The Performance of a Mobile Phone Respiratory Rate Counter Compared to the WHO *ARI Timer*

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ABSTRACT

OBJECTIVE: To compare the accuracy and efficiency of the respiratory rate (RR) *RRate* mobile application to the WHO *ARI Timer*. METHODS: Volunteers used both devices to measure RR from reference videos of infants and children. Measurements were compared using correlation, Bland-Altman analysis, error metrics and time taken. RESULTS: Measurements with either device were highly correlated to the reference ($r = 0.991$ and $r = 0.982$), and to each other ($r = 0.973$). *RRate* had a larger bias than the *ARI Timer* (0.6 vs. 0.04 br/min), but tighter limits of agreement (–4.5 to 3.3 br/min vs. –5.5 to 5.5 br/min). *RRate* was more accurate than the *ARI Timer* (percentage error 10.6% vs. 14.8%, root mean square error 2.1 vs. 2.8 br/min and normalized root mean square error 5.6% vs. 7.5%). *RRate* measurements were 52.7 seconds (95% CI 50.4 s to 54.9 s) faster. CONCLUSION: During video observations, *RRate* measured RR quicker with a similar accuracy compared to the *ARI Timer*.

Keywords: mobile health, respiratory rate, global health, pneumonia, respiratory diseases

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1. INTRODUCTION

Pneumonia is a leading cause of death in children worldwide, with the majority of these deaths occurring in resource-limited countries [1]. Pneumonia can be distinguished from other respiratory illnesses using simple clinical signs such as respiratory rate and chest indrawing [2].

Respiratory rate (RR) plays a fundamental role in clinical assessments for disease diagnosis, prognosis, triage and treatment [3]. However, many studies have shown the measurement to be inaccurate, lacking both reliability and reproducibility in a variety of health care settings [4–6].

In order to improve the measure of RR in resource limited settings, the Acute Respiratory Infection (ARI) Timer was introduced by the World Health Organization (WHO) in 1990. However, international and non-governmental organizations have reported limitations of the *ARI Timer* [7,8]. It requires the community health worker (CHW) to count the number of breaths a child takes over 60 seconds. Many CHWs worry that they may fail to see all of the breaths or lose track of the number of breaths taken. Many are also distracted by the ticking sound, resulting in some counting the ticks rather than the breaths [9]. Thus, there is an urgent need for a robust, low-cost device that can help front-line healthcare workers to measure RR quickly and accurately.

Mobile technology is ubiquitous, even in rural parts of the world [10]. A growing number of initiatives are leveraging the wide availability of mobile phones to tackle the health needs of developing countries [10]. The *RRate* mobile application [11,12] is one such example. It utilizes the mobile phone as a timer and a counter, and measures RR from the median time interval between breaths. Using a mobile device, the time intervals between breaths are measured as the user taps on the touch sensitive screen in time with inspiration. We previously described the development and implementation of the *RRate* app, and reported a clinically acceptable error of 5.6% (normalized root mean square error) [13].

In this study, we directly compared the performance of *RRate* against the *ARI Timer* in terms of accuracy and efficiency. We hypothesize that RR measurement using *RRate* can be performed with similar accuracy compared to the *ARI Timer*, but in a significantly shorter time.

2. METHODS

2.1. *RRate* Mobile App

The *RRat*e mobile application [11,12] measures RR by recording the time interval in between breaths as the user taps on the touch sensitive screen of a mobile device in time with inspiration (Figure 1A).

Each time the user taps on the screen, a breathing sound is played as feedback to the user that a tap has been registered, and the time interval between the last two taps is recorded. The RR is calculated from dividing 60 seconds by the median time interval of a set of consecutive taps, provided that the tap intervals are within a consistency range [13]. The consistency range is the median time interval +/− a user-specified percentage (the consistency threshold). Once a consistent set of taps has been achieved, a chime noise is played and the result displayed (Figure 1B).

