Wearables for continuous patient monitoring on COVID-19 isolation wards

Cristian Roman[1], Sarah Vollam[2], Peter Watkinson[2], Lionel Tarassenko[1]

***Abstract*— An ambulatory monitoring system for the continuous monitoring of heart rate, respiratory rate and oxygen saturation, using wearable devices was implemented at the start of the COVID-19 pandemic on selected isolation wards in a large UK hospital. We have retrospectively analysed the data and nurse observations from two groups of patients on these wards: those whose care was escalated so that they were admitted to the Intensive Care Unit (ICU); and those who were discharged home or to a non-isolation ward (stepping down).**

The computation of population averages for these two groups 24h prior to an ICU admission or prior to stepping down provides evidence for the value of wearable monitoring for the early identification of physiological deteriorations in COVID-19 patients. The continuous data from the finger-worn pulse oximeter reveals clinically significant changes between 2 and 3 hours ahead of the regular vital-sign observations by the nursing staff. We also show how a hybrid score based on six physiological parameters (calculated from a mixture of continuous and intermittent vital-sign data) can provide early warning of deterioration for high-risk patients.

***Clinical relevance*— Clinical deterioration is often preceded by deviations in physiological parameters. Episodes of desaturation, including silent hypoxia, in hospitalized patients with SARS-COV-2 infection are common and often not detected by routine vital-sign observations. Evidence is provided to show that continuous remote monitoring using wearable devices is able to identify patient deterioration early.**

I. Introduction

Continuous monitoring of vital signs using wearable devices has the potential to enable earlier detection of physiological deterioration than intermittent vital-sign observations by nursing staff [1].

Prior to the pandemic, we had been evaluating clinical-grade wearables for monitoring heart rate, respiratory rate and oxygen saturation in the context of a Virtual High-Dependency Unit (vHDU) project at our local hospital (John Radcliffe Hospital in Oxford). The aim of the project was to investigate how high-risk patients could be monitored and managed on a general ward using wearables and smart alerting algorithms, with full integration of the periodic nurse observations of the full set of vital signs - not only heart rate, respiratory rate and oxygen saturation but also blood pressure, temperature and level of consciousness.

In the vHDU Ambulatory Monitoring System (AMS), the wearable devices, a chest patch (VitalPatch®, VitalConnect, US) and a finger-worn pulse oximeter (WristOx$_2$® 3150 BLE, Nonin, US) are linked via Bluetooth to an Android tablet by the bedside of ambulatory patients on the ward [2]. It became clear at the end of February 2020 that the AMS technology and software developed for the vHDU project could be adapted for the main COVID-19 isolation ward. The patients were remotely monitored within the hospital: they were in individual rooms on the isolation ward, with the nursing staff caring for them situated in another location nearby. The amount of contact between the infected patients and the nursing staff was to be minimised, with the frequency of nurse observations, which required the use of Personal Protective Equipment (PPE), decreased as much as possible, whilst maintaining patient safety.

The system went live with its first ambulatory patients on 23rd March 2020, becoming part of usual care for the patients on the main isolation ward (not ill enough to go to Intensive Care or stepping down from it) as part of a local service evaluation (DATIX: 5973). The wearable vital-sign data was made available to the nursing staff outside the isolation rooms using the hospital Wi-Fi, and displayed on a dashboard which allowed the physiological status of the patients to be tracked in real-time but with no audible alerts implemented. In addition, the clinical staff were informed that the wearable finger-worn pulse oximeter tended to under-estimate oxygen saturation values by approximately 2%, with respect to the values recorded by the Philips MX450 pulse oximeter used by the nurses during their vital-sign observation rounds [3].

The electronic system used by the nurses to record the patient's vital signs on the isolation wards during the period analysed in this paper computed a Centile-based Early Warning Score (CEWS), named MCEWS (Manual CEWS [4]),

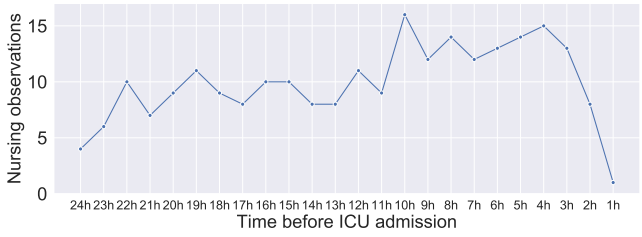

Fig. 1. Number of vital-sign observations made by the nursing staff on the isolation wards in the 24 hours prior to ICU admission.

