Original Article

Should respiratory rate be measured on admission over a few seconds by a smartphone application or over 15 minutes by a piezoelectric device? A prospective observational pilot study of acutely ill medical patients admitted to a low-resource Ugandan hospital

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Abstract

Background: the optimal period over which respiratory rate should be measured is uncertain.
Setting: medical ward of low resource Ugandan hospital,
Methods: comparison of the first respiratory rates measured on admission over seconds using a smartphone application with measurements over 15 minutes using a piezoelectric device.
Results: There was a poor correlation between respiratory rates measured by the piezoelectric device and rates measured by a smartphone application. Although the discrimination for mortality of piezoelectric respiratory rates were slightly higher than those derived from the application, there were not statistically significant differences.
Conclusion: this study could not demonstrate potential clinical benefits that justify measuring the first respiratory rate after admission over 15 minutes by a device.

Keywords

respiratory rate, early warning scores, physiology, acute medicine, technology

Key points

- The first respiratory rate after admission with the highest association with mortality, measured by either method, is approximately ≥25 bpm.
- Clinically significant benefits that justify measuring the first respiratory rates after admission over 15 minutes by a device could not be demonstrated.
- A larger study might show the mortality discrimination of piezoelectric respiratory rates and NEWS calculated from them are higher than those derived from the RRate app.

Introduction

Respiratory rate is, arguably, the most important vital sign[1] and a component of most early warning systems.[2] Despite this, it is often recorded inaccurately or not at all,[3,4] and there is no gold standard for its measurement. Although it is quantified in breaths per minute (bpm), there is no evidence that a minute is the optimal period for its measurement. Nevertheless, it is still commonly measured by counting the rate for just 15 seconds and then multiplying by four. The smartphone RRate app[5] contains an algorithm that calculates the respiratory rate from the interval between taps on a smartphone screen. We have shown it measures respiratory rate nearly as quickly and more reliably than traditional 15 second observations multiplied by four.[6]

Until recently the capnograph has been the only device used routinely to measure respiratory rate. Rates measured over 5 minutes by a piezoelectric belt correlated poorly with measurements by nurses yet had a stronger association with patient mortality,[7] which suggested that the nurses' measurements were inaccurate.[8] Several other respiratory rate devices using different technical approaches are now available,[9] including a non-invasive, wireless, body worn, motion-tolerant and continuous respiratory rate monitor, which has comparable accuracy to the capnograph. This *RespiraSense*™ piezoelectric device reports the average respiratory rate every 15 minutes[10] and uses a disposable wearable sensor.[11] In contrast, the RRate app is free, and works on any android smartphone.

In this study we compared the first respiratory rates measured on admission over a few seconds using the free RRate app with those measured over 15 minutes by an piezoelectric device in a convenient sample of acutely ill medical patients admitted to a low resource Ugandan hospital. We also examined if using the piezoelectric device respiratory rates to calculate the National Early Warning Score (NEWS)[12] changed its performance.

Methods

Setting

This prospective, observational pilot study was conducted in Kitovu Hospital from 18th May 2023 to 22nd November 2023 and conforms with STROBE guideline.[13] Kitovu Hospital has 248 beds, 50 of which are adult medical, and is located near Masaka, Uganda, 140 km from the capital city of Kampala. It is a private not-for-profit hospital, accredited by the Uganda Catholic Medical Bureau.

Participants and study process

Participants were a convenient sample of consenting non-pregnant acutely ill patients aged 18 year of age or older who were admitted to the hospital's medical ward. The clinical status and vital signs on admission of every participant were entered at the bedside using tablet computers into a clinical database system,[14] which required that the patient's mental alertness, mobility, and complaints were entered each time the vital signs were measured. The system automatically calculated and stored the original National Early Warning Score (NEWS)[12] and recorded patient's status at discharge. All data entries were automatically time and date stamped. Patients who were alert, attentive, calm, and coherent provided written informed consent, all other patients were assessed as having altered mental status and written informed consent was provided by their next of kin.

All participating patients were admitted through a common emergency and out-patient department, which is only a few feet from the medical ward. Therefore, there was no delay to entering the medical ward once the decision to admit had been made. On admission respiratory rates were counted using the RRate app,[5] which calculates the respiratory rate from the interval between taps on a smartphone screen.[6] The respiratory rate measuring piezoelectric device (RespiraSense™, PMD Solutions, Cork, Ireland) was applied as soon as possible after admission to the patient and continuously streamed date and time stamped respiratory rate data by wireless to a secure server. The research nurses were unaware of this data, which was not available until after the study was completed. Attaching the device takes approximately 5 minutes. If the device did not have to be removed for clinical or operational reasons it remained on the patient up to 7 hours after admission.

