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[Farah Q. Al-khalidi](#), [Reza Saatchi](#), [Derek Burke](#), [Heather Elphick](#) ...+1 more authors

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► **To cite this version:**

Farah Q Al-Khalidi, Reza Saatchi, Derek Burke, Heather E Elphick, Stephen Tan. Respiration Rate Monitoring Methods: A Review. *Pediatric Pulmonology*, Wiley, 2011, 46 (6), pp.523. 10.1002/ppul.21416 . hal-00612787

HAL Id: hal-00612787

<https://hal.archives-ouvertes.fr/hal-00612787>

Submitted on 31 Jul 2011

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Journal:	<i>Pediatric Pulmonology</i>
Manuscript ID:	PPUL-10-0195.R2
Wiley - Manuscript type:	State of the Art
Date Submitted by the Author:	19-Nov-2010
Complete List of Authors:	Al-Khalidi, Farah; Sheffield Hallam University, Faculty of ACES Saatchi, Reza; Sheffield Hallam University, Faculty of ACES Burke, Derek; Sheffield Children's Hospital, Emergency Department Elphick, Heather; Sheffield Children's Hospital Tan, Stephen; Sheffield Hallam University, Faculty of ACES
Keywords:	respiratory, thermal imaging, non-contact

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Respiration Rate Monitoring Methods: A Review

F.Q. AL-Khalidi¹, R. Saatchi¹, D. Burke², H. Elphick² and S. Tan¹

¹ Faculty of ACES, Sheffield Hallam University, Sheffield, U.K.

² Sheffield Children's NHS Foundation Trust, Sheffield, U.K.

Author for correspondence:

Name: Heather E Elphick

Address: Floor E, Stephenson Unit, Sheffield Children's Hospital, Western Bank,

Sheffield S10 2TH, UK

Tel: (0)114 2717585

Email: Heather.Elphick@sch.nhs.uk

Short Title: Respiration Rate Monitoring Methods

Summary

Respiration rate is an important indicator of a person's health, and thus it is monitored when performing clinical evaluations. There are different approaches for respiration monitoring, but generally they can be classed as contact or noncontact. For contact methods, the sensing device (or part of the instrument containing it) is attached to the subject's body. For noncontact approaches the monitoring is performed by an instrument that does not make any contact with the subject.

In this paper a review of respiration monitoring approaches (both contact and noncontact) is provided. Concerns related to the patient's recording comfort, recording hygiene, and the accuracy of respiration rate monitoring have resulted in the development of a number of noncontact respiration monitoring approaches.

A description of thermal imaging based and vision based noncontact respiration monitoring approaches we are currently developing is provided.

Keywords: Respiratory, thermal imaging, noncontact

1. Introduction

Breathing is an important physiological task in living organisms. For humans, this process results in air containing oxygen being inhaled into the lungs, where gas exchange occurs across the alveolar-capillary membrane (1). Carbon Dioxide is excreted as part of the process, in the air released through the nose or mouth. The entire process from the inhalation to exhalation is known as a breathing (or respiration) cycle.

Respiratory rate is a vital sign used to monitor the progression of illness and an abnormal respiratory rate is an important marker of serious illness. There is substantial evidence that alterations in respiratory rate can be used to predict potentially serious clinical events such as cardiac arrest or admission to the intensive care unit (2-5). These studies have shown respiratory rate to be better than other vital measurements such as pulse and blood pressure in discriminating between stable patients and patient at risk (3). Using changes in respiratory rate measurements patients could have been identified as high risk up to 24 hours before the event with a specificity of 95% (5). Hospital systems such as the Paediatric Early Warning System (PEWS) have been developed to encourage appropriate responses to abnormal vital signs including an elevated respiratory rate.

Evidence from a recent audit of febrile children in our unit suggests that in both the emergency department and the acute medical admissions unit, respiratory rate was only measured in around two thirds of children on arrival. Reasons for omission were given as "crying" or "unsettled" and in many of these children experienced nursing

1
2 staff were unable to obtain an accurate reading. However, it is in these children that
3
4 this measurement would potentially be most useful and important.
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10 According to Murthy (6), existing devices for monitoring respiratory rate only estimate
11 the actual breathing rate due to their limitations. These devices can be classified in
12 different ways, depending on the manner in which they operate and how they are
13 used. In this paper, respiration rate monitoring devices are grouped as either contact
14 or noncontact. In contact respiration rate monitoring, the instrument makes direct
15 contact with the subject's body. However, in noncontact monitoring, the respiration
16 rate is measured without the instrument making contact with the subject's body.
17
18 There are clear advantages to noncontact respiration monitoring methods. These
19 include improved patient comfort (especially for long term monitoring) as the subject
20 is not tied to an instrument and improved accuracy as distress caused by a contact
21 device may alter the respiration rate.
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33 There have been several studies reporting developments in both contact and non-
34 contact respiration monitoring. A review of non-invasive respiratory monitoring in
35 medical care was provided by Folke et al. (7). This paper aims to review the
36 literature on contact and non-contact methods of respiratory rate monitoring,
37 including two methods currently being developed by our unit.
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47 **2. Contact Based Respiration Monitoring**

48 Contact respiration rate monitoring instruments are usually based on measuring one
49 of the following parameters: respiratory sounds, respiratory airflow, respiratory
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1
2 related chest or abdominal movements, respiratory CO₂ emission and oximetry
3
4 probe SpO₂. Respiration rate can also be derived from the electrocardiogram
5
6 (ECG).
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9

10 11 **2.1 Acoustic Based Methods**

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13
14 Respiratory sound can be measured using a microphone placed either close to the
15
16 respiratory airways or over the throat to detect the variation of sound. Then a
17
18 frequency analysis and estimation of the loudness of the sound can be carried out
19
20 (8).
21

22
23 Werthammer et al. (9) reported a respiratory sounds measurement system to detect
24
25 sleep apnea in infants. The system depended on recording a signal derived from
26
27 breathing sounds from the nose. This method was applied to eight premature
28
29 infants. Snorting, speaking, crying, coughing etc had a negative effect on the
30
31 operation of the system.
32

