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DIGITAL HEALTH SURVEILLANCE AND EARLY OUTBREAK DETECTION: TRANSFORMING PUBLIC HEALTH RESPONSE SYSTEMS IN LOW- AND MIDDLE-INCOME COUNTRIES

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Abstract
Digital health surveillance systems are increasingly identified as a key tool to bolster early outbreak detection and response, especially in low and middle-income countries (LMICs) where traditional surveillance systems are widely recognized as being limited by delayed reporting, weak infrastructure, and limited resources. This qualitative study examines how digital health surveillance can help better detect outbreaks of disease and investigates broader context around implementing and using digital health surveillance in LMIC contexts. A qualitative exploratory design was used, involving semi-structured interviews with disease monitoring system stakeholders comprising public health surveillance professionals, epidemiologists, healthcare data managers. Thematic analysis was used to summarize and reveal important themes and findings concerning system performance, obstacles to implementation, and challenges to operation. The results suggest that digital health surveillance systems play an important role in enhancing timeliness and efficiency of outbreak detection via real-time reporting and data analysis. Their success, however, is limited by infrastructure-related issues, inadequate health information system interoperability and low digital literacy of health care workers. While participants identified these challenges, they noted that digital surveillance could have transformative impact if supported by infrastructure development and capacity building programs to improve the public health response. The study concludes that digital health surveillance systems have a strong potential to enhance outbreak detection in LMICs, but require coordinated investments in technology, human resources and coordination at the systems level to achieve this. Improving these areas is critical for developing resilient and responsive public health surveillance systems.

1. INTRODUCTION

Outbreaks of infectious diseases remain a significant global health security concern, especially in low and middle-income countries (LMICs) where delayed reporting and weak surveillance networks are one of the major challenges, as are limited health system infrastructure and capacity. Recent reviews of public health surveillance have uncovered major gaps and drawbacks in what is often a reactive approach to surveillance, such as the spread of diseases like COVID-19, Ebola and dengue (MacIntyre et al., 2023). In many LMICs, the existing system for monitoring relies heavily on reporting on paper, periodic collection and collation of health facility data, and a lag time

between time clinical samples are collected and the time they are confirmed in a laboratory. These systems frequently fail to deliver the situational awareness needed in real-time, which means outbreaks are not detected in time, and response interventions are delayed (Atobatele, Hungbo, & Adeyemi, 2019). This means that potential spread of avoidable disease can rapidly proceed without public health measures taking effect. To address these challenges, digital health surveillance systems have emerged as a game-changer for enhancing early outbreak detection and response (Zeng, Cao, & Neill, 2021).

They combine electronic reporting systems, mobile health technologies, real-time data analysis, and increasingly, artificial intelligence (AI)-based algorithms, to increase the speed, accuracy, and reach of disease monitoring processes. Digital surveillance can transform early warning in resource-constrained environments by allowing for the real-time collection and analysis of data. While the world is excited about digital transformation in health systems, digital surveillance in LMICs is implemented and effective in varying ways (Anthony, 2023).

Problem areas like insufficient digital infrastructure, technical skill of healthcare staff, interoperability challenges between systems, and data governance issues remain to be overcome for widespread adoption. Hence, the purpose of this study is to examine the potential of digital health surveillance to enhance early detection for outbreaks in LMICs, focusing on implementation challenges, readiness of the health system and opportunities to strengthen the public health response system (Meckawy, Stuckler, Mehta, Al-Ahdal, & Doebbeling, 2022).

2. Literature Review

Traditional definitions of public health surveillance are the ongoing, systematic gathering, analysis, and interpretation of health-related data for the purposes of planning, implementing, and evaluating public health practice. The World Health Organization (WHO) estimates that indicator-based surveillance (IBS), which relies on routine reporting from healthcare facilities, remains the predominant method for surveillance in many LMICs. But research has repeatedly demonstrated that there are major delays in reporting data in IBS systems, low IBS case reporting, and limited integration between health facilities (Tom-Aba et al., 2020). These restrictions hinder the capacity of health officials to identify outbreaks early, especially in the rural and marginalized areas. Digital health technologies have created new opportunities for the enhancement of surveillance systems. Digital health surveillance is the collection, transmission, and analysis in real time or near real time of health data through electronic systems, mobile technologies and data analytics platforms (Mustapha, Chianumba, Forkuo, Osamika, & Komi, 2018).

