Exploratory study to evaluate respiratory rate using a thermal imaging camera

ELPHICK, Heather, ALKALI, Abdulkadir, KINGSHOTT, Ruth, BURKE, Derek and SAATCHI, Reza <http://orcid.org/0000-0002-2266-0187>

Exploratory Study to Evaluate Respiratory Rate Using a Thermal Imaging Camera

Short title: Thermal Imaging and Respiratory Rate

Heather Elphick MD[1], Abdulkadir Hamidu Alkali PhD[2], Ruth Kingshott PhD[1], Derek Burke MB ChB[1], Reza Saatchi PhD[2]

[1] Sheffield Children's NHS Foundation Trust, Sheffield, U.K.

[2] Faculty of ACES, Sheffield Hallam University, Sheffield, U.K.

Address for correspondence:

Name: Heather E Elphick

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

Tel: (0)114 2717400

Fax: (0)114 2717672

Email: Heather.Elphick@sch.nhs.uk

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Abstract

Background: Respiratory rate is a vital physiological measurement used in the immediate assessment of unwell children and adults. Convenient electronic devices exist for measurement of pulse, blood pressure, oxygen saturation and temperature. Although devices which measure respiratory rate exist, none has entered everyday clinical practice for acute assessment of children and adults. An accurate and practical device which has no physical contact with the patient is important to ensure readings are not affected by distress caused by the assessment method.

Objective: To evaluate the use of a thermal imaging method to monitor respiratory rate in children and adults.

Methods: Facial thermal images of adult volunteers and children undergoing elective polysomnography were included. Respiration was recorded for at least two minutes with the camera positioned one metre from the subject's face. Values obtained using the thermal imaging camera were compared with those obtained from contact methods such as nasal thermistor, respiratory inductance plethysmography, nasal airflow and End Tidal Carbon Dioxide (CO_2).

Results: A total of 61 subjects, including 41 adults (age range 27 to 46 years) and 20 children (age range 0.5 to 18 years) were enrolled. The correlation between respiratory rate measured using thermal imaging and the contact method was r=0.94. Sequential refinements to the thermal imaging algorithms resulted in the ability to perform real-time measurements and an improvement of the correlation to r=0.995.

Conclusion: This exploratory study shows that thermal imaging derived respiratory rates in children and adults correlate closely with the best performing standard method. With further refinements, this method could be implemented in both acute and chronic care in children and adults.

Abstract word count 247

Introduction

It is recognised that deterioration in a patient's physiological condition is a predictive factor for serious outcomes [1,2]. Evidence from the literature shows a high prevalence of abnormal vital signs in the hours leading up to an inpatient cardiac arrest [3,4], and subsequent studies indicate that respiratory rate (RR) may be the most important predictor of cardiac arrest [1,5]. Respiratory rate has also been shown to be superior to heart rate and blood pressure in discriminating between stable patients and patients at risk, with a high association with mortality rate [6,7]. Convenient electronic devices exist in the UK and other developed countries for measurement of pulse, blood pressure, oxygen saturation and temperature. Although devices which measure RR exist [8], none has entered everyday clinical practice for non-invasive acute assessment of respiratory rate. In children especially, a major limitation is a requirement for body contact which can be distressing and lead to an increase in RR.

Manual nursing assessments continue to be the mainstay of triage evaluation of RR in acute clinical settings such as the emergency department. Such assessments are subjective and difficult to measure in distressed children and data are often missing compared to the other physiological parameters which are recorded with devices [9]. During the last 10 years, nursing workload, particularly the administrative aspects, has increased greatly and since current methods for measuring RR are time consuming, this may be one reason why frequency of measurement of RR has not improved [10,11]. A recent study found poor agreement between observers for RR measurements in 507 children in a tertiary hospital in the UK [12]. Other studies assessing the inter-observer agreement of RR report a wide range of inter-observer variability in both children and adults [13-19]. This may reflect the heterogeneity of the studies, with many assessing the variability in RR measurements as part of a wider clinical score and the range of settings including Canada and Mozambique with implications on available resources.

Devices for monitoring RR have been developed, but many provide only an estimate of breathing rate due to the complexities associated with measuring this physiological parameter [8]. Conventional measuring methods commonly require physical contact with the patient's body. These include nasal or oronasal thermistor which measures changes in the temperature of exhaled air [20], air pressure transducers [21,22)] exhaled CO_2 [23], respiratory sound analysis [24,25] and inductance plethysmography [22,26]. Respiratory rates can also be derived from the electro-cardiogram (ECG) [27-29]. These methods have limitations including sensor displacement, dead space caused by requirement for facemasks and alterations in RR itself caused by the attachment of a sensor to the subject which might make them anxious.

