Thermal imaging developments for respiratory airflow measurement to diagnose apnoea

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Thermal Imaging Developments for Respiratory Airflow Measurement to Diagnose Apnoea

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DECLARATION

This is to certify that I am responsible for the work submitted in the thesis, that the original work is my own except the acknowledgements, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

Signed:

Name: Muhammad Usman

Date: 19/11/2018

Abstract

Sleep-disordered breathing is a sleep disorder that manifests itself as intermittent pauses (apnoeas) in breathing during sleep. The condition disturbs the sleep and can results in a variety of health problems. Its diagnosis is complex and involves multiple sensors attached to the person to measure electroencephalogram (EEG), electrocardiogram (ECG), blood oxygen saturation (pulse oximetry, SpO_2) and multiple sensors to record breathing. The current gold standard sensors to diagnose apnoeas require a combination of nasal pressure sensors, nasal airflow sensors and thoraco-abdominal bands. The nasal prongs, directly measures respiratory nasal pressure flow by being inserted into the nares of the nose. Alongside this sensor, the nasal thermistor monitors airflow and the chest and abdominal wall movements are measured by respiratory inductance bands. All of these sensors are required to accurately detect respiratory apnoeas. Unfortunately, the two nasal sensors are poorly tolerated by children and thus clinicians rely on thoracic and abdominal movement detection bands alone to detect respiratory events. Therefore there is a need for a new accurate method of measuring respiratory airflow and nasal pressure. Respiration results in an increase in temperature of skin surface during exhalation and a reduction in its temperature during inhalation. In this study thermal imaging was employed and further evaluated to record these temperature differences and from it measure respiratory airflow to assist with apnoea diagnosis.

A problem associated with using thermal imaging for respiratory airflow measurement is dealing with head and body movements during the recordings. As part of dealing with this problem two tracking methods were adapted and their effectiveness compared. The first was based on template matching. However the method proved ineffective as regions with similar temperature pattern as the respiratory region of interest (ROI, nostril region) that acted as the template were found in other parts of the face. Therefore the conventional template matching method was developed in a novel manner to track the ROI in two successive stages. First a larger region covering the nose and mouth acted as the template. Then the identified regions were processed again with a new template that only covered the nostril region. The method successfully tracked the required ROI. The performance of the improved template matching method was compared with another tracking method called the Kanade-Lucas-Tomasi tracking. This is a well-known feature tracker that proved robust in several applications.

The respiratory signals obtained using thermal imaging utilising both tracking algorithms were compared with the existing contact methods that consisted of nasal pressure sensors, thermistor and thoracic and abdominal bands. The comparison was based on the recordings from 11 healthy adult volunteers recorded in four breathing scenarios as well as three children that were undergoing investigation for sleep-disordered breathing in the sleep laboratory of a local children's hospital. For the 11 volunteers there were a total of 88 respiratory events. Out of these in 63 cases the results of thermal imaging matched the standard sensor in place. In 9 cases the results of thermal imaging partially matched with the standard sensors in place while 15 cases were found where the ROI was not available. One hypopnoea event was not picked by thermal imaging. The thermal imaging successfully represented the respiratory signal and detected apnoea events in the patients recorded at hospital.

The study successfully demonstrated the efficacy of thermal imaging for respiratory airflow measurement and thus the work can be of importance for detecting apnoea and hypopnoea.

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Contents

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List of Abbreviations

AHI   Apnoea hypopnoea index

BPM   Breathe per minute

COPD   Chronic obstructive pulmonary disease

CSA   Central sleep apnoea

DFT   Discrete Fourier transform

DBS   Disclosure and barring service

ED   Emergency department

EEG   Electroencephalography

EOG   Electrooculogram

EMG   Electromyogram

ECG   Electrocardiogram

FFT   Fast Fourier transform

FLIR   Forward looking infrared

FOV   Field of view

FPA   Focal plane array

HIT   Health information technology

HRTI   High resolution thermal imaging

ITDSs   Infrared thermal detecting systems

IR   Infrared

IRTI   Infrared thermal imaging

IB   Irregular breathing

KLT   Kanade-Lucas-Tomasi tracking algorithm

LWIR   Long wave infrared

MSA   Mixed sleep apnoea

MWIR   middle wave infrared

MRA   Multiresolution analysis

NHS   National Health Service

NIR   Near infrared

OSA   Obstructive sleep apnoea

OI   Osteogenesis imperfecta

PSG   Polysomnography

QB   Quiet breathing

ROI   Region of interest

RR   Respiration rate

SCH   Sheffield children hospital

SBD   Sleep-disordered breathing

SHURA   Sheffield Hallam University research archive

SWIR   Short wave infrared

STFT   Short time Fourier transform

SHU   Sheffield Hallam University

VLWIR   Very long wave infrared

WFT   Windowed Fourier transform

XLHED   X-linked hypohidrotic ectodermal dysplasia

List of Symbols

℃	Degree Celsius
P_n	Nasal pressure
$P_E CO_2$	Expired carbon dioxide
T	Temperature
λ	Wavelength
K	Kelvin
c	Speed of light
h	Plank's constant
σ	Stefan-Boltzman's constant
α	Absorption coefficient
ε_λ	Emissivity
μm	Micro meter
Φ	Radiation power
A	Area
F(Hz)	Frequency
ψ	Scaling parameter
τ	Parameter of translation
k	Boltzmann's constant

Chapter 1

Introduction

1.1 Introduction

The incorporation of diagnosis, prognosis and treatment in clinical practice is well established [1]. Traditionally diagnosis is considered as the standard guide to prognosis (consequences of the diagnosed disease) and treatment and is still very much the primary element in clinical practice. Patients health in future (prognosis) is very much dependant on the diagnosis and the diagnosis lead treatment. Clinicians making diagnosis may make diagnostic errors and the possibility of these diagnostic errors could be avoided up to large extent through an effective use of improved technology [2]. Unaided clinicians are often susceptible to frail human memory, varying disease conditions, lapses in concentration and judgement and clinical procedures affected by lapses in communication posting a major threat to reliable and timely diagnosis.