33
34 Corbishley and Rordriguez-Villegas (10) proposed a miniaturised and wearable
35
36 respiration monitoring respiration system. It used a microphone mounted on the
37
38 neck to obtain the largest breathing acoustic.
39

40 **2.2 Airflow Based Methods**

41
42 Airflow can be detected because exhaled air is warmer, has higher humidity and
43
44 contains more CO₂ than inhaled air. These variations can be used for indicating the
45
46 respiratory rate. Most airflow-sensing methods need a sensor, attached to the
47
48 airways (7). The measurement of the airflow can be achieved by using a nasal or
49
50 oronasal thermistor which detects changes in temperature between the inhaled and
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1
2 exhaled air. This gives a semi-quantitative estimate of airflow, but the method is
3
4 limited due to a high incidence of thermistor displacement (11).
5
6

7 The nasal pressure transducer is another sensor used to measure respiration rate.
8
9 Nasal pressure is a more accurate measure of airflow than others as it based on the
10 actual volume of the air exhaled (8,12). It can be measured via nasal cannulae,
11
12 mouthpiece or facemask. A problem with airflow measurement is that some patients
13
14 may not feel comfortable with the sensor (13). The collector can also affect
15
16 respiratory activity by increasing deadspace.
17
18

19 Folke et al. (14) have reported a CO₂ sensor to measure respiration rate. Their study
20
21 also indicated that subtle design changes in the collecting device could introduce
22
23 large differences in sensor performance.
24
25

26 **2.3 Chest and Abdominal Movement Detection**

27

28 Chest and abdominal wall movements can best be measured by either mercury
29
30 strain gauges or impedance methods. Respiratory inductance plethysmography is a
31
32 non-invasive technique whereby two bands measure the respiration rate, the
33
34 thoracic band which is placed around the rib cage and the abdominal band which is
35
36 placed over the abdomen at the level of the umbilicus. The bands are made from an
37
38 extendible/deformable conducting material, either a very fine wire or thin foil such
39
40 that the conductivity can be maintained during the stretching process (12,15). The
41
42 principle of the strain gauge sensor is based on increase in the resistance of a
43
44 conductor when the area of the conductor is increased during the respiration
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46 process.
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1
2 Normally the inspiratory thoracic and abdominal expansion is almost synchronous.
3
4 However, if the upper airway is partially obstructed, there may be a change in the
5
6 phase angle and timing of the movements of the thorax and abdomen (16). The
7
8 movements become asynchronous, ie the thorax moves inwards, and the abdomen
9
10 outwards. During expiration this pattern is then reversed. Thoraco-abdominal
11
12 asynchrony is a normal finding in infants in whom chest wall compliance is greater
13
14 (17) and is exacerbated by respiratory disease or respiratory muscle weakness (18).
15

16
17 Nepal et al. (19) studied the abdominal strain gauge transducer for measuring
18
19 respiration rate. The strain gauge was strapped around the patient's chest and
20
21 changes in thoracic or abdominal circumference during breathing were measured.
22
23 The method involved a classification algorithm to separate respiratory signals as
24
25 apnoea, respiration, or respiration with motion, by using a second order
26
27 autoregressive modelling and zero cross algorithm.
28

29 **2.4 Transcutaneous CO₂ Monitoring**

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31

32
33 In transcutaneous CO₂ monitoring a heated electrode (about 42° C) is applied to the
34
35 skin (usually an arm). This method relies on the diffusion of gas to the skin and
36
37 provides an overall estimate of change in CO₂ level rather than minute by minute
38
39 readings. The electrode is surrounded by a solution to provide conductivity. Care
40
41 needs to be taken to avoid skin burning on sensitive and neonatal skin (12).
42
43 Transcutaneous CO₂ monitoring therefore allows measurements of consequences of
44
45 abnormal ventilation rather than a measure of the respiratory rate itself.
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2.5 Oximetry Probe (SpO₂) Based

Blood-Oxygen saturation (SpO₂) measurement is another technique for monitoring the consequences of abnormal ventilation. When air enters the lungs its oxygen binds to the haemoglobin in red blood cells. The oxygen is then transported throughout the body in arterial blood. A pulse oximeter uses the red and infrared frequencies to determine the percentage of haemoglobin in the blood that is saturated with oxygen. This percentage is called blood saturation, or SpO₂ (20). An oximeter simultaneously displays the SpO₂ level as well as the pulse rate and plethysmogram.

There have been studies indicating that respiration rate can be extracted from plethysmograms. Plethysmograms from ten healthy adults were processed using wavelet transforms (21). Respiration waveform was observed in the plots of the wavelet transforms. In another study involving 14 infants, of median age 2 days, the feasibility of extracting respiratory information from the plethysmogram traces was also demonstrated (22). The magnitude frequency spectra of the plethysmogram traces showed peaks associated with respiration rate.

2.6 Electrocardiogram (ECG) Derived Respiration Rate

This method is based on the fact that respiration has a modulating effect on the ECG. In this respiration rate monitoring approach, ECG electrodes are attached to the subject in order to record an ECG. By measuring the fluctuation in ECG, the respiration rate can be derived. This technique is called ECG-Derived Respiration (EDR) and is based on a process known as sinus arrhythmia, i.e. the modulation of ECG by the breathing process (23).

1
2 EDR is believed to be based on small ECG morphology changes during the
3 respiratory cycle caused by movement of the heart position relative to the electrodes
4 and the change in lung volume. Principal component analysis has been used to
5 identify which ECG lead was most effective before extracting the respiration rate
6 (24).
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11
12 EDR monitoring has also been performed by using a single-channel that did not
13 have to be a precordial lead (25). In contrast to a number of other studies that used
14 ECG characteristic waves (e.g. QRS complex), this study used the higher order
15 statistics of ECG recording (such as the 4th order cumulant).
16
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21 A study carried out a quantitative comparison of EDR monitoring techniques based
22 on direct measurement of the modulation components versus techniques based on
23 calculation of the mean electrical axis variation (26). The study concluded that single
24 lead respiration rate estimates are more robust than the methods based on the
25 mean electrical axis.
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31
32 Tarassenko et al. (27) looked at three methods: The EDR, the electrical impedance
33 pneumography (IP) signal across the chest, and the ECG or the changes in light
34 absorption which is known as photoplethysmogram (PPG) across a finger. They
35 obtained estimates of the breathing rate by adding the individual estimated outputs
36 for both the IP and PPG channels after applying the Kalman filters for both
37 waveforms. A limitation of these methods is that movement artefacts introduce
38 errors in estimating the breathing rates.
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3 Noncontact Respiratory Monitoring Methods

3.1 Radar Based Respiration Rate Monitoring

Grekeker (28) reported one of the first noncontact respiration rate monitoring systems. The system was called the Radar Vital Signs Monitor (RVSM). It was developed to monitor the performance of Olympic athletes at distances exceeding 10 meters. The RVSM detected breathing-induced movements of the chest using the Doppler phenomenon. A limitation of this method was motion artefact which corrupted the breathing signals. There have been no published studies describing the use of this method in children.