For the rapid assessment of children required in the emergency department, non-contact methods have been considered [30,31]. Ultrasound [32,33], radar [34], microwave [35,36], video image processing [37], optical image processing [38] and thermal image processing [39,40] are all approaches that have been used to facilitate non-contact respiration monitoring. Koolen 2015 [41] used a Eulerian video magnification to amplify respiratory movements.

They used this to analyse the RR in seven neonates. Arlotto et al(2014) developed an ultrasonic contactless sensor that measures the frequency shift produced by the velocity difference between the exhaled air flow and the ambient environment to derive a RR [42]. Mobile applications provide a portable way of measuring RR. Philips vital sign mobile application measures both heart rate and respiratory rate using the in-built camera on a mobile device [43]. Karlen et al (2014) have produced another mobile application to measure RR [44]. In addition to the limitations of contact methods described, there are also hygiene and cost advantages in making use of a reusable device. These methods are all experimental and require further clinical validation.

Infrared Thermography, or thermal imaging, is being more frequently used in the medical field where it has demonstrated utility in assessing burn depth and monitoring therapeutic response to drugs in rheumatoid arthritis. Advantages of thermal imaging in medicine include safety, tolerance, reproducibility and affordability. In this study, thermal imaging was used to compare RR readings from adults and children with conventional contact methods to determine its accuracy in a non-emergency setting. This setting was chosen as a more stable setting for initial exploratory research. In order to produce a respiration signal, an algorithm for automatic tracking of the temperature of the skin surface centred on the tip of the nose (respiration “region of interest”, ROI) in facial thermal images has been developed. The study builds on previous work in this field by our group in which measurements were recorded and analysed later [45]. This technique has been demonstrated to work well in resting children, and when compared with conventional contact methods a close correlation was seen (correlation coefficient = 0.994). However this technique requires further refinement as in its current form would not be a viable option to be used in everyday clinical practice due to the current cost of thermal cameras and the further developments needed to deal with very large head and body movements and switching between nose and mouth breathing.

This study aimed to improve the method by incorporating refined and improved algorithms, to accommodate larger head movements in children that may be moving during recordings and allowing real-time respiratory rate measurements, as would be required in acute clinical practice.

Methods

Subjects were recruited at Sheffield Children's NHS Foundation Trust Sleep Unit from May to October 2014 after obtaining local Ethics approval from Leeds West Ethics committee (13/YH/0316) and Sheffield Hallam University. The parents of the children were appropriately informed regarding the nature of the study and provided informed consent for their children's data to be used in the study. The children, wherever possible, assented to their participation. Convenience samples of approximately 20 participants were recruited to each part of the study. All children recruited were undergoing polysomnography studies in a diagnostic sleep unit for a range of chronic sleep conditions, as requested by their physician (Figure 1). Eligibility criteria for the children to be recruited into the research were: age 0-16 years; undergoing a clinical sleep study; parents able to give written informed consent; and the research staff and thermal imaging equipment were available on the night of the clinical sleep study. This group of children were chosen because they were already having contact gold standard measures of respiration rate as part of their clinical investigation during sleep. Thermal imaging recordings were carried out in conjunction with these standard respiratory monitoring methods. As the children were being recorded asleep, these were performed with the children lying comfortably in a bed shortly after sleep onset. The recorded room temperature was about 25^{o}C. The duration of each thermal imaging recording was at least two minutes. Adult participants were staff at Sheffield Children's Hospital and were recruited via word-of-mouth. The adult participants were not asleep and were therefore positioned sitting in a chair one metre from the camera, with respiratory inductance plethysmography bands places around the thorax and abdomen for the sole purpose of the research study. We therefore did not record the other channels.