*The research was funded by the National Institute for Health Research (NIHR) Oxford Biomedical Research Centre (BRC). The views expressed are those of the author(s) and not necessarily those of the NHS, the NIHR or the Department of Health. The research has been enabled by the Oxford University Hospitals NHS Foundation Trust Clinical Data Warehouse, which is supported by the NIHR Oxford Biomedical Research Centre and Oxford University Hospitals NHS Foundation Trust.

[1]Institute of Biomedical Engineering, Department of Engineering Science, University of Oxford, Oxford, United Kingdom

[2]Critical Care Research Group, Nuffield Department of Clinical Neurosciences, University of Oxford, Oxford, United Kingdom

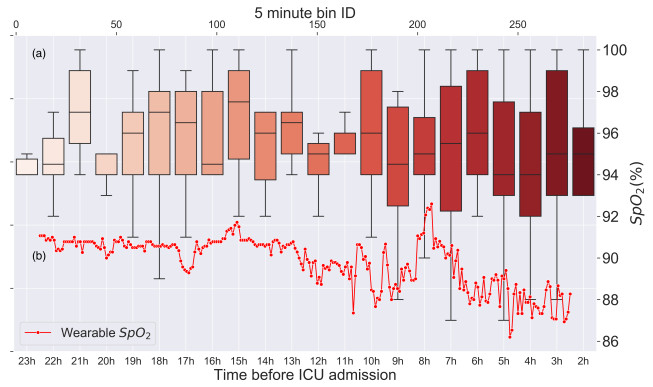

Fig. 2. (a) Box plots of SpO_2 values recorded by nurses during their vital-sign observation rounds, shown in 1-hour intervals for the 24 hours prior to an ICU admission, averaged for all patients in *group 1* (horizontal line indicates median and edges of box show upper and lower quartiles). (b) SpO_2 values acquired by the wearable pulse oximeter for each 5-minute bin during the 24 hours prior to an ICU admission, averaged for all patients in *group 1*.

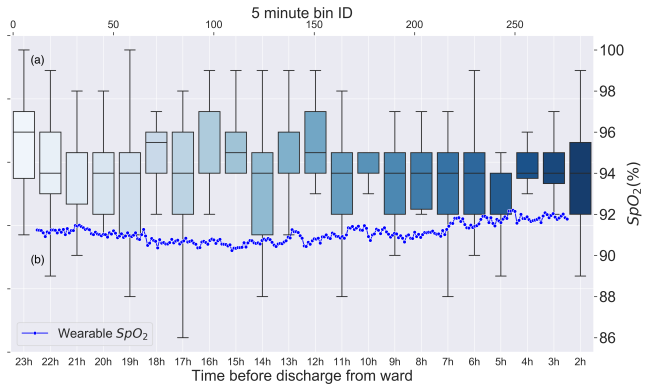

Fig. 3. (a) Box plots of SpO_2 values recorded by nurses during their vital-sign observation rounds, shown in 1-hour intervals for the 24 hours prior to stepping down, averaged for all patients in *group 2* (horizontal line indicates median and edges of box show upper and lower quartiles). (b) SpO_2 values acquired by the wearable pulse oximeter for each 5-minute bin during the 24 hours prior to stepping down, averaged for all patients in *group 2*.

with the vital-sign data and the score fed via the hospital Wi-Fi into the patient's Electronic Patient Record (Cerner Millennium). With MCEWS, the individual score assigned to each of the six vital-sign observations increases according to how far it departs from normality. When the MCEWS score reaches a value of 3, either because a single vital-sign is highly abnormal or several vital signs are deviating from normality, an alert is generated. The patients were nominally on 4-hourly observations, but if the MCEWS score reached the alerting threshold, either the frequency of observations was increased, or a decision was made by the clinical team on the ward to admit the patient to the Intensive Care Unit (ICU).

