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Published version

STRATTON, Howard, SAATCHI, Reza, EVANS, Ruth and ELPHICK, Heather (2021). Noncontact Respiration Rate Monitoring: An Evaluation of Four Methods. In: USB proceedings of The Seventeenth International Conference on Condition Monitoring and Asset Management – CM 2021, held virtually from 14-18 2021. The British Institute of Non-Destructive Testing.

Noncontact Respiration Rate Monitoring: An Evaluation of Four Methods

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Abstract

Respiratory rate (RR) is an important diagnostic indicator of deterioration in critically ill patients therefore an accurate method for its measurement is needed. The existing methods for RR measurement are typically contact-based, i.e. the sensing unit is attached to the patient's body. Some young children do not tolerate contact-based methods. Contact-based methods may also cause stress, affecting RR value. The operations of four non-contact RR measurement methods were compared. These were: infrared thermal imaging, airflow sensing, vision based chest movement tracking and respiratory airflow sensing. The study showed that all four methods could measure RR. The strengths and limitations of each method are explained.

Keywords: Non-contact respiration measurement, health monitoring

1. Introduction

There is a clinical need for a device to measure respiration rate (RR) in a reliable and cost-effective manner as RR it is an important measure of deterioration in critically ill patients. Recent technological developments in sensor, microprocessor and signal processing have made development of more practical RR monitors timely. RR is the average number of breaths per minute (bpm, i.e. number of times air is inhaled and exhaled). Its value is around 15 bpm in healthy adults and up to 40 bpm in healthy children. RR in clinical environments is typically measured subjectively by visually counting, manually feeling or listening to the chest movements via a stethoscope. As these methods can upset children, often a recording cannot be obtained and the subjectivity of the methods results in inaccuracies.

Studies have highlighted the importance and difficulties associated with accurately measuring RR [(1-8)]. Abnormal respiration could indicate serious events such as cardiac arrest and the need for admission to intensive care unit [(4)]. Every year people die because their deteriorating physiological condition is not detected in a timely manner. This can be associated with inaccurate monitoring of their vital signs, particularly RR [(9)]. Earlier detection would result in a more timely treatment thus reducing the risk of complications and would improve patient care overall.

RR can be measured using contact or non-contact methods. In contact approaches, the sensing unit or an element of it is attached to the subject's body. These methods include:

- *Nasal prongs:* placed in the nostril to directly measure respiratory airflow. They are typically used for overnight monitoring of patients with respiratory problems such as sleep apnoea (10). Their intrusive nature causes them to have low acceptability in very young children.
- *Microphone:* records respiratory sounds (11) however it is susceptible to background audio interference.
- *Thermistor and thermocouple:* these sensors are taped beneath the nostril. They measure relative air temperature during expiration and inspiration (12). This approach, like respiratory sounds measurement provides an indirect method of indicating respiratory air volume. Its signal amplitude provides an approximate measure of respiratory air flow and its operation can be affected by skin and ambient temperatures.
- *Pulse oximetry:* is based on the absorption of emitted light by the blood as it is propagated through or reflected from the soft tissues such as those in the fingers (13). Careful signal processing is required to extract RR from the pulse oximetry signal.
- *Electrocardiogram (ECG) derived:* various physiological effects such as modulation effect of respiration on heart rate (heart rate increases during inspiration and decreases during expiration), facilitate extraction of RR from an ECG signal (14).

It is important to measure RR from an adequate distance (this may depend on age etc.) from the child's face as causing distress to the child can alter respiration rate (15). Therefore RR measurement approaches that utilise non-contact means (i.e. sensing unit not attached to the patient's body) can be advantageous. Non-contact RR measurement methods include:

- *Infrared thermal imaging:* This approach relies on skin surface temperature differential centred on the nose during breathing. The skin surface temperature increases and decreases as air is exhaled and inhaled respectively. Several studies have demonstrated the efficacy of the approach (16-19). The method is unaffected by background light and can be performed in the dark. This is an advantage during overnight recording. The main challenge associated with this approach is dealing with body movements during long term (e.g. overnight) monitoring. A number of tracking algorithms have been reported for this purpose (17).
- *Vision based imaging:* This approach uses one or more vision camera(s) to track chest movements caused by respiration (20). As air is inhaled, the chest moves forward, and it returns to its original position, as air is exhaled. An advantage over the thermal imaging based method is that vision cameras generally have a lower cost than a thermal imaging camera. However the method relies on the background light and, as with thermal imaging, is susceptible to body movements.
- *Respiratory airflow measurement:* This approach directly senses the expiration at a distance. A portable RR monitor based on this approach has been reported (21). The details of this approach are discussed in the results section of this paper.
- *Ultrasound (US):* The US transmitter emits a high frequency sound focused on the chest. A portion of this signal is reflected back to the US receiver. Time of flight can be used to determine the distance of the chest to the receiver. As air is inhaled the chest moves forward thus reducing its distance to the US receiver. As air is exhaled, its distance reduces. These variations in the distance are converted to a respiratory signal. This approach has been integrated with the Internet of Things (IOT) that allows remote RR monitoring (22).

- *CO_2 sensing:* Using a CO_2 sensor to monitor respiration, also known as capnometry, is well-established. This method typically relies on a mask or nasal prongs [(23-25)] however RR can also be measured by sensing CO_2 at a distance from subject. The details of this approach are included in the result section of this paper.

2. Methodology

In this section RR measurement using infrared thermal imaging, vision based chest movement tracking, airflow sensing and CO_2 sensing are compared.

2.1 Infrared thermal imaging

Respiratory signals were recorded using a FLIR T630sc thermal camera. The specifications of the camera are provided in Table 1.

Table 1 FLIR T630sc thermal camera specifications

Temperature sensitivity	40 mK
Image resolution	640 × 480 pixels
Spectral range	7.5-13 μm
Accuracy	±1 °C
Dynamic range	14 bit
Operating temperature	-14°C to 50°C
Frame capture rate	Up to 30 frames/second

The camera was connected to laptop computer via a USB link to be able store the recorded images. The thermal images were processed using Matlab© (version 2017). The thermal camera was placed on a tripod 1 m away from the participant's face. The frame capture rate was set to 30 frames per second. The steps involved in processing the recorded thermal video were:

- *Region of interest (ROI) identification:* The ROI represents an area centred on the tip of the nose. The skin surface in this region becomes warmer as air is exhaled and reduces in temperature during inhalation. This region was manually selected by displaying the first image on the computer screen and using the Matlab© cropping facility segmented.
- *Tracking:* This operation is needed as head movements result in the selected ROI not appearing in the same location of each of the recorded images. Tracking realigns the ROI across all recorded images. There are a number of tracking approaches. The approach used is this study was template matching. It quantifies the similarity of the selected ROI from the first image (i.e. the template) with successive areas in each of the following images using the normalized cross correlation to find the closet match [(26)].
- *ROI averaging:* The aligned ROIs across all recorded images were averaged. This was performed to reduce random thermal noise.
- *ROI feature representation:* The pixel values (representing temperatures) within the ROI were averaged to obtain a single value representing the region.
- *Creation of respiratory signal:* The respiratory signal was created by merging the ROI averaged pixel values across all images.
- *Filtering:* The respiratory signal was filtered using a second order digital Butterworth filter with cutoff frequency of 2 Hz. This removed unwanted frequency components.

2.2 Vision based chest movement tracking

The vision based respiratory signal was obtained by tracking chest movement using a visual camera. The camera had an image capture rate of 20 frames per second. The subject sat on a chair about 1 m from the camera with the chest in the camera's field of view. The subject wore a patterned T-shirt. The pattern was necessary as without it chest movement would not be adequately detected. During inhalation the chest moves forward thus the pattern on the shirt appears larger. During exhalation, it appears smaller

- *Image subtraction:* Each image was subtracted from its previous recorded image. The subtraction was done on a pixel by pixel basis. This resulted in image differences.
- *Feature extraction:* The pixel values in the image differences were averaged to represent each image difference by a single feature value.
- *Produce signal:* A respiratory signal was produced by merging the extracted features.
- *Filtering:* The respiratory signal was digitally filtered using a second order digital Butterworth filter with cutoff frequency 2 Hz.

2.3 Airflow sensing

The respiratory airflow sensing device is shown in Figure 1.