Health information technology (HIT) instruments and mechanisms have the potential that can help clinicians by playing an integral part to overcome or at least reduce the above mentioned human limitations [1]. The advancements in clinical practice are of significant importance and needs to be validated by better results and more effective and enhanced delivery of health care. The effectiveness of the designed diagnostic approaches and diagnosis lead treatment needs to be justified by the possibility of patients classified by diagnosed disease are better off or the patients classified without disease remain unharmed. Diagnosis is also of key importance for clinicians in treatment decision making, as it can provide the basis of prognosis by analysing the information provided by the patient symptoms, signs and investigations in a more effective manner.

In the field of diagnostic research the importance of affirmation cannot be ignored to validate a new diagnostic method in terms of improved results, before allowing it in clinical practice. This can be achieved either by the association of the advancements in disease diagnosis with the existing proofs for the efficacy of the treatment or by illustrating that the new diagnostic processes are cost effective or improve patient safety. On the other hand the evaluation of the new diagnostic process is of extreme

importance to make sure whether it makes any difference in decision making, improves results in patients classified for the disease and also ensures any unnecessary treatment in patients without any disease classification. The vindication for peculiarity for the new diagnostic process is whether or not it improves the prognosis of the patient and the unavailability of the sufficient evidence is possible in this regard.

This study was carried out to use effective technology for non-contact monitoring of respiratory airflow in paediatrics. Respiration in humans is one of the most fundamental and vital processes [3]. Healthy respiration is the basic element for providing necessary oxygen to the body for the functioning of many important purposes and eliminate by products of the metabolism such as carbon dioxide. Problems in correct respiration could lead to significant complications to the human health and the consequences could be life threatening. Respiratory airflow morbidities in children could become a cause of disruption in the continuity of sleep [4]. The process of not having healthy respiration could lead to breathing difficulties such as emphysema, COPD (chronic obstructive pulmonary disease) and breathing disorders like apnoea and hypopnoea [5].

1.2 Purpose of Study

Healthy sleep is one of the fundamental biological functions along with naturally fair and appropriate diet for good quality of life [4]. Respiratory airflow difficulties are a major problem worldwide leading to growing morbidity and mortality despite making enormous progress in advancement and understanding the mechanism of respiration [6]. The prevalence of Obstructive Sleep Apnoea (OSA) and different types of SDB in paediatrics is evaluated to be 1-5.8% [7]. Another study by Chang and Chae reported the prevalence of apnoea in children to be around 3% [8].The patients suffering from a respiratory disease have to undergo a respiratory study that involves monitoring and recording of different body signals. For this, different sensors are attached to the patient's body such as nasal airflow sensor and thermistor in the proximity of nose. The presence of these sensors is not convenient for some patients and thus they affect their quality of sleep especially children. Sheffield Children's Hospital (SCH) audited 100 respiratory sleep studies to investigate the percentage tolerance of these sensors in children during a sleep study. Figure 1 and 2 shows the percentage tolerance of nasal airflow and thermistor

respectively. The study showed that about 50% of children refuse the nasal pressure sensor that is the gold standard for respiratory airflow measurement. Of the rest that initially accepted this sensor, about 50% later on remove it. Without the presence of this sensor diagnosis of apnoeas and hypopneas relies on less reliable sensors.
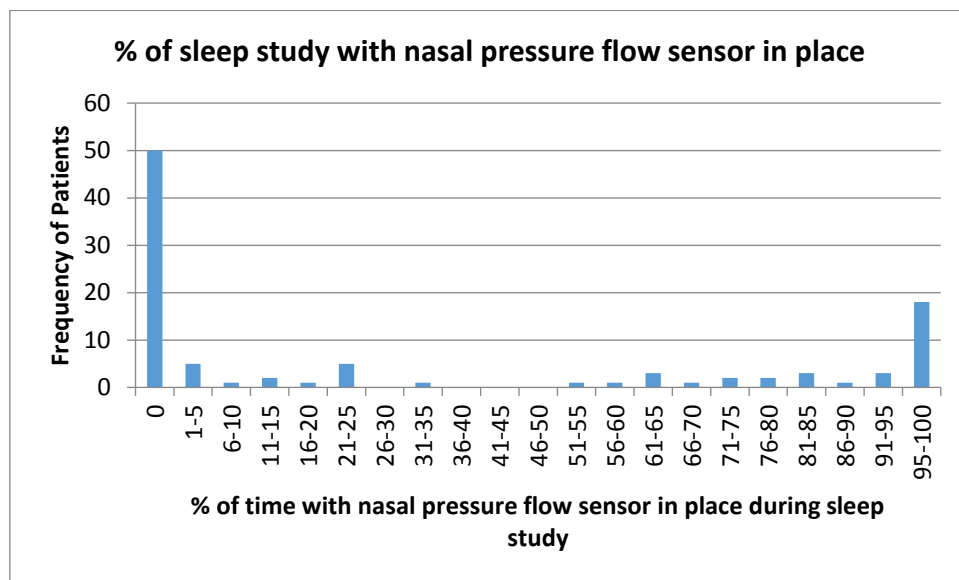
Figure 1 Histogram of the percentage time that the nasal airflow sensor was in place in 100 sleep studies.
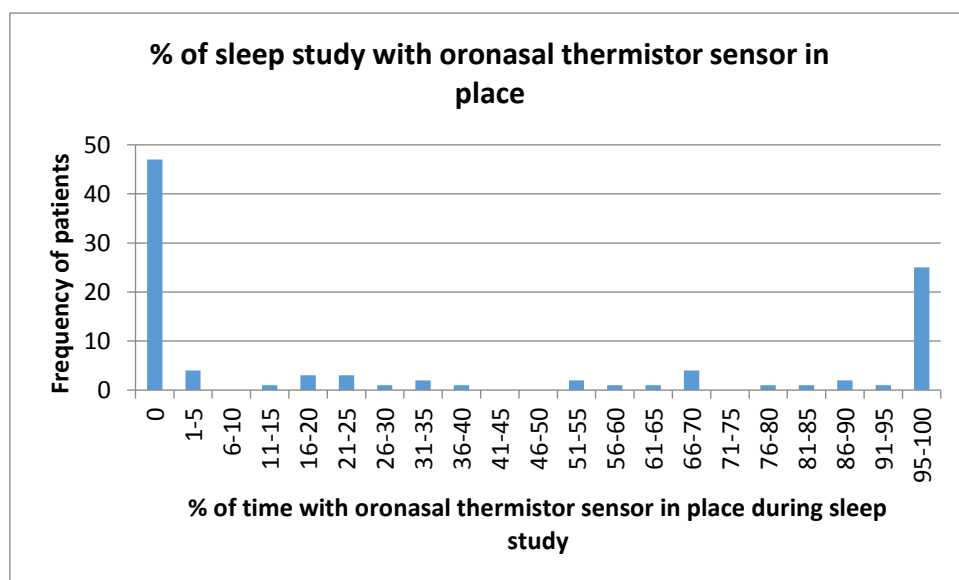
Figure 2 Histogram of the percentage time that the thermistor sensor was in place in 100 sleep studies

