Early detection of patient deterioration at home using smart medical sensors

Bachelor Thesis

Proposal

submitted to
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1 Background

Clinical deterioration is a critical concern in healthcare, particularly for vulnerable populations such as the elderly and chronically ill patients. It refers to a decline in a patient's health status and may lead to adverse outcomes, including hospitalization, longer stays in intensive care units, and increased healthcare costs. Early warning scores (EWS) have been widely adopted internationally for preemptive detection of deteriorating patients[1]. A large body of scientific evidence validates the effectiveness of EWS in assessing severity of illness, and in predicting adverse clinical events, such as severe deterioration, likelihood of intensive care unit (ICU) admission, and mortality, both in hospital wards[2, 3, 4, 5, 6, 7] and in ambulatory care [8, 9, 10].

Two commonly used clinical scores are the *National Early Warning Score 2* (NEWS2) and the *Modified Early Warning Score* (MEWS)[9]. Both are calculated by capturing various vital parameters from the patient at a specific point in time, followed by numerical aggregation of the captured data according to the score being used[2, 11]. For MEWS, each measured physiological parameter is assigned an individual score based on which range it is in. The ranges for scoring each parameter are shown in Table 1. The individual scores are then added together to produce the final MEWS.

Individual Score	**+3**	**+2**	**+1**	**+0**	**+1**	**+2**	**+3**
Systolic Blood Pressure [mmHg]	< 70	$71 - 80$	$81 - 100$	$101 - 199$		≥ 200	
Heart Rate [bpm]		< 40	$41 - 50$	$51 - 100$	$101 - 110$	$111 - 129$	≥ 130
Respiratory Rate [bpm]		< 9		$9 - 14$	$15 - 20$	$21 - 29$	≥ 30
Temperature [°C]		< 35		$35 - 38.4$		≥ 38.5	
AVPU				alert	reacting to voice	reacting to pain	unresponsive

Table 1: MEWS calculation ranges

Traditionally, doctors and nursing staff perform collection and evaluation of the data manually, often inputting data into an EWS-calculator by hand. However, as Eisenkraft et al. mentioned in 2023, "some known setbacks of the NEWS and other scales are the frequency of scoring and response, integration into practice, and miscalculation by healthcare providers [...]"[12](p.2).

Remote patient monitoring (RPM) can improve deterioration detection[13] by greatly reducing the amount of human interaction required to take measurements and perform EWS calculations. A number of studies have explored RPM combined with automated EWS calculation in hospitals[12, 14, 15, 16]. With hospitals facing overwhelming patient load during the SARS-CoV-2 pandemic, interest in exploring remote patient monitoring options surged, and NEWS2 emerged as an effective tool for predicting severe infection outcomes[14, 17, 18, 19] while reducing person-to-person contact during patient monitoring. Since then, a variety of wearable medical sensors capable of continuously recording vital parameters have been developed and are commercially available[20, 21, 22, 23, 24].

2 Review of existing literature

In order to examine the current state of scientific knowledge about the use of wearable devices for automated EWS monitoring of patients at home, a comprehensive review of the existing literature was conducted. By systematically examining and synthesizing the current body of knowledge, this review identified a variety of approaches for utilizing smart medical devices in post-discharge patient care, as well as existing limitations and challenges in future research in this rapidly evolving field.

2.1 Search strategy

A systematic search strategy was implemented on the Scopus database, aimed to encompass a broad spectrum of literature relevant to the use of smart medical devices for automated early warning score monitoring of patients dismissed from ambulant or hospital care. The search focused on topics related to the research area, encompassing the examination of EWS, hospital admission, care escalation, and medical emergencies in combination with IT automation, medical wearables and Internet of Things (IoT). The Scopus database was chosen for its extensive coverage of scholarly literature across multiple disciplines.

