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Validation of a Wearable Respiratory Rate Monitor for Early Detection of Clinical Deterioration

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ABSTRACT

Background: Respiratory rate (RR) is a sensitive but under-monitored vital sign, and intermittent ward observations create blind intervals during which clinical deterioration can progress undetected. Objective: This narrative review synthesizes published evidence on wearable and contactless RR monitoring technologies and their integration into early warning systems. Methods: We reviewed peer-reviewed validation studies of chest-worn strain and impedance sensors, acoustic and capacitive transducers, photoplethysmography/electrocardiography-derived algorithms, and radar-based contactless devices, alongside trials linking continuous RR monitoring to early warning score-triggered escalation. Findings: Device-level validation studies generally report mean absolute errors within a few breaths per minute of capnography or plethysmography references under resting conditions, but accuracy declines with motion, and manual-counting reference standards are themselves imprecise. Continuous ward-based monitoring trials show feasibility and earlier deterioration detection but inconsistent effects on mortality, limited by small, heterogeneous studies. Conclusions: Wearable RR monitoring is technically capable of clinically useful accuracy, but larger, standardized, outcome-focused trials are needed before continuous monitoring can be considered a proven driver of improved patient outcomes.

Keywords: *wearable respiratory rate monitoring; clinical deterioration detection; early warning score validation; contactless vital sign sensing; continuous ward-based monitoring*

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Introduction

Respiratory rate (RR) is widely regarded as the most sensitive, yet most neglected, vital sign in acute care. An abnormal RR frequently precedes cardiac arrest, unplanned intensive care unit (ICU) admission, and in-hospital death by hours, making it a cornerstone variable in composite early warning tools such as the National Early Warning Score (NEWS) and its successor NEWS2 [1,2,3]. Despite this recognized importance, RR is measured manually by counting chest excursions for 15–60 seconds, a method prone to observer bias, rounding to preferred digits, and outright omission on busy wards [4]. Intermittent spot-checks, typically performed every four to eight hours on general wards, create long blind intervals during which deterioration can progress undetected, a gap increasingly termed the "monitoring gap" between the ICU and the ward [5,6].

Wearable, continuous RR monitors have emerged as a candidate solution to this gap. Chest-worn accelerometers and impedance patches, acoustic sensors, photoplethysmography (PPG)-derived algorithms embedded in pulse oximeters and smartwatches, and contactless radar or optical systems have all been proposed and, to varying degrees, clinically validated against reference standards such as capnography, spirometry, or trained observers [7,8,9]. Several single-centre and multicentre trials have tested whether continuous wearable monitoring, when linked to a hospital early warning system, translates into earlier recognition of deterioration and improved outcomes [10,11,12].

This narrative review synthesizes the published evidence on wearable RR monitoring technologies, summarizes their validation against reference measurement methods, and examines how continuous RR data has been integrated into ward-based early warning systems for detecting clinical deterioration. Rather than describing a single new device, the review draws on the existing peer-reviewed literature spanning sensing physics, clinical accuracy studies, and pragmatic trials of continuous monitoring, with the aim of clarifying what is established, what remains uncertain, and where implementation

barriers persist.

Sensing Technologies for Wearable Respiratory Rate Monitoring

Wearable approaches to RR estimation broadly fall into four families. The first, and most mature, comprises chest-worn strain and impedance sensors that directly transduce the mechanical expansion of the thoracoabdominal wall during breathing. Stretchable strain-gauge patches, including devices built from conductive elastomer composites, have been shown to track both respiratory rate and tidal volume changes with correlation coefficients exceeding 0.9 against a calibrated spirometer in laboratory and ambulatory settings [13]. Bioimpedance-based patches, worn as a single adhesive sensor on the chest, similarly derive RR from cyclic impedance changes and have been deployed in multi-day ward monitoring studies [10,12].

The second family exploits acoustic and capacitive transduction. Acoustic sensors placed over the trachea or chest wall detect breath sounds and airflow turbulence, while capaciflector sensors measure the changing capacitance between an electrode and the skin as the chest wall moves; a validation study of a capaciflector device against a pneumotachograph reference reported mean absolute errors under 1 breath per minute (brpm) at rest, rising modestly during exercise [14].