So the purpose of this study is to develop a non-contact method based on the principles of thermal imaging to monitor respiration in order to assist clinicians with detection and diagnosis of different types of apnoea in paediatric patients with suspected sleep-disordered breathings.

1.3 Aims and Objectives

1.3.1 Aim

To develop a high resolution thermal imaging (HRTI) technique for measuring respiratory airflow as part of assisting clinicians with the detection and diagnosis of different types of apnoea.

1.3.2 Objectives

i. To undertake thermal imaging recordings of healthy volunteers at the university using a nasal airflow sensor and respiratory thoraco-abdominal effort bands with different breathing patterns mimicking central apnoea, obstructive apnoea and hypopnoea.

ii. Investigate and further develop thermal imaging techniques such as facial tracking to identify the respiratory Region of Interest (ROI).

iii. Implement suitable signal processing techniques for accurate extraction of respiratory air flow signal from the extracted ROIs.

iv. Evaluate the efficacy and accuracy of the developed techniques on a number of patients with suspected sleep-disordered breathing.

1.4 Study's Contributions

In this study an alternative method for respiratory airflow monitoring has been developed based on thermal imaging. This could detect apnoea induced pauses in breathing. Thermal imaging can be used to measure respiratory related skin temperature changes centred under the tip of the nose [9]. Exhalation of respiratory air increases the temperature while inhalation reduces the skin surface temperature in this region Figure 3 shows some of the images of the subjects from this study where brighter areas are warmer regions and darker regions are colder.
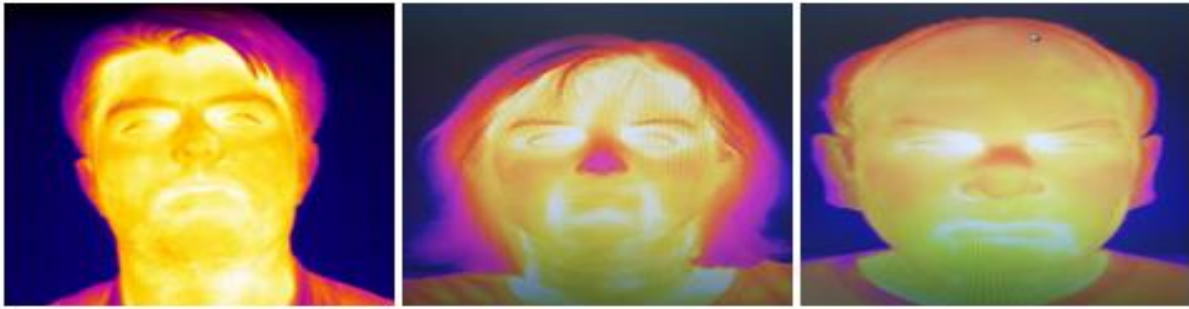
Figure 3 some thermal images from the participants in the study

i. Two tracking algorithms were used to identify and track the respiratory region of interest (ROI). The first was Kanade-Lucas-Tomasi (KLT) tracking algorithm which is discussed in detail in section 6.4.2 and the sections 6.5, 6.6 and 6.7 further explained the procedure of getting the respiration induced pauses in breathing using different image and signal processing techniques. The results show the effectiveness of this approach of heathy volunteers before commencing the data collection of children undergoing PSG. Out of the total 88 events recorded for 11 volunteers, 63 were matched, 9 were partially matched, in 15 cases the ROI was not available and only 1 event was not picked by thermal imaging using this method.

ii. The second tracking method was based on template matching and the process of its employing this method and extracting the respiration signal from the recorded data is explained in detail in sections 7.2, 7.3 and 7.4. This method also proved successful in identifying the ROI under consideration and extracting the respiration signal by employing suitable signal and image processing techniques explained in 7.5 in detail.

iii. The developed thermal imaging methods were further evaluated on three children patients admitted to hospital for respiratory related disorders. These patients have overnight monitoring in the sleep laboratory of the hospital and had multiple sensors attached for their routine monitoring and thermal imaging was performed simultaneously. An experienced medical practitioner

scored the apnoea events from the routine contact sensors. The thermal imaging method effectively represented both normal breathing as well as apnoea events.

1.5 Overview of the Following Chapters

Chapter 2: Literature Review.
This chapter summarises the work that has been done in the field of respiration monitoring and apnoea diagnosis and highlights their strengths and weaknesses.

Chapter 3: Sleep Breathing Disorders (SBD).
This Chapter explain different types of SBD's especially apnoea and hypopnoea with their different types. It also explains the symptoms related to apnoea and its consequences.

Chapter 4: Thermal Imaging and Image and Signal Processing Techniques.
This chapter explains the theoretical and practical background of infrared thermography. It also explains different signal and image processing techniques used in the study. It also briefly explains the process of tracking an object in terms of detection, classification and then tracking.