3.2 Optical Based Respiration Rate Monitoring

Aoki et al. (29) reported a non-restrictive visual sensing method to detect the respiration pattern by using a Fiber Grating (FG) vision sensor and processor unit. Their system consisted of two parts. The first was the Fibre Grating projecting device. This provided an array of invisible infra-red light spots (wavelength 810nm). The second part was a Charge-Coupled Device (CCD) camera with an optical band-pass filter. Infrared light was used to project a set of bright spots on the subject, while the CCD camera was used to capture the scene of bright spots. The moving distances of bright spots in each image were extracted and analysed to monitor respiration.

Nakajima et al. (30) used a static camera to detect thoracic movements to determine respiration rate. The projection of the surface of the thorax was represented as a region with a range of brightness intensities. Respiration was monitored by quantifying the variations of the locations of the image intensities over time.

1
2 Non-invasive optical methods have not previously been described in children,
3
4 however, in a study carried out by our group, a high speed desktop computer
5
6 connected to a video camera (webcam) was used to record respiration related chest
7
8 and abdominal movements in children in a sleep unit (31). The video consisted of a
9
10 series of sequential images, each marked with an individual time stamp (t),
11
12 corresponding to the time of the recording. An algorithm was designed to subtract
13
14 the current image at time t (i.e. img_t) and the image a few time frames before at time
15
16 $t-td$ (i.e. img_{t-td}). The value of td was determined practically. An increase in the value
17
18 of td caused faster algorithm operation, but decreased the resolution of the algorithm
19
20 in detecting movements. In this study a value of 0.5 second was used for td as it was
21
22 observed to provide an acceptable compromise between the resolution and speed.
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24 The resulting difference images (img_{diff}) were then thresholded to produce binary
25
26 images (img_x). The sum of pixel values in each binary image was determined to
27
28 produce a set of data values (x). The magnitude of each data value in x represented
29
30 the movement between the time t and $t-td$. These values were then plotted against
31
32 time to obtain a respiration signal.

33
34
35 A plot of the values of x during exhalation and inhalation is provided in Fig.1. The
36
37 vertical axis of the plot represents chest and abdominal movements. Two lobes were
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39 observed, the lobe representing inhalation being larger. During exhalation, the
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41 chest's wall initially moves slowly inward, its movement increases with time, reaching
42
43 a peak and then, the amount of movement decreases. A similar process occurs
44
45 during inhalation, but this time the chest's wall moves outward. Fig. 2 shows the plot
46
47 of $x(t)$ during three respiration cycles. An algorithm was developed to extract the
48
49 respiration rate from the recorded signal in real-time.
50

3.3 Thermal Sensor and Thermal Imaging Based Respiration Rate Monitoring

Hsu and Chow (32) have reported a thermal sensor based respiration rate monitoring system. In this approach there was no contact with the child's skin. The sensor could detect temperature changes induced by respiration and then the data were corrected and analysed simultaneously by a personal computer that was linked to a central nursery room. To avoid missing the breathing signals, an ellipsoid-shaped mask was made and the thermo sensors were placed on the mask so that breathing could be detected when the child's head turned. The problem with this method was that a mask had to be placed close to the child's face.

Zhu et al. (33) developed an infrared imaging based respiration rate monitoring method. They designed a tracking algorithm that could follow facial features related to respiration. These features were selected manually from a reference image (i.e. the first image in the video) by specifying three windows. Two of these windows covered the areas between the bridge of nose and the inner corner of the eyes (i.e. the periorbital regions) and represented the warmest facial areas. Another window was placed on the apex of nose to represent the coolest facial area. Their algorithm tracked these three windows in the following recorded images. The respiration signal was obtained from a rectangular region under the nose.

Instead of using a focal plane array of mid-wave infra-red sensors, Chekmenev, et al. (34) used a thermal camera consisting of a focal plane array for a long-wave infra-red (6-15 μm) sensor. They measured the temperature changes around the neck region, carotid vessel complex, and the nasal region. The selection of these regions was carried out manually. A wavelet analysis technique was developed to extract the ECG and the respiration rate.

1
2 In a study carried out by our group, the FLIR A40 thermal camera was used to
3 monitor respiration related skin surface temperature variation in area centred on the
4 tip of the nose (35). The thermal sensitivity of the camera is 0.08 Kelvin. The camera
5 was fixed on a tripod in front of the subject at a distance of about one meter. The
6 image capture rate was 50 frames per second, thus providing 3000 images per
7 minute. The recording time was two minutes. The images were segmented and then
8 an algorithm was used to locate and track a circular area centred on the tip of the
9 nose. The segmentation and tracking algorithms are described Al-Khalidi et al. (36).
10 The chosen area was divided into eight equal concentric segments as shown in
11 Fig.3. The pixel values within each of the eight segments were averaged to obtain a
12 single value representing the skin temperature in that segment. The process was
13 repeated for each image. Plots of the average temperature against time for the
14 segments were obtained (see Fig.4). These plots represented the respiration signal
15 associated with the segments. The respiration signal reduces in amplitude during
16 inhalation and increases in amplitude during exhalation. The clarity of the signals
17 varied, with segments 3 and 7 providing the most clear signals and segment 1
18 providing the least clear signal. This result indicated that for respiration monitoring, it
19 would be advisable to consider all the eight segments and then to select the
20 segments that provide the clearest respiration signal. An algorithm was produced to
21 automatically extract the respiration rate from the recorded signal.
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45 **4. Discussion**

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47 Respiration rate monitoring has evolved from the days when it could only be
48 measured by placing the back of the hand close to the nose to monitor exhaled air. It
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1
2 is very important to develop a reliable, accurate and objective method of monitoring
3 respiratory rate in children which is non-invasive and therefore will not cause distress
4 to the child which may lead to inaccuracies in the measurement. The gold standard
5 is still to place a thermistor in a nostril to monitor exhaled air. However, a variety of
6 contact and noncontact respiration monitoring devices have been developed,
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8

Deleted: to overcome the shortcomings of contact methods.