Outcomes

In-hospital mortality and mortality within 24 hours of admission, and at 1,2,3,4,5, and 6 days after admission.

Statistic methods and data analysis

Data was interrogated using Microsoft Excel and Epi-Info version 6.0 (Centre for Disease Control and Prevention, USA). Numeric variables were tested for homogeneity by Bartlett's method. If normally distributed continuous variables were compared using ANOVA and if non-parametric by the Krustal-Wallis method. Categorical variables were compared using Chi squared analysis with Yates' continuity correction. Youden's J statistic (i.e., sensitivity + specificity – 1) was used to determine respiratory rates with the highest association with mortality at different times after measurement.[15] The p-value for statistical significance was 0.05. Respiratory rate recordings were compared by histogram inspection.[3,16] The C-statistics of the ability to discriminate between survivors and those who died in hospital at different times after respiratory rate measurement were determined by the method of Hanley and McNeil.[17] The c-statistic calculation of respiratory rates weighted them to capture the mortality risk associated with low rates: each rate was assigned to its appropriate NEWS weighted value (i.e., rates ≥12 and ≤20 bpm scored 0 points; rates ≥9 and ≤11 bpm scored 1 point; rates ≥21 and ≤24 bpm scored 2 points; and rates ≥8 or ≤25 scored 3 points).[12] The c-statistics of NEWS were calculated twice, once using the RRate app measured respiratory rate and again using the piezoelectric device measured rate.

Ethics

Ethical approval for the study was obtained from the Kampala International University (KIU-2021-45) and the Uganda National Council for Science and Technology (UNCST HS2792ES). The study conforms to the principles outlined in the Declaration of Helsinki.

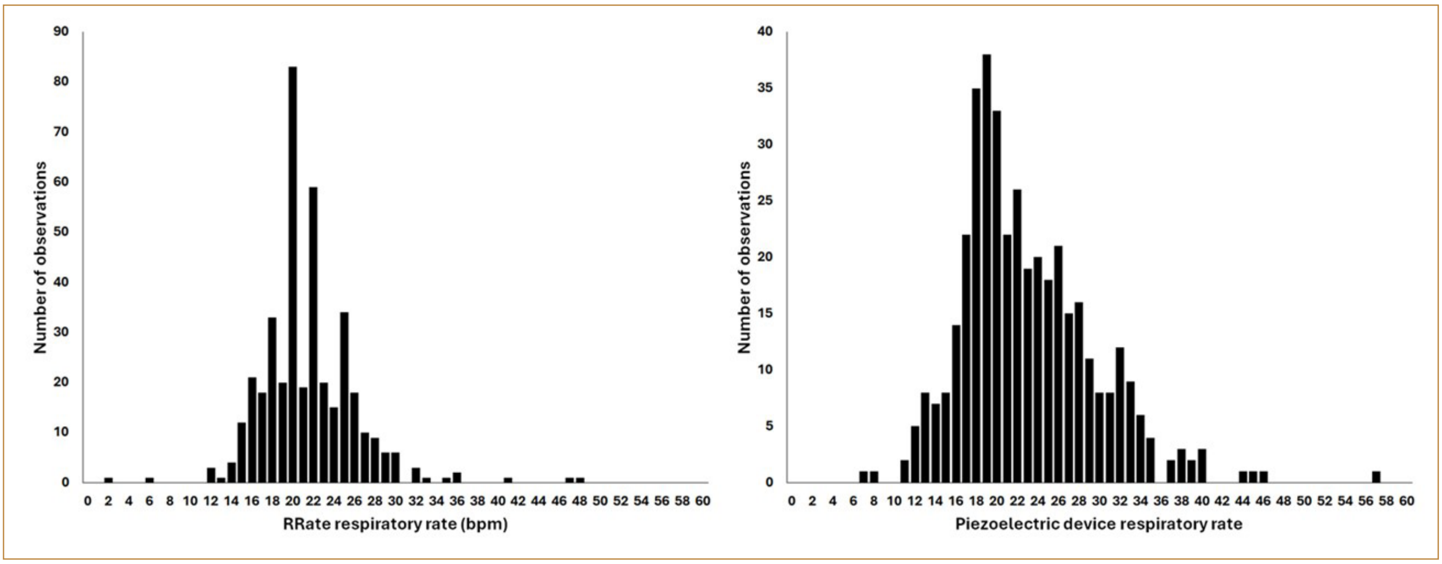

Figure 1. Histograms of respiratory rates measured by the RRate app compared to those measured by the piezoelectric device.