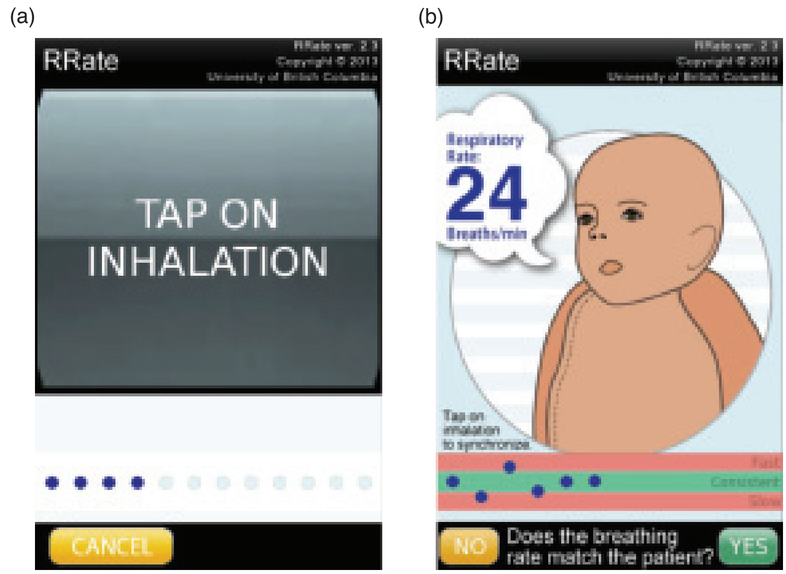

Figure 1. Screen captures from the *RRate* app. The tap screen includes a large button for tapping and an indicator of how many taps have been performed (a). The results screen includes the calculated RR, an animated baby breathing at the rate calculated, a visualization of the tap timing, and a confirmation question about the rate (b).

As with any observation, there is a trade-off between accuracy and efficiency. Increasing the number of time intervals in a set or tightening the consistency threshold improves accuracy but lengthens the time taken for measurement. For this study, *RRate* was set to use three time intervals within a consistency threshold of 12%, a combination that was previously found to give a reasonable compromise between accuracy and efficiency. The *RRate* application was installed on an iPod Touch 3rd generation (Apple, Inc., Cupertino, CA, USA).

A special version of *RRate* (v2.2) was created for use in the study and finalized on September 24, 2013. This version allowed the study investigators to enter the subject's name and video ID number before each video and recorded all tap timing information to a file for analysis. The current version of *RRate* available on the iTunes store [11] and Google Play [12] is version 2.4, published on January 23, 2014. This version includes an added Settings screen for choosing the number of taps and consistency threshold, and it also provides the option of device vibration instead of making breathing noises.

2.2. *ARI Timer*

The *ARI Timer* is a simple and affordable timing aid distributed by WHO and United Nations Educational, Scientific, and Cultural Organization (UNESCO) for community health workers in resource-poor settings (Figure 2). The *ARI Timer* makes a ticking

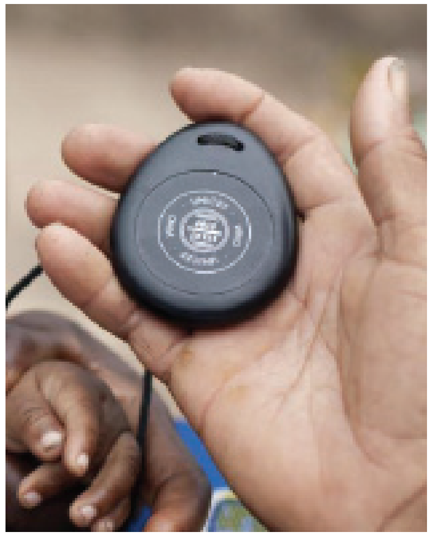

Figure 2. The WHO/UNESCO *ARI Timer* [14].

sound every second and has an alarm after 30 seconds as well as a final alarm to inform the user that 1 minute has passed. The user must press the button to start the 1 minute timing, during which a child's breaths are counted.