9
10
11
12 Several techniques are available for measurement of respiratory rate via nasal
13 prongs, masks, thermistor or respiratory impedance plethysmography. These
14 methods all involve some contact with the child. A pneumotachograph has the
15 advantage that it gives quantitative assessments of flows, from which respiratory rate
16 can be derived, and may be important in a research setting. The thermistor is a
17 commonly used technique to detect temperature changes breath by breath at the
18 nostril, thereby giving the number of breaths per minute. This technique has been
19 formally validated in the measurement of respiratory rate for the purposes of sleep
20 studies (11). A semi-quantitative measure of airflow and tidal volume can be derived
21 from respiratory inductance plethysmography (RIP). The technique has been
22 demonstrated to work well in measuring tidal volume in infants (37).
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25
26 However, from a clinical perspective the main disadvantage of these methods is that
27 they require connection to the child, some to the facial area, which disturbs many
28 children and may be poorly tolerated. In addition, in infants and children, the added
29 dead space of the equipment required for some of these techniques may have an
30 influence on breathing patterns (38).
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There are extensive opportunities to further improve noncontact respiration
monitoring schemes. Radar, infrared imaging and optical imaging have all been
used to monitor respiration rate. Advances in computing technology have resulted in

1
2 realisation of complex algorithms for respiration monitoring. For example, it has been
3
4 possible to use 3-dimensional vision algorithms and two web cameras to monitor
5
6 respiration in manikins (36).
7

8
9 Currently noncontact respiration monitoring methods have not yet reached the level
10
11 of maturity that can be used routinely in clinical environments. Concerns related to
12
13 patient safety, electromagnetic interference with existing medical equipments,
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15 complexity of using the systems have been factors in their slow take up in clinical
16
17 environments. With further development, noncontact methods will gradually become
18
19 more and more viable and will effectively complement contact based respiration rate
20
21 monitoring methods.
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24 We have developed two novel methods for non contact respiratory rate monitoring in
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26 children which, whilst currently are sophisticated, high technology devices are
27
28 undergoing further evaluation in acute clinical settings and will serve as a basis for
29
30 future development to produce an inexpensive, user friendly device for use in the
31
32 clinical environment.
33

34 35 36 **5. Conclusions** 37

38
39 Monitoring respiration rate is an important task when evaluating a subject's health.
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41 Respiration rate monitoring devices can be classified by a number of ways
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43 depending on the manner of their use and their operation. In this review paper, they
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45 were grouped into contact and noncontact. This review has highlighted the advances
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47 made to improve the effectiveness of respiration monitoring. The potential for
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49 noncontact respiration monitoring is emphasised. Noncontact respiration rate
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2 monitoring devices have a distinct advantage over contact methods, especially in
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4 children, as they cause least disturbance to the patient. Studies are still ongoing to
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6 produce more effective respiration monitoring devices.
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For Peer Review

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Respiration Rate Monitoring Methods: A Review

F.Q. AL-Khalidi¹, R. Saatchi¹, D. Burke², H. Elphick² and S. Tan¹

¹ Faculty of ACES, Sheffield Hallam University, Sheffield, U.K.

² Sheffield Children's NHS Foundation Trust, Sheffield, U.K.

Author for correspondence:

Name: Heather E Elphick

Address: Floor E, Stephenson Unit, Sheffield Children's Hospital, Western Bank,
Sheffield S10 2TH, UK

Tel: (0)114 2717585

Email: Heather.Elphick@sch.nhs.uk

Short Title: Respiration Rate Monitoring Methods

Summary

Respiration rate is an important indicator of a person's health, and thus it is monitored when performing clinical evaluations. There are different approaches for respiration monitoring, but generally they can be classed as contact or noncontact. For contact methods, the sensing device (or part of the instrument containing it) is attached to the subject's body. For noncontact approaches the monitoring is performed by an instrument that does not make any contact with the subject.

In this paper a review of respiration monitoring approaches (both contact and noncontact) is provided. Concerns related to the patient's recording comfort, recording hygiene, and the accuracy of respiration rate monitoring have resulted in the development of a number of noncontact respiration monitoring approaches.

A description of thermal imaging based and vision based noncontact respiration monitoring approaches we are currently developing is provided.

Keywords: Respiratory, thermal imaging, noncontact

1. Introduction

Breathing is an important physiological task in living organisms. For humans, this process results in air containing oxygen being inhaled into the lungs, where gas exchange occurs across the alveolar-capillary membrane (1). Carbon Dioxide is excreted as part of the process, in the air released through the nose or mouth. The entire process from the inhalation to exhalation is known as a breathing (or respiration) cycle.

Respiratory rate is a vital sign used to monitor the progression of illness and an abnormal respiratory rate is an important marker of serious illness. There is substantial evidence that alterations in respiratory rate can be used to predict potentially serious clinical events such as cardiac arrest or admission to the intensive care unit (2-5). These studies have shown respiratory rate to be better than other vital measurements such as pulse and blood pressure in discriminating between stable patients and patient at risk (3). Using changes in respiratory rate measurements patients could have been identified as high risk up to 24 hours before the event with a specificity of 95% (5). Hospital systems such as the Paediatric Early Warning System (PEWS) have been developed to encourage appropriate responses to abnormal vital signs including an elevated respiratory rate.