For the search strategy, the following inclusion and exclusion criteria were employed to select relevant articles:

Inclusion criteria:

- Articles focusing on the utilization of medical wearable devices for remote patient monitoring
- Articles addressing the automated calculation of early warning scores
- Articles discussing the application of early warning scores outside of medical care facilities

Exclusion criteria:

- Non-English language articles
- Publications for which full-text access was not available
- Duplicate articles
- Articles outside of the "Computer Science" subject area

The following Scopus query was used to identify relevant literature:

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TITLE-ABS-KEY(("patient" OR "clinical" OR "medical") AND
    ("deterioration" OR "instability" OR "decompensation" OR
    "admission" OR "hospitalization" OR "escalation" OR "triage" OR
    "emergency")) OR ("early warning" OR "early warning score" OR
    "warning" OR "score*" OR "EWS") AND TITLE-ABS-KEY("system" OR
    "automat*" OR "smart*" OR "wearable*" OR "internet of thing*" OR
    "iot" OR "digital" OR "sensor*" OR "signal" OR "intelligen*" OR
    "predict*" OR "monitor*" OR "sreen*" OR "remote" OR "it" OR
    "comput*" OR "mobile" OR "5G" OR "network" (("vital*" OR "bio*")
    AND ("marker*" OR "sign*" OR "monitor*"))) AND
    TITLE-ABS-KEY("home" OR "domestic" OR "community" OR "remote" OR
    "longterm" OR "nursing" OR "rehabilitation" OR "outof*hospital"
    OR "telemedicine" OR "ehealth" OR "mhealth")
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2.2 Results

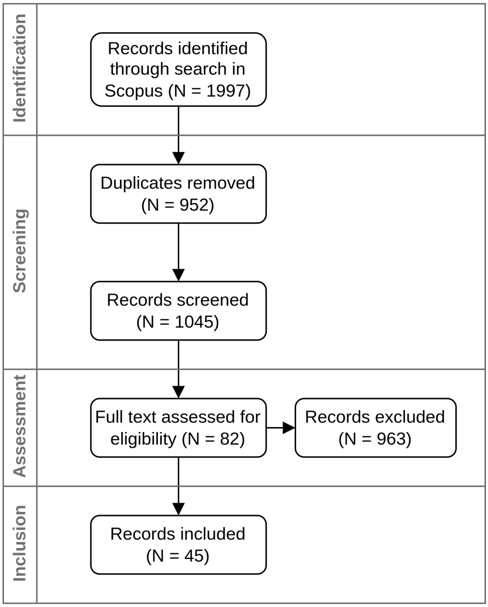

Figure 1: PRISMA flowchart showing screening and assessment of identified literature

An initial query on Scopus yielded a total of $N = 1997$ records. After removing duplicates, $N = 952$ records were excluded, resulting in $N = 1045$ unique records. Upon screening the titles and abstracts, $N = 963$ records did not meet the inclusion criteria, leaving $N = 82$ articles to be assessed for eligibility in full text. Finally, after a thorough evaluation, $N = 45$ articles were included for the literature review, providing insight into the current state of research on the use of smart medical devices for automated early warning score monitoring in patients transitioning from ambulant or hospital care. Figure 1 shows the literature assessment process. The list of reviewed literature is shown in Table 2.