2.3. Standard Videos and Reference RR

With approval of the Children's & Women's Health Centre of BC Research Ethics Board, University of British Columbia, and parental informed consent, de-identified video footages of 23 anesthetized children, aged 0 to 5 years, breathing for a period of 3–5 minutes, were recorded. Only the exposed chest and abdomen where included in the field of view of the video. No facial features or any other identifiable features were recorded.

Five cases of controlled and five cases of spontaneous ventilation were selected to encompass a range of RR from 17 to 59 breaths per minute (br/min) (Table 1). The videos were each cropped down to 60 seconds. A still image of the first frame was played for 10 seconds at the start of each video to allow observers time for orientation to the child's position and anatomy. To confirm the RR of the selected videos, two independent observers counted the number of breaths from the final videos by slowing the playback speed to 50% of the recorded speed. Each observer repeated the counting until the RR measurements from three consecutive counts were in agreement.

2.4. Data Collection

Adult subjects were recruited from the British Columbia Children's Hospital nursing staff and trainee population. Their age, gender, education level and profession were recorded. Participants chose one or more descriptors from a list of International Data Corporation phone user labels (Table 2) [15] that they felt applied to their mobile phone use familiarity.

Table 1. Ventilation mode, age and respiratory rate in breaths per min (br/min) for the standard video recordings used in this study

Ventilation	Age (months)	Respiratory rate (br/min)
Controlled	<1	56
	23	33
	23	59*
	36	47*
	43	51*
Spontaneous	23	30
	23	38
	25	24
	53	17
	59	17

*Fast breathing for the corresponding age.

Table 2. International data corporation 2003 categorization of mobile users [15]

Label of users	Description
Display Mavens	Users who primarily use their devices to deliver presentations and fill downtime with entertainment applications to a moderate degree
Mobile Elites	Users who adopt the latest devices, applications, and solutions, and also use the broadest number of them
Minimalists	Users who employ just the basics for their mobility needs;the opposite of the Mobile Elite
Voice/Text Fanatics	Users who tend to be focused on text-based data and messaging; a more communications-centric group

Each subject measured RR from the video recordings using two different methods: 1) measuring RR using the *RRate* mobile application; and 2) counting breaths for 1 minute using the *ARI Timer*. Subjects measured RR in a randomized double crossover study design (Figure 3).

2.5. Accuracy-Comparison of Measured RR

Correlations between each method and the reference RR, and the correlations between the two methods, were calculated using the Pearson's product-moment correlations. Measurements from both methods were compared to the reference RR and to each other using the Bland–Altman analysis for repeated measurements [16,17]. Bias, limits of agreement (LoA), percentage error (PE), and within-subject and between-subject

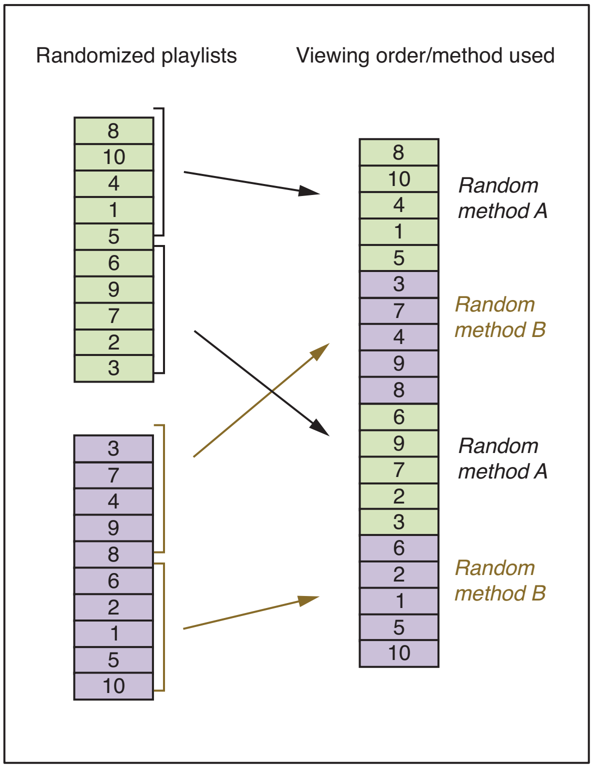

Figure 3. Subjects measured respiratory rate in a randomized double crossover study design. For each subject, two randomized playlists of the 10 standard videos were generated and combined. The respiratory rates were measured using one method (the *ARI Timer* or the *RRate* app) for the first playlist (videos 1 to 5 and videos 11 to 15), and using the second method for the second playlist (videos 6 to 10 and videos 16 to 20). The order of the method of measurement was also randomized.