A similar approach has been used by others in COVID-19 wards, with wearable continuous monitoring being assessed as superior to intermittent nurse observations in detecting vital-sign deviations [5]. Wearable devices have also been assessed in the home setting for early detection of infection with mixed results [6].

The aim of the data analysis reported in this paper is to investigate whether the real-time wearable data identified physiological deterioration in COVID-19 patients earlier than the intermittent vital-sign observations recorded by the nursing staff.

II. Methods

Given the criticality of the situation on hospital wards in the first few months after the start of the pandemic, patients were not asked whether they would consent to their data being analysed. Instead, we have now obtained the permissions required to analyse the data retrospectively. All patient data, limited to the duration of hospital admission, is anonymised and no patient identifiable information is used for the analysis period.

The vital-sign data from all patients diagnosed with COVID-19 and admitted to the three isolation wards which were using the ambulatory system between 23rd March 2020 and 28th February 2021, corresponding to the first two waves of the COVID-19 pandemic in the UK, has therefore been analysed. A total of 165 unique patients were registered on the vHDU AMS. After removing the data from patients who had indicated their wish to opt out of any data analysis and from those who had incorrect information in their record, full data was available for analysis for 144 patients.

There are three groups of patients whose data could be investigated for retrospective analysis:

1) Those whose care was escalated so that they were admitted to the ICU;
2) Those stepping down (discharged home or to a non-isolation ward in the hospital);
3) Those who died on the ward (for whom we did not analyse the data for this paper due to clinical and ethical considerations).

There were 41 admissions to ICU with 10 transfers directly from one ICU ward to another. Out of the 31 first ICU admissions, 9 admissions occurred before the vHDU AMS could be connected to the patient; 22 admissions occurred afterwards. For the latter, there are 15 patients for whom we have the vHDU data for up to 24 hours prior to the ICU admission.

For patients in group 2, there are 72 instances for which we have vHDU data for up to 24 hours prior to discharge from the isolation wards (36 discharged home and 36 to a non-isolation ward within the hospital).

The main analysis presented in this paper is a comparison of the vital-sign trajectories for the patient populations in groups 1 and 2.

For the vital-sign nursing observations we investigated the observations in the 24 hours prior to ICU admission/ward discharge and synchronised these with respect to the ICU admission/discharge time. Figure 1 shows the total number of vital-sign observations made by the nursing staff of patients in group 1 in each one-hour interval in the 24 hours prior to ICU admission/ward discharge. The 1-hour bin (1 hour before admission/discharge) and 24-hour bins have fewer observations than the other bins, and the data from these

(a) Oxygen Mask Ratio (Patients on Mask / Total number of patients)

	23h	22h	21h	20h	19h	18h	17h	16h	15h	14h	13h	12h	11h	10h	9h	8h	7h	6h	5h	4h	3h	2h	1h
To ICU	13/15	14/15	13/15	13/15	13/15	13/15	13/15	13/15	13/15	14/15	14/15	14/15	14/15	14/15	13/15	13/15	13/15	14/15	14/15	14/15	14/15	14/15	14/15
Discharged from ward (Another ward)	24/36	29/36	28/36	30/36	31/36	32/36	33/36	34/36	34/36	34/36	34/36	34/36	34/36	34/36	34/36	34/36	34/36	34/36	35/36	35/36	35/36	35/36	35/36
Discharged from ward (Home)	19/36	16/36	15/36	14/36	9/36	9/36	9/36	10/36	10/36	10/36	10/36	10/36	10/36	8/36	8/36	7/36	7/36	7/36	7/36	7/36	7/36	7/36	6/36

(b) Oxygen Mask Adjustments (Mask Changes - Removal of mask)

