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## Respiration Rate Monitoring Methods: A Review

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Review

**Respiration Rate Monitoring Methods: A Review**

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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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9  
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  
50  
51  
52

1  
2 related chest or abdominal movements, respiratory CO<sub>2</sub> emission and oximetry  
3  
4 probe SpO<sub>2</sub>. Respiration rate can also be derived from the electrocardiogram  
5  
6 (ECG).  
7  
8  
9

## 10 11 **2.1 Acoustic Based Methods**

12  
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 CO<sub>2</sub> 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 CO<sub>2</sub> 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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2 Normally the inspiratory thoracic and abdominal expansion is almost synchronous.  
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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 Nepal et al. (19) studied the abdominal strain gauge transducer for measuring  
17  
18 respiration rate. The strain gauge was strapped around the patient's chest and  
19  
20 changes in thoracic or abdominal circumference during breathing were measured.  
21  
22 The method involved a classification algorithm to separate respiratory signals as  
23  
24 apnoea, respiration, or respiration with motion, by using a second order  
25  
26 autoregressive modelling and zero cross algorithm.  
27

#### 28 29 **2.4 Transcutaneous CO<sub>2</sub> Monitoring**

30  
31  
32 In transcutaneous CO<sub>2</sub> monitoring a heated electrode (about 42° C) is applied to the  
33  
34 skin (usually an arm). This method relies on the diffusion of gas to the skin and  
35  
36 provides an overall estimate of change in CO<sub>2</sub> level rather than minute by minute  
37  
38 readings. The electrode is surrounded by a solution to provide conductivity. Care  
39  
40 needs to be taken to avoid skin burning on sensitive and neonatal skin (12).  
41  
42 Transcutaneous CO<sub>2</sub> monitoring therefore allows measurements of consequences of  
43  
44 abnormal ventilation rather than a measure of the respiratory rate itself.  
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## 2.5 Oximetry Probe (SpO<sub>2</sub>) Based

Blood-Oxygen saturation (SpO<sub>2</sub>) 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 SpO<sub>2</sub> (20). An oximeter simultaneously displays the SpO<sub>2</sub> 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  
4 respiratory cycle caused by movement of the heart position relative to the electrodes  
5  
6 and the change in lung volume. Principal component analysis has been used to  
7  
8 identify which ECG lead was most effective before extracting the respiration rate  
9  
10 (24).

11  
12 EDR monitoring has also been performed by using a single-channel that did not  
13  
14 have to be a precordial lead (25). In contrast to a number of other studies that used  
15  
16 ECG characteristic waves (e.g. QRS complex), this study used the higher order  
17  
18 statistics of ECG recording (such as the 4th order cumulant).  
19

20  
21 A study carried out a quantitative comparison of EDR monitoring techniques based  
22  
23 on direct measurement of the modulation components versus techniques based on  
24  
25 calculation of the mean electrical axis variation (26). The study concluded that single  
26  
27 lead respiration rate estimates are more robust than the methods based on the  
28  
29 mean electrical axis.  
30

31  
32 Tarassenko et al. (27) looked at three methods: The EDR, the electrical impedance  
33  
34 pneumography (IP) signal across the chest, and the ECG or the changes in light  
35  
36 absorption which is known as photoplethysmogram (PPG) across a finger. They  
37  
38 obtained estimates of the breathing rate by adding the individual estimated outputs  
39  
40 for both the IP and PPG channels after applying the Kalman filters for both  
41  
42 waveforms. A limitation of these methods is that movement artefacts introduce  
43  
44 errors in estimating the breathing rates.  
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### 3 Noncontact Respiratory Monitoring Methods

#### 3.1 Radar Based Respiration Rate Monitoring

Greneker (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.  
23  
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  
38  
39 observed, the lobe representing inhalation being larger. During exhalation, the  
40  
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  $\mu\text{m}$ ) 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,

**Deleted:** to overcome the shortcomings of contact methods.

Several techniques are available for measurement of respiratory rate via nasal prongs, masks, thermistor or respiratory impedance plethysmography. These methods all involve some contact with the child. A pneumotachograph has the advantage that it gives quantitative assessments of flows, from which respiratory rate can be derived, and may be important in a research setting. The thermistor is a commonly used technique to detect temperature changes breath by breath at the nostril, thereby giving the number of breaths per minute. This technique has been formally validated in the measurement of respiratory rate for the purposes of sleep studies (11). A semi-quantitative measure of airflow and tidal volume can be derived from respiratory inductance plethysmography (RIP). The technique has been demonstrated to work well in measuring tidal volume in infants (37).