Number	Title	Author(s), Year
1	Internet of things enabled in-home health monitoring system using early warning score[25]	Anzanpour 2015
2	Context-Aware Early Warning System for In-Home Healthcare Using Internet-of-Things[26]	Anzanpour 2016
3	An IoT based system for remote patient monitoring[27]	Archip 2016
4	Wireless sensor network-based smart room system for healthcare monitoring[28]	Arnil 2011
5	Design and Development of IOT Based Multi-Parameter Patient Monitoring System[29]	Athira 2020
6	Medical warning system based on Internet of Things using fog computing[30]	Azimi 2016
7	Self-aware early warning score system for IoT-based personalized healthcare[31]	Azimi 2017
8	Review on IoT based Healthcare systems[32]	Krishna 2022
9	Effectiveness of Early Warning Scores for Early Severity Assessment in Outpatient Emergency Care: A Systematic Review[9]	Burgos-Esteban 2022
10	A QRS Detection and R Point Recognition Method for Wearable Single-Lead ECG Devices[33]	Chen 2017
11	Adopting the Internet of Things technologies in health care systems[34]	Chiuchisan 2014
12	An Efficient Wireless Health Monitoring System[35]	Chowdary 2018
13	DeepSigns: A predictive model based on Deep Learning for the early detection of patient health deterioration[36]	da Silva 2021
14	Use of ultra-low cost fitness trackers as clinical monitors in low resource emergency departments[37]	Dagan 2020
15	A data fusion algorithm for clinically relevant anomaly detection in remote health monitoring[38]	de Mello Dantas 2020
16	Patient attitudes towards remote continuous vital signs monitoring on general surgery wards: An interview study[1]	Downey 2018
17	Developing a real-time detection tool and an early warning score using a continuous wearable multi-parameter monitor[12]	Eisenkraft 2023
18	An IoT-Based Healthcare Platform for Patients in ICU Beds During the COVID-19 Outbreak[14]	Filho 2021
19	Patient Monitoring System Based on Internet of Things[39]	Gomez 2016
20	Continuous monitoring is superior to manual measurements in detecting vital sign deviations in patients with COVID-19[40]	Gronbaek 2023
21	Secure and lightweight privacy preserving Internet of things integration for remote patient monitoring[41]	Imtyaz 2022
22	Remote Continuous Health Monitoring System for Patients[42]	Jagadish 2018
23	Cost utility analysis of continuous and intermittent versus intermittent vital signs monitoring in patients admitted to surgical wards[43]	Javanbakht 2020
24	Wearable sensors to improve detection of patient deterioration[44]	Joshi 2019
25	Intelligent Healthcare[45]	Kale 2021
26	A Hospital Healthcare Monitoring System Using Internet of Things Technologies[16]	Karvounis 2021
27	All-day mobile healthcare monitoring system based on heterogeneous stretchable sensors for medical emergency[46]	Lee 2020
28	Analysis of the early warning score to detect critical or high-risk patients in the prehospital setting[47]	Martin-Rodriguez 2019
29	An IoT-based framework for early identification and monitoring of COVID-19 cases[18]	Otoom 2020
30	A conceptual IoT-based early-warning architecture for remote monitoring of COVID-19 patients in wards and at home[10]	Paganelli 2022
31	Personalized Mobile Health for Elderly Home Care: A Systematic Review of Benefits and Challenges[48]	Pahlevanynejad 2023
32	CuraBand: Health Monitoring and Warning System[49]	Phaltankar 2021
33	Internet of Things in Healthcare, A Literature Review[50]	Quraishi 2021
34	Vital Sign Monitoring System for Healthcare Through IoT Based Personal Service Application[51]	Sahu 2022
35	Internet-of-Things-Enabled Early Warning Score System for Patient Monitoring[52]	Sahu 2022
36	Cloud-Based Remote Patient Monitoring System with Abnormality Detection and Alert Notification[53]	Sahu 2022
37	Remote patient monitoring using artificial intelligence: Current state, applications, and challenges[13]	Shaik 2023
38	Prototype development of continuous remote monitoring of ICU patients at home[54]	Thippeswamy 2021
39	IoT based Smart Healthcare Monitoring Systems: A Review[55]	Tiwari 2021
40	Observational study on wearable biosensors and machine learning-based remote monitoring of COVID-19 patients[15]	Un 2021
41	Adaptive threshold-based alarm strategies for continuous vital signs monitoring[56]	van Rossum 2022
42	A retrospective comparison of the Modified Early Warning Score (MEWS) and machine learning approach[57]	Wu 2021
43	IoT based Real Time Health Monitoring[58]	Yeri 2020
44	Vital Signs Prediction and Early Warning Score Calculation Based on Continuous Monitoring of Hospitalised Patients Using Wearable Technology[59]	Youssef Ali Amer 2020
45	Features of electronic Early Warning systems which impact clinical decision making[60]	Zarabzadeh 2012

Table 2: List of included articles

2.3 Discussion

While the application of EWS in ambulant care facilities and hospitals has been thoroughly investigated, very little research has been done to assess their practicability for remote monitoring of at-risk patients at home. Furthermore, it was observed that previous research on the use of IoT-devices for this purpose was largely conducted in experimental settings, limiting the generalizability of the results. Some studies have examined monitoring vital signs of at-home-patients for abnormalities, however in most of them, no automated EWS calculations were made[27, 30, 35, 58, 46, 29, 49, 54]. In 2015, Anzanpour et al. developed a monitoring system which collects vitals data and calculates EWS, however due to limited or nonexistent availability of wireless sensors for all relevant vital signs, the work was limited to using a laboratory prototype and required manual interaction in transferring vitals data[25]. Sahu et al. documented their development of an EWS-supported digital early warning system using the PM6750[52], an experimental vitals data monitoring device capable of taking continuous measurements in a laboratory setting[61]. However, the methodology they used to calculate EWS in real-time with laboratory data is both inconsistent and weak.