	23h	22h	21h	20h	19h	18h	17h	16h	15h	14h	13h	12h	11h	10h	9h	8h	7h	6h	5h	4h	3h	2h	1h
To ICU	0 - 0	2 - 0	0 - 1	2 - 0	0 - 1	2 - 0	0 - 0	0 - 1	0 - 2	1 - 0	3 - 1	0 - 2	1 - 2	4 - 0	4 - 2	3 - 0	1 - 2	4 - 3	2 - 3	2 - 0	2 - 0	2 - 0	1 - 0
Discharged from ward	7 - 2	2 - 3	3 - 1	2 - 1	6 - 2	4 - 0	5 - 3	3 - 2	1 - 1	5 - 1	3 - 0	3 - 0	4 - 0	4 - 2	5 - 3	3 - 2	8 - 3	7 - 1	11 - 1	6 - 1	10 - 5	2 - 2	3 - 4

Fig. 4. (a) Ratio of patients wearing an oxygen mask to total number of patients; (b) number of oxygen delivery device adjustments, in both cases for patients admitted to ICU (group 1) and those stepping down (discharged to another, non-isolation, ward or discharged home) (group 2).

two bins is therefore excluded from further analysis.

The analysis of the vital-sign data acquired with the wearables is as follows:

1) For each patient in the two groups, the median SpO_2 value from the pulse oximeter is computed for each 5-minute bin for the 24 hours prior to ICU admission (group 1) or stepping down (group 2).
2) For each patient, the latest 5-minute median SpO_2 value is held until there is another valid 5-minute median value, thus avoiding any gaps in the 5-minute bin estimates; this is a representation of what happened on the isolation wards as the nurses would have seen the latest SpO_2 value on the dashboard with an 'x minutes ago' footer.
3) For each group, we calculate the average of the SpO_2 values within each 5-minute bin for all patients within that group.

The same methodology is used for the heart rate and respiratory rate acquired by the chest patch and used in the computation of the hybrid score providing an early warning of deterioration, which we name Continuous MCEWS (C-MCEWS). The scoring system is based on the same six physiological parameters measured by MCEWS: heart rate (HR), respiratory rate (RR), oxygen saturation SpO_2, systolic blood pressure (SBP), temperature (TEMP) and level of conciousness (Alert-Verbal-Painful-Unresponsive (AVPU scale)). A score of 0, 1, 2 or 3 is allocated to each parameter. A higher score indicates that the parameter is deviating further from its normal range of values. The score is updated every five minutes with median values of SpO_2, heart rate and respiratory rate, derived from the wearable devices, whilst the values of the three other vital signs (blood pressure, temperature and level of consciousness) are held until the next set of nurse observations. The ranges for each parameter used for the MCEWS (and C-MCEWS) scoring can be found in [4].

III. Results

Figures 2(a) shows the SpO_2 values recorded by nurses during their vital-sign observation rounds, for the 24 hours prior to an ICU admission, averaged for all patients in that group. Figure 2(b) shows the SpO_2 values acquired by the wearable pulse oximeter for each 5-minute bin during the same period.

The SpO_2 values measured by the wearable pulse oximeter are below 90% between 13 hours and 8 hours prior to ICU admission (Figure 2(b)), but this is not fully reflected in the corresponding nurse observations (Figure 2(a)). However, we can surmise that the nursing staff will have reacted to the worsening SpO_2 values, closely tracked by the wearable pulse oximeter, as Figure 4 reveals a high number of changes in the oxygen masks applied to the patients between 10 and 9 hours prior to ICU admission. Nurses will have realised that the patients were having difficulties breathing and attempted to increase the delivered oxygen through the use of a high-flow mask. The application of the latter causes a recovery in the SpO_2 values, clearly seen in the wearable data (Figure 2(b)) up to 8 hours before ICU admission and to a lesser extent, and with a delay of nearly 2 hours, in the nursing observations (Figure 2(a)).

The recovery in SpO_2 values only lasts a short time, however, with rapid deterioration, as evidenced by the wearable data, setting in 8 hours prior to admission to ICU, despite the increased oxygen delivery. Again, this is only identified in the nursing observations approximately three hours later. This analysis of data in Figure 2 provides the evidence for the value of wearable monitoring for the identification of physiological deteriorations in COVID-19 patients, with the continuous data showing clinically significant changes between 2 and 3 hours ahead of the regular vital-sign observations by the nursing staff.