variances were reported. The PE was calculated as 1.96 times standard deviation divided by the mean, as defined by Tibballs et al. [18] and recommend by Critchley and Critchley [19]. The PE allows for comparison across study populations with different means. A maximum PE of 30% has been recommended for acceptance [19].

Finally, RR measured using both methods were compared to the reference RR and to each other by standard error metrics: root mean square error (RMSE) and the RMSE normalized by the mean RR (NRMSE). The RMSE and the NRMSE can be calculated using eqns. 1 and 2 below:

$$RMSE(br/min) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(RR_i - RR_{\mathrm{Ref}}\right)} \tag{1}$$

$$NRMSE\ (\%) = \frac{RMSE}{\frac{1}{n}\sum_{i=1}^{n}(RR_{\mathrm{Ref}})} \tag{2}$$

2.6. Efficiency-Comparison of Measurement Time

It takes 60 seconds to measure RR using the *ARI Timer*. The time taken for measurement using *RRate* depends on the RR measured and the length of time for the user to make a set of consecutive taps within the specified consistency threshold. The times taken for measurement were reported as medians and interquartile ranges (IQR), and compared using a random intercept model that incorporates within-video correlation and between-video variability [20].

2.7. Statistical Calculations

All data analysis and plots were performed using R (version 2.15.0, R Foundation for Statistical Computing, Vienna, Austria) running on R studio (version 0.98.994, R Studio Inc., Boston MA, USA).

3. RESULTS

3.1. Data Collected

Twenty adult subjects were recruited from the BC Children's Hospital nursing staff and trainee population. Subject demographics and mobile phone use familiarity [15] are summarized in Table 3.

Table 3. Subject demographics and mobile phone use familiarity

Age (average 26.7 years)	***n***	***%***
Below 30 years	19	95%
30 years and above	1	5%
Gender	***n***	***%***
Female	19	95%
Male	1	5%
Education	***n***	***%***
High school	4	20%
College/University	16	80%
Profession	***n***	***%***
Registered nurse	13	65%
Student nurse	7	35%
Type of mobile user	***n***	***%***
Voice/Text Fanatic	13	65%
Mobile elite	10	50%
Display maven	8	40%
Minimalist	5	25%