Evidence from a recent audit of febrile children in our unit suggests that in both the emergency department and the acute medical admissions unit, respiratory rate was only measured in around two thirds of children on arrival. Reasons for omission were given as “crying” or “unsettled” and in many of these children experienced nursing

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3 staff were unable to obtain an accurate reading. However, it is in these children that
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5 this measurement would potentially be most useful and important.
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11 According to Murthy (6), existing devices for monitoring respiratory rate only estimate
12 the actual breathing rate due to their limitations. These devices can be classified in
13 different ways, depending on the manner in which they operate and how they are
14 used. In this paper, respiration rate monitoring devices are grouped as either contact
15 or noncontact. In contact respiration rate monitoring, the instrument makes direct
16 contact with the subject's body. However, in noncontact monitoring, the respiration
17 rate is measured without the instrument making contact with the subject's body.
18 There are clear advantages to noncontact respiration monitoring methods. These
19 include improved patient comfort (especially for long term monitoring) as the subject
20 is not tied to an instrument and improved accuracy as distress caused by a contact
21 device may alter the respiration rate.
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41 There have been several studies reporting developments in both contact and non-
42 contact respiration monitoring. A review of non-invasive respiratory monitoring in
43 medical care was provided by Folke et al. (7). This paper aims to review the
44 literature on contact and non-contact methods of respiratory rate monitoring,
45 including two methods currently being developed by our unit.
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57 **2. Contact Based Respiration Monitoring**

58 Contact respiration rate monitoring instruments are usually based on measuring one
59 of the following parameters: respiratory sounds, respiratory airflow, respiratory
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3 related chest or abdominal movements, respiratory CO₂ emission and oximetry
4 probe SpO₂. Respiration rate can also be derived from the electrocardiogram
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6 (ECG).
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10 11 12 13 14 **2.1 Acoustic Based Methods** 15 16

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18 Respiratory sound can be measured using a microphone placed either close to the
19 respiratory airways or over the throat to detect the variation of sound. Then a
20 frequency analysis and estimation of the loudness of the sound can be carried out
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22 (8).
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28 Werthammer et al. (9) reported a respiratory sounds measurement system to detect
29 sleep apnea in infants. The system depended on recording a signal derived from
30 breathing sounds from the nose. This method was applied to eight premature
31 infants. Snorting, speaking, crying, coughing etc had a negative effect on the
32 operation of the system.
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40 Corbishley and Rordriguez-Villegas (10) proposed a miniaturised and wearable
41 respiration monitoring respiration system. It used a microphone mounted on the
42 neck to obtain the largest breathing acoustic.
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49 **2.2 Airflow Based Methods** 50

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52 Airflow can be detected because exhaled air is warmer, has higher humidity and
53 contains more CO₂ than inhaled air. These variations can be used for indicating the
54 respiratory rate. Most airflow-sensing methods need a sensor, attached to the
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56 airways (7). The measurement of the airflow can be achieved by using a nasal or
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58 oronasal thermistor which detects changes in temperature between the inhaled and
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3 exhaled air. This gives a semi-quantitative estimate of airflow, but the method is
4
5 limited due to a high incidence of thermistor displacement (11).
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9 The nasal pressure transducer is another sensor used to measure respiration rate.
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11 Nasal pressure is a more accurate measure of airflow than others as it based on the
12
13 actual volume of the air exhaled (8,12). It can be measured via nasal cannulae,
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15 mouthpiece or facemask. A problem with airflow measurement is that some patients
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17 may not feel comfortable with the sensor (13). The collector can also affect
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19 respiratory activity by increasing deadspace.
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24 Folke et al. (14) have reported a CO₂ sensor to measure respiration rate. Their study
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26 also indicated that subtle design changes in the collecting device could introduce
27
28 large differences in sensor performance.
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31 32 **2.3 Chest and Abdominal Movement Detection**

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35 Chest and abdominal wall movements can best be measured by either mercury
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37 strain gauges or impedance methods. Respiratory inductance plethysmography is a
38
39 non-invasive technique whereby two bands measure the respiration rate, the
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41 thoracic band which is placed around the rib cage and the abdominal band which is
42
43 placed over the abdomen at the level of the umbilicus. The bands are made from an
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45 extendible/deformable conducting material, either a very fine wire or thin foil such
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47 that the conductivity can be maintained during the stretching process (12,15). The
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49 principle of the strain gauge sensor is based on increase in the resistance of a
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51 conductor when the area of the conductor is increased during the respiration
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53 process.
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3 Normally the inspiratory thoracic and abdominal expansion is almost synchronous.
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5 However, if the upper airway is partially obstructed, there may be a change in the
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7 phase angle and timing of the movements of the thorax and abdomen (16). The
8
9 movements become asynchronous, ie the thorax moves inwards, and the abdomen
10
11 outwards. During expiration this pattern is then reversed. Thoraco-abdominal
12
13 asynchrony is a normal finding in infants in whom chest wall compliance is greater
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15 (17) and is exacerbated by respiratory disease or respiratory muscle weakness (18).
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20 Nepal et al. (19) studied the abdominal strain gauge transducer for measuring
21
22 respiration rate. The strain gauge was strapped around the patient's chest and
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24 changes in thoracic or abdominal circumference during breathing were measured.
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26 The method involved a classification algorithm to separate respiratory signals as
27
28 apnoea, respiration, or respiration with motion, by using a second order
29
30 autoregressive modelling and zero cross algorithm.
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35 36 **2.4 Transcutaneous CO₂ Monitoring** 37

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39 In transcutaneous CO₂ monitoring a heated electrode (about 42° C) is applied to the
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41 skin (usually an arm). This method relies on the diffusion of gas to the skin and
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43 provides an overall estimate of change in CO₂ level rather than minute by minute
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45 readings. The electrode is surrounded by a solution to provide conductivity. Care
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47 needs to be taken to avoid skin burning on sensitive and neonatal skin (12).
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49 Transcutaneous CO₂ monitoring therefore allows measurements of consequences of
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51 abnormal ventilation rather than a measure of the respiratory rate itself.
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2.5 Oximetry Probe (SpO₂) Based

Blood-Oxygen saturation (SpO₂) measurement is another technique for monitoring the consequences of abnormal ventilation. When air enters the lungs its oxygen binds to the haemoglobin in red blood cells. The oxygen is then transported throughout the body in arterial blood. A pulse oximeter uses the red and infrared frequencies to determine the percentage of haemoglobin in the blood that is saturated with oxygen. This percentage is called blood saturation, or SpO₂ (20). An oximeter simultaneously displays the SpO₂ level as well as the pulse rate and plethysmogram.