Results

A convenient sample of 403 patients participated in the study; their length of hospital stay was 3.5 SD 3.7 days (IQR 1,5 days), their mean age was 54.3 SD 23.0 years, and 167 (41.4%) of them were men. On admission 169 (41.9%) patients needed help to walk or were bedbound, 51 (12.7%) had altered mental status, and 268 (66.5%) had an RRate calculated NEWS ≥3.

Thirty-four patients (8.4%) died while in hospital; on admission 23 (67.6%) of these patients needed help to walk or were bedbound, 14 (41.2%) had altered mental status, and 29 (85.3%) had an RRate calculated NEWS ≥3. All 34 deaths occurred within 14 days of admission, 13 (38.2%) within 24 hours, and 27 (79.4%) within 7 days. Of the 13 patients who died within 24 hours, all had an RRate calculated NEWS ≥3 and needed help to walk or were bedbound, and 11 had altered mental status. Patients who died were older than survivors (64.9 SD 19.9 versus 53.3 SD 23.0 years, p 0.005) but had the same length of hospital stay (3.9 SD 3.7 versus 3.4 SD 3.7 days).

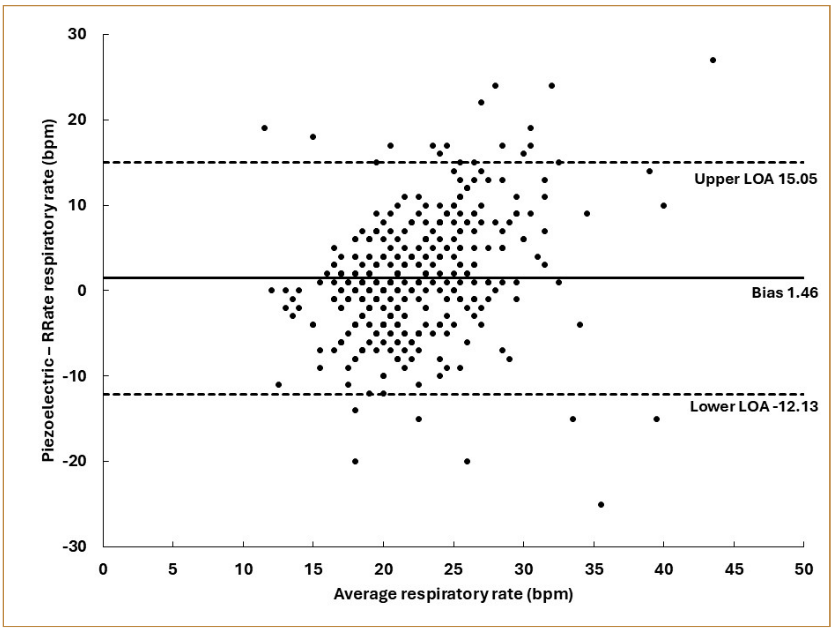

Figure 2. Bland-Altman plot of respiratory rate measured by the piezoelectric device compared to those measured by the RRate app. LOA = limits of agreement

The histogram of RRate app measured respiratory rate (aRR) had a more normal distribution than piezoelectric respiratory rate measurements (pRR), which were skewed to the left. Compared to the pRR histogram that of the aRR measurements showed an irregular distribution with clustering of rates and digit preference (Figure 1). The correlation between aRR and pRR was 0.26, and the Bland-Altman graph showed a bias of 1.46 bpm, lower limits of agreement of -12.13 bpm, and upper limits of agreement of 15.05 bpm (Figure 2).

The pattern of distribution of aRR and pRR associated with in-hospital mortality varied (Figure 3); aRR showed a linear increase in mortality with respiratory rate, whereas for pRR the relationship was U-shaped. The respiratory rate value that provided the highest odds ratio for mortality (i.e., with the highest Youden number) varied slightly with the time after measurement (i.e., between 0 and 14 days) and ranged from 23 to 25 bpm for pRR and from 23 to 26 bpm for aRR. Within 24-hours of admission and respiratory rate measurement, the odds ratio of death was 12.22 (95%CI 3.40 - 44.52) for an aRR >26 bpm and 6.52 (95%CI 1.60 – 30.74) for a pRR >24 bpm. The odds ratio for in-hospital mortality (i.e., within 14 days of measurement) was 3.13 (95%CI 1.19 – 8.07) for an aRR >26 bpm, and 2.53 (95%CI 1.17 – 5.50) for a pRR >24 bpm.