The value of continuous pulse oximetry using wearables for ambulatory patients is confirmed by two other plots, Figures 3 and 5. Figure 3 shows the SpO_2 values recorded by nurses during their vital-sign observation rounds and the values acquired by the wearable pulse oximeter for each 5-minute bin for patients in group 2, during the 24 hours preceding discharge from the ward, either home or to a non-isolation ward. This shows a gradually increasing trend in the oxygen saturation values, indicating the reliability of wearable monitoring for ambulatory in-hospital patients, over a prolonged period of time (24 hours).

Figures 2 and 3 have presented the evidence from computation of population averages. This can mask the greater impact of wearable monitoring on an individual basis, when the changes may be even more marked. In Figure 5, the wearable SpO_2 data for one of the 15 patients in group

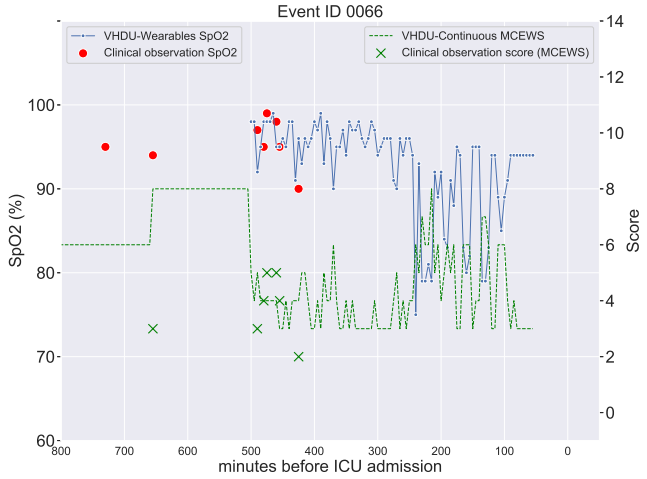

Fig. 5. The continuous SpO_2 data captured by the vHDU AMS (from finger-worn pulse oximeter) shows a marked deterioration after the last intermittent observation was performed by the nursing staff, 420 minutes before admission to ICU.

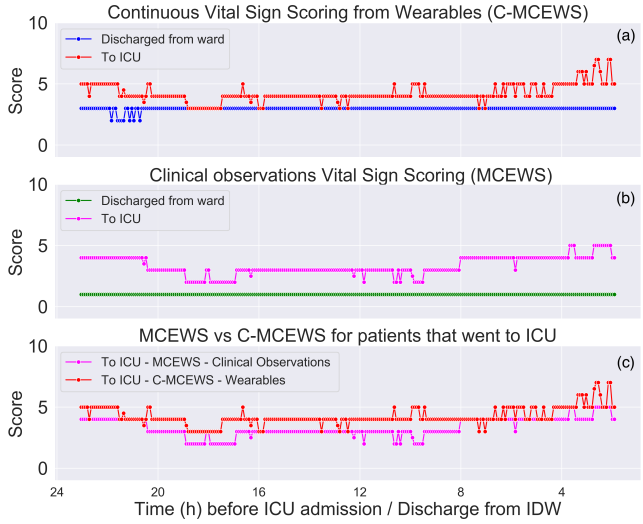

Fig. 6. Comparison between (a) continuous, hybrid Early Warning Score (C-MCEWS) computed from the wearable devices (SpO_2, HR and RR) and the most recent observations (SBP, TEMP and AVPU); (b) Early Warning Scores (MCEWS) calculated from the intermittent observations of the six vital signs by nurses. Plot (c) superimposes plots (a) and (b) for group 1 patients to show that the hybrid EWS (C-MCEWS) is more sensitive to physiological deterioration and identifies it earlier.

1 shows a marked deterioration after the last vital-sign observation by a nurse was performed 420 minutes before an admission to ICU.