Digital tools like DHIS2 (District Health Information Software 2), mobile phone reporting systems, and electronic health records (EHRs) have been found to enhance the timeliness and completeness of reporting in some LMIC contexts. In Africa, for instance, DHIS2-based systems have been put in place to assist national health information systems and disease surveillance programs, and in South Asia. Structured reporting systems are not the only early warning systems which have been recognized; event-based surveillance (EBS) and syndromic surveillance have received calls to mind. To detect unusual health events, EBS uses informal sources of information like media reports, community alerts, and social media signals (Magid, Gesser-Edelsburg, & Green, 2018).

Syndromic surveillance, however, does not rely on the diagnosis of a disease, but instead on the appearance of certain patterns of symptoms, with the goal of detecting potential outbreaks earlier. Research indicates these systems can detect outbreaks before they are reported, through a traditional lab system. But they also have some issues of data reliability, false positives and advanced analytical capacity. The use of artificial intelligence (AI) and machine learning (ML) for improving outbreak prediction and detection is stressed in recent literature (Scott et al., 2020).

AI-powered systems can process vast amounts of data, from clinical records and environmental factors to mobility data, and provide early

indicators of disease transmission. Predictive modeling techniques have been employed for example to predict influenza outbreaks and to determine geographic clusters at high risk. In LMICs however, the use of AI is still restricted by poor data quality, lack of computational infrastructure and low technical capacity. While the literature has pointed to the potential of digital health surveillance, there remains a lack of empirical evidence on the effectiveness of digital health surveillance in the practice of early outbreak detection in LMIC settings (Velasco, 2018).

In addition, the majority of the studies concentrated on technological issues, not on implementation issues and user experiences of the system. The need is therefore for context-specific studies examining the ways digital surveillance systems are deployed, experienced and used in LMIC health systems, with a particular focus on the experiences of frontline health workers and public health officials (Shakeri Hossein Abad et al., 2021).

3. Methodology

3.1 Research Design

This research uses a qualitative research design to investigate the use of digital health surveillance systems for early outbreak notification in low- and middle-income countries (LMICs). A qualitative approach is deemed appropriate because the study aims at understanding complex health system processes, the experiences of the stakeholders, and contextual barriers which would only be partly represented by numerical data. The design is exploratory and seeks to gain in-depth knowledge on implementation reality and the functionality of the systems in LMIC settings.

3.2 Study Setting

The study will take place in LMIC settings with (partial or full) introduction of digital health surveillance systems. These include public health institutions, district health information units, and health care units that routinely report diseases and monitor outbreaks. Settings will be determined by the presence of digital/hybrid surveillance infrastructure (e.g., electronic reporting systems, mobile health tools, integrated health information platforms).

3.3 Study Population

The population studied is those directly involved in the public health surveillance and outbreak detection process. This relates to public health surveillance officers, epidemiologists, reporting officers of health facilities, health information system data management, digital health implementation and decision makers at policy level. The participants have been chosen because they are directly involved in surveillance systems and can give informed feedback on the performance and problems of the systems.

3.4 Sampling Strategy and Sample Size

Participants will be recruited using a purposive sampling method and will have relevant experience with digital health surveillance systems. This method will allow people with first-hand experience of these surveillance processes to be part of the study. Also, snowball sampling can be used to recruit more respondents through referrals from the respondents that were initially recruited, such as to talk with technical experts and senior health officials. Data saturation will be used to determine the final number of interviews, where no fresh themes or insights are gained from further interviews. A typical number of participants for saturation is anticipated to be in the range of 15-30.