The correlation co-efficient between RRate calculated NEWS and piezoelectric calculated NEWS was 0.83, and the Bland-Altman plot had a bias of

Table 1. Agreement between NEWS calculated using piezoelectric device measured respiratory rate (pNEWS) and NEWS calculated using respiratory rate measured by RRate app (aNEWS)

	pNEWS																
aNEWS	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**>=15**	**Total**
0	15	0	8	8	0	0	0	0	0	0	0	0	0	0	0	0	**31**
1	0	24	0	14	14	0	0	0	0	0	0	0	0	0	0	0	**52**
2	9	0	24	3	7	9	0	0	0	0	0	0	0	0	0	0	**52**
3	3	9	2	27	7	3	11	0	0	0	0	0	0	0	0	0	**62**
4	0	6	13	4	22	6	9	3	0	0	0	0	0	0	0	0	**63**
5	0	0	6	6	4	11	5	3	3	0	0	0	0	0	0	0	**38**
6	0	0	0	2	7	1	12	8	2	3	0	0	0	0	0	0	**35**
7	0	0	0	0	0	6	1	9	5	1	1	0	0	0	0	0	**23**
8	0	0	0	0	0	2	0	0	11	1	0	0	0	0	0	0	**14**
9	0	0	0	0	0	0	3	0	1	6	2	0	0	0	0	0	**12**
10	0	0	0	0	0	0	0	0	1	2	3	2	0	0	0	0	**8**
11	0	0	0	0	0	0	0	0	1	0	1	2	0	0	0	0	**4**
12	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	**3**
13	0	0	0	0	0	0	0	0	0	0	1	0	0	3	0	0	**4**
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**
Totapl	27	39	53	64	61	38	41	23	24	14	8	4	1	4	1	1	**403**
Agreement	**55.6%**	**61.5%**	**45.3%**	**42.2%**	**36.1%**	**28.9%**	**29.3%**	**39.1%**	**45.8%**	**42.9%**	**37.5%**	**50.0%**	**100.0%**	**75.0%**	**100.0%**	**100.0%**	

0.24 NEWS points, lower limits of agreement of -3.03 points, and upper limits of agreement of 3.51 points. The agreement between piezoelectric calculated NEWS and RRate calculated NEWS varied according to NEWS values: averaging 53% for NEWS 0-2, 36% for NEWS 3-8, 42% for NEWS 9-11, and 86% for NEWS >12 points (Table 1).

The discrimination between survivors and decedents of both NEWS weighted respiratory rates and NEWS calculated from RRate and piezoelectric rates declined with the time after measurement, and although the c-statistic of pRR and piezoelectric calculated NEWS were always slightly higher than aRR and RRate calculated NEWS, this difference was never statistically different (Table 2). Nevertheless, we found that if the trigger for an urgent clinical review was an RRate calculated NEWS ≥4 then 2 of the 13 (15.4%) patients who died within 24 hours would have been overlooked, whereas no patients died within 24 hours with a piezoelectric calculated NEWS <7.

Discussion

Main findings

This pilot study found that there was a poor correlation between piezoelectric rates measured over 15 minutes (pRR) and RRate rates measured over a few seconds (aRR), and the patterns of association between mortality and piezoelectric and RRate measurements are markedly different. Also, the distribution of RRate app respiratory rates was less left skewed than piezoelectric rates. Up to 14 days after measurement the respiratory rate with the highest association with mortality, measured by either method, is approximately ≥25 bpm. The discrimination for mortality of NEWS calculated using piezoelectric respiratory rates appears to be superior to the discrimination to NEWS calculated using RRate rates, which in a larger study might achieve statistical significance.

Interpretation

We have previously shown that the histogram of respiratory rates measured by the RRate app in over 4,500 out-patients was markedly superior to that of traditional counts at the bedside, as it showed no clustering of rates or digit preference, was left skewed, and closely resembled the piezoelectric rate histogram in this study[18] and confirms the findings of others that respiratory rates measured by piezoelectric devices are not normally distributed and skewed to the left.[19] We had hoped to show there would be little difference between the device measurements and those of the RRate app. Unfortunately, in this study the RRate histogram shows little difference from those previously

Table 2. The c-statistic at different times after measurement for National Early Warning Score (NEWS) weighted respiratory rates measured by the piezoelectric device (pRR) and by the RRate app (aRR), and NEWS calculated using respiratory rates measured by the piezoelectric device and by the RRate app. 95% CI = 95% confidence interval, SE = standard error.

