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Contactless monitoring of respiratory rate (RR) and heart rate (HR) in non-acuity settings: a clinical validity study

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ABSTRACT

Objective Patient monitoring in general wards primarily involves intermittent observation of temperature, heart rate (HR), respiratory rate (RR) and blood pressure performed by the nursing staff. Several hours can lapse between such measurements, and the patient may go unobserved. Despite the growing widespread use of sensors to monitor vital signs and physical activities of healthy individuals, most acutely ill hospitalised patients remain unmonitored, leaving them at an increased risk. We investigated whether a contactless monitoring system could measure vital parameters, such as HR and RR, in a real-world hospital setting.

Design A cross-sectional prospective study.

Setting and participants We examined the suitability of employing a non-contact monitoring system in a low-acuity setup at a tertiary care hospital in India. Measurements were performed on 158 subjects, with data acquired through contactless monitoring from the general ward and dialysis unit.

Outcome measures Vital parameters (RR and HR) were measured using a video camera in a non-acuity setting.

Results Three distinct combinations of contactless monitoring afforded excellent accuracy. Contactless RR monitoring was linearly correlated with Alice NightOne and manual counts, presenting coefficients of determination of 0.88 and 0.90, respectively. Contactless HR monitoring presented a coefficient of determination of 0.91. The mean absolute errors were 0.84 and 2.15 beats per minute for RR and HR, respectively.

Conclusions Compared with existing Food and Drug Administration-approved monitors, the findings of the present study revealed that contactless monitoring of RR and HR accurately represented study populations in non-acuity settings. Contactless video monitoring is an unobtrusive and dependable method for monitoring and recording RR and HR. Further research is needed to validate its dependability and utility in other settings, including acute care.

Trial registration number CTRI/2018/11/016246.

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ Consumer grade devices compared with gold standard in the non-contact settings and more than one device included for comparison.
⇒ The data acquisition was done in real time simultaneously with gold standard.
⇒ The study was conducted at a single site only.
⇒ Only a limited portion of the participant's hospital stay was covered.

INTRODUCTION

Patient monitoring involves repeated or continuous observation of vital signs and physiological function. It is essential to assess the clinical progress, ensure patient safety and guide therapeutic interventions. Currently, most advanced cardiorespiratory monitoring systems involve expensive equipment, apart from rigorous manual evaluation. Therefore, continuous advanced cardiorespiratory monitoring is mainly restricted to intensive care units (ICUs), high-dependency units, operating rooms and postanaesthesia care units. In most medical and surgical wards, patient monitoring remains basic and intermittent.[1] Patients are monitored by nursing staff, who perform regular observation rounds at a frequency dictated by the hospital protocol and patient status. Some at-risk patients may deteriorate and experience unanticipated adverse events between observation rounds. Despite the widespread use of sensors to monitor vital signs and physical activity, most hospitalised patients remain unmonitored, leaving them at risk of clinical deterioration or catastrophic events going unnoticed.[2 3] On average, 50% of hospital deaths have been documented in the unmonitored patient population.[4 5] Outcomes of catastrophic cardiorespiratory events in unmonitored general care wards are significantly worse than those in monitored wards and ICUs.[6–8]

Although several medical devices are available for frequent patient monitoring,[9] current sensor-based electronic modalities

are often associated with high costs, suboptimal ergonomics and poor patient acceptance.[2] Likewise, wearable devices capable of patient monitoring may not be suited to all populations, especially the elderly, and may be associated with a degree of physical discomfort.[10 11]

Contactless monitoring technology, as discussed in the present study, measures the vital signs of a person using video data obtained with a camera. The respiratory rate (RR) is derived from the chest movements, whereas the pulse rate (PR) is derived from the minute colour changes caused by blood volume variations in the face with each cardiac pulse.[12–15] This technology affords an easy, hassle-free and unobtrusive method for monitoring RR and PR. To the best of our knowledge, the present study is the first to investigate the reliability of contactless monitoring, using video, of vital signs,[13] (RR and heart rate (HR)) in a non-acuity hospital setting in India. This study was designed to assess the relative agreement between contactless monitoring and standard clinical practice of vital sign measurements in a non-acuity hospital setting.