Chapter 5: Methodology.
This chapter discuss the ethics, the infra-red camera used for recordings, and the subject recruitment process related to children and adults.

Chapter 6: Results and Discussions of Testing the Method on Adults.
This chapter details the process of obtaining the results from the data of 11 adult volunteers recorded in the university. It further compares these results with the ground truth sensors and bands in place to check the accuracy of this method.

Chapter 7: Results and Discussions of Testing the Method on Paediatric Patients.
This chapter discusses the measurement of airflow to assist with the diagnosis of apnoea in respiratory related paediatric patients from Sheffield Children Hospital. It

compares the results of this study with the results of routine contact sensors scored by an experienced medical practitioner.

Chapter 8: Conclusion and Further Work.
This chapter elaborates the study's conclusion, important findings and recommendations for further work.

1.6 Summary

Chapter 1 summarises the importance of respiration for good sleep and health along with highlighting the prevalence of apnoea in children due to SDB and other problems in respiration. It further explains the purpose of carrying out this study along with its aims and objectives. Moreover the contribution of this study is highlighted with some results of the study. Lastly it also briefly provides an overview of the following chapters.

Chapter 2
Sleep-Disordered Breathing (SDB)

2.1 Introduction

The term sleep-disordered breathing (SDB) is not new in the field of respiratory health but in recent times the amount of studies to investigate and diagnose sleep disorders has resulted in increasing our overall awareness towards them in general [10]. This whole scenario poses a real threat to our health system because of their pervasiveness, morbidity and mortality with collateral socio-economic consequences. Sleep of good quality and adequate length are prerequisites for good health [11]. The essentiality of good sleep increases particularly in infants and children due to the additional physiological burden of growth and development, as compared to their adult counterparts.

The repercussions of SDB may vary with respect to the age group and gender. In adults, males are more likely to get affected by Obstructive Sleep Apnoea (OSA) in their middle age [12]. In females there is an increased risk of SDB in menopause, pregnancy and polycystic ovaries. SDB affects around 30-40% of infants and school children that leads to frequent sleep disruptions at night resulting in poor sleep and affecting the overall health [13]. Problems during sleep are common in both infants and children and can result in neurocognitive and psychosocial ailments which translate in more caregiver burden as well [14]. Many children get affected by SDB at the age of four to eight years showing changing clinical symptoms at different ages [15]. Generally infants suffer from noisy breathing and interrupted nocturnal sleep. Toddlers and pre-schoolers suffer from snoring and breathing from mouth, and preadolescents and adolescents suffer from behavioural and dental problems.

The diagnostic process of SDB has become faster in recent times but it still faces multiple problems [16]. There is a high probability of diagnosing a SDB as a psychiatric problem as the symptoms could be the same in many cases such as excessive sleepiness, cognitive dysfunction, insomnia and depression. Most of the physicians or for that matter even psychiatrists are not able to diagnose these symptoms as sleep related problems because they do not ask the patients about sleep related disturbances. Therefore it is increasingly important to recognise these

symptoms for an early diagnosis because the cost of untreated apnoea could be life threatening and also can result in neurobehavioral and cardiovascular problems [12].

Due to these above mentioned problems, the demand of sleep investigations has increased rapidly; yet the healthcare systems have not responded adequately [10]. This whole scenario resulted in pressure on sleep units which means long patient waiting times. In addition to this, there is a percentage of respiratory specialists who have far less knowledge of SDB. This whole scenario resulted in professionals finding difficulties in diagnosis and treatment at different medical facilities. All the aforementioned problems are pointing to changes in the way we deal with sleep related problems because the care provided in several countries regarding sleep medicine require improvements.

2.2 Respiratory Studies
The prevalence of respiratory diseases has enhanced rapidly in today's world due to different factors and it has been proportional to the enormous advancements in the knowledge of their diagnosis, epidemiology, treatment options and etiology [17]. Respiratory studies are required for diagnosis of SDB. Respiratory studies are complex and compound to implement due to specific medicinal knowledge required to handle different clinical instruments used for disease management.

2.3 Types of SDB's
There are several types of SDB and each type comprises of different sleep related breathing disturbances [18]. These include asthma, snoring, apnoea and different types of apnoea which includes obstructive sleep apnoea (OSA), central sleep apnoea (CSA), mixed apnoea and hypopnoea.

2.3.1 Asthma
Asthma is a chronic inflammatory disease of the airways leading to airflow obstruction in association with airway hyper responsiveness and airway inflammation, resulting in frequent symptoms of chest tightness, rhonchus, wheezing, coughing and dyspnoea, or shortness of breath [19] [20] [21]. These symptoms occur in association with varying airflow obstruction in the lungs which reverses naturally or with the help of due asthma treatment [19]. More than 300 million individuals are

suffering from asthma along with 250,000 yearly deaths approximately, all over the world [20]. It is to be noted that the greater percentage of asthmatic patients is of children as compared to other age groups. In United States asthma is more prevalent in early adolescents and this decrease with age, reducing from (7.7%) in individuals over age 18 to (6.6%) in individuals over age 65 [22]. Studies estimate that by 2025, the number of patients will increase by more than 100 million [20].

Asthma diagnosis needs observation of its symptoms and validation of reversible airway obstruction by spirometry [23]. It is advantageous to identify the clinically important allergen sensitivities. The standard procedural care for persistent asthma is the maintenance with corticosteroids during daily inhalation but the short term β_2-agonists can also contribute towards rapid relief of acute symptoms. In addition to this, in case of moderate and severe asthma, the controller medications may include long-acting bronchodilators and biological agents used against proteins associated in the pathogenesis of asthma.

2.3.2 Apnoea

Apnoea is a breathing disorder that causes pauses in breathing during sleep and thus interrupts air flow to the lungs. In apnoea the patient is affected by repeated cessation of breathing ≥ 90% of the baseline and hence the condition degrades the quality of sleep [24] [25]. This results in repeated arousals from sleep and the patient suffers from daytime sleepiness, which is one of the common symptoms of apnoea.