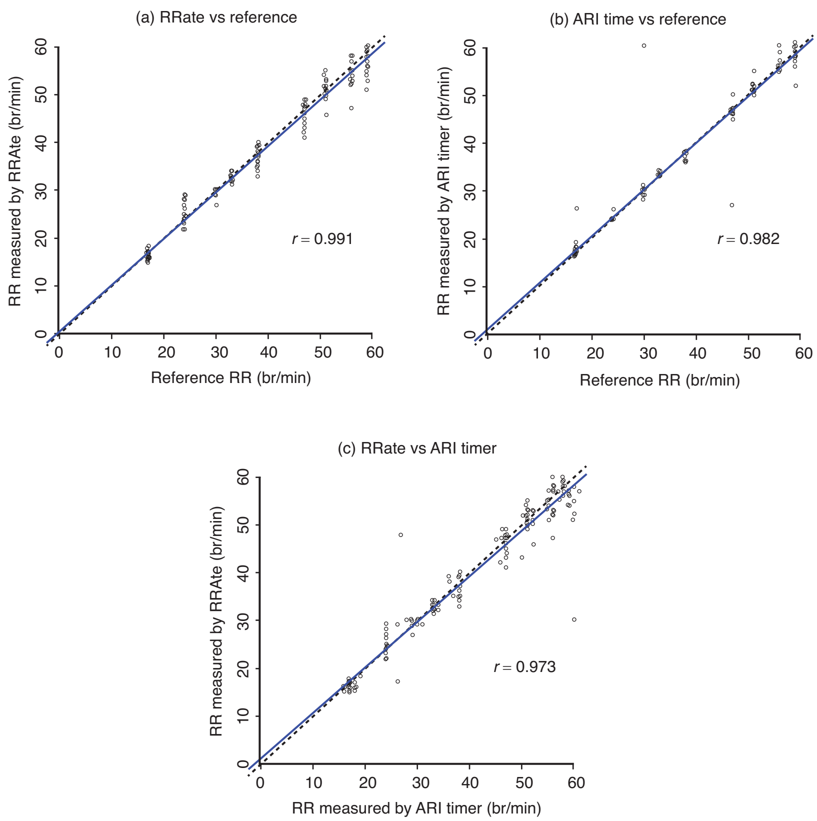

Figure 4. Scatterplots comparing (a) RR measured using *RRate* to the reference RR, (b) RR measured using the *ARI Timer* to the reference RR, and (c) RR measured using *RRate* to RR measured using the *ARI Timer*. Solid blue line: line of best fit; dashed line: line of equality; RR: respiratory rate; br/min:breaths per minute.

3.2. Accuracy Results

The RR measurements using the *RRate* app and the *ARI Timer* were highly correlated to the reference RR ($r = 0.991$, $p < 10^{-15}$ and $r = 0.982$, $p < 10^{-15}$, respectively), as well as to each other ($r = 0.973$, $p < 10^{-15}$) (Figure 4).

When compared to the reference RR, the *RRate* app had a larger bias than the *ARI Timer* (0.6 vs. 0.04 br/min), but with tighter LoA (–4.5 and 3.3 br/min vs. −5.5 and 5.5 br/min) and smaller percentage error (10.6% vs. 14.8%). Compared to each other, the bias was 0.7 br/min, with LoA of −7.4 and 6.1 br/min (Figure 5) and percentage error of 19.2%.

The *RRate* app was more accurate than the *ARI Timer* (RMSE 2.1 vs. 2.8 br/min and NRMSE 5.6% vs. 7.5%) when compared to the reference RR (Table 4). Compared to each other, the error metrics were higher (RMSE 3.5 br/min and NRMSE 9.4%).