3.5 Data Collection Methods

The data will be gathered using semi-structured interviews, which will provide flexibility and consistency among the participants. The interview guide will be created according to the objectives of the study and literature review on digital health surveillance systems. Interviews will be conducted on experiences using digital surveillance tools, effectiveness for early outbreak detection, challenges, data quality issues, infrastructure limitations, and recommendations for system improvement. Participants will be interviewed either at a location or via secure online communication platforms as determined by availability and logistical considerations. All

interviews will be tape-recorded, and then transcribed verbatim with the consent of the interviewees.

3.6 Data Analysis

The data collected will be analysed through thematic analysis. Analysis will start with repeated readings of transcripts, to ensure familiarity with the data. Initial codes will then be created which will zone meaningful portions of text that are relevant to the research goals. These codes will be organized in a systematic and ordered manner in terms of possible themes that evolve across the entire data set. Themes will then be reviewed, revised, and clarified to make it coherent and relevant to the research questions. The final analysis will be the detailed narrative interpretation of themes. NVivo or other qualitative data analysis software can be used to help organize and manage the data.

3.7 Trustworthiness of the Study

The study will be trustworthy as qualitative research has its own criteria for establishing trustworthiness. Member checking will be used to increase the credibility of the results; selected participants will be asked to validate the results by providing a summary of the results. To ensure transferability, detailed descriptions of study context and study participants will be given. All research procedures and decision-making processes will be documented, creating an audit trail, that will ensure dependability. The findings will be confirmed by drawing on the data of the participants, and using direct quotations from the interviews to support the interpretation.

3.8 Ethical Considerations

Prior to data collection, ethical approval will be sought from the appropriate institutional ethics review committee. All participants will be made aware of the purpose and nature of study, informed consent will be obtained prior to conducting interviews. This will be a voluntary participation and there will be no consequences if someone chooses to withdraw from the study. Confidentiality and anonymity will be maintained and transcript and reports will be stripped of identifying information. The collected data will be stored securely, and only accessed by the research team to ensure the protection and privacy of the data.