Figure 1 The general ward and dialysis room setup for the non-contact monitoring.

METHODS

Study design and population

We adopted a cross-sectional, prospective study design to investigate and determine the suitability of deploying a contactless monitoring system in a low-acuity setup at a tertiary care hospital. Here, we included patients undergoing dialysis and medical treatment for various conditions. A target sample size of 158 participants was calculated. Inclusion criteria were: (1) patients who consented to study participation, (2) patients in the general ward in non-acuity settings and (3) patients aged >18 years. Exclusion criteria were as follows: (1) patients requiring acute care and (2) patients in high-acuity hospital settings. Patients requiring acute care were defined as those presenting a modified early warning score (MEWS) greater than 4; the urine output component was excluded, as patients with chronic kidney disease were recruited in the present study.

Study setting and the experimental setup

The study was conducted at the dialysis and general medical units of the Kasturba Hospital, Manipal, India (figure 1). Data collection units were established according to the study protocol guidelines. The data collection environment was safe and secure to ensure participant comfort and better data acquisition. The assessment room was equipped with adequate lighting and curtains to minimise errors and facilitate measurement uniformity. The technical support team was responsible for setting up and managing equipment. Prior to enrolment, each participant was evaluated for MEWS to identify patients at risk of deterioration, which involved monitoring the PR, RR, blood pressure, temperature and level of consciousness, followed by the readiness to lie down on the bed for 30 min as assessed by the study nurse. The assessment devices were placed on either side of the participant's bed for effortless assessment of parameters. The participants were placed in a supine position with a pillow supporting the head. As shown in figure 2, the camera was mounted 4–5 feet, focusing on the patient's face and upper torso. The nasal prongs were positioned into the nostrils, curving downward, with the other end attached to the Alice NightOne device. The feed captured from the camera was transferred to a laptop, and the data were stored.

Study devices

1. The Philips Alice NightOne device, a US Food and Drug Administration (FDA)-approved sleep study device, was used as the reference device for pulse and RR measurements.
2. The data acquisition system comprised.

- A laptop HP ZBook 15 G3.
- Camera system: off-the-shelf IDS UI3060 camera and Tamron CCTV lens connected to one USB port of the laptop, both of which are CE certified.
- A software running to acquire signals from the camera.
- An external USB-hard drive (Western Digital My Book Duo 12 TB) was used to save data.
- Philips's IntelliVue MP40 Patient monitor.
- The nurse used a Maxbell USB wireless remote control as a ticker for manually counting respiration.
- Temp Teller Plus (GS-9030) infrared thermometer was used for temperature measurement.

Measurements

Figure 3 shows the detailed study protocol. The patient was attached to Alice NightOne sensors (nasal cannula and pulse oximeter probe) and requested to lie supine on the bed. Video recording was performed for 30 min.

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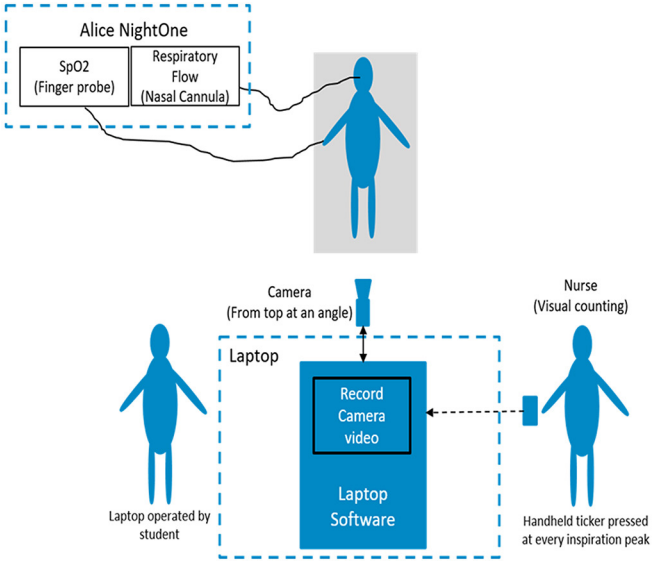

Figure 2 Outline of the study protocol.