However, from a clinical perspective the main disadvantage of these methods is that they require connection to the child, some to the facial area, which disturbs many children and may be poorly tolerated. In addition, in infants and children, the added dead space of the equipment required for some of these techniques may have an influence on breathing patterns (38).

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,  
14  
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.  
22

23  
24 We have developed two novel methods for non contact respiratory rate monitoring in  
25  
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.  
40  
41 Respiration rate monitoring devices can be classified by a number of ways  
42  
43 depending on the manner of their use and their operation. In this review paper, they  
44  
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

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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 CO<sub>2</sub> emission and oximetry  
4 probe SpO<sub>2</sub>. 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

51  
52 Airflow can be detected because exhaled air is warmer, has higher humidity and  
53 contains more CO<sub>2</sub> 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  
16  
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 CO<sub>2</sub> 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  
40  
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  
44  
45 extendible/deformable conducting material, either a very fine wire or thin foil such  
46  
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  
6  
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  
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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  
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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  
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28 apnoea, respiration, or respiration with motion, by using a second order  
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30 autoregressive modelling and zero cross algorithm.  
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#### 35 36 **2.4 Transcutaneous CO<sub>2</sub> Monitoring**

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40 In transcutaneous CO<sub>2</sub> monitoring a heated electrode (about 42° C) is applied to the  
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42 skin (usually an arm). This method relies on the diffusion of gas to the skin and  
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44 provides an overall estimate of change in CO<sub>2</sub> level rather than minute by minute  
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46 readings. The electrode is surrounded by a solution to provide conductivity. Care  
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48 needs to be taken to avoid skin burning on sensitive and neonatal skin (12).  
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50 Transcutaneous CO<sub>2</sub> monitoring therefore allows measurements of consequences of  
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52 abnormal ventilation rather than a measure of the respiratory rate itself.  
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## 2.5 Oximetry Probe (SpO<sub>2</sub>) Based