		NEWS weighted respiratory rates							
		Piezoelectric measurement (pRR)				RRate measurement (aRR)			
Days after measurement	No deaths	C-statistic	95% CI		SE	C-statistic	95% CI		SE
0	13	0.735	0.577	0.893	0.0804	0.732	0.574	0.890	0.0806
1	19	0.698	0.564	0.833	0.0685	0.646	0.509	0.783	0.0699
2	23	0.640	0.515	0.766	0.0639	0.622	0.496	0.747	0.0640
3	23	0.640	0.515	0.766	0.0639	0.622	0.496	0.747	0.0640
4	24	0.649	0.527	0.772	0.0625	0.622	0.499	0.745	0.0627
5	25	0.657	0.537	0.777	0.0611	0.623	0.502	0.744	0.0615
6	27	0.648	0.532	0.763	0.0591	0.619	0.503	0.736	0.0593
14	34	0.624	0.519	0.728	0.0532	0.575	0.471	0.680	0.0532
		Piezoelectric calculated NEWS				RRate calculated NEWS			
Days after measurement	No deaths	C-statistic	95% CI		SE	C-statistic	95% CI		SE
0	13	0.918	0.814	1.022	0.0529	0.879	0.757	1.001	0.0621
1	19	0.870	0.765	0.974	0.0531	0.825	0.709	0.941	0.0592
2	23	0.807	0.697	0.916	0.0557	0.770	0.655	0.885	0.0587
3	23	0.807	0.697	0.916	0.0557	0.770	0.655	0.885	0.0587
4	24	0.806	0.699	0.913	0.0546	0.768	0.655	0.881	0.0577
5	25	0.815	0.711	0.918	0.0527	0.777	0.668	0.887	0.0559
6	27	0.811	0.711	0.911	0.0511	0.763	0.656	0.870	0.0548
14	34	0.752	0.655	0.849	0.0496	0.700	0.598	0.801	0.0518

reported for traditional bedside counts.[3,16] There is no obvious explanation for these findings. Both research nurses have used the RRate app over several years, so these results cannot be explained by lack of training or measurement error. As this study was small, the 'law of large numbers'[20] suggests that a larger study may improve the shape of the RRate histogram.

In contrast to the out-patients included in our previous study,[18] most of the patients in this study were extremely ill, and it has been suggested that nurse