2.3.2.1 Types of Apnoea

Sleep apnoea can be classified into obstructive, central and mixed sleep apnoea [26] and could be explained as in the next sections.

2.3.2.1.1 Obstructive Sleep Apnoea (OSA)

Obstructive sleep apnoea is characterised by obstructive apnoeas where there is complete collapse of the upper airway and a temporary cessation of airflow at the mouth or nose for at least 10 seconds (adult criteria), or two missed breaths (paediatric criteria) in the presence of continued respiratory effort (i.e. the chest continue to move during the event [25] [26] [27]. It is the most common type of sleep apnoea and approximately 85% patients suffering from SDB are classified as having obstructive sleep apnoea.

2.3.2.1.2 Central Sleep Apnoea (CSA)

Central sleep apnoea can be defined as the repetitive episodes of apnoea without any respiratory effort (i.e. no chest movements) or airflow at the nose or mouth [25] [26] [28]. This type of apnoea occurs due to the absence of central drive to breathe while sleeping and the brain does not signalling the muscles to aid respiration [29]. The apnoea diagnosis is referred as CSA when ≥ 50 of the events scored are central in pattern and origin. It is not as common as OSA and accounts for only 5-10% of the apnoea patients [26] [28]. However it is very common in patients with cardiovascular failure and patients suffering from some sort of neurological disorder [28].

2.3.2.1.3 Mixed (complex) Sleep Apnoea (MSA):

As the name suggests, mixed sleep apnoea is type of apnoea in which both the conditions of OSA and CSA occurs. In MSA, at the start of the event there is absence of the respiratory effort followed by an upsurge in the respiratory effort in the latter half of the event [25]. It is the least common type of apnoea and observed only in 5% from the apnoea patients [26]. Fig 4 helps to understand the above classified types of apnoea.
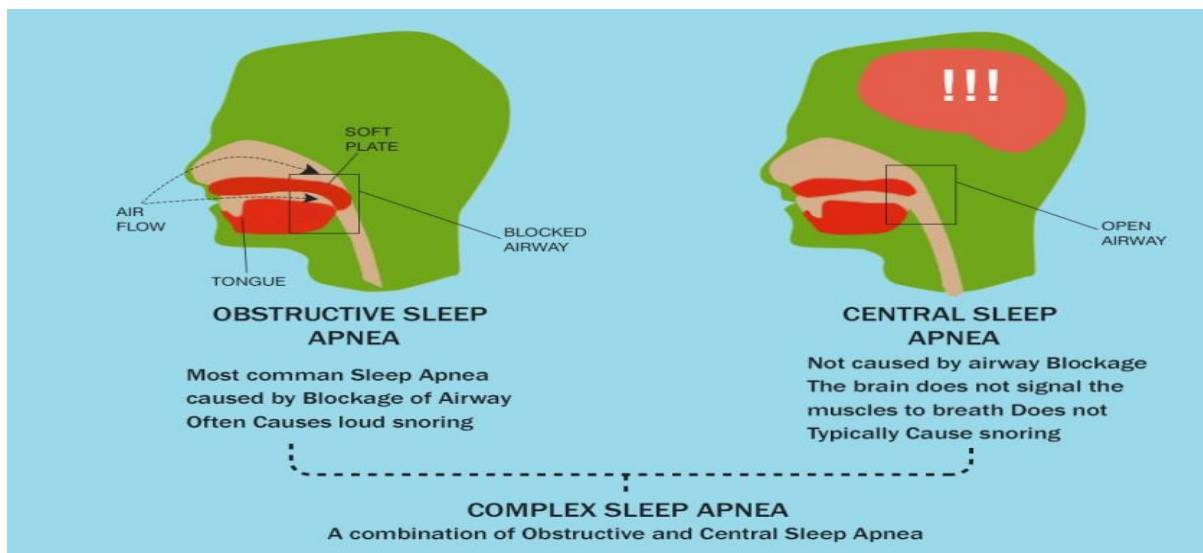
Figure 4 Classification of apnoea [30]

2.3.3 Hypopnoea

Hypopnoeas are partial collapse of the upper airway and are categorized as the reduction of airflow ≥ 30% of the baseline for at least 10 seconds (adult criteria), two missed breaths (paediatric criteria) along with blood oxygen desaturation of 3% or an

arousal from sleep [25] [27]. Hypopnoea event categorization varies with varying parameters. It can also be categorized as the reduction of airflow ≥ 50% of the baseline for at least 10 seconds along with blood oxygen desaturation of 3% [25] [26].

2.4 Severity Classification of Apnoea

In medical practice, for the evaluation of the severity of apnoea subjects, apnoea-hypopnoea index (AHI) is commonly used [27]. Apnoea-hypopnoea index (AHI) could be defined as the number of apnoeas and hypopneas occurring per hour of sleep [25] [31]. Table 1 shows the severity classifications for apnoea based on the AHI.

Table 1 Severity classification of apnoea based on AHI

Clinical Severity of Apnoea	Apnoea-Hypopnoea Index (AHI)
Mild	5 to 14
Moderate	15 to 30
Severe	30 or more

The result of the AHI varies with changing hypopnoea scoring criterion [32]. It is seen in many studies that the AHI may not be able to deal with all the complications involved in the process and hence may not be appropriate as a reference for diagnosis [31]. The development of a new index to evaluate the disease severity is recommended to tackle the inability of the AHI in the current diagnosis.