The study nurse performed a visual counting of respiration for a 1 min duration at 0, 10 and 20 min by clicking the ticker at inspiration peaks. In addition, the MEWS of the patient was evaluated before the start of recording, at 15 min, and at the end of the recording.

Data analysis

Figure 4 shows the devices used t0 acquire data in the present study. Video recording was performed along with its associated parameters for a 30 min duration. For reference, two modalities were employed: (1) Alice NightOne, which measures the flow signal and PR for the entire measurement session (30 min) and (2) manual counting of respiration, performed at three time points for 1 min durations for each subject at 0, 10 and 20 min. Manual count windows were used as references for spot-check measurement sessions. For the spot-check use case, the contactless monitoring measurement was reset at the start of the manual count windows to avoid bias in test measurements. The respiratory flow waveform was peak-annotated and used for RR computation. The manual count provided information regarding inspiration peaks, similarly allowing RR computation. Contactless monitoring can extract pulse-related and respiration-related signals from the video and derives the PR and RR values every second, allowing evaluation from a continuous measurement perspective and analysis was also performed in this regard; however, the analysis was restricted to the spot-check use case, which will be the need in low-acuity settings.

Figure 4 Devices used for monitoring of respiratory rate (RR) and heart rate (HR) measurements.

Spot-check rate calculation

The RR and PR were obtained as a continuous stream of values for each second. The arithmetic mean of all values obtained within the spot-check window of a 1 min duration was considered the spot-check measurement value. The contactless monitoring was reset at the start of the window to simulate a real-life scenario.

Sample size

Each subject was assessed for 30 min, and three spot-check measurements of RR were performed at 10 min intervals, at 0, 10 and 20 min. We used the methodology defined in Equation,[16] to calculate the sample size of the present study. To show agreement between measurement techniques, the average absolute difference between measurements, target difference T, should be less than the measurement noise, that is, the SD σ. Therefore, we consider a T value of 0.35σ, implying that the standardised difference (target difference/SD) was 0.35. Based on the nomogram of Gore and Altman, for a statistical significance of 5% and power of 95%, the nomogram constant C was 13. Therefore, the number of measurement samples

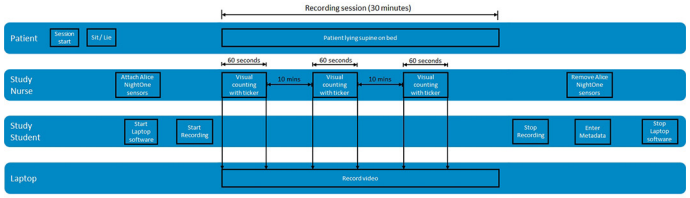

Figure 3 Block diagram of the study protocol.

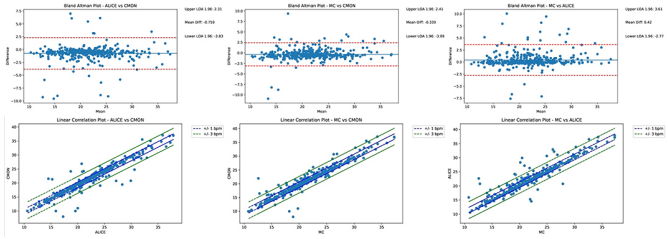

Figure 5 Bland-Altman and linear correlation plots for the various combinations of Alice NightOne (ALICE), contactless monitoring (CMON) and manual count (MC), considering the respiratory rate (RR).

required was 2×2 × 13/ (0.35)^2=425. This translated to 142 subjects (with each subject having a maximum of three scheduled measurements). Assuming a drop-out rate of 10% (eg, some subjects may not participate for the entire 30 min duration or data acquisition issues), the total sample size required was 157 subjects. We included one more subject than the target number; therefore, measurement data were obtained from 158 subjects. Notably, a similar sample size calculation for PR would yield a lower sample size, given that 'T' can be higher for the PR (because of the higher PR value). Hence, the sample size based on the calculation of the RR was sufficient for the PR.