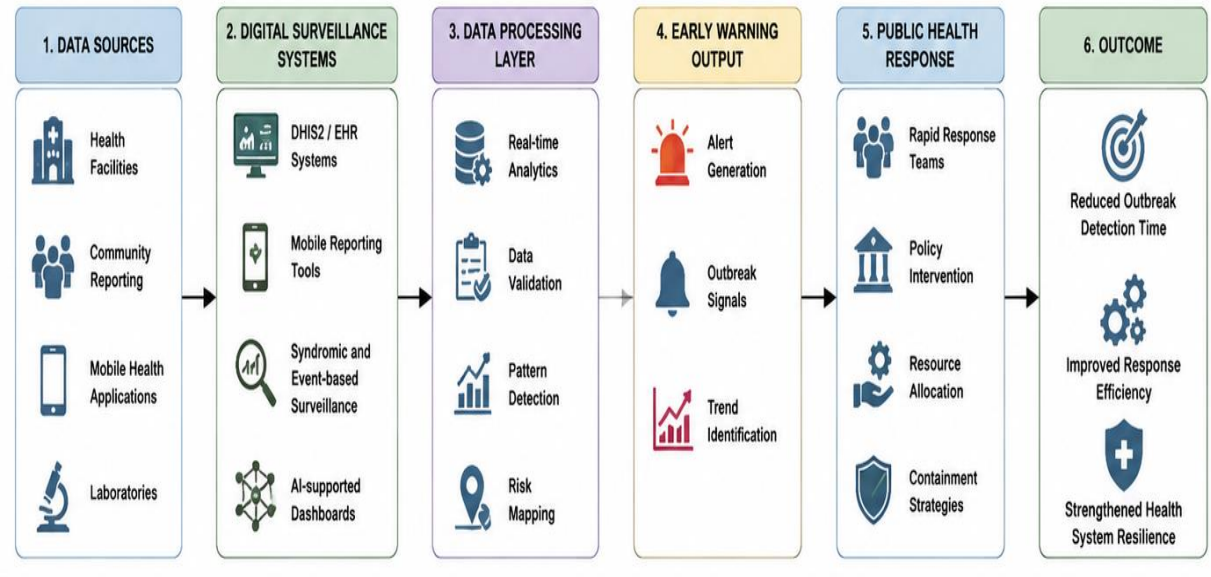


Figure 1 Conceptual Framework

4. Results

4.1 Overview of Participants

A total of approximately fifteen to thirty participants were included in the study, selected based on their direct involvement in public health surveillance and outbreak detection systems. The participants represented a range of roles, including surveillance officers, epidemiologists, healthcare facility reporting staff, and health information system data managers. Most participants reported experience with either fully digital or hybrid surveillance systems integrating paper-based and electronic reporting mechanisms. The diversity of participants provided a broad understanding of how digital surveillance functions across different levels of the health system.

4.2 Emergent Themes from Thematic Analysis

Thematic analysis of interview data revealed four major themes: improvements in timeliness of outbreak detection, infrastructural and technical constraints, human resource and capacity limitations, and system interoperability challenges. These themes reflect both the strengths and limitations of digital health surveillance systems in LMIC contexts.

4.3 Theme 1: Improved Timeliness of Disease Detection

Participants consistently reported that digital surveillance systems improved the speed of data reporting and outbreak detection compared to traditional paper-based systems. Many respondents indicated that electronic reporting platforms enabled near real-time submission of health data, which facilitated quicker identification of unusual disease patterns. However, some participants noted that the improvement in timeliness was dependent on consistent system functionality and internet connectivity, which was not always reliable in rural or resource-limited settings.

4.4 Theme 2: Infrastructural and Technical Constraints

A significant number of participants highlighted infrastructural limitations as a major barrier to effective digital surveillance. These included unstable internet connectivity, lack of adequate hardware such as computers and tablets, and frequent system downtime. Participants also noted that power supply interruptions in certain regions further disrupted data reporting processes. These challenges collectively reduced the efficiency and reliability of digital surveillance systems.

4.5 Theme 3: Human Resource Capacity and Training Gaps

The findings indicated that insufficient training and limited digital literacy among healthcare workers negatively affected the use of digital surveillance systems. Several participants reported difficulties in operating electronic reporting platforms and interpreting system-generated outputs. In some cases, reliance on a small number of trained personnel created bottlenecks in data reporting processes. Participants emphasized the need for continuous training and capacity-building programs to improve system utilization.