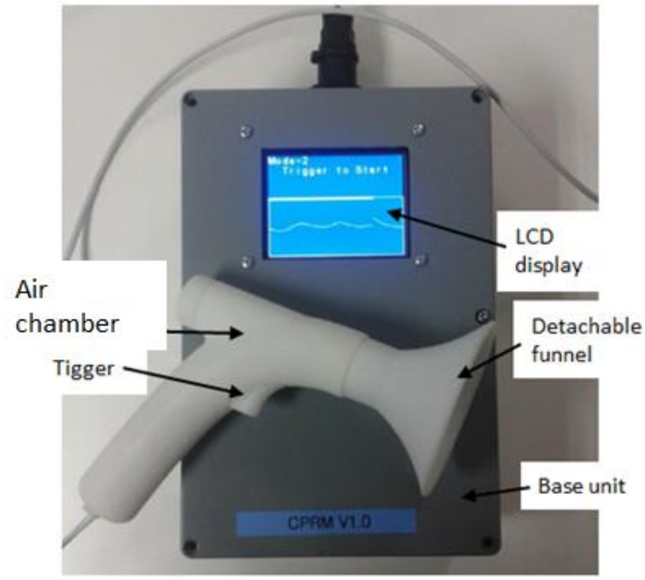

Figure 1 Airflow sensing RR measurement unit

The device consists of:

- *Detachable funnel:* The device was designed to operate at a distance of around 30 cm from the subject's face. The expired respiratory air was guided into an air chamber by the funnel. Computational fluid dynamics was used to design the funnel to provide maximum capture of expired air.
- *Air chamber:* The device contains a self-heating thermistor. The temperature of the thermistor was set to be higher than the ambient temperature. The respiratory airflow passing through the air chamber cools the thermistor.

- *Base unit:* The signal generated by detecting the thermistor's temperature variations were amplified and filtered in the base unit. The base unit has a rechargeable battery and a liquid crystal display (LCD) to display respiratory signal and respiration rate.

In order to measure respiration rate, the funnel was held in front of the subject's fact at a distance of about 30 cm and the start measurement trigger (shown in Figure 1) was pressed. The device currently requires 30 seconds for its measurements to display however we are currently working on reducing this time interval to 15 seconds. RR was determined by performing a fast Fourier transform on the recorded signal, identifying the frequency associated with the largest peak in the magnitude frequency spectrum, and multiplying the identified frequency by 60 to obtain the RR in bpm.

2.4 CO_2 sensing

The device measured the expired air CO_2 at a range distances (from 20 to 60 cm) from the face and results noted. It consisted of the following:

- A non-dispersive infrared (NDIR) CO_2 sensor used in the system is capable of detecting human respiratory CO_2 reliably.
- A silent pump guides air toward the sensor optics in the 2.8 ml measurement chamber, determining the response time of the sensor to the CO_2 concentrations. The gas exchange rate, is the amount of time it takes for the gas to enter the measurement chamber, to be measured and then refreshed.
- Microprocessor to control the device for signal processing and interpretation of the CO_2 signal. A display interface for the user.
- Wireless unit to transmit the measured respiratory signal from the sensor to the microcontroller for processing. The microcontroller transmits the processed signal to the user interface on a laptop.

The method of determining RR from the recorded signal was the same as that used in the airflow sensing system.

3. Results and discussion

The results obtained in evaluating the RR monitors referred to in the methodology sections are described in this section.

3.1 Infrared thermal imaging

Figure 2 shows a respiratory signal obtained using infrared thermal imaging. The vertical axis represents temperature variations. The method is effective in determining RR but requires further technological developments for routine clinical use. The main issues are:

- Failure to detect breathing via the mouth as the ROI currently represents breathing via the nose only.
- For long term (e.g. overnight) monitoring, body movement can cause the face to move out of the camera's field of view. A feedback mechanism to reposition the thermal camera would be needed. If the face is covered by hand or bedding etc., the monitoring cannot continue.