There have been studies indicating that respiration rate can be extracted from plethysmograms. Plethysmograms from ten healthy adults were processed using wavelet transforms (21). Respiration waveform was observed in the plots of the wavelet transforms. In another study involving 14 infants, of median age 2 days, the feasibility of extracting respiratory information from the plethysmogram traces was also demonstrated (22). The magnitude frequency spectra of the plethysmogram traces showed peaks associated with respiration rate.

2.6 Electrocardiogram (ECG) Derived Respiration Rate

This method is based on the fact that respiration has a modulating effect on the ECG. In this respiration rate monitoring approach, ECG electrodes are attached to the subject in order to record an ECG. By measuring the fluctuation in ECG, the respiration rate can be derived. This technique is called ECG-Derived Respiration (EDR) and is based on a process known as sinus arrhythmia, i.e. the modulation of ECG by the breathing process (23).

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3 EDR is believed to be based on small ECG morphology changes during the
4 respiratory cycle caused by movement of the heart position relative to the electrodes
5 and the change in lung volume. Principal component analysis has been used to
6 identify which ECG lead was most effective before extracting the respiration rate
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13 (24).

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16 EDR monitoring has also been performed by using a single-channel that did not
17 have to be a precordial lead (25). In contrast to a number of other studies that used
18 ECG characteristic waves (e.g. QRS complex), this study used the higher order
19 statistics of ECG recording (such as the 4th order cumulant).
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26 A study carried out a quantitative comparison of EDR monitoring techniques based
27 on direct measurement of the modulation components versus techniques based on
28 calculation of the mean electrical axis variation (26). The study concluded that single
29 lead respiration rate estimates are more robust than the methods based on the
30 mean electrical axis.
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38 Tarassenko et al. (27) looked at three methods: The EDR, the electrical impedance
39 pneumography (IP) signal across the chest, and the ECG or the changes in light
40 absorption which is known as photoplethysmogram (PPG) across a finger. They
41 obtained estimates of the breathing rate by adding the individual estimated outputs
42 for both the IP and PPG channels after applying the Kalman filters for both
43 waveforms. A limitation of these methods is that movement artefacts introduce
44 errors in estimating the breathing rates.
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3 Noncontact Respiratory Monitoring Methods

3.1 Radar Based Respiration Rate Monitoring

Grener (28) reported one of the first noncontact respiration rate monitoring systems. The system was called the Radar Vital Signs Monitor (RVSM). It was developed to monitor the performance of Olympic athletes at distances exceeding 10 meters. The RVSM detected breathing-induced movements of the chest using the Doppler phenomenon. A limitation of this method was motion artefact which corrupted the breathing signals. There have been no published studies describing the use of this method in children.

3.2 Optical Based Respiration Rate Monitoring

Aoki et al. (29) reported a non-restrictive visual sensing method to detect the respiration pattern by using a Fiber Grating (FG) vision sensor and processor unit. Their system consisted of two parts. The first was the Fibre Grating projecting device. This provided an array of invisible infra-red light spots (wavelength 810nm). The second part was a Charge-Coupled Device (CCD) camera with an optical band-pass filter. Infrared light was used to project a set of bright spots on the subject, while the CCD camera was used to capture the scene of bright spots. The moving distances of bright spots in each image were extracted and analysed to monitor respiration.

Nakajima et al. (30) used a static camera to detect thoracic movements to determine respiration rate. The projection of the surface of the thorax was represented as a region with a range of brightness intensities. Respiration was monitored by quantifying the variations of the locations of the image intensities over time.

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3 Non-invasive optical methods have not previously been described in children,
4 however, in a study carried out by our group, a high speed desktop computer
5 connected to a video camera (webcam) was used to record respiration related chest
6 and abdominal movements in children in a sleep unit (31). The video consisted of a
7 series of sequential images, each marked with an individual time stamp (t),
8 corresponding to the time of the recording. An algorithm was designed to subtract
9 the current image at time t (i.e. img_t) and the image a few time frames before at time
10 $t-td$ (i.e. img_{t-td}). The value of td was determined practically. An increase in the value
11 of td caused faster algorithm operation, but decreased the resolution of the algorithm
12 in detecting movements. In this study a value of 0.5 second was used for td as it was
13 observed to provide an acceptable compromise between the resolution and speed.
14 The resulting difference images (img_{diff}) were then thresholded to produce binary
15 images (img_x). The sum of pixel values in each binary image was determined to
16 produce a set of data values (x). The magnitude of each data value in x represented
17 the movement between the time t and $t-td$. These values were then plotted against
18 time to obtain a respiration signal.
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43 A plot of the values of x during exhalation and inhalation is provided in Fig.1. The
44 vertical axis of the plot represents chest and abdominal movements. Two lobes were
45 observed, the lobe representing inhalation being larger. During exhalation, the
46 chest's wall initially moves slowly inward, its movement increases with time, reaching
47 a peak and then, the amount of movement decreases. A similar process occurs
48 during inhalation, but this time the chest's wall moves outward. Fig. 2 shows the plot
49 of $x(t)$ during three respiration cycles. An algorithm was developed to extract the
50 respiration rate from the recorded signal in real-time.
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3.3 Thermal Sensor and Thermal Imaging Based Respiration Rate Monitoring

Hsu and Chow (32) have reported a thermal sensor based respiration rate monitoring system. In this approach there was no contact with the child's skin. The sensor could detect temperature changes induced by respiration and then the data were corrected and analysed simultaneously by a personal computer that was linked to a central nursery room. To avoid missing the breathing signals, an ellipsoid-shaped mask was made and the thermo sensors were placed on the mask so that breathing could be detected when the child's head turned. The problem with this method was that a mask had to be placed close to the child's face.

Zhu et al. (33) developed an infrared imaging based respiration rate monitoring method. They designed a tracking algorithm that could follow facial features related to respiration. These features were selected manually from a reference image (i.e. the first image in the video) by specifying three windows. Two of these windows covered the areas between the bridge of nose and the inner corner of the eyes (i.e. the periorbital regions) and represented the warmest facial areas. Another window was placed on the apex of nose to represent the coolest facial area. Their algorithm tracked these three windows in the following recorded images. The respiration signal was obtained from a rectangular region under the nose.