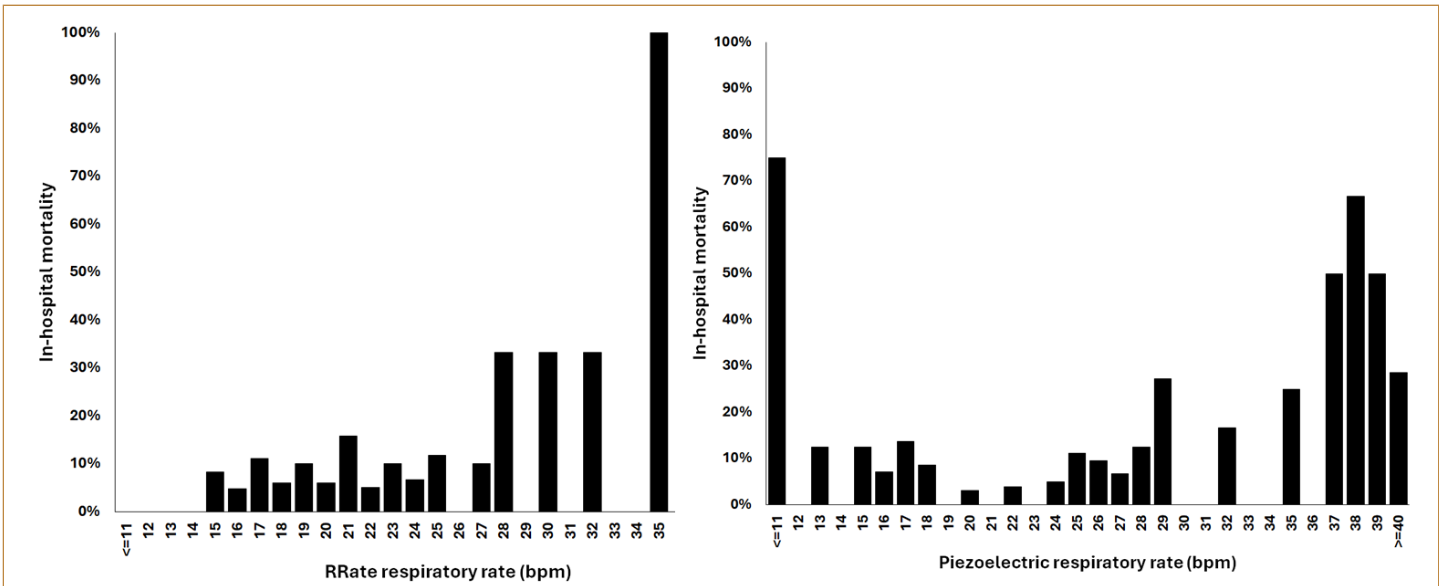

Figure 3. In-hospital mortality according to respiratory rate measured by the RRate app compared to those measured by the piezoelectric device

recordings of respiratory rates are strongly biased by the nurses' concern for the patient.[21] However, Drummond[22] has shown that acutely ill medical patients often have abnormal breathing patterns and has argued that these variations may explain the frequently observed discrepancies in respiratory rate measurement.[23] Therefore, it is possible that our severely ill patients had variation in their breathing rates, which could not be captured by a single measurement over a few seconds.

Clinical significance

How a patient is managed in hospital may be heavily dependent on the risk assessment at the time of admission. This study was confined to examination of the first respiratory rate measured by two different methods on admission to hospital and their association with the patients' subsequent outcome. The NEWS values commonly recommended to trigger an urgent clinical review are between 3[24] and 7 points,[25] with values ≥5 increasingly being adopted as an indicator of sepsis.[26] NEWS was designed to identify patients at risk of death within 24 hours to ensure that patients who need to be seen and reviewed urgently are efficiently identified. This study shows that NEWS has excellent discrimination for early mortality when calculated with either piezoelectric or RRate rates. However, if the trigger for an urgent clinical review was a NEWS calculated from RRate rates ≥4 then 2 of the 13 (15.4%) patients who died within 24 hours would have been overlooked, whereas no patients died within 24 hours with a piezoelectric calculated NEWS <7.

Our findings highlight the need to establish the optimal time over which respiratory should be measured.[23] It may be that repeated RRate measurements in patients with an RRate calculated NEWS >3 over 15 minutes might show the same improvement in discrimination as piezoelectric measurements. Although the benefits of continuous monitoring of vital signs by wearable devices have yet to be established,[27,28] there may be certain patients for whom it is justified, such as selected patients with cardiac or respiratory conditions who might benefit form continuous respiratory rate monitoring.[11]

The pattern of distribution of RRate and piezoelectric respiratory rates with mortality were markedly different, with RRate measurements failing to identify patients with low respiratory rates who died. Nevertheless, NEWS weighted respiratory rates measured by either method have reasonable discrimination for imminent mortality, and the respiratory rate with the highest Youden value up to 14 days after measurement is around ≥25 bpm, which corresponds to a NEWS of 3 points. Therefore, any respiratory rate above this value, measured by any method, should be a cause of concern.

Limitations

The size of this single site study was limited by the resources available and was not large enough to show, for example, statistically significant differences in discrimination. Measurements could not be contemporaneous as RRate measurements were performed over a few seconds, whereas piezoelectric measurements required time to set-up and apply the device and a further delay for the first 15 minutes of data to be recorded. We used the original version of NEWS as it remains comparable to the new NEWS2 version,[29] requires less data, is easier to calculate, and is, therefore, more appropriate to a low resource setting.

The patients enrolled in this study did not present consecutively, but were a convenient sample of very sick patients, many of whom would have been in intensive care in better resourced settings. Therefore, our results may not be applicable to acutely ill patients attending emergency departments or admitted to acute medical wards elsewhere. For example, only 30% of patients admitted to UK hospitals have a NEWS ≥3,[30] compared to 66% of our patients.