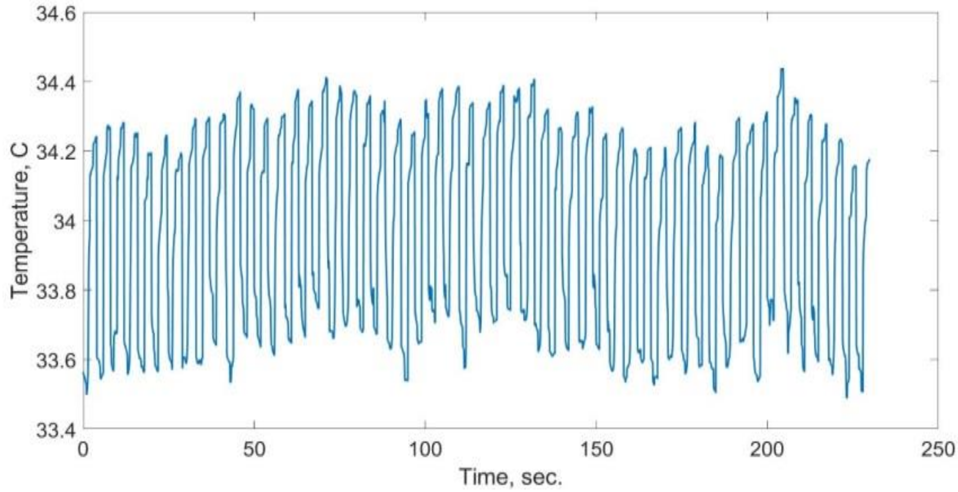

Figure 2 Infrared thermal imaging based recorded respiratory signal.

3.2 Vision based chest movement tracking

Figure 3 shows a respiratory signal obtained by tracing chest movement using a visual camera. The signal magnitude frequency spectrum is also shown. The magnitude spectrum of the signal has a dominant peak at 0.8 Hz. This corresponds to respiration of 42 bpm. The main limitations of this RR measurement method are:

- During long term (e.g. overnight) monitoring, if patient's body is covered or the patient's chest moves out of camera's field of view, respiratory signal would not be recorded.
- The method requires sufficient background light. This might disturb some patients' sleep.

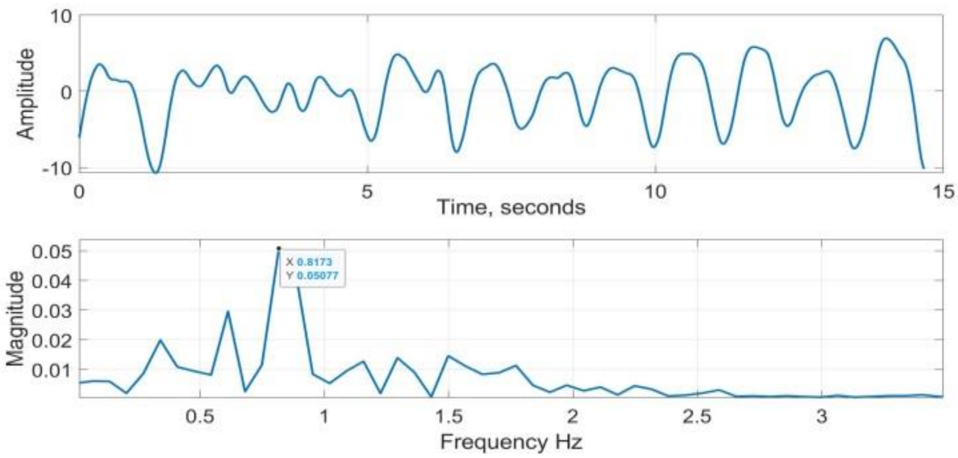

Figure 3 Vision based recorded respiratory signal (top), its magnitude frequency spectrum (bottom).

3.3 Airflow sensing

In our earlier study [(21)], the airflow sensing device was evaluated on 52 healthy adult volunteers by comparing its accuracy against respiratory inductance plethysmography (RIP) bands (gold standard, established contact method). The effectiveness of two differently shaped, computational fluid dynamics designed funnels was also explored to establish which funnel guided the respiratory airflow more effectively. The airflow sensing device provided good agreement with RIP, with intra-class correlation coefficient (ICC): 0.836, mean difference 0.46 and 95% limits of agreement of -5.90 to 6.83. A stronger agreement was observed with an elliptical shaped air funnel (compared with circular shaped inlet funnel); ICC 0.908, mean difference 0.37 with 95% limits of agreement -4.35 to 5.08. It was concluded that the airflow sensing device could accurately and quickly measure respiratory rate and could be useful triage tool in the clinical assessment of patients.