Oxygen saturation was rapidly established at the start of the pandemic as the marker of physiological deterioration in COVID-19 patients. However, within hospitals, Early Warning Scores (EWS) continued to be used to manage patients. In Figure 5, we show that our early warning score, calculated from a mixture of continuous and intermittent vital-sign data can provide earlier warning of patient deterioration, ahead of the next set of intermittent observations by the nursing staff. The hybrid EWS in Figure 5 is mainly driven by the changes in SpO_2, as COVID-19 patients only experienced minor deviations in heart rate, blood pressure or temperature [5]. Figure 6, which compares the hybrid EWS (C-MCEWS) with the EWS calculated using only the intermittent observations (MCEWS) for both groups of patients, shows that the C-MCEWS is more sensitive to physiological deterioration and identifies it earlier in patients admitted to ICU (group 1).

IV. Conclusion

We have shown in this paper that wearable devices can be used to monitor SpO_2 in COVID-19 patients and track patient status reliably over time, with the advantage that physiological deterioration may be identified early, between intermittent nursing observations. We note that our data is from a single hospital, with a small number of ICU admissions with sufficient high-quality data, and this may limit the generalisability of our findings. However, we agree with [7] that, in the hospital of the future, ICU beds may be reserved for patients requiring organ support. Other high-risk patients needing close attention could safely stay on general wards, provided that they were nursed with real-time, continuous wearable monitoring and smart alerting systems. With this in mind, we are currently in the early stages of a randomized controlled trial whose aim is to test this hypothesis, using real-time wearable monitoring as described in this paper, but with additional alerting based on the real-time computation of a hybrid EWS, for optimal management of high-risk post-surgical patients on a general ward [8].

References

[1] Watkins T, Whisman L, Booker P. Nursing assessment of continuous vital sign surveillance to improve patient safety on the medical/surgical unit. J Clin Nurs Blackwell Publishing Ltd; 2016 Jan 1;25(1–2):278–281. PMID:26531215

[2] Santos MD, Roman C, Pimentel MAF, Vollam S, Areia C, Young L, Watkinson P, Tarassenko L. A Real-Time Wearable System for Monitoring Vital Signs of COVID-19 Patients in a Hospital Setting. Front Digit Health. 2021 Sep 7;3:630273. doi: 10.3389/fdgth.2021.630273. PMID: 34713102; PMCID: PMC8521865.

[3] Santos M, Vollam S, Pimentel MA, Areia C, Young L, Roman C, Ede J, Piper P, King E, Harford M, Shah A, Gustafson O, Tarassenko L, Watkinson P. The Use of Wearable Pulse Oximeters in the Prompt Detection of Hypoxemia and During Movement: Diagnostic Accuracy Study. J Med Internet Res. 2022 Feb 15;24(2):e28890. doi: 10.2196/28890. PMID: 35166690; PMCID: PMC8889481.

[4] Watkinson PJ, Pimentel MA, Clifton DA, Tarassenko L. Manual centile-based early warning scores derived from statistical distributions of observational vital-sign data. Resuscitation. 2018 Aug 1;129:55-60

[5] Grønbæk KK, Rasmussen SM, Langer NH, Vincentz M, Oxbøll AB, Søgaard M, Awada HN, Jensen TO, Jensen MT, Sørensen HB, Aasvang EK. Continuous monitoring is superior to manual measurements in detecting vital sign deviations in patients with COVID-19. Acta Anaesthesiologica Scandinavica. 2023 May;67(5):640-8.

[6] Mitratza M, Goodale BM, Shagadatova A, Kovacevic V, Van de Wijgert J, Brakenhoff TB, Dobson R, Franks B, Veen D, Folarin AA, Stolk P. The performance of wearable sensors in the detection of SARS-CoV-2 infection: a systematic review. The Lancet Digital Health. 2022 May 1;4(5):e370-83.

[7] Michard F, Saugel B, Vallet B. Rethinking the post-COVID-19 pandemic hospital: more ICU beds or smart monitoring on the wards? Intensive Care Med. Springer; 2020. p. 1792–1793. [doi: 10.1007/s00134-020-06163-7]

[8] vHDU Phase 5: Impact of an Ambulatory Monitoring System on Deterioration Detection and Clinical Outcomes (protocol under review) - https://clinicaltrials.gov/ct2/show/NCT05118477