Standard Contact Respiration Rate Measurement Methods

Thoracic and abdominal respiratory inductance plethysmography (RIP) bands were used to record respiratory signal from the adult subjects enrolled at the hospital, while the thermistor, flow and CO_2 monitors were included for the children (according to clinical need, or tolerance of sensors) during their admission. All of the standard methods require at least one sensor that can detect breathing which is in direct contact with the child as this is standard practice for polysomnography recording. Channels for all four methods were integrated for polysomnography to the ALICE 5 Sleep System (Philips, Respironics, Chichester, UK). Analysis of respiratory rate using each of these methods was carried out by manually selecting the two-minute epoch which coincided with the thermal imaging recording time. All contact methods only produced a respiration signal, not a respiratory rate. Therefore, to determine the respiratory rate, the number of observed respiration cycles in the respiratory signal, were either counted manually or determined using Fast Fourier Transform (FFT) analysis. The frequency of the largest peak in the magnitude frequency spectrum obtained using FFT indicated respiration in breath per second and once this was multiplied by 60, it indicated respiration rate in breath per minute. In cases where more than one contact method was used, the correlation between the thermal imaging method and each of the standard methods was calculated individually. In addition, the respiration signals from the sleep system were exported in an anonymous American Standard Code for Information Interchange (ASCII) text file so that they could be directly compared to the thermal imaging respiration pattern.

Thermal Imaging Respiration Rate Measurement Methods

The experimental methods utilised the variation in the amount of infrared radiation emitted from the skin centered on the tip of the nose using a thermal camera (Flir A40 model). The FLIR A40 camera has a thermal sensitivity of 0.08^{o} Kelvin with maximum image capture rate of 50 frames per second. The thermal camera was mounted on a tripod beside the bed where the adult subject lay comfortably. For the children, monitoring only began when they were asleep as this way they would be least disturbed. The tripod arm holding the camera was then extended such that it was about 1 m from the subject's face and the subject's face was contained in the camera's field of view. Each subject was monitored for at least 2 minutes but typically more than 10 minutes. A typical setup during adult monitoring is shown in Figure 2.

The camera's emissivity setting was 0.98^{o} (this is human skin emissivity). The mean temperature and relative humidity of the room were 24.4°C (standard deviation of 0.35) and 45% (standard deviation of 0.71) respectively and the camera's setting were changed to reflect these values. Images were recorded at 50 frames per second that corresponded to the maximum capture rate for the camera. This produced 6000 thermal images in a two-minute recording (i.e. 120 seconds x 50 images).

The respiration "region of interest" (ROI) tracking method [45-49] was used to accommodate head movement during recording (Figure 3). This method uses algorithms to capture images and detect the location of the face in each image and was refined sequentially in terms of increasing ability to deal with larger head movements:

<u>Method 1. (Template Method)</u>

Method 1 used a preselected template and a "point of interest" (POI). During monitoring, the location of the POI was automatically updated by locating the closest match for the template on the face. The processed pixel values within the POI over time produced a respiration signal from which the respiration rate was obtained. Images were processed in real-time using LabVIEW© (National Instruments©).

<u>Method 2: (Feature Detection Based on Facial Profiles)</u>

Method 2 detected the face of the subject in real time, then located the two corners of the eyes and thereafter the tip of the nose in thermal images. Method 2 used the facial profile to detect features on the face of a subject.

Method 3: (Feature Detection Based on Thresholding)

Method 3 used a fully automated thresholding technique. The amount of emitted infrared radiation was then determined from a created region of interest around the tip of the nose using the algorithm.

Data Analysis and Statistics

The data from the standard respiratory monitoring methods (RIP, CO2 and flow channels) were used for analysis if they met the criteria for clinical analysis. These recordings were analysed separately by a second assessor (RK), who was blind to the results of the thermal imaging method. In all comparisons, the correlation between the thermal imaging method and the standard respiratory monitoring method was obtained by calculating the correlation coefficient (r) using MS Excel© and verified using MATLAB© [50] and LabVIEW©.

Results

A total of 61 subjects comprising of 41 adults (age range 27 to 46 years) and 20 children (age range 0.5 to 18 years) were enrolled for the study. The correlation between the respiratory rate measured using thermal imaging and the standard method (RIP) for the group as a whole was r= 0.94 (Figure 4).

Method 1: (Template Method)

Twenty adults (median age 35.7 years, range 27.0-45.7 years) and 20 children (median age 6.4 years, range 0.5-18 years) were measured using Method 1.

In the adults, median respiratory rate per minute was 14.8 breaths per minute (range 7.7-20.5) using thermal imaging, 14.6 (range 8.1-20.4) using thoracic bands and 14.6 breaths per minute (range 8.1-20.5) using abdominal bands. The correlation between the thermal imaging method and the standard methods was r=0.980.