Recent studies indicate a growing trend towards investigating automated EWS calculations in real-world scenarios[1, 16, 32, 37]. Notably, the availability of comprehensive, mobile vital signs monitoring equipment has seen a significant increase, especially in the wake of the COVID-19 pandemic[10, 14, 18, 40]. This surge in accessibility has paved the way for more extensive and continuous monitoring of patients in non-medical care settings. Moreover, there is a growing interest in incorporating machine learning algorithms to enhance the predictive capabilities of deterioration detection[15, 36, 38]. This demonstrates the evolving landscape of remote patient monitoring, aiming to improve clinical outcomes and alleviate the burden on hospital wards.

Despite the wealth of literature reviewed, no existing empirical studies evaluating the use of early warning scores for patients at home were identified. This highlights a crucial research gap and prompts the need for further investigation in this area, potentially warranting the development of an EWS specialized for use outside of medical care facilities.

2.4 Interpretation of Results

Based on the findings, several key implications can be drawn. Firstly, the improved availability of smart sensors and the demonstrated effectiveness of EWS in predicting deterioration in direct medical care settings warrant research into their utilization at home. By remotely monitoring patients, it may be possible to identify early signs of deterioration, enabling earlier dismissal from hospital care and thereby freeing up valuable resources. Additionally, this approach holds the potential to reduce mortality rates and minimize the frequency of adverse clinical outcomes.

However, it is important to acknowledge the lack of research on the use of EWS at home, which calls for a feasibility study in this specific context. This study would need to address challenges such as the frequency of measurements required and the absence of immediate diagnosis from qualified medical staff. Overcoming these obstacles is essential to ensure the safety and efficacy of automated remote patient monitoring in home-based settings.

In conclusion, the literature review highlights the increasing interest in using smart medical devices and EWS for remote patient monitoring, particularly in real-world scenarios. The absence of studies evaluating the application of EWS in patients at home underscores the need for further investigation in this area. Conducting a feasibility study to explore the practicality and challenges of implementing EWS in home-based care would contribute significantly to the existing body of knowledge and help advance the field of automated early warning score monitoring in non-medical care settings.

3 Motivation

Installing and operating traditional continuous monitoring systems, like the vital sign monitors used in medical facilities, demands specialized equipment and technical expertise. Furthermore, these systems are cumbersome for patients, as they involve connecting patient and sensor device with numerous electrodes and cables, restricting patient mobility to the bed area, and physically tying the monitoring equipment to a single location. Conversely, battery-powered, wireless vitals monitoring devices, such as wearable armbands or smartwatches, can combine several biometric sensors into one device, allowing for a much higher degree of patient mobility, faster deployment and better scalability[15]. Therefore, utilizing such devices for RPM is a suitable approach.

In summary, with the current availability of wearable, networked biosensors and the validated effectiveness of EWS in medical facilities, combining both aspects presents an important and interesting research opportunity which could help reduce mortality and improve clinical outcomes for patients at risk of deterioration, both in their homes and on the go.

4 Objectives

The objective of this research is to explore the practical feasibility of using an existing, clinically validated EWS to remotely monitor patients who are still at risk of deterioration after having been dismissed from medical care facilities, utilizing smart medical sensor devices. Taking measurements using the devices should be as easy and unintrusive as possible for the patient, enabling them to take vital sign readings easily from the comfort of their home or while out of the house.

This will be accomplished by developing and subsequently evaluating a digital system capable of capturing, processing and monitoring patient vitals data. The system will consist of a network of smart medical sensors and a centralized web application used to store and process the data. Patients and, potentially, medical staff can interact with the application to visualize and utilize captured data. In addition to monitoring individual physiological parameters for abnormalities, the application will calculate the patient's current MEWS, and send alerts when an increased risk of deterioration is detected. A visualization depicting the main flow of data in the system is shown in Figure 2.

