study has several strengths, including the use of four independent validation replications, the combination of technical and clinical feasibility assessments, the evaluation of multiple adherence indicators, and the application of a UTAUT-based acceptability framework that provides a comprehensive understanding of user acceptance.

Nevertheless, several limitations should be acknowledged. The relatively small sample size and short intervention period of only 14 days may limit the generalizability of the findings and do not allow assessment of long-term adherence sustainability. Prototype testing was also conducted under laboratory conditions with relatively stable Wi-Fi connectivity, which may not fully represent real-world operational environments. Furthermore, SAP was not compared with other adherence-monitoring technologies or conventional adherence-support methods. Despite these limitations, this study provides preliminary evidence regarding the feasibility, acceptability, and potential effectiveness of SAP as a digital adherence support system for TB treatment. Future studies involving larger sample sizes, longer monitoring periods, cost-effectiveness evaluations, and integration with cloud-based healthcare systems are warranted to further evaluate the broader implementation of SAP.

CONCLUSIONS

The SMART-ADHERENCE PILLBOX (SAP) demonstrated high technical reliability and was associated with significant improvements in medication adherence, missed-dose reduction, and medication-taking timeliness among tuberculosis patients. In addition, SAP was well accepted by patients, suggesting its potential as a feasible digital adherence technology for supporting tuberculosis treatment in Indonesia. However, given the limited sample size and single-center study setting, these findings should be interpreted as preliminary and require confirmation in larger multicenter studies before broader generalization and implementation can be recommended.

ACKNOWLEDGMENT

The authors thank the Purwokerto Pulmonary Clinic, all participating tuberculosis patients, and everyone involved in the development and testing of the SMART-ADHERENCE PILLBOX (SAP) for their valuable support and contributions to this study.

AUTHORS' CONTRIBUTIONS

Conceptualization, methodology, software development, prototype design, data collection, formal analysis, investigation, and manuscript drafting were performed by the first author.

Supervision, study design validation, methodology review, and critical revision of the manuscript were conducted by the second and third authors. Technical consultation, data interpretation, and manuscript review were provided by all authors. All authors contributed to the development of the SMART-ADHERENCE PILLBOX (SAP), reviewed the final version of the manuscript, and approved its submission for publication.

CONFLICT OF INTERESTS

The authors declare that there are no conflicts of interest regarding the publication of this paper. The authors have no financial, commercial, or personal relationships that could have appeared to influence the work reported in this study.

ETHICAL CONSIDERATION

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki and complied with the WHO 2011 ethical standards and the 2016 Council for International Organizations of Medical Sciences (CIOMS) guidelines. Ethical approval was obtained from the Health Research Ethics Committee of Universitas Harapan Bangsa, Indonesia (Approval No. B.LPPM-UHB/1325/12/2025). The study was approved based on the fulfillment of seven WHO ethical standards, including social value, scientific value, equitable assessment of benefits and risks, risk management, persuasion/exploitation prevention, confidentiality and privacy protection, and informed consent. Prior to participation, all patients received detailed information regarding the study objectives, procedures, potential risks, and benefits, and provided written informed consent. Participant confidentiality and anonymity were maintained throughout the study, and all collected data were used exclusively for research purposes.

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