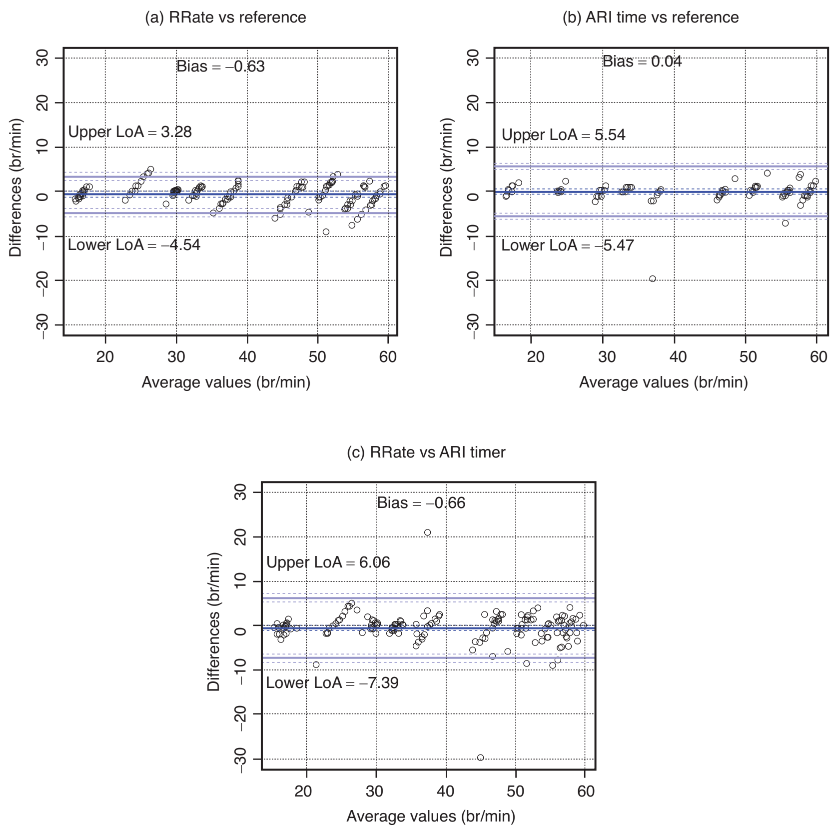

Figure 5. Bland-Altman plots comparing (a) RR measured using *RRate* to the reference RR, (b) RR measured using the *ARI Timer* to the reference RR, and (c) RR measured using *RRate* to RR measured using the *ARI Timer*. Solid blue lines: bias and upper and lower limits of agreement; dotted blue lines: 95% confidence intervals; LoA: limit of agreement; br/min: breaths per minute.

3.3. Efficiency Results

The median times taken (interquartile range) for RR measurement using the *ARI Timer* and *RRate* were 60 seconds (60–60 seconds) and 5.9 seconds (3.8 – 10.9 seconds), respectively. RR measurements using the *RRate* app were 52.7 seconds (95% CI 50.4 sec to 54.9 sec) faster compared to using the *ARI Timer*.

4. DISCUSSION

RR measurements using the *RRate* application had excellent correlation and agreement with the reference RR and to measurements made using the *ARI Timer*. The mean differences of 0.63 br/min compared to the reference RR and 0.66 br/min compared to the *ARI Timer* are not likely to be clinically important.

Table 4. Comparison of measured RR

	***RRate* vs. Reference**	***ARI Timer* vs. Reference**	***RRate* vs. *ARI Timer***
Pearson's product-moment correlation	**0.991**	**0.982**	**0.973**
95% CI	0.988 to 0.993	0.976 to 0.986	0.964 to 0.979
Bias, *br/min*	**–0.63**	**0.04**	**–0.67**
95% CI	−1.28 to 0.02	–0.42 to 0.49	−1.30 to -0.03
Lower LoA, *br/min*	**–4.54**	**–5.47**	**–7.39**
95% CI	–5.64 to -3.90	–6.24 to –4.85	−8.41 to -6.59
Upper LoA, *br/min*	**3.28**	**5.54**	**6.06**
95% CI	2.64 to 4.38	4.92 to 6.31	5.26 to 7.08
PE, *%*	**10.6**	**14.8**	**18.2**
Within-subject variance	**3.4**	**7.9**	**11.6**
+/– standard error	+/– 0.3	+/– 0.8	+/– 1.2
Between-subject variance	**0.7**	**0.01**	**0.2**
+/– standard error	+/– 0.4	+/– 0.2	+/– 0.4
RMSE, *br/min*	**2.1**	**2.8**	**3.5**
NRMSE, *%*	**5.6**	**7.5**	**9.4**

CI: confidence interval; br/min: breaths per minute; LoA: limit of agreement; PE: percentage error; RMSE: root mean square error; NRMSE: normalized root mean square error.

The *RRate* application had slightly tighter limits of agreement and slightly smaller percentage error than the *ARI Timer*. Figure 4B illustrates that on two occasions, RR measurements using the *ARI Timer* gave results with very large errors. On one occasion, the RR of a 36-month old child was measured as 27 br/min (normal range) when the reference RR was 47 br/min (fast breathing). On the other occasion, the RR of a 23-month old child was measured as 60 br/min (fast breathing) when the reference RR was only 30 br/min (normal range). On this second occasion, it seemed that the user was influenced by the ticking sound of the *ARI Timer*, which is one of the reported shortcomings of the *ARI Timer* [9]. Normal RR was miscategorized as fast breathing, or vice versa, on these two occasions.