Patient and public involvement

No patient was actively involved in developing the research question, outcome measures or study design. Patients were not involved in data interpretation or writing up of the findings, and there were no plans to disseminate the findings to the patient community impacted by this research.

Table 1 Sample characteristics presented in frequency and percentage (N=158)

Sample characteristics	Frequency	Percentage
Age (N=154)		
Age range 18–59 years	109	48.1
Age range >60–80years	45	48.1
Gender		
Male	76	48.1
Female	82	51.9
Weight (N=155)		
Mean±SD (kg)	59 ± (kg)	
Skin type*		
I	8	5.1
II	30	19.0
III	80	50.6
IV	39	24.7
V	1	0.6
Ward		
Dialysis	37	23.4
General ward	121	76.6

*Fitzpatrick scale types 1–6, where type 1 is the lightest and type 6 is the darkest.

Table 2 Accuracy range analysis for respiratory rate measurements

Bpm within	Distribution range		
±3	93.14	96.57	93.57
±2	89.97	92.08	90.24
±1	74.93	74.14	76.78

RESULTS

Participant demographics

In total, 158 patients were enrolled in the present study. Most participants (N=82; 51.9%) ranged between 40 and 60 years of age, and 82 (51.9%) were female. The mean weight of participants was 59±12.5 kg. Eighty (50.6%) participants were Fitzpatrick type 4 skin type, and 121 (76.6%) were from the general ward as shown in table 1.

Accuracy analysis of RR

As shown in figure 5, the top row presents the Bland-Altman plots for all three distinct combinations (manual counting, Alice NightOne and contactless monitoring), where the average RR difference was −0.76 and −0.3 breaths per minute (bpm), respectively, that is, less than 1 bpm. In the bottom row of figure 5, the linear correlation plot presents Alice NightOne and manual count with coefficients of determination of 0.88 and 0.90, respectively; the root-mean-square errors were 1.73 and 1.47 breaths per minute.

As shown in table 2, compared with Alice NightOne, the accuracy range analysis was within ±3 bpm for 93% of measurements and 96% for manual counting. The accuracy was further evaluated statistically by dividing the data into age (5-year bins), sex (male and female), skin type (Fitzpatrick scale), weight and ward/unit (dialysis and general) categories to assess the performance variations within these categories. Given the presence of large, one-sided outliers in the absolute error, the logarithm of the absolute error between contactless monitoring and references was selected as the dependent variable to improve the model residual normality. Table 3 summarises the analysis of variance (ANOVA) marginal test results. We noted that age, sex, skin type, weight and ward type did not impact the performance of contactless monitoring.

Measurements that were outside the limits of agreement in the Bland-Altman plot were defined as outliers, representing 4% of total measurements. One of the major causes underlying these outliers was the periodic curtain movement in the patient's background.

Table 3 Analysis of variance marginal test results of categorical data for respiration rate