In the children, the correlation between thermal imaging and RIP bands was r=0.998. One child (subject 14) was excluded because the subject's face had moved out of the camera's field of view during the recording. In nine subjects that had the thermistor in addition to the RIP bands, the correlation between the thermistor and the abdominal and thoracic bands was r=0.775 and r=0.750 respectively. For eight subjects that had flow derived respiration rates the correlation coefficient between the thermal imaging and flow method was r=0.999. In five subjects that also had end tidal CO_2 derived respiration monitored, the correlation coefficient was r=0.999.

Method 2: (Feature Detection Based on Facial Profiles).

Fifteen adults were included (median age 35.6 years, range 22-55 years). The thermal imaging derived respiratory rates of two subjects were considered unacceptable and thus regarded as failure of monitoring by the method representing 13.3% failure. This failure was caused by the subject's face moving out of the camera's field of view due to very large head movements. The correlation coefficient was r=0.938 as compared against both thoracic and abdominal bands derived respiration rates. When the two failures were excluded, the correlation coefficient was r=0.997.

Method 3: (Feature Detection Based on Thresholding)

Six adult subjects were included (median age 38.7 years, range 33-41 years). Four unspecified respiration regions of interest (ROIs) were investigated and the correlation coefficients of the respiration rates against RIP were 0.998, 0.998, 0.999 and 0.998 for the regions of interests ROI1, ROI2, ROI3 and ROI4 respectively.

Discussion

In this study a thermal imaging-based method to automatically monitor respiratory rate by measuring skin surface temperature centered on the tip of the nose was evaluated. There was a close correlation between the thermal imaging derived measurements and those obtained using the best conventional contact method in children undergoing polysomnography in a diagnostic sleep unit. The study indicates that thermal imaging could be an effective tool for monitoring respiration and suggests that further development and evaluation of this technique are justified. The main benefits of thermal imaging respiration monitoring over current methods are that it is non-contact and gives respiratory rate automatically and objectively.

The aim of this study was to evaluate a method that, with further enhancements and evaluations, could potentially be used to measure respiratory rate in the Emergency Department triage room where a rapid method of assessment is needed in order to pick up those children who are seriously ill. Counting respiratory rate is a core skill of clinical staff, as is counting pulse rate and measuring blood pressure. The latter two skills have been replaced by technology in recent times in developed countries, in recognition of the understanding that humans are subject to error, and to aid more rapid assessment of patients in busy departments. Thermistor, nasal flow and inductance bands are the current techniques for measurement of respiratory rates and breathing patterns in children undergoing polysomnography in the UK [21,22]. The primary limitation of these techniques is the fact that they are in contact with the child. In an acute setting such as the Emergency Department, this can cause distress and therefore distort results. Whilst devices cannot replace the clinician's evaluation, they are used to document other physiological measurements such as pulse rate and temperature and we believe that an accurate non-contact device is needed to overcome the limitations of the existing techniques.

Currently, the main disadvantages of the thermal imaging method are the cost of the camera, although costs are falling, and the cost of training an operator. However, having demonstrated that the method is reliable, in the future we will work on developing a custom-built thermal imaging-based respiration monitor that will become more cost effective and easier to operate. We recognize that this technique is being designed with developed countries in mind due to current cost considerations but may be useful in developing countries in the future if the price of thermal imaging becomes significantly lower.

There are some limitations to the analysis methods used in this study and further work is needed to refine the process. Three methods were used, building on the initial algorithm used in a previous study [45], each improving the ability of the thermal imaging to measure respiration rate during increasing movement of the head, in recognition of some of the difficulties faced when assessing respiratory rate in clinical practice. Each method produced results that gave excellent correlation with the standard contact methods, although results were invalidated if the child's head moved completely out of the view of the camera. However, in nine subjects that had the thermistor in addition to the RIP bands, the correlation coefficient was r=0.760. In these cases, the correlation between the thermistor and the abdominal and thoracic bands was r=0.775 and r= 0.750 respectively, suggesting that the low correlation between the thermal imaging-based method and the thermistor based method was due to failure in the thermistor monitoring. These evaluations were carried out on children undergoing routine investigations and adult volunteers in order to test efficacy of the method. Therefore, further testing will need to take place in an acute clinical environment to test the robustness of the technique in clinical practice in awake and potentially agitated children. Future research collaboration between clinician's and engineers is planned to continue in this area of non-contact measures of respiratory rate, and other medical applications of thermal imaging.