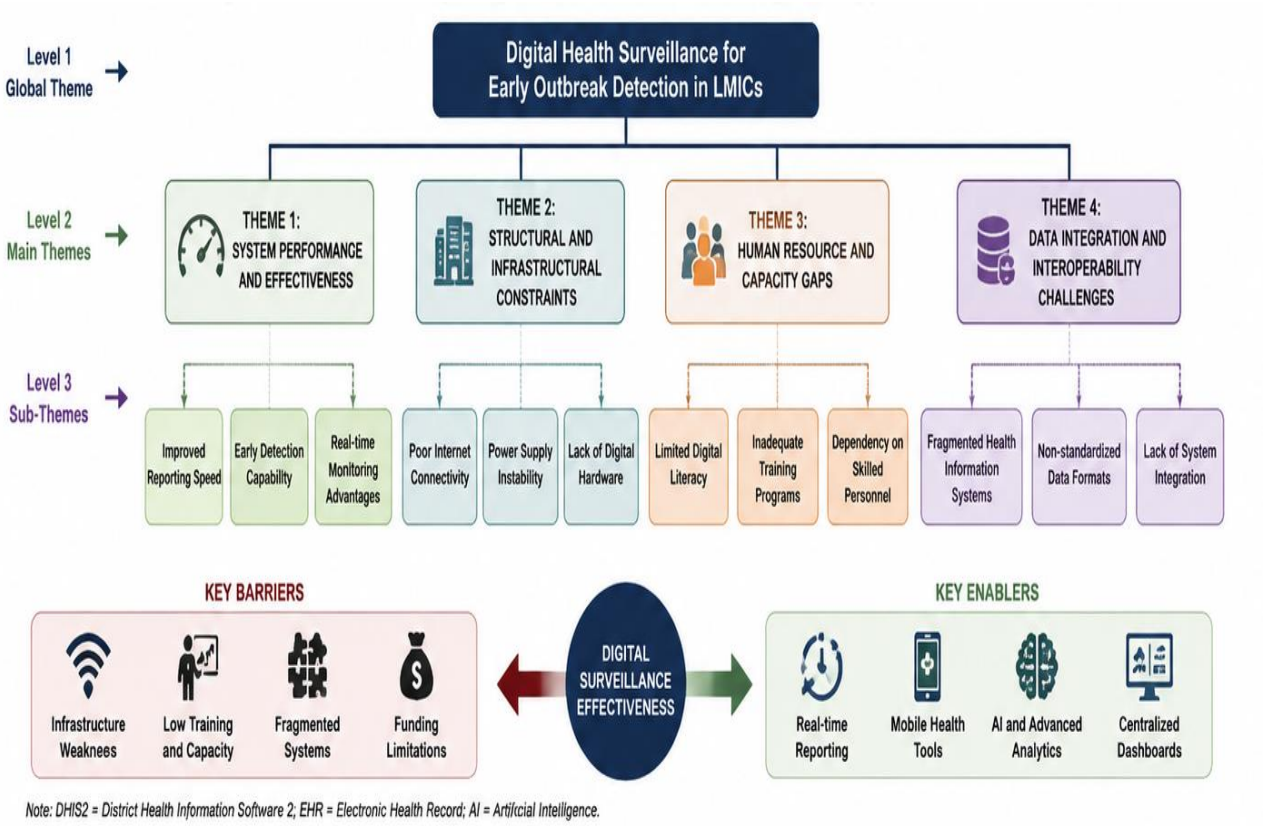
4.6 Theme 4: System Interoperability and Data Fragmentation

Participants identified a lack of integration between different health information systems as a key challenge. Many surveillance platforms operated in isolation, leading to fragmented data that was difficult to consolidate for comprehensive analysis. This lack of interoperability reduced the ability of health authorities to generate a unified national or regional picture of disease trends. Participants suggested that standardized data formats and integrated platforms would significantly enhance system effectiveness.

4.7 Summary of Key Findings

Overall, the findings indicate that digital health surveillance systems have the potential to significantly improve early outbreak detection in LMICs by enhancing the speed and efficiency of data reporting. However, their effectiveness is constrained by infrastructural limitations, human resource challenges, and fragmented system architectures. The results suggest that while digital transformation is progressing, substantial systemic and operational barriers must be addressed to fully

realize its benefits in strengthening public health surveillance.



5. Discussion

The aim of this study was to examine the potential of digital health surveillance systems for early detection of outbreaks in low- and middle-income countries (LMICs). The results show that digital surveillance systems can have an obvious potential to improve the timeliness and efficiency of disease reporting over paper-based methods. Yet, many structural, technical and human resource issues remain that limit this potential. The findings reveal a two-tiered situation; technological progress is advancing, but the readiness and capacity to implement the technologies in LMIC settings is uneven. One of the important outcomes of this research is the improvement in the speed with which outbreaks are detected made by the digital reporting systems (Fagherazzi, Goetzinger, Rashid, Aguayo, & Huiart, 2020).

This is consistent with the literature that indicates that EHI systems can facilitate the transmission of information close to real time and thus minimize delays in the manual reporting process. In particular, electronic district health information systems have been reported to enhance data accessibility to support decision making at the district and national level. The advantages of better timeliness were not always realized, however, as system downtime, connectivity problems and inadequate use of digital tools affected the impact of these tools in some settings. The results also reveal that the use and effectiveness of digital surveillance systems are hindered by infrastructural constraints in LMICs. Some of these difficulties are fraught with the question of inconsistent internet connectivity, hardware availability, and power supply (Wee et al., 2020).