Effect	Effect size	P value
Contactless Monitoring vs Alice NightOne		
Age (80 wrt 20 years)	−0.044 (−0.29 to 0.38)	0.79
Gender: Female wrt Male	−0.037 (−0.18 to 0.15)	0.67
Weight (97 wrt 32 kg)	0.16 (−0.2 to 0.9)	0.47
Skin type: V wrt IV	0.067 (−0.15 to 0.39)	0.60
Skin type: III wrt IV	0.0095 (−0.17 to 0.27)	0.93
Skin type: II wrt IV	−0.12 (−0.36 to 0.33)	0.50
Ward: General wrt Dialysis	0.092 (−0.13 to 0.43)	0.47
Alice NightOne (38 wrt 11 BPM)	0.59 (0.078 to 1.6)	0.02*
Contactless Monitoring & Manual count		
Age (80 wrt 20 years)	−0.11 (−0.3 to 0.17)	0.38
Gender: Female wrt Male	0.021 (−0.095 to 0.17)	0.74
weight (97 wrt 32 kg)	−0.012 (−0.26 to 0.42)	0.94
Skin type: V wrt IV	−0.053 (−0.2 to 0.15)	0.56
Skin type: III wrt IV	−0.044 (−0.18 to 0.13)	0.59
Skin type: II wrt IV	0.088 (−0.19 to 0.55)	0.60
Ward: General wrt Dialysis	−0.099 (−0.26 to 0.12)	0.34
Alice NightOne (38 wrt 11 bpm)	0.29 (−0.043 to 0.87)	0.10
Manual count & Alice NightOne		
Age (80 wrt 20 years)	0.073 (−0.11 to 0.48)	0.54
Gender: Female wrt Male	−0.071 (−0.16 to 0.06)	0.25
weight (97 wrt 32 kg)	0.031 (−0.17 to 0.6)	0.84
Skin type: V wrt IV	0.14 (−0.027 to 0.45)	0.12
Skin type: III wrt IV	0.055 (−0.065 to 0.26)	0.44
Skin type: II wrt IV	0.12 (−0.11 to 0.73)	0.41
Ward: General wrt Dialysis	0.093 (−0.057 to 0.37)	0.29
Alice NightOne (38 wrt 11 bpm)	0.38 (0.014 to 1.4)	0.04*

Effect sizes reported based on median expected values in absolute respiratory rate (RR) difference in beats per minute (bpm) (for categorical independent variables computed with respect to (wrt) an arbitrary base category, for continuous variables computed between minimum and maximum of independent effect values in the model data). The 95% CIs are shown in parentheses.
*Effects with p<0.05 (not corrected for multiple testing) are denoted with an asterisk.

Accuracy analysis of PR

According to the Bland-Altman plot in figure 6, the mean difference between contactless monitoring and Alice NightOne with PR was −1.27 bpm. We found large outliers in the negative direction, indicating an underestimation

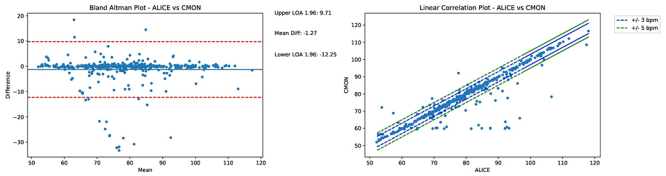

Figure 6 Bland - Altman and linear correlation plots for pulse rate measurements. ALICE, Alice NightOne; CMON, contactless monitoring; LOA, limits of agreements.

by the contactless monitoring solution. Figure 6 shows that contactless monitoring was linearly related to Alice NightOne, with a coefficient of determination of 0.91 and a mean absolute error of 2.15 bpm.

The PR values obtained by contactless monitoring were within ±3 bpm of those obtained by Alice NightOne for 85% of the measurements, with 91% of measurements within ±5 bpm, as shown in table 4 with an accuracy range plot. Given the presence of large, one-sided outliers in the absolute error, the logarithm of the absolute error between the camera and reference was selected as the dependent variable to improve the model residual normality. The intraclass correlation was 0.39, indicating that patient clusters did not primarily account for the total variance. Based on the ANOVA marginal test results shown in table 5, age, sex, weight and skin type did not impact the performance of contactless monitoring, with only ward type inducing a significant difference.

Considering one type of outlier (defined as measurements within an absolute difference of 7 bpm), we found that contactless monitoring provided a flat rate of 60 bpm in certain subjects in the dialysis ward (this affected 6% of total measurements); this outlier was not detected in general ward subjects. The underlying cause for this observation was analysed and attributed to ambient light variations caused by the blinking lights of nearby dialysis machines. On excluding measurement results impacted by this outlier type, the performance further improved, as shown in figure 7. The average of differences reduced to −0.3 bpm, the Pearson's correlation coefficient improved to 0.974, the mean absolute error improved to 1.01 bpm, and the percentage of points between (±3 and 5 bpm) improved (92 and 97%, respectively). We noted that another type of outlier, attributed to substantial facial movement and talking, affected approximately 3% of

Table 4 Accuracy range for pulse rate measurements

Bpm within	Distribution range
Total patient	100.0
±5	90.55
±4	87.81
±3	84.83
±2	81.09
±1	72.39

Bpm, beats per minute.