A similar study investigated mid-range feature phones running different Java applications to measure RR in children [21]. All the applications in that study had limits of agreement much greater than *RRate*. An important feature of *RRate* that makes it accurate is the built-in quality control algorithm that eliminates inconsistent time intervals. This assurance of accuracy in RR measurement gives confidence to the clinician who uses the measured RR to make a clinical decision. In fact, an electronic aid to clinical decision-making can be incorporated into the mobile phone along with *RRate*. For an inexperienced CHW in a limited-resource setting, the mobile phone becomes a diagnostic and treatment advisory device.

The median time taken for measurement using the *RRate* application was only 5.9 seconds, significantly quicker than 60 seconds using the *ARI Timer*. In a busy clinical setting, where the clinician may only have 5 to 10 minutes to spend with each patient, the advantage of the increased efficiency in RR measurement is obvious, particularly when it comes without any compromise in accuracy and reliability.

One of the possible factors affecting the accuracy of the *RRate* application is the touch responsiveness of the device used. Current smartphone devices have 60 Hz touch screens capable of generating a "touch" event every 16.667 ms (1/60 s). If a press occurs just after the previous sensor scan, this could cause a delay of two entire scans, a potentially 33 ms latency. The host touch driver may add up to another 1 ms before reporting the "touch" event. The *RRate* application records the timing of the "touch" event at this stage. Thus, further latency down the line, leading to updates of the user interface and graphical display, does not affect the recorded time intervals. A maximum latency of 34 ms would translate to a theoretical maximum error of 2.3% at an RR of 40 br/min, and 3.3% at an RR of 60 br/min. In practice, because *RRate* uses three consecutive time intervals to calculate the final RR, which is rounded to the nearest whole number, the effect of touch latency on measurement error is not likely to be significant.

WHO recommends measuring RR over 60 seconds [22,23]. One of the justifications for this was the concern about irregular breathing rates. Periodic breathing is typically seen in the newborns and is not seen in rapidly breathing children with pneumonia. However, if an episode of breath holding occurred during 60 seconds of observation, this may significantly affect the clinical interpretation of the measured RR. Since the *RRate* application requires a set of consecutive consistent time intervals, it may take longer to measure the RR during irregular breathing, up to a maximum of 12 breaths, after which the *RRate* offers the user the option to display the measured RR despite the irregular breathing. Another important feature of the *RRate* application is that after each measurement, an animation is displayed of the respiratory rate measured (which can be easily synchronized in phase with the patient's breathing). This allows the user to rapidly confirm the clinical accuracy of the measurement.

The limitations of the *ARI Timer* and *RRate* are similar. Both methods require the CHW to observe the patient. In a child who is distressed and/or has high breathing rates, this poses challenges even to experienced observers. Unobtrusive and automated methods of measuring respiratory rate, such as pulse oximeter signal analysis [24], or monitoring of temperature changes in breathing air flow [25] are possible alternatives.

The study was conducted in a busy pediatric ward with distracting noise and passing traffic mimicking a typical clinical environment. The participants in this study were nursing staff and trainees, experienced in measuring RR by counting breaths in a fixed time period. Therefore, measuring RR using the *ARI Timer* should be a familiar routine. None of the participants had used the *RRate* app before the study, but after only a 30-second practice run, were able to use it to measure RR as accurately as the *ARI Timer*.

5. CONCLUSIONS

The *RRate* mobile application is a favorable alternative to the *ARI Timer*, measuring RR significantly quicker with comparable accuracy. As with any novel technology, usability and reliability, as well as further development, will be determined by user feedback from the field.

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CONFLICT OF INTEREST

The authors indicated no potential conflicts of interest.

NOMENCLATURE

br/min	Breaths per minute
ms	Milliseconds
s	Seconds

ABBREVIATIONS

CI	Confidence interval, br/min
LoA	Limit of agreement, br/min
NRMSE	Normalized root mean square error, %
PE	Percentage error, %
RMSE	Root mean square error, br/min
RR	Respiratory rate, br/min

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