Conclusion

There was a poor correlation between the first respiratory rates measured after admission over 15 minutes by a piezoelectric device and rates measured after admission over a few seconds by the RRate app. Up to 14 days after measurement the respiratory rate with the highest association with mortality, measured by either method, is approximately ≥25 bpm. Although the mortality discrimination of piezoelectric respiratory rates and NEWS calculated from them were higher than those derived from the RRate app, they did not reach statistical significance. However, of the 13 patients who died within 24 hours, none had a piezoelectric calculated NEWS <7, whereas 2 (15.4%) had an RRate calculated NEWS <5. Nevertheless, this small pilot study could not demonstrate clinical benefits sufficient to justify the cost and delay of measuring the first respiratory rates after admission over 15 minutes by a device.

Acknowledgements

The authors wish to acknowledge Mr Pedro Asensio and Dr Rezvan Pakdel of PMD Solutions for their technical help.

Funding and Conflict of interest statement

PMD Solutions supplied their *RespiraSense*™ devices free of charge, all other costs were borne by the authors. None of the authors have a potential conflicts of interest.

Ethics Declaration

Ethical approval for the study was obtained from the Kampala International University (KIU-2021-45) and the Uganda National Council for Science and Technology (UNCST HS2792ES). The study conforms to the principles outlined in the Declaration of Helsinki.

Authors contribution

FS and JK conceptualisation, data analysis and drafting of the paper, IN and JN collected data, SN and AL administered the study and supervised data collection. All authors reviewed the final manuscript and corrected any errors.

Data Availability Statement

Anonymized data of this study are available to all interested parties upon request.

Acronyms

ANOVA = analysis of variance
SD = standard deviation
aRR = respiratory rate measured by RRate app
pRR = respiratory rate measured by piezoelectric device
NEWS = National Early Warning Score
aNEWS = National Early Warning Score calculated using respiratory rate measured by RRate app
pNEWS = National Early Warning Score calculated using respiratory rate measured by piezoelectric device

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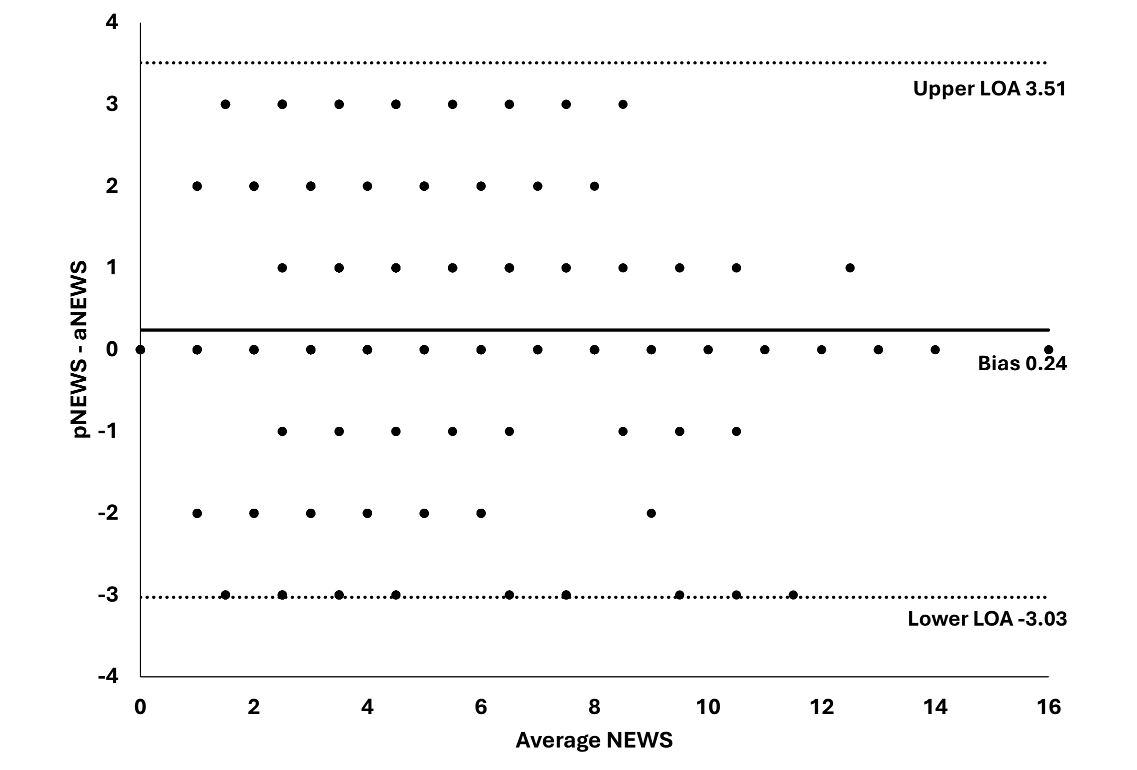

Supplementary Figure.