Instead of using a focal plane array of mid-wave infra-red sensors, Chekmenev, et al. (34) used a thermal camera consisting of a focal plane array for a long-wave infra-red (6-15 μm) sensor. They measured the temperature changes around the neck region, carotid vessel complex, and the nasal region. The selection of these regions was carried out manually. A wavelet analysis technique was developed to extract the ECG and the respiration rate.

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3 In a study carried out by our group, the FLIR A40 thermal camera was used to
4 monitor respiration related skin surface temperature variation in area centred on the
5 tip of the nose (35). The thermal sensitivity of the camera is 0.08 Kelvin. The camera
6 was fixed on a tripod in front of the subject at a distance of about one meter. The
7 image capture rate was 50 frames per second, thus providing 3000 images per
8 minute. The recording time was two minutes. The images were segmented and then
9 an algorithm was used to locate and track a circular area centred on the tip of the
10 nose. The segmentation and tracking algorithms are described Al-Khalidi et al. (36).
11 The chosen area was divided into eight equal concentric segments as shown in
12 Fig.3. The pixel values within each of the eight segments were averaged to obtain a
13 single value representing the skin temperature in that segment. The process was
14 repeated for each image. Plots of the average temperature against time for the
15 segments were obtained (see Fig.4). These plots represented the respiration signal
16 associated with the segments. The respiration signal reduces in amplitude during
17 inhalation and increases in amplitude during exhalation. The clarity of the signals
18 varied, with segments 3 and 7 providing the most clear signals and segment 1
19 providing the least clear signal. This result indicated that for respiration monitoring, it
20 would be advisable to consider all the eight segments and then to select the
21 segments that provide the clearest respiration signal. An algorithm was produced to
22 automatically extract the respiration rate from the recorded signal.
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55 **4. Discussion**

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58 Respiration rate monitoring has evolved from the days when it could only be
59 measured by placing the back of the hand close to the nose to monitor exhaled air. It
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3 is very important to develop a reliable, accurate and objective method of monitoring
4 respiratory rate in children which is non-invasive and therefore will not cause distress
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6 to the child which may lead to inaccuracies in the measurement. The gold standard
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8 is still to place a thermistor in a nostril to monitor exhaled air. However, a variety of
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10 contact and noncontact respiration monitoring devices have been developed.
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15 Several techniques are available for measurement of respiratory rate via nasal
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17 prongs, masks, thermistor or respiratory impedance plethysmography. These
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19 methods all involve some contact with the child. A pneumotachograph has the
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21 advantage that it gives quantitative assessments of flows, from which respiratory rate
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23 can be derived, and may be important in a research setting. The thermistor is a
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25 commonly used technique to detect temperature changes breath by breath at the
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27 nostril, thereby giving the number of breaths per minute. This technique has been
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29 formally validated in the measurement of respiratory rate for the purposes of sleep
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31 studies (11). A semi-quantitative measure of airflow and tidal volume can be derived
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33 from respiratory inductance plethysmography (RIP). The technique has been
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35 demonstrated to work well in measuring tidal volume in infants (37).
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43 However, from a clinical perspective the main disadvantage of these methods is that
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45 they require connection to the child, some to the facial area, which disturbs many
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47 children and may be poorly tolerated. In addition, in infants and children, the added
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49 dead space of the equipment required for some of these techniques may have an
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51 influence on breathing patterns (38).
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55 There are extensive opportunities to further improve noncontact respiration
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57 monitoring schemes. Radar, infrared imaging and optical imaging have all been
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59 used to monitor respiration rate. Advances in computing technology have resulted in
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3 realisation of complex algorithms for respiration monitoring. For example, it has been
4 possible to use 3-dimensional vision algorithms and two web cameras to monitor
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6 respiration in manikins (36).
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11 Currently noncontact respiration monitoring methods have not yet reached the level
12 of maturity that can be used routinely in clinical environments. Concerns related to
13 patient safety, electromagnetic interference with existing medical equipments,
14 complexity of using the systems have been factors in their slow take up in clinical
15 environments. With further development, noncontact methods will gradually become
16 more and more viable and will effectively complement contact based respiration rate
17 monitoring methods.
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28 We have developed two novel methods for non contact respiratory rate monitoring in
29 children which, whilst currently are sophisticated, high technology devices are
30 undergoing further evaluation in acute clinical settings and will serve as a basis for
31 future development to produce an inexpensive, user friendly device for use in the
32 clinical environment.
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44 **5. Conclusions**

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47 Monitoring respiration rate is an important task when evaluating a subject's health.
48 Respiration rate monitoring devices can be classified by a number of ways
49 depending on the manner of their use and their operation. In this review paper, they
50 were grouped into contact and noncontact. This review has highlighted the advances
51 made to improve the effectiveness of respiration monitoring. The potential for
52 noncontact respiration monitoring is emphasised. Noncontact respiration rate
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3 monitoring devices have a distinct advantage over contact methods, especially in
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5 children, as they cause least disturbance to the patient. Studies are still ongoing to
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7 produce more effective respiration monitoring devices.
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For Peer Review