Blood-Oxygen saturation (SpO<sub>2</sub>) 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 SpO<sub>2</sub> (20). An oximeter simultaneously displays the SpO<sub>2</sub> 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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39 Tarassenko et al. (27) looked at three methods: The EDR, the electrical impedance  
40 pneumography (IP) signal across the chest, and the ECG or the changes in light  
41 absorption which is known as photoplethysmogram (PPG) across a finger. They  
42 obtained estimates of the breathing rate by adding the individual estimated outputs  
43 for both the IP and PPG channels after applying the Kalman filters for both  
44 waveforms. A limitation of these methods is that movement artefacts introduce  
45 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,  
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5 however, in a study carried out by our group, a high speed desktop computer  
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7 connected to a video camera (webcam) was used to record respiration related chest  
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9 and abdominal movements in children in a sleep unit (31). The video consisted of a  
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11 series of sequential images, each marked with an individual time stamp ( $t$ ),  
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13 corresponding to the time of the recording. An algorithm was designed to subtract  
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15 the current image at time  $t$  (i.e.  $img_t$ ) and the image a few time frames before at time  
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17  $t-td$  (i.e.  $img_{t-td}$ ). The value of  $td$  was determined practically. An increase in the value  
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19 of  $td$  caused faster algorithm operation, but decreased the resolution of the algorithm  
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21 in detecting movements. In this study a value of 0.5 second was used for  $td$  as it was  
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23 observed to provide an acceptable compromise between the resolution and speed.  
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25 The resulting difference images ( $img_{diff}$ ) were then thresholded to produce binary  
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27 images ( $img_x$ ). The sum of pixel values in each binary image was determined to  
28  
29 produce a set of data values ( $x$ ). The magnitude of each data value in  $x$  represented  
30  
31 the movement between the time  $t$  and  $t-td$ . These values were then plotted against  
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33 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  
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45 vertical axis of the plot represents chest and abdominal movements. Two lobes were  
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47 observed, the lobe representing inhalation being larger. During exhalation, the  
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49 chest's wall initially moves slowly inward, its movement increases with time, reaching  
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51 a peak and then, the amount of movement decreases. A similar process occurs  
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53 during inhalation, but this time the chest's wall moves outward. Fig. 2 shows the plot  
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55 of  $x(t)$  during three respiration cycles. An algorithm was developed to extract the  
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57 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  $\mu\text{m}$ ) 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  
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5 respiratory rate in children which is non-invasive and therefore will not cause distress  
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7 to the child which may lead to inaccuracies in the measurement. The gold standard  
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9 is still to place a thermistor in a nostril to monitor exhaled air. However, a variety of  
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11 contact and noncontact respiration monitoring devices have been developed.  
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16 Several techniques are available for measurement of respiratory rate via nasal  
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18 prongs, masks, thermistor or respiratory impedance plethysmography. These  
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20 methods all involve some contact with the child. A pneumotachograph has the  
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22 advantage that it gives quantitative assessments of flows, from which respiratory rate  
23  
24 can be derived, and may be important in a research setting. The thermistor is a  
25  
26 commonly used technique to detect temperature changes breath by breath at the  
27  
28 nostril, thereby giving the number of breaths per minute. This technique has been  
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30 formally validated in the measurement of respiratory rate for the purposes of sleep  
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32 studies (11). A semi-quantitative measure of airflow and tidal volume can be derived  
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34 from respiratory inductance plethysmography (RIP). The technique has been  
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36 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  
48  
49 dead space of the equipment required for some of these techniques may have an  
50  
51 influence on breathing patterns (38).  
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56 There are extensive opportunities to further improve noncontact respiration  
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58 monitoring schemes. Radar, infrared imaging and optical imaging have all been  
59  
60 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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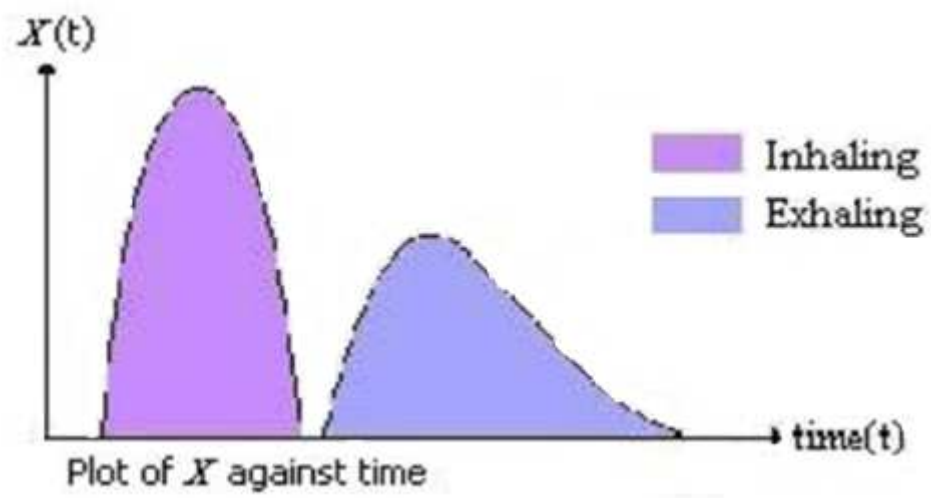
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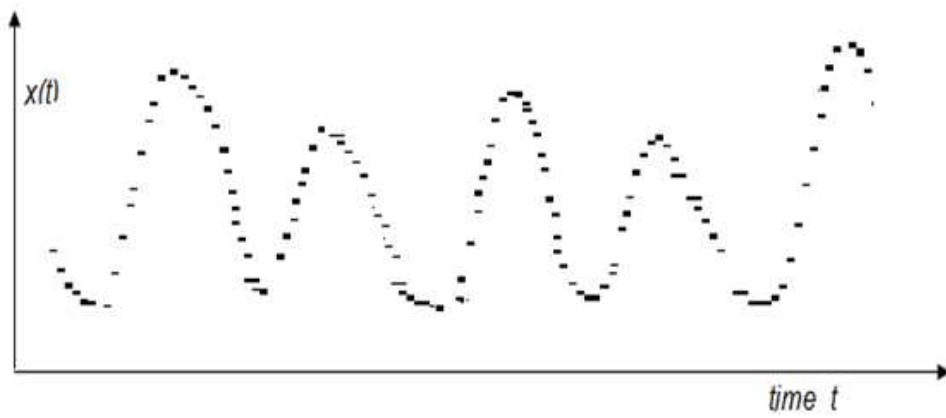
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A plot of values of  $x$  during inhalation and exhalation.  
128x68mm (96 x 96 DPI)