Supplementary Table 1. Odds ratio of mortality at different times after measurement of respiratory rates with the highest Youden number. pRR = respiratory rate measured over 15 minutes by piezoelectric device; aRR = respiratory rate measured by RRate app.

Day after measurement	Piezoelectric rate (pRR) Rate with highest Youden number	Odds ratio mortality *(95% CI)*			RRate rate (aRR) Rate with highest Youden number	Odds ratio mortality *(95% CI)*		
0	>24 bpm	6.52	(1.60 -	30.74)	>26 bpm	12.22	(3.40 -	44.52)
1	>23 bpm	4.46	(1.45 -	14.66)	>26 bpm	7.74	(2.59 -	22.85)
2	>25 bpm	3.15	(1.24 -	8.08)	>23 bpm	3.23	(1.27 -	8.22)
3	>25 bpm	3.15	(1.24 -	8.08)	>23 bpm	3.23	(1.27 -	8.22)
4	>25 bpm	3.42	(1.37 -	8.66)	>23 bpm	2.95	(1.18 -	7.35)
5	>25 bpm	3.70	(1.50 -	9.26)	>26 bpm	4.92	(1.77 -	13.39)
6	>25 bpm	3.61	(1.51 -	8.70)	>24 bpm	2.91	(1.21 -	6.96)
14	>24 bpm	2.53	(1.17 -	5.50)	>26 bpm	3.13	(1.19 -	8.07)

Supplementary Table 2. Number and percent of patients who died who were below different National Early Warning Score (NEWS) threshold values on admission that should trigger an urgent clinical review according to the time of death after admission. pNEWS = NEWS calculated using respiratory rate measured by the piezoelectric device; aNEWS = NEWS calculated using respiratory rate measured by the RRate app.

For example, of the patients admitted with a pNEWS of 6, 2 died within 48 hours representing 10.5% of all the 19 deaths at 48 hours, whereas of the patients with an aNEWS of 6, 6 died within 48 hours, representing 31.6% of all deaths within 48 hours.

	NEWS values that trigger an urgent clinical review									
	NEWS >=3		NEWS >=4		NEWS >=5		NEWS >=6		NEWS >=7	
Days to death	pNEWS (%)	aNEWS (%)	pNEWS (%)	aNEWS (%)	pNEWS (%)	aNEWS (%)	pNEWS (%)	aNEWS (%)	pNEWS (%)	aNEWS (%)
0	0 (0.0%)	0 (0.0%)	0 (0.0%)	2 (15.4%)	0 (0.0%)	2 (15.4%)	0 (0.0%)	2 (15.4%)	3 (23.1%)	3 (23.1%)
1	0 (0.0%)	0 (0.0%)	0 (0.0%)	2 (10.5%)	2 (10.5%)	5 (26.3%)	2 (10.5%)	6 (31.6%)	7 (36.8%)	8 (42.1%)
2	2 8.7%	2 (8.7%)	2 (8.7%)	4 (17.4%)	4 (17.4%)	8 (34.8%)	5 (21.7%)	9 (39.1%)	10 (43.5%)	11 (47.8%)
3	2 (8.7%)	2 (8.7%)	2 (8.7%)	4 (17.4%)	4 (17.4%)	8 (34.8%)	5 (21.7%)	9 (39.1%)	10 (43.5%)	11 (47.8%)
4	2 (8.3%)	2 (8.3%)	2 (8.3%)	4 (16.7%)	4 (16.7%)	8 (33.3%)	5 (20.8%)	10 (41.7%)	11 (45.8%)	12 (50.0%)
5	2 (8.0%)	2 (8.0%)	2 (8.0%)	4 (16.0%)	4 (16.0%)	8 (32.0%)	5 (20.0%)	10 (40.0%)	11 (44.0%)	12 (48.0%)
6	2 (7.4%)	3 (11.1%)	2 (7.4%)	5 (18.5%)	5 (18.5%)	9 (33.3%)	6 (22.2%)	11 (40.7%0	13 (48.1%)	13 (48.1%)
14	3 (8.8%)	5 (14.7%)	4 (11.8%)	8 (23.5%)	10 (29.4%)	16 (47.1%)	13 (38.2%)	18 (52.9%)	19 (55.9%)	20 (58.8%)