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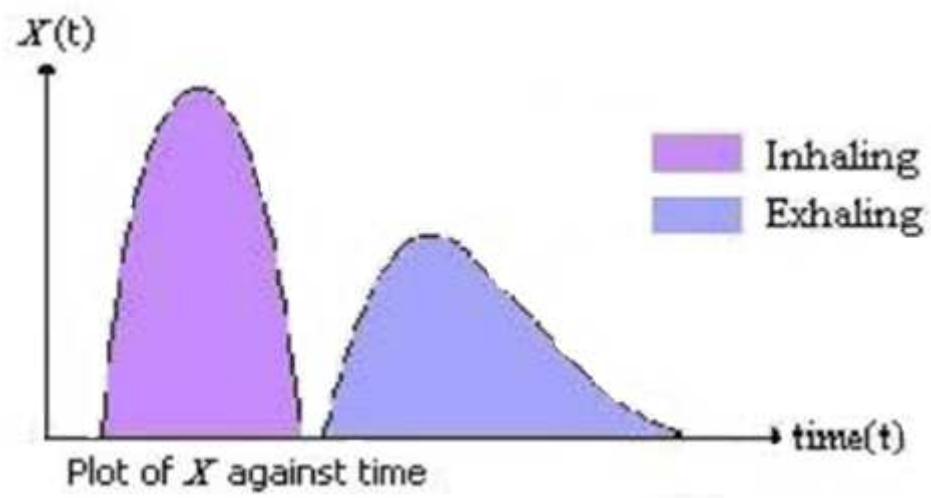
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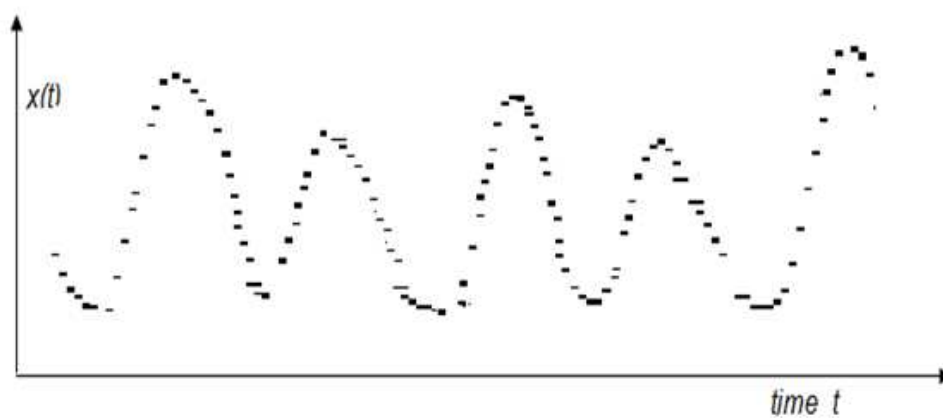
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A plot of values of x during inhalation and exhalation.
128x68mm (96 x 96 DPI)

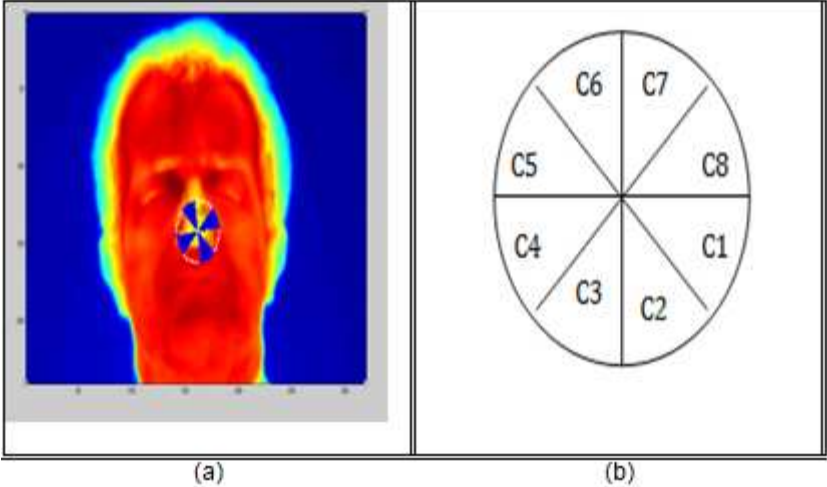
Peer Review



Plot $x(t)$ against time during three respiration cycles.
154x69mm (96 x 96 DPI)

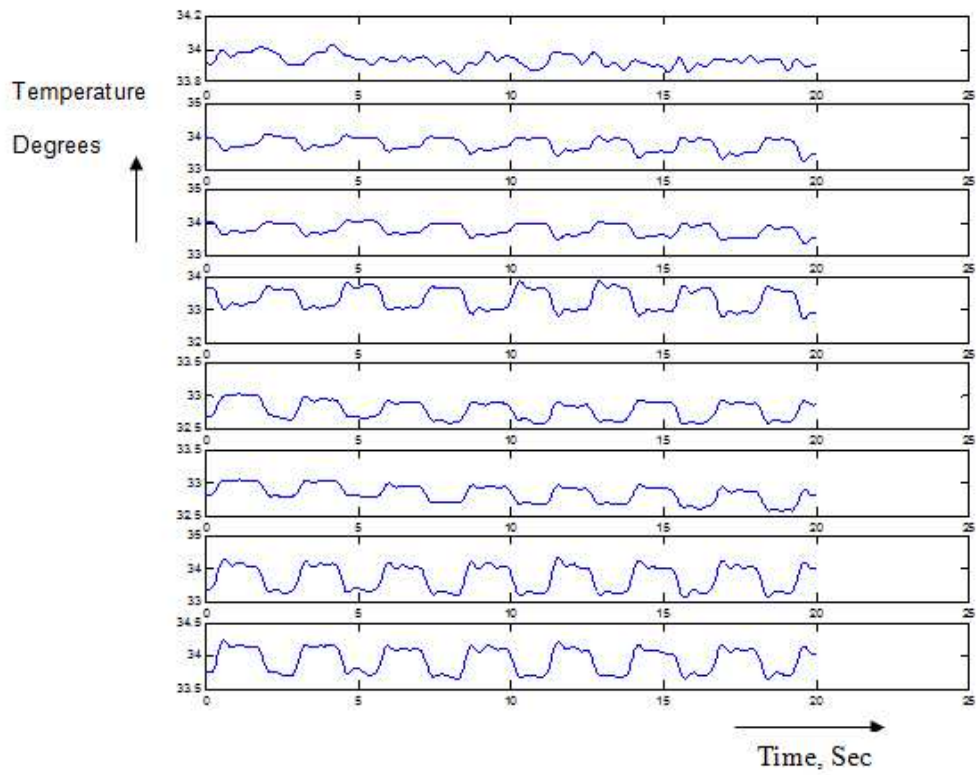
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(a) A thermal image with tip of the nose represented by a circle, (b) the eight segments of the selected respiration region.
110x65mm (96 x 96 DPI)

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Respiration signals obtained from segments 1 to 8 (from top to bottom respectively).
148x116mm (96 x 96 DPI)