Respiratory rate measurement using the thermistor was the least reliable method in this study. Thermistor readings in children can be affected by the sucking of pacifiers. As the child sucks the pacifier, his/her mouth and the region below the nose move thereby affecting the position of the thermistor. It also does not allow free flow of expired air from the nose which flows back and saturates the thermistor. The thermal imaging camera failed to produce a reading in three out of 77 subjects. This failure rate was lower than each of the standard methods and was caused by the subject's face moving out of the camera's field of view for a significant proportion of recordings. Using the thermal imaging camera, errors may occur due to large head movement, subjects wearing glasses or a blocked nose. Head movement has been overcome to some extent by the refinement in the algorithms but further work is needed. Additional work will be required to investigate differences between nose and mouth breathing which is an important factor in young children with respiratory illnesses.

Conclusion

We have shown that thermal imaging using custom-made software with algorithms developed to overcome some of the difficulties faced in using a device in clinical practice can be effective in measuring respiratory rate, when compared to currently-used contact-based methods. This method may be useful for both acute and continuous monitoring of respiratory rate, although for long-term monitoring, the subjects face would be required to remain within the field of view of the camera. Future studies of this technique in an acute clinical environment will include different study populations, sequential measurements and assessments of the distance of the child from the camera and variability of movement, temperature and humidity as well as developing a monitor that is more cost-effective. The advantage of this method is that it is non-contact, which may be more objective and reliable than other methods for monitoring respiratory rate in children.

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Figures

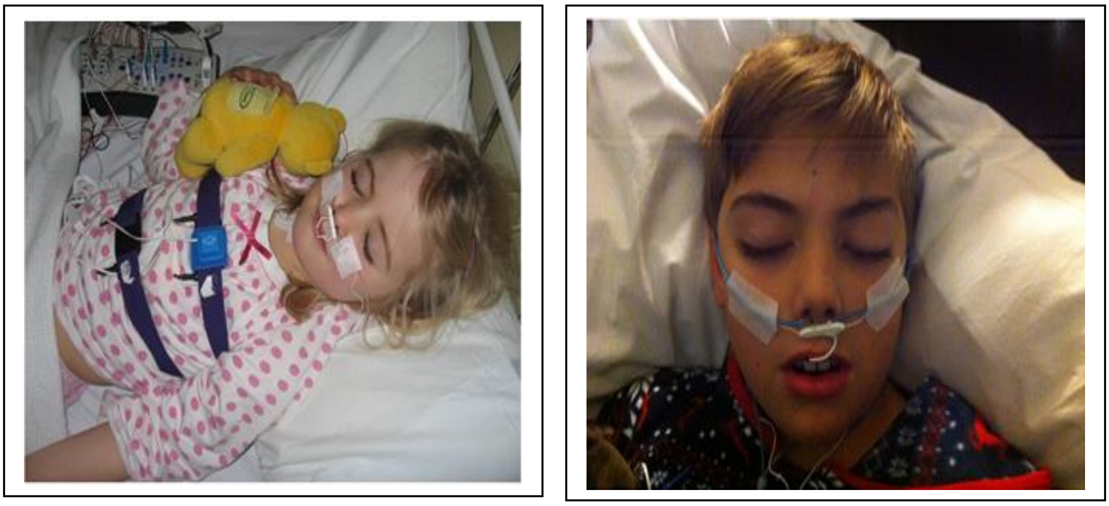

Figure 1 A Close up of the Nasal Flow and Thermistor Sensors Used During Overnight Polysomnography (reprinted with permission)

Figure 2 Set-up of the thermal imaging camera during adult testing.