3.4 CO_2 sensing

Figure 4 shows a CO_2 sensing based respiratory signal plotted as detected CO_2 (in parts per million, ppm) against time. The recording distance from the face was about 40 cm and recording duration 1 minute, indicating a RR of 16 breaths per minute.

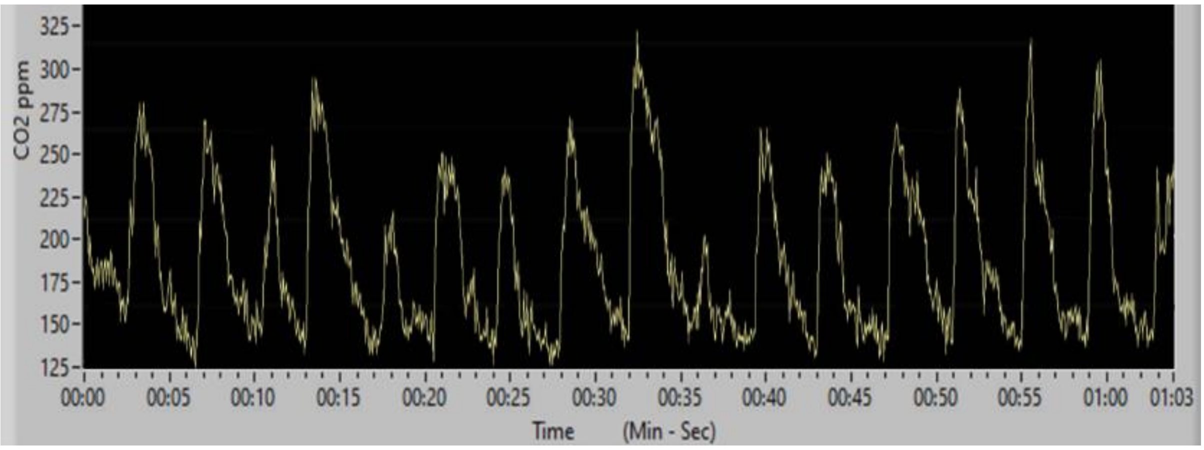

Figure 4 CO_2 sensing based respiratory signal recording.

Figure 5 shows a polar plot to assess the detection capability of the device at different distances and angles with reference being in front of the face. The measured CO_2 parts per million values indicated, shows that the sensing device is capable of measuring the CO_2 output at distances of up to 60 cm at a broad angle of angles from the face.

With recent developments in CO_2 sensors this method of measurement is becoming more viable. Comparing this approach to airflow sensing that uses a thermistor as a sensor, this approach is more costly as the CO_2 sensor is more expensive than a thermistor. This approach also requires a pump that increases the cost.