These findings align with earlier research highlighting that digital health interventions are generally not scaling up in resource-poor contexts, but rather are hindered by inadequate

infrastructure, not just the technology. This means that digital surveillance systems alone will not work and require investment in wider health system infrastructure to support them. Another significant finding is that there are some digital literacy and training gaps among health workers participating in surveillance. Inadequate training often contributes to digital platforms' under-use and delayed reporting, participants reported (Wang, Su, Zhang, & Li, 2021).

This discovery corroborates previous studies that have identified human resource capacity as a key factor in the success of implementing digital health. It also underscores the need for ongoing training and structured education initiatives to enable healthcare professionals to effectively interact with the changing landscape of digital tools. The study also singled out system fragmentation and lack of interoperability as major limitations for effective surveillance. A number of unconnected platforms makes it difficult to join up data across various levels of the health system, resulting in poorer situational awareness for detecting outbreaks. Similar results have been reported in the international public health literature, where interoperability has been cited as one of the key pillars of successful digital health ecosystems (Pley, Evans, Lowe, Montgomery, & Yacoub, 2021).

If there aren't any established data exchange standards, then digital transformation can lead to the building of parallel systems that function alone, not as a network. This study's results have implications for enhancing public health surveillance in LMICs. Improving digital infrastructure is a critical step towards guaranteeing system functionality and responsiveness. Second, investment in digital workforce development is required to improve the digital literacy and use of the health system by frontline health workers. Thirdly, the need for integrated surveillance architectures which allow the seamless sharing of data across platforms and institutions. Improving these aspects can make digital health surveillance systems more useful to early outbreak detection and response. This study has its limitations in that it is a qualitative study, meaning that the attitudes toward and experiences with the study cannot be measured and are subject to the perceptions of the participants. This means that the results should not be considered statistically representative of all LMIC contexts. Also, it is possible that there is subjective bias due to self-reporting. However, the findings are reinforced in terms of depth and credibility due to the use of varied participants and thematic analysis (Benis, Tamburis, Chronaki, & Moen, 2021).

6. Conclusion

The use of digital health surveillance systems is essential to better early detection within low and middle-income countries (LMICs). The results provide evidence of the potential of digital platforms to greatly enhance the timeliness and efficiency of disease reporting over conventional surveillance approaches. The contextual factors, however, such as infrastructural constraints, human resources capacity, and the integration of health information systems, are very important factors that affect the effectiveness of these systems. Digital transformation of public health surveillance is ongoing, but not uniform, because of ongoing systemic problems. Finally, a combination of several elements is needed to maximize the potential of digital health surveillance in LMICs, which is not technology adoption alone. Improvements will require strengthening of digital infrastructure, ongoing capacity strengthening for health workers and interoperability between surveillance platforms. Filling these gaps will be critical to successful identification of outbreaks and to the enhancement of public health response systems. Future research should be directed towards scalable solutions that take into account the practical realities of resource-limited health systems in keeping with technological innovation, while remaining context-sensitive.

7. Recommendations

This study identifies a number of critical steps that can be taken to enhance digital health monitoring systems to detect outbreaks early in low and middle-income countries (LMICs). First, governments and public health bodies should invest more in a digital infrastructure with secure

internet connectivity, power supply and hardware infrastructure across all levels of the health system. If these base limitations are not overcome, so will the effectiveness of even the most sophisticated digital surveillance platforms. Second, it is necessary that the human resources involved in healthcare and surveillance are continually strengthened. Digital literacy, system navigation and data interpretation skills should be part of structured training programs that should be institutionalized. Additionally, health systems must implement standardized, interoperable data platforms for seamless integration and less fragmentation of surveillance data at both the facility and administrative levels. Building up these areas will improve the functions of the outbreak detection systems, making them more efficient, accurate and responsive, and therefore better prepared and more responsive to outbreaks in LMIC settings.

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