A third family derives RR indirectly from photoplethysmographic or electrocardiographic waveforms already captured by pulse oximeters, wrist-worn optical sensors, or ECG leads, exploiting respiratory sinus arrhythmia and baseline-wander modulation of the pulse waveform. A comprehensive review of ECG- and PPG-derived breathing-rate algorithms catalogued more than 300 published methods and highlighted that fusion of multiple extraction techniques (amplitude, frequency, and baseline modulation) improves robustness over single-feature approaches, though accuracy degrades substantially during motion artifact and low perfusion states [8].

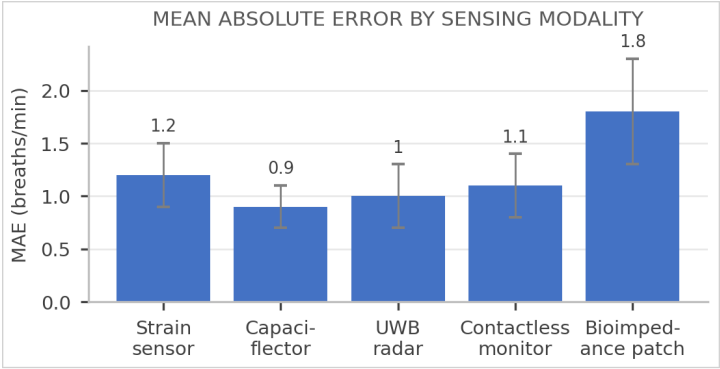
The fourth family comprises contactless technologies, principally continuous-wave and ultra-wideband (UWB) radar, and radio-frequency identification (RFID)-based backscatter sensing, which estimate chest-wall displacement remotely without skin contact. A UWB radar-based bedside device validated against manual counting and capnography across clinical and non-clinical settings reported a mean absolute error near 1 brpm across the tested range [15], and a further clinical validation of a contactless respiration monitor in a hospital population confirmed comparably close agreement with a reference nasal cannula-capnography signal [16]. A wearable RF backscatter patch has likewise demonstrated concurrent respiratory rate, respiratory volume, and heart-rate sensing without adhesive electrodes [17]. These contact-free options are attractive for populations in whom adhesive sensors are poorly tolerated, including neonates, patients with fragile skin, or those requiring monitoring during sleep, and have seen particular interest for remote and home-based respiratory surveillance, including during the COVID-19 pandemic when minimizing physical contact with symptomatic patients was a priority [18].

Across all four families, comparative reviews converge on two themes: mean absolute error against a criterion-standard reference is generally within 1–3 brpm under resting, low-motion conditions, but accuracy deteriorates markedly during ambulation, speech, or high respiratory rates, and reporting of validation methodology (reference standard, population, and statistical agreement metric) is heterogeneous across studies, complicating cross-device comparison [7,19,9].

Selected wearable and contactless respiratory rate sensing technologies, their transduction principle, and reported validation performance against reference standards.

Technology	Transduction principle	Reference standard	Reported accuracy	Source
Stretchable strain sensor patch	Chest-wall strain/impedance	Calibrated spirometer	Correlation r > 0.9 for rate and volume	Chu et al. 2019
Capaciflector sensor	Capacitive chest-wall displacement	Pneumotachograph	MAE < 1 brpm at rest	Hayward et al. 2022
UWB radar (bedside/contactless)	Radar-based chest-wall displacement	Manual counting / capnography	MAE approximately 1 brpm	Lauteslager et al. 2021
Contactless respiration monitor	Optical/radar chest-wall motion	Nasal cannula capnography	Close agreement, low bias	Bujan et al. 2023
Wireless multiparameter patch	Bioimpedance pneumography	Bedside reference monitor	Lower reliability than heart rate channel	Breteler et al. 2020

Reported mean absolute error (breaths/min) of representative wearable and contactless respiratory rate sensing modalities against reference standards (capnography, spirometry, or manual counting) in resting conditions, drawn from published validation studies [13,14,15,16,12].