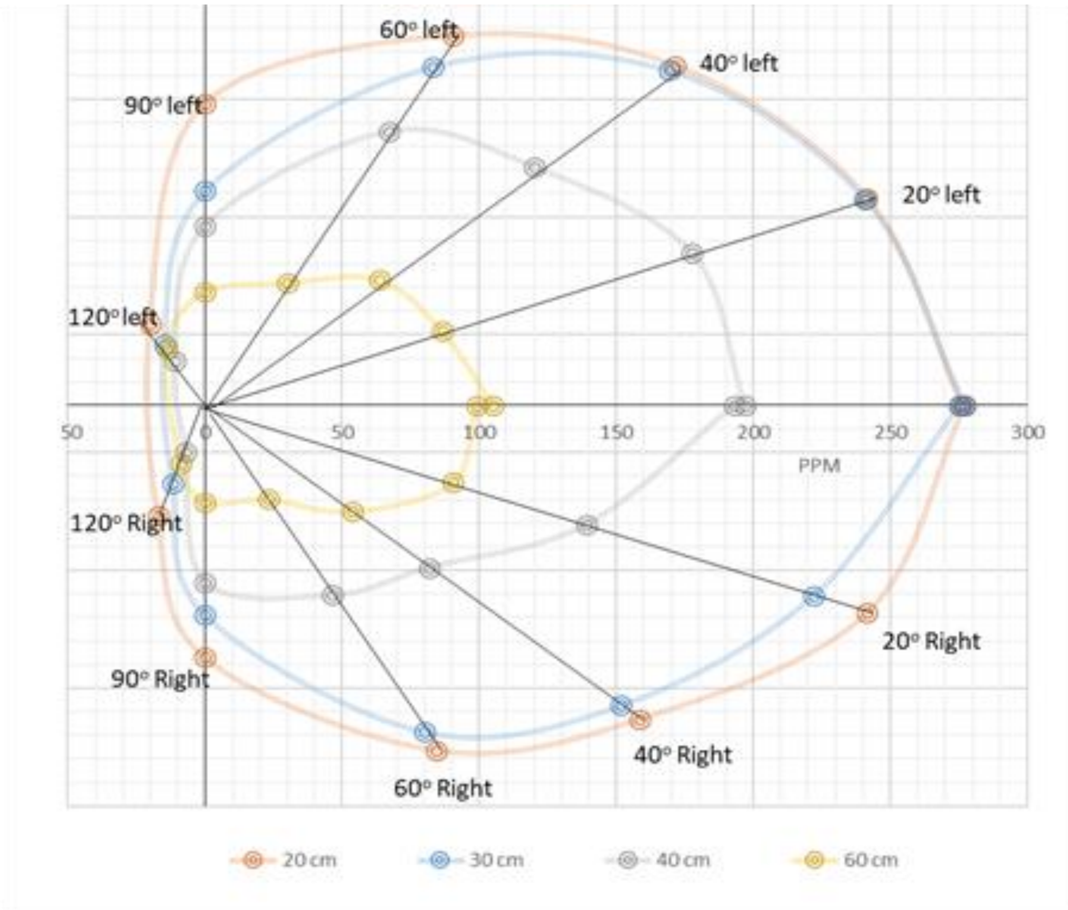

Figure 5 A polar plot demonstrating the effectiveness of the CO_2 sensing device at different distances and measurement angles.

4. Conclusion

The study reviewed contact and non-contact respiration rate (RR) monitors. The operations of infrared thermal imaging, respiratory airflow sensing, vision based chest movement tracking and expired air CO_2 sensing based RR were compared. It was found that all four methods can have viable applications for measuring RR. Each method has distinct strengths and limitations. Further work in this area is continuing to overcome the limitations of these approaches.

References

1. S Rolfe, 'The importance of respiratory rate monitoring', British Journal of Nursing, Vol 28, No 8, pp 504-508, 2019.
2. W Daw, R Kingshott, R Saatchi, et al. (2016), 'Medical devices for measuring respiratory rate in children: a review', Journal of Advances in Biomedical Engineering and Technology, Vol 3, pp 21-27, 2016.
3. F Q Al-Khalidi, R Saatchi, D Burke, H Elphick and S Tan, 'Respiration rate monitoring methods: a review', Pediatric Pulmonology, Vol 46, No 6, pp 523-529, 2011.