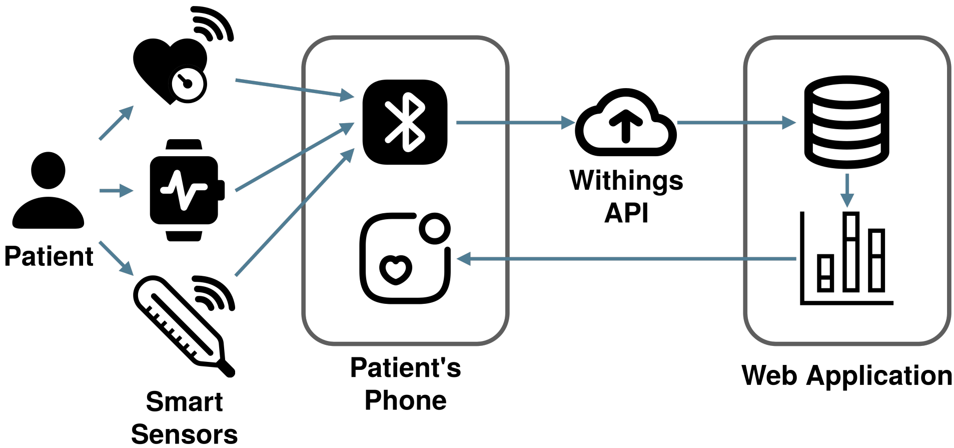

Figure 2: Data flow of the proposed early warning system

The following vital signs will be captured and processed by the application:

- Heart Rate (HR)
- Blood Pressure (BP)
- Body Temperature (TEMP)
- Blood Oxygen Saturation (SPO2)
- Respiratory Rate (RR) [1]
- AVPU Score [2]

The devices listed in Table 3 will be used to measure the patient's vital signs, while the web application and its alert system prompts the patient periodically to take new measurements.

Following the technical implementation of the described system, its day-to-day usability and effectiveness will be evaluated in a case study. Over the course of a week, a test subject, representing a patient recently dismissed from an accident and emergency hospital department (A&E) will be using the system both at home and while out and about. While awake, the patient will be prompted by the system via

[1] Determining the respiration rate of a mobile subject accurately using currently available electronic monitoring equipment presents a major challenge. Leveraging available SPO2 readings alongside asking the subject whether they are experiencing any shortness of breath may, however, provide a suitable compromise.

[2] Determining the AVPU score of a patient requires examination by qualified medical staff, but prompting the user to answer a simple question coherently to determine whether they are alert or not may be a suitable option.

Device Name	Device Type	Captured Vitals Parameter
Withings Scanwatch	Wearable Smartwatch	HR, SPO2, RR (while asleep)
Withings Thermo	Handheld Smart Thermometer	TEMP
Withings BPM Core	Smart Blood Pressure Cuff	BP, HR
Patient's phone	Smartphone	AVPU

Table 3: Smart devices used for data capture

smartphone notifications to take new measurements every two hours. The captured data and resulting MEWS records will be periodically reviewed by another person representing medical staff during this time.

Overall, the proposed research is aimed at answering the following scientific inquiries:

1. What are the challenges of developing and utilizing a remote patient monitoring system using smart medical sensors, given the currently available technology?
2. Can smart medical sensors be used effectively to determine MEWS remotely for patients discharged from A&E, hospital wards and ambulant care?

5 Tasks

The following milestones are defined for the research project:

1. Application design
   - Detailed software architecture design, data model design
2. Application development and unit testing
   - Database, API, authentication
   - MEWS algorithm, alerts
   - User interface
3. Application integration and deployment
   - SSL certificate installation, deployment to public webserver
4. Case study data collection
5. Case study data analysis and interpretation
6. Written compilation of findings
7. Reviews and adjustments

The total available time for the project is 12 weeks. A timeline for each defined milestone is displayed in Figure 3.

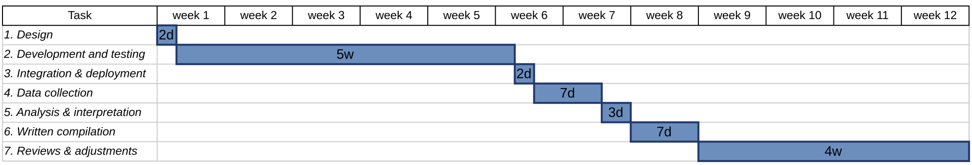

Figure 3: Project Timeline

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