Clinical Validation Against Reference Standards

Formal clinical validation of wearable RR monitors typically benchmarks device output against one of three reference measurements: capnography-derived RR, manual breath counting by a trained observer, or a calibrated respiratory inductance plethysmograph. A systematic review and meta-analysis of novel wearable and contactless heart rate, RR, and oxygen saturation devices pooled data from dozens of validation studies and found that pooled RR accuracy, while generally acceptable at rest, showed wide heterogeneity across device types and study populations, with several devices failing to meet the ISO-recommended limits of agreement for RR monitors [9]. This heterogeneity is compounded by the recognized unreliability of the manual-counting reference itself: a recent prospective ward-based study comparing manual and automated RR measurement found frequent discrepancies and evidence of digit preference in nurse-recorded counts, underscoring that the comparator against which wearables are validated is imperfect [4].

Multi-day inpatient validation studies provide the most clinically relevant evidence. In a cohort of high-risk surgical patients, a

wireless patch system continuously measuring RR, heart rate, and other vital signs demonstrated close agreement with reference monitoring and was capable of detecting deteriorations that were missed by standard intermittent nursing rounds, although RR measurement reliability was lower than for heart rate, reflecting the intrinsic difficulty of motion-robust respiratory sensing [12]. Similarly, a pilot study of wearable multiparameter monitoring on a general ward found continuous measurements feasible and broadly concordant with manual vital-sign checks, while identifying signal loss and false alerts as practical limitations requiring further engineering refinement [10]. A subsequent cluster-randomized pilot trial of a wearable wireless patch in surgical ward patients confirmed the feasibility of continuous RR and heart-rate monitoring relative to intermittent nursing observations, though it was underpowered to demonstrate a difference in clinical outcomes and again reported technical connectivity issues as a barrier to sustained data capture [11].

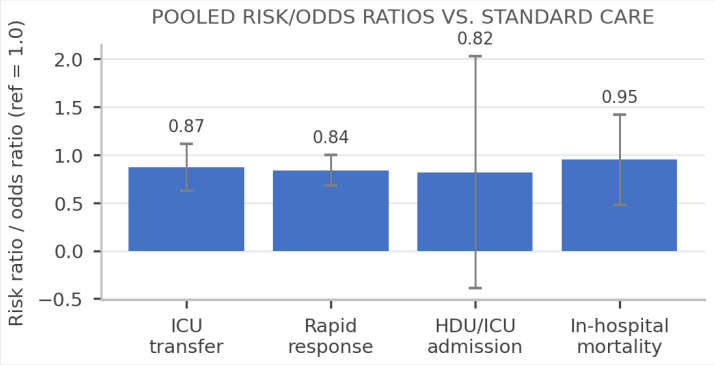
Summary of ward-based trials evaluating continuous wearable vital-sign monitoring linked to early warning score escalation pathways.

Study	Setting	Design	Key finding
Weenk et al. 2020	General ward	Randomized controlled pilot	Continuous monitoring feasible; concordant with manual checks, with signal-loss limitations
Downey et al. 2018	Surgical ward	Cluster-randomized pilot trial	Feasible continuous RR/HR monitoring; underpowered for outcome differences
Breteler et al. 2020	High-risk surgical patients	Prospective clinical validation	Detected deteriorations missed by intermittent rounds; RR less reliable than HR
Areia et al. 2021	Multiple hospital wards (meta-analysis)	Systematic review and meta-analysis	Point estimates favored monitoring (ICU transfer RR 0.87; rapid response RR 0.84) but not statistically significant
Bowles et al. 2024	General wards (RCTs only)	Systematic review and meta-analysis	HDU/ICU admission OR 0.82 and mortality OR 0.95, neither statistically significant

Taken together, these validation studies show that wearable RR monitors can achieve clinically useful accuracy in controlled and semi-controlled inpatient conditions, but that agreement with reference standards, sensor adherence, and signal continuity all decline in the less controlled environment of an active general ward, a pattern echoed across the broader literature on contact-based sensing [7].