4. M A Cretikos, R Bellomo, K Hillman, J Chen, S Finfer and A Flabouris, 'Respiratory rate: the neglected vital sign', MJA, Vol 188, No 11, pp 657-659, 2008.
5. N Marjanovic, O Mimoz and J Guenezan, 'An easy and accurate respiratory rate monitor is necessary', Journal of Clinical Monitoring and Computing, 2019, https://doi.org/10.1007/s10877-019-00357-1, last accessed 22/11/2019.
6. J Hogan, 'Why don't nurses monitor the respiratory rates of patients?', Br J Nurs., Vol 15, No 9, pp 489-492, 2006.
7. K Philip, R Richardson, M Cohen,. 'Staff perceptions of respiratory rate measurement in a general hospital', Br J Nurs., 2013; Vol 22, No 10, pp 570–574, 2013.
8. C Kelly, 'Respiratory rate: why measurement and recording are crucial'. Nurs Times, Vol 114, No 4, pp 23–24, 2018.
9. Resuscitation Council Guidelines, 2015, (http://www.resus.org.uk/pages/poihca.pdf).
10. E Ballester, J R Badia, L Hernández, R Farré, D Navajas, J M Montserrat, 'Nasal prongs in the detection of sleep-related disordered breathing in the sleep apnoea/hypopnoea syndrome', Eur Respir J, Vol 11, pp 880–883, 1998, DOI: 10.1183/09031936.98.11040880
11. Y Nam, B A Reyes and K H Chon, 'Estimation of respiratory rates Using the built-in microphone of a smartphone or headset, IEEE Journal of Biomedical and Health Informatics, Vol 20, No 6, pp 1493- 1501, November 2016.
12. R G Norman, M M Ahmed, J A Walsleben and D M Rapoport, 'Detection of respiratory events during NPSG: Nasal cannula/pressure sensor versus thermistor', Sleep, Vol 20, No 12, pp 1175-1184, 1997.
13. M Wesseler, R Saatchi and D Burke, 'Child-friendly wireless remote health monitoring system'. In 2014 9th International Symposium on Communication Systems, Networks & Digital Sign (CSNDSP), (pp. 198-202). Institute of Electrical and Electronics Engineers, 2014, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6923824.
14. P Janbakhshi, M B Shamsollahi, 'ECG-derived respiration estimation from single-lead ECG using gaussian process and phase space reconstruction methods', Biomedical Signal Processing and Control, Vol 45, pp 80–90, 2018.
15. A Hill, E Kelly, M S Horswill and M O Watson, 'The effects of awareness and count duration on adult respiratory rate measurements: an experimental study', J Clin Nurs., Vol 27, No 3-4, pp 546–554, 2018.
16. H Elphick, A Alkali, R Kingshott, D Burke and R Saatchi, (2019) 'Exploratory study to evaluate respiratory rate using a thermal imaging camera' , Respiration: International Journal of Thoracic Medicine. http://doi.org/10.1159/000490546.
17. A Alkali, R Saatchi, H Elphick and D Burke (2017), 'Thermal image processing for real-time noncontact respiration rate monitoring', IET Circuits, Devices and Systems, Vol 11, No 2, pp 142-148, 2017.
18. F. Al-Kalidi, H Elphick, R Saatchi, D Burke (2015), 'Respiratory rate measurement in children using a thermal camera', International Journal of Scientific and Engineering Research, Vol 6, No 4, pp 1748-1756, 2015.
19. F. Al-Khalidi, R Saatchi, H Elphick, D Burke (2011), 'An evaluation of thermal imaging based respiration rate monitoring in children', American Journal of Engineering and Applied Sciences, Vol 4, No 4, pp 586-597, 2011.
20. K S Tan, R Saatchi, H Elphick, D Burke , 'Real-time vision based respiration monitoring system'. In Z Ghassemlooy, W P Ng, W.P. (Eds.) Proceeding of the seventh, IEEE, IET international symposium on Communication Systems, Networks

and Digital Signal Processing (CSNDSP), 21-23 July 2010, Northumbria University, Newcastle upon Tyne, pp 770-774, 2010.

21. W Daw, R N Kingshott, R Saatchi, D Burke, R Evans, A F Holloway, et al., ' A novel, contactless, portable “spot-check” device accurately measures respiratory rate', Journal of Medical Devices, 2020. http://doi.org/10.1115/1.4046923.
22. T Abdulqader, R Saatchi, H Elphick, 'Respiration Measurement in a Simulated Setting Incorporating the Internet of Things', Technologies, Vol 9(2), 2021. http://doi.org/10.3390/technologies9020030.
23. M S Siobal, 'Monitoring exhaled carbon dioxide', Respiratory Care, Vol 61, No 10, pp 1397-1416, 2016.
24. A S Ginsburg, J L Lenahan, R Izadnegahdar, J M Ansermino, 'A systematic review of tools to measure respiratory rate in order to identify childhood pneumonia', American Journal of Respiratory and Critical Care Medicine, Vol 197, No 9, pp 1116-1127, 2018.
25. I Kerslake, F Kelly, 'Uses of capnography in the critical care unit', BJA Education, Vol 17, No 5, pp 178–183, 2017.
26. J P Lewis, 'Fast template matching', In Proceedings of the Vision Interface 95, Canadian Image Processing and Pattern Recognition Society, Quebec City, QC, Canada, 15–19 May 1995; pp 120–123, 1995. Available online: http://scribblethink.org/Work/nvisionInterface/vi95_lewis.pdf.