2.5 Apnoea Symptoms and Consequences

The clinical symptoms of sleep apnoea include snoring and daytime sleepiness because of disrupted sleep [33] [34] [35]. Patients experiencing daytime sleepiness are more likely to fall asleep at improper timings (e.g. while driving or in school) and have a higher risk of 2.5 times of having an accident than a normal person [34]. This is due to the fact that the condition of daytime sleepiness affects their sleep in such a way which results in an increased reaction time in such conditions. Sleep apnoea symptoms are shown in Figure 5. The figure shows sleep apnoea symptoms circle. It starts with symptoms like excessive sleepiness which leads to irritability in the

patient, causing depression, anxiety and stress problems and resulting in excessive weight gain or obesity.
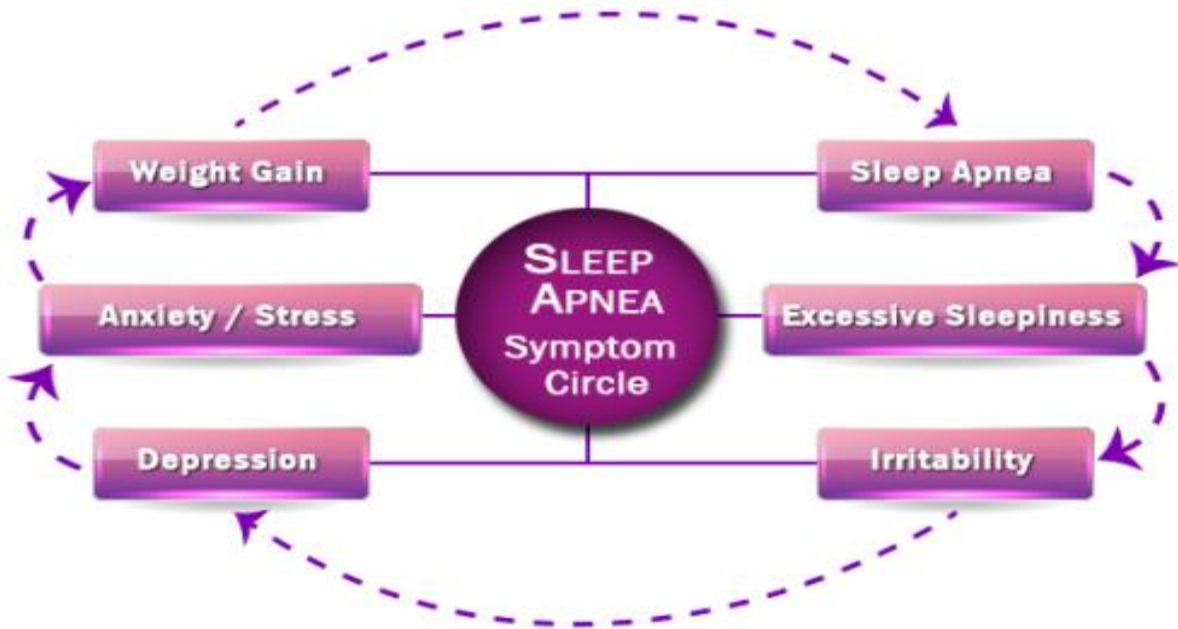
Figure 5 Symptoms of Apnoea [36]

In addition to that the low quality of sleep due to apnoea can also lead to anxiety, high rates of depression and decreased performance at work. Sleep apnoea is also associated with obesity, diabetes, increased risk of cardiovascular disease, metabolic syndrome, hypertension, gastroesophageal reflux, insulin resistance and hyperlipidaemia [34] [35]. Figure 6 shows many of the consequences of sleep apnoea.
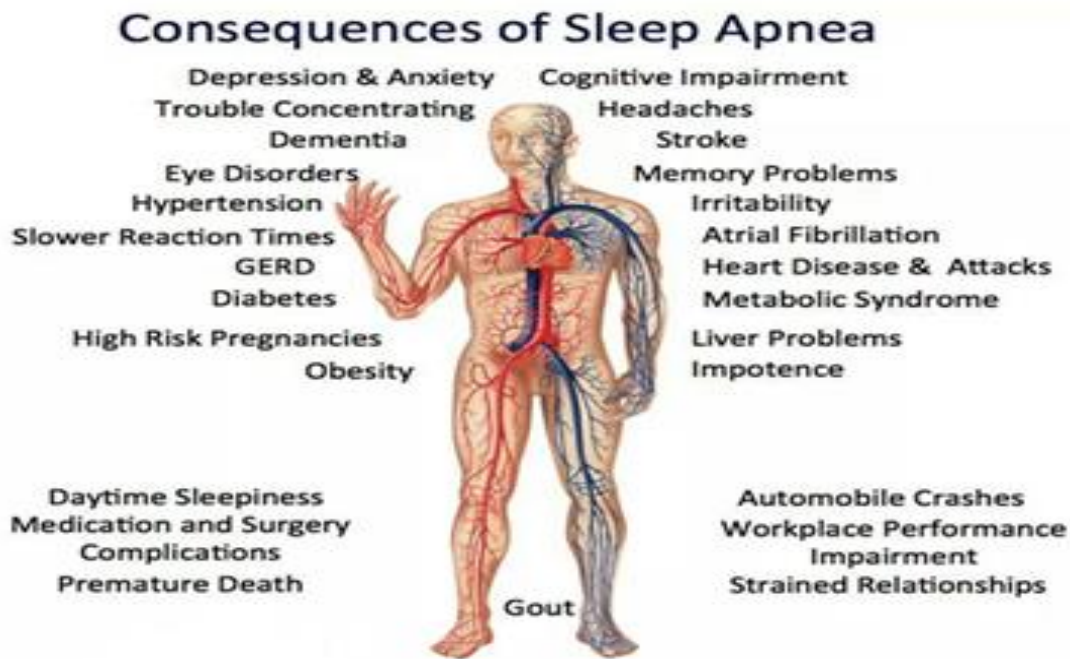
Figure 6 Consequences of Apnoea [37]

A contemporary statistical analysis of different studies has shown that sleep apnoea could also be a reason of deficiency in neurocognitive functions such as processing speed, vigilance, learning, psychomotor function and executive functioning [33] [38]. Such anomalies are the result of regular interruptions of oxygenation to brain while a person is asleep and also due to repeated arousals induced by breathing disruptions due to apnoea. It also found that 1 out of every 4 newly diagnosed OSA patients were suffering from some sort of neurocognitive impairment. The best example of neurological consequences is stroke that also overlaps with cardiovascular consequences of OSA. In older patients, prominent evidence of disturbed balance and way of walking increases the chances of falling down leading to injury, disability and even death.