Integration into Early Warning Systems for Clinical Deterioration

Pooled risk ratios (Areia et al.) and odds ratios (Bowles et al.) for ICU transfer/admission, rapid response activation, and in-hospital mortality with continuous wearable vital-sign monitoring versus standard intermittent care; a ratio of 1.0 indicates no difference. Error bars show 95% confidence intervals [6,20].



The clinical rationale for continuous wearable RR monitoring rests on its potential integration into early warning score (EWS) frameworks such as NEWS2, in which RR is one of the most heavily weighted parameters for triggering escalation [3,2]. Because EWS systems were originally designed around intermittent, manually charted observations, translating continuous wearable data into an EWS-compatible alerting pipeline requires decisions about update frequency, smoothing algorithms, and alarm thresholds to avoid excessive false-positive alerts while preserving sensitivity to genuine deterioration.

Evidence on whether this integration improves outcomes remains mixed. A systematic review and meta-analysis of wearable continuous vital-sign monitoring found point estimates favoring monitoring for unplanned ICU transfer (pooled risk ratio 0.87) and rapid response or cardiac arrest activation (pooled risk ratio 0.84), but neither reached statistical significance, and the authors concluded there was no definitive evidence that such monitoring improves deterioration detection or clinical outcomes, reflecting small sample sizes, heterogeneous outcome definitions, and risk of bias in the underlying trials [6]. A broader systematic review and meta-analysis restricted to randomised controlled trials of continuous ward-based vital-sign monitoring similarly found non-significant point estimates favoring the intervention for HDU/ICU admission (pooled odds ratio 0.82) and in-hospital mortality (pooled odds ratio 0.95), again reflecting the modest size and number of available trials [20]. A systematic review focused specifically on the evidence base for wearable wireless vital-sign monitoring in hospitalized adults concluded that while feasibility and patient acceptability were generally favorable, evidence for improved clinical outcomes remained preliminary and called for larger, adequately powered trials with standardized alerting protocols [21].

Several practical barriers recur across implementation studies. False and nuisance alarms generated by motion artifact or sensor displacement can lead to alarm fatigue among clinical staff, undermining the value of continuous monitoring even when underlying sensor accuracy is adequate [22]. Battery life, adhesive skin tolerance for multi-day wear, and integration with existing electronic health record and EWS charting systems represent further engineering and workflow challenges that have slowed translation from validation studies to routine practice [19,17]. Contactless radar and RF-based sensors, by removing the adhesive interface, may mitigate some of these barriers for

long-duration monitoring, but at the cost of sensitivity to patient positioning and multi-person interference in shared clinical spaces [15,16].

Conclusion

The published literature demonstrates that wearable and contactless respiratory rate monitoring technologies, spanning strain and impedance sensors, acoustic and capacitive transducers, PPG/ECG-derived algorithms, and radar-based systems, can achieve clinically acceptable agreement with reference measurements under controlled conditions, typically within a few breaths per minute of capnography or calibrated plethysmography [13,14,15,8]. Translating this bench-level accuracy into reliable ward-based continuous monitoring remains more challenging, with motion artifact, sensor adherence, and alarm management persisting as unresolved obstacles [10,11,9]. Early evidence linking continuous wearable RR monitoring to early warning score-triggered escalation suggests a plausible benefit for earlier deterioration detection, but current trials are too few, too small, and too heterogeneous to confirm a mortality benefit [6,20,21]. Future validation work should prioritize standardized reference comparisons, transparent reporting of accuracy across activity states, and adequately powered multicentre trials that directly link continuous RR data streams to clinical outcomes, so that the promise of continuous respiratory surveillance can be rigorously distinguished from its current, still-developing evidence base.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Makinen A conceived the review, conducted the literature search, and drafted the manuscript. Jensen A contributed to the literature screening and technical framing and critically revised the manuscript for important intellectual content. Petrov G contributed additional context and approved the final version for submission.

Ethics Statement

Not applicable. This is a narrative review of previously published literature and did not involve new experimental data, human participants, or animal subjects.

Data Availability

No new data were generated or analyzed for this review. All sources synthesized are cited in the reference list and are available through their original publishers.

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