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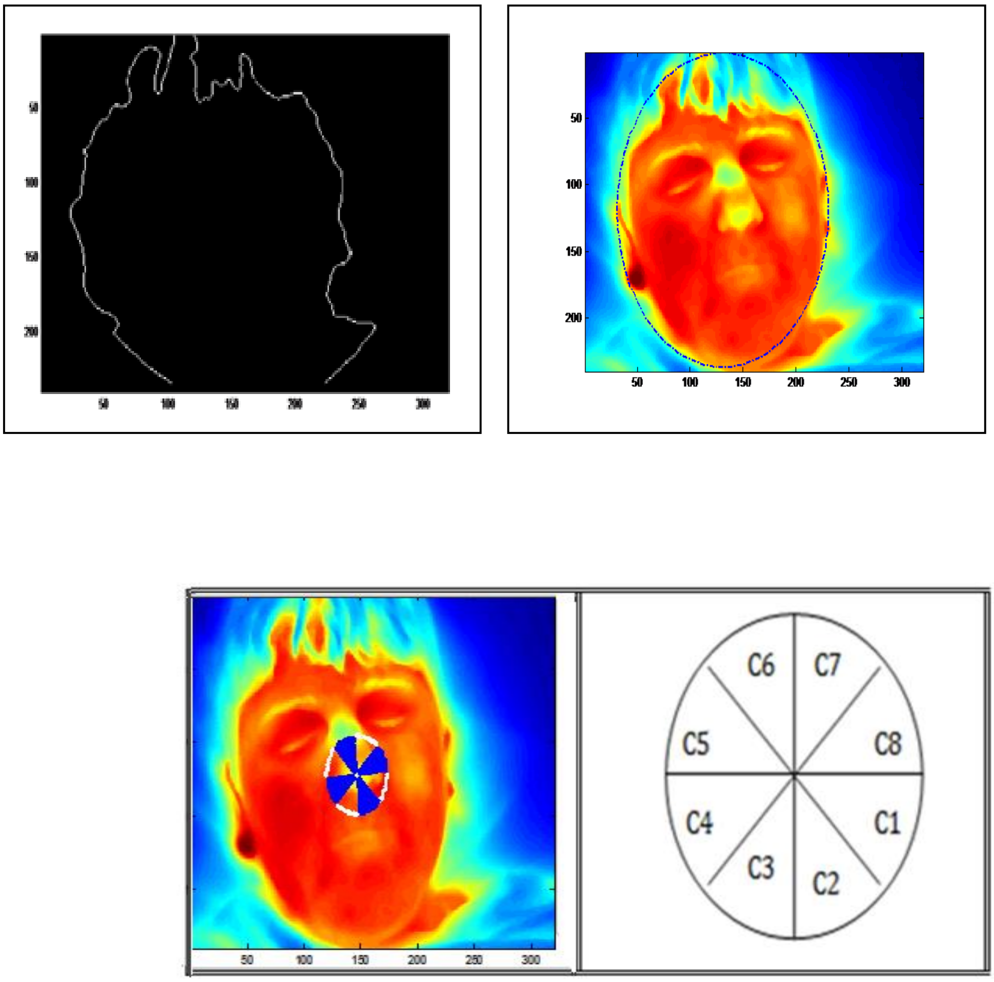

Figure 3 The respiration "region of interest" (ROI) tracking method [45-49] was used to accommodate head movement during recording

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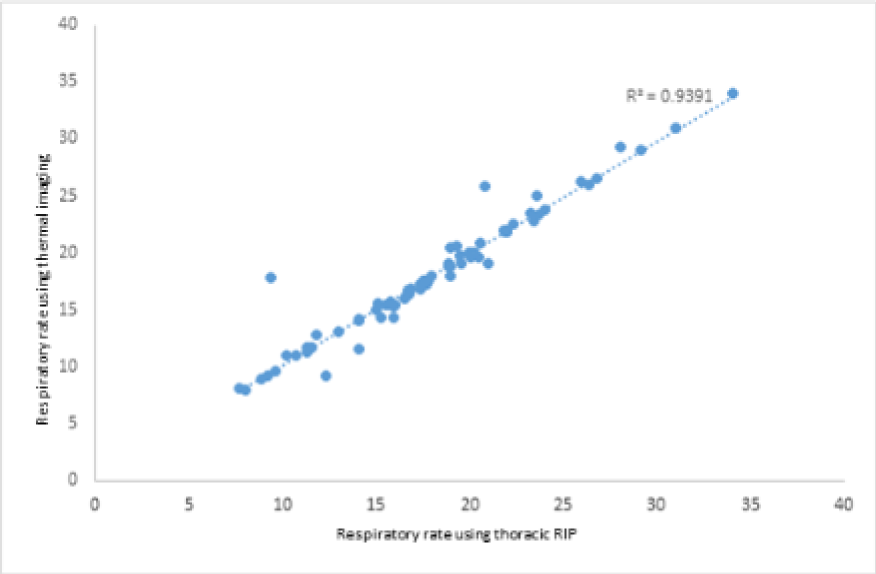

Figure 4 The correlation between the respiratory rate measured using thermal imaging and the standard method (RIP)