A number of epidemiological studies have demonstrated increasing association between OSA and cardiovascular risk factors including obesity, glucose intolerance and hypertension. These risk factors increase with increasing severity of the apnoea. Different analytical studies have also noticed that OSA is also associated with other cardiovascular issues such as cerebrovascular disease, cardiac arrhythmias, atrial fibrillation, coronary artery disease and heart failure leading to mortality due to the complexity of the diseases. The immediate and correct detection and diagnosis of apnoea is therefore really important because it will lead to effective treatment of

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apnoea and will reduce the cardiovascular risk associated with apnoea as well [33] [38].

2.6 Diagnosis of Apnoea

The current gold standard apnoea diagnostic procedure is an overnight sleep study referred as polysomnography (PSG) [39] [40]. PSG is defined as monitoring and measurement of different physiological signals such as electroencephalography (EEG), electrooculogram (EOG), electromyography (EMG), electrocardiogram (ECG), body position, oxygen saturation, respiratory effort, snoring sounds, video and nasal airflow [39] [41].

2.6.1 Electroencephalography EEG

Electroencephalography (EEG) is comparatively a less expensive way of analysing neurophysiological activity [42]. The basic objective of EEG is to understand the primary neural functions based on complex higher-order cognitive actions and practical domains. In simple words the purpose of EEG is to interpret how human brain works by recording the bran's electrical activities. EEG is used in polysomnography to determine whether a person is awake or sleep and what sleep stage they are in.

2.6.2 Electrooculography EOG

Electrooculography is a technique for assessing the resting possibility of retina or to record eye movements [43]. The signal is referred as electrooculogram. The device used for EOG is known as electrooculograph that works on the principle of measuring the voltage between the two electrodes positioned on the face of the patient to measure the eye movements. EOG is utilised in polysomnography to detect eye movements to help determine when the patient is awake or asleep and to help classify sleep stages such as REM (Rapid Eye Movement) sleep.

2.6.3 Electromyography EMG

Electromyography (EMG) is used to measure the electrical activities within the muscles and it should be considered as an extension of medical investigation [44]. It is done by attaching surface electrodes to the muscles in the chin that causes contraction or bending that corresponds to electrical movements detected by electrodes and displayed on the polysomnography. The EMG is utilised in the PSG to determine when a patient moves or arouses from sleep.

2.6.4 Electrocardiography ECG

Electrocardiography (ECG) is a routine test used to evaluate the patients with cardiovascular problems [45]. This is the test used to detect abnormal heart rhythms and to investigate chest problems. ECG is used to identify the patients with the suspected heart dysfunctions and to refer the diagnosed patients for echocardiography. ECG is used in a sleep study to determine heart rate and basic heart rhythms.

2.6.5 Body Position

Body position is also one of the parameters that are measured frequently during PSG [46]. The body position is of less importance in paediatrics as compared to adults because the cause of sleep disordered breathing in paediatrics is more variable, where it is more position related in adults.

2.6.6 Oxygen Saturation or Pulse Oximetry

This is the test to check the oxygen circulation in the body. A maximum of 3 seconds of signal average time should be used in pulse oximetry to measure the oxygen in the blood [47]. It aims to measure the oxygen saturation level of the blood. This test is performed by placing a clip like probe on a patient's finger, ear lobe or toe that checks the amount of oxygen in the blood by using light. This parameter is used to help classify hypopnoea events.

2.6.7 Respiratory Effort

Respiratory inductance plethysmography is the most common way of measuring the chest and abdominal respiratory effort by using chest and abdominal belts and piezo

electrodes [46] [47]. This process is generally used in uncalibrated mode in paediatrics because the calibration mode needs to be calibrated again after body movements. These two channels will show whether there is respiratory effort during an apnoea to aid classification of the event. In addition to the two channels, there is also a sum channel which is the sum data of the two channels combined.

2.6.8 Nasal Airflow

Airflow measurement is the gold standard in PSG for detecting and classifying apnoeas as it directly measures the respiratory [48]. Nasal airflow is measured by two sensors: Nasal Pressure Flow and Oronasal Thermistors. The nasal pressure flow sensors are nasal cannulas inserted in the entrance of the nostrils and these plastic tubes connecting it to an electronic measurement unit. A less accurate means of respiratory airflow is by thermistor placed near the patient's nose and mouth and measures the difference in temperature as the person breaths in and out because the expired air is warmer as compared with inhaled air. That is the reason a thermistor produces a sinusoidal looking waveform showing the temperature difference of expiration and inspiration. A point to be noted here is that there is no correlation between the waveform pattern and the amount of air expired or inspired. The nasal cannula pressure transducer gives the linear approximation of airflow. Both sensors are used in PSG and are considered a valuable source to identify reduction in airflow but the problem with thermistor is that it may not be as accurate as airflow to differentiate an apnoea event from hypopnoea.

While a positive result of a PSG study helps in apnoea diagnoses but the problem is a negative PSG result does not rule out the presence of apnoea due to the factors of possible technician error, higher values of variability and lack of standardization involved in testing [39]. The equipment involved utilises several sensors that are attached to the patient's body by wires that may result in distress, soreness and discomfort especially in children [24] [49]. These sensors include nasal air flow sensor (nasal prongs) and thermistor as mentioned earlier. The Thermistor is placed in the proximity of the nose while nasal prongs are placed in the nares of the nose thus affecting the child's sleep. In many cases children either do not accept these

sensors or they remove them during recording hence important information needed for an accurate scoring of the apnoea events will not be available. The wires may pose a safety risk as they may entangle the patient.

Unavailability of clinicians with the ability of technical competency and the problematic procedure of overnight sleep study and also the problems with contact sensors as mentioned earlier require further developments in this area [41] [50]. Developments that could lead to unobtrusive and contactless monitoring have therefore distinct advantages.