Table 5 Analysis of variance marginal test results of categorical data for pulse rate

Effect	Effect size	P value
Alice NightOne (118 wrt 52 bpm)	0.46 (10.043 to 1.9) bpm	0.09
Age (85 wrt 20 years)	−0.21 (−0.42 to 0.36) bpm	0.34
Weight (97 wrt 28 kg)	−0.52 (−0.69 to 0.12) bpm	0.08
Gender: female wrt male	−0.21 (−0.35 to 0.029) bpm	0.08
Skin type: V wrt IV	0.11 (−0.17 to 0.7) bpm	0.53
Skin type: III wrt IV	−0.1 (−0.25 to 0.18) bpm	0.39
Skin type: II wrt IV	0.13 (−0.23 to 1.1) bpm	0.62
Ward: general wrt dialysis	−0.51 (−0.7 to −0.095) bpm	0.02*

Effect sizes reported based on median expected values in absolute pulse rate difference in beats per minute (bpm) (for categorical independent variables computed with respect to (wrt) an arbitrary base category, for continuous variables computed between minimum and maximum of independent effect values in the model data). The 95% CI are shown in parentheses.
*Effects with p<0.05 (not corrected for multiple testing) are denoted with an asterisk.

total measurements. Please note that, to improve discrimination of true measurements versus outliers, Bandpass filtering is used. However, remaining outliers consist of estimates that deviate from the reference but still fall within the physiologically plausible ranges that we aim to cover.

Coverage of contactless monitoring

As shown in figure 8, contactless monitoring could provide results for 91% of RR measurements, whereas the reference device, Alice NightOne, provided results for 87.6% of measurements. Furthermore, contactless monitoring provided results for 90% of PR measurements. Conversely, Alice NightOne provided results for 94% of PR measurements.

DISCUSSION

Given the shift towards remote access and virtual meetings in the current postpandemic world, contactless monitoring could afford a giant technological leap, ensuring that modern medicine is ready for the future.

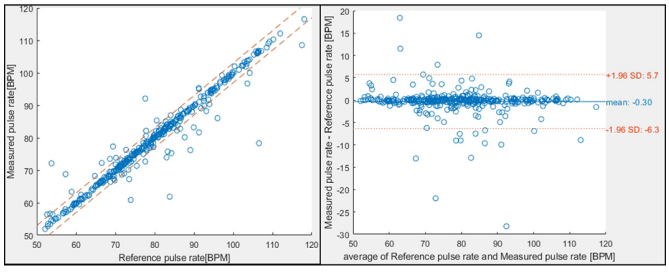

Figure 7 Accuracy range analysis plot for pulse rate measurements. BPM, beats per minute.

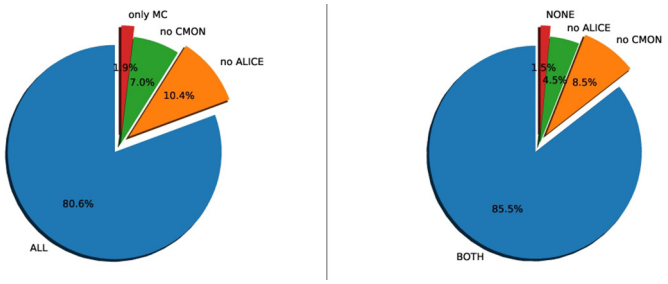

Figure 8 Coverage plot for respiratory rate (left) and pluse rate (right) measurements. ALICE, Alice NightOne; CMON, contactless monitoring; MC, manual count.