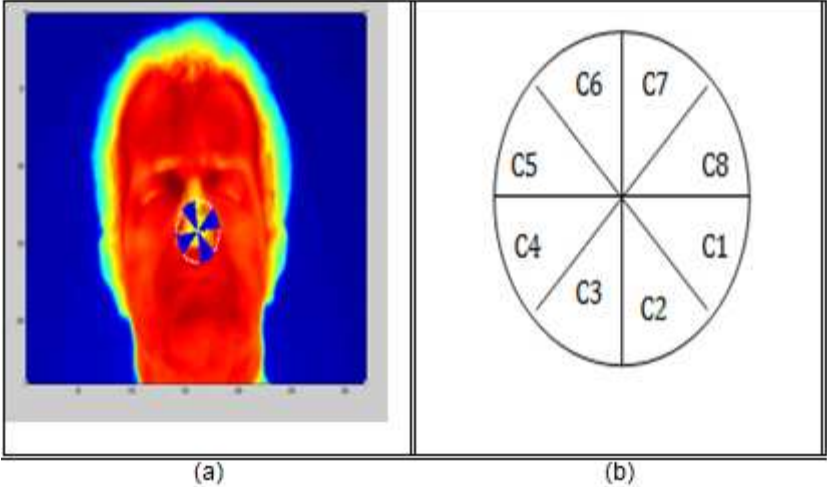
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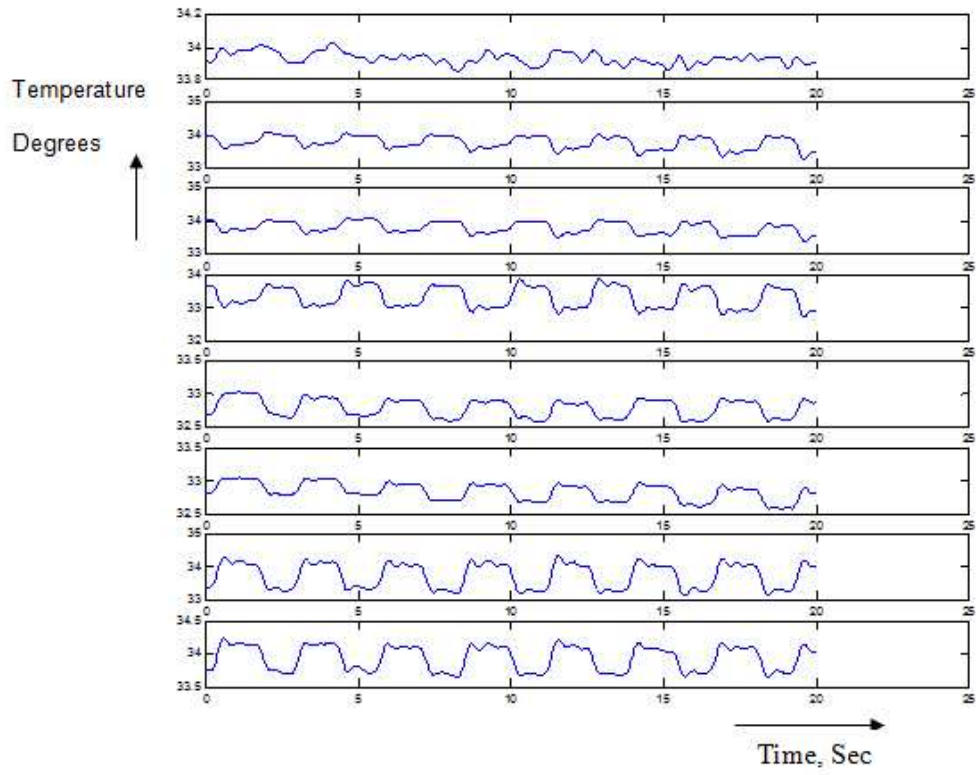
Plot  $x(t)$  against time during three respiration cycles.  
154x69mm (96 x 96 DPI)

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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)



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

Review