The contactless monitoring technique employed in the present study could measure patient PR and RR values from video data obtained using an off-the-shelf camera.[17]

The present study was conducted before the COVID-19 pandemic to compare the technology with the gold standard in real-world hospital settings. This study was conducted in a general ward setting, as these wards have a smaller nurse-to-patient ratio and less monitoring equipment. Hence, these patients are less frequently monitored and are at the highest risk of clinical deterioration or catastrophic events going unnoticed when the patient's condition deteriorates. Notably, outcomes of catastrophic cardiorespiratory events in unmonitored general wards are significantly worse than those in monitored wards and ICUs.[1] In addition, the study was undertaken in the dialysis ward while patients were undergoing intermittent dialysis, given that these patients experience major fluid shifts and have shallow reserves to tolerate acute medical events requiring corrective interventions.[18]

RR is one of the first vital signs to indicate the deterioration of a patient's condition. Recent evidence suggests that an adult with an RR of >20 breaths per minute is probably unwell, and an adult with an RR of >24 breaths per minute is likely to be critically ill.[13 14] Furthermore, the measurement of PR and RR alone can be as effective as MEWS for predicting deterioration.[2] This study was conducted using a camera to acquire RR values from the patient's chest movement and HR from the blood flow in the patient's face.[12 17 19]

To the best of our knowledge, this is the first study undertaken in India to compare contactless monitoring technology in a real-world setting with a gold standard FDA-approved monitor. The results showed comparable readings for both measured parameters. The difference in the RR was less than 1 breath/min, and the HR was within 3 bpm. Based on our findings, the performance of contactless monitoring is not affected by age, sex, weight and skin type.[14] However, given the benefits of contactless monitoring technology, one would accept these differences from a clinical perspective. Notably, a critical care outreach team can benefit from this technology.

We observed some interference in data capture owing to patient movements, which could pose difficulties in performing measurements in agitated patients. Furthermore, data from patients undergoing dialysis were skewed

in some cases, owing to background flashing lights from the dialysis machines. Consistently, it has been reported that motion artefacts and interactions between clinical staff and the patient were the main causes impacting the accurate estimation of the patient's HR.[18] In addition, our study was limited to RR and PR and lacked blood pressure, oxygen saturation and temperature measurements.

Measurement of RR traditionally involves the use of flow measurement sensors such as a nasal cannula to obtain a superior quality reading or impedance-based methods using ECG electrodes to obtain a fair reading. Likewise, the measurement of PR typically necessitates the application of a finger clip sensor, which poses a cross-infection risk.[20] Current modalities are associated with high device costs or low ergonomic/patient acceptance. Alternatively, wearable devices can also be employed for monitoring patients; however, such devices may be unsuitable across all populations, especially the elderly, and may be associated with a degree of physical discomfort. Another disadvantage of contact-based monitoring is that restless or psychiatric patients may physically damage the equipment.

Contactless monitoring is an easy, hassle-free and unobtrusive method for monitoring RR and PR. Another advantage of contactless monitoring is that it will significantly reduce the exposure of healthcare professionals to hazardous infectious agents, which is of particular relevance in the current scenario of COVID-19 and considering the possibility of future pandemics.[20]

CONCLUSIONS

Contactless video monitoring provides an unobtrusive and reliable modality for monitoring and recording RR and HR. The accuracy level may be impacted by an individual's movements, obstructive facial fixtures and ambient light. However, considering the scope of spot-check measurement of 1 min duration, the patient can be asked to remain motionless, and the environment can be controlled to ensure sufficient clinical accuracy. We believe that contactless monitoring could be employed as an effective adjunct to traditional monitoring methods and affords promise as a groundbreaking alternative. These limitations can be overcome with improved algorithms and the use of deep learning and machine learning techniques. Further studies are warranted to substantiate the reliability and utility of contactless monitoring in other settings and acute care.

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Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Consent obtained directly from patient(s).

Ethics approval The institutional review board of Kasturba Medical College, Manipal, approved the study protocol and monitored the study processes (EC No-MAHE EC/014/2018).The study was registred under Clinical Trial Registry of India(CTRI) and the number is CTRI/2018/11/016246. Current status is post results. Before study enrollment, the purpose of the study was explained to the participants, and the study nurse obtained written informed consent. The study participants were ascertained to be clinically stable and were enrolled between October 2018 and September 2019.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on resonable request. Data supporting the findings of this study are available upon request from the corresponding author.

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