2.7 Summary

This chapter summarises SDB along with different types of SDB. It elaborates the respiratory studies along with the general way of detecting and diagnosing SDB. It further describes different types of apnoea and hypopnoea that are referred as SDB. This chapter then classify apnoea on basis of severity based on AHI and symptoms and consequences attached to apnoea. The chapter then elaborate different procedures used in detecting and diagnosing different parameters in a sleep study. Lastly the gold standard sensors for monitoring respiration attached to the patient undergoing PSG are discussed along with the existing problems patients face due to these sensors.

Chapter 3
Literature Review

3.1 Introduction

The connection between the diseases and body temperature is not new to the field of medicine, but the recent advancements in technologies has paved way for skin temperature to be used as an advantageous and efficacious diagnostic bases to diagnose different diseases [51]. Thermal imaging or infrared imaging or infrared thermography is a non-invasive and non-contact tool that allows clinicians to measure the distribution of temperature on the tissues and organs both [52] [53]. The basic principle of using thermal imaging in medical diagnosis is the change in skin temperature due to the blood flow corresponding to a particular disease [54]. The use of thermal imaging as a clinical diagnostic tool in the area of medical diagnosis, specifically in the evaluation of the body shell has been established over the years [55]. The availability of thermal homeostasis of particular body regions with notable impact from the inflammatory and circulatory conditions and disorders also plays an important part for establishing infrared imaging as a reliable source for diagnostic means.

Thermal imaging is being used in different fields of medicine for diagnostic purposes especially in adults, but that is not the case in infants and adolescents because its utilization in children has not been explored thoroughly [54]. Another reason for an increasing trend towards using thermal imaging is due to the improvements in technology over the years allowing patients to be recorded with increased accuracy and precision, showing a way forward in this field of research. This literature review was done performing independent searches through Google Scholar and SHURA (Sheffield Hallam University Research Archive). The specifications of the thermal cameras used in this research for recordings have also taken into account. Articles published from 2005 to 2017 were used for the literature review. The approach adopted for search was to consider articles that cover the clinical diagnostic areas using thermal imaging in general and respiration monitoring and apnoea diagnosis in particular in paediatrics.

3.2 Thermal Imaging in Pediatrics

The use of thermal imaging is well-documented in terms of its usage in the field of clinical diagnosis with significant foothold in various vital areas in adults such as rheumatoid arthritis, Raynaud's disease, flow of blood, muscular performance and identification of the breast cancer in human body however the usage of thermal imaging specifically in children has not been widely investigated [51] [54] [55]. A recent study by Owen and Ramlakhan has provided a sound investigation of the possible utilization of thermal imaging for clinical diagnosis in paediatrics [54]. This literature review is also intended to investigate the usage of thermal imaging in paediatrics for clinical diagnosis especially with respect to respiration monitoring and apnoea diagnosis.

3.2.1 Skin Temperature

In early clinical examination the most prevailing medical condition was fever [56]. Physicians have acknowledged the significance of increased temperature in case of fever and it is believed that wet mud was used to apply on the skin to examine the swift drying of mud over a tumorous swelling part of the body. Until sixteenth century, when the concept of measuring temperature was first developed this was regarded as a subjective skill. Infrared imaging works on the principle that any subject having a temperature more than absolute zero emits IR radiation, even if it is weekly to say the least. Kolosovas- Machuca $et\,al$ [56]assessed the distribution of skin temperature on different parts of the body of 25 healthy children. Out of these 25 children 15 were male and 10 were female, with age ranging from 2 to 14 years with a (mean age of 7.8 years).

Infrared camera (FlexCam-S, Infrared Solutions Inc., Plymouth, MN, USA) was used in examining the participants of the study. The camera used had a thermal sensitivity higher than 0.1℃ along with an accuracy of ±2℃ at temperature of 30℃ and a spectral range from 8 to 14 μm. The emissivity of the camera was set at 0.97 for all respective measurements. The camera used provided thermal information of the ROI of the subject under consideration in real time with pixel resolution of 120×160. This information was then saved in digital format for further processing. The temperature measurements of all the participants were taken in a closed room at 22±1℃ from a

distance of 1.5m and in an atmospheric humidity of 40%. Air convection in the room was minimized and it was made sure that no radiation sources were present. The participants were asked not to take part in any physical activities 2 hours before the measurements.

For each participating child at least ten thermographs were taken and in case of taller children this number was even higher to measure 84 points of skin temperature. These points were then entered into a database for further processing and analysis. The camera used in the study was not able to save the thermal images in radiometric format so the thermographs were saved in JPG format and then analysed using LABVIEW, which provides the exact temperature at any point of the thermograph. In order to extract the radiometric information from the JPG images, interpolation was used. The colour-coded image was transformed to a matrix of temperatures by interpolating the colour scale with the temperature range set on the camera. These matrices of temperature were saved in a database for further analysis.

They observed the highest temperature difference of 5.1 ℃ along y-axis. On the other hand the temperature difference of the body along x-axis was lower and the highest temperature difference observed along the y-axis was 0.7℃. They also cited a similar study for adult patients from china reporting that the maximum skin temperature difference was 9 ℃ along the y-axis and the maximum temperature difference of 1.8 ℃ along the x-axis. They argued that this increasing difference of skin temperature along the x and y axes could be the result of higher fat distribution in adults in comparison with young children. This reduced variation in results for children may highlight the increased effectiveness of thermal imaging in children as compared to adults.

In a study of skin temperature responding to cold challenge a close conclusion was also reported by Symonds *et al* [57]. The thermal imaging camera they used in this study was (FLIR b60 2.3 Megapixel Infrared Camera; FLIR Systems AB, Danderyd, Sweden). The camera was set on a tripod stand 1m away from the subject and and at a set distance of 1m above the floor to ensure comfortable positioning for the

participants. To represent a control period, 5 thermal images were taken at intervals of 1 minute before each thermal challenge. Every subject then dipped 1 hand or both feet into cool tap water (19℃-20℃). Sequentially captured images using thermal imaging camera were saved in JPEG format along with encoded radiometric data. This acquired sequence of images was then processed using the FLIR ThermaCam QuickReport 1.2 proprietary software (FLIR Systems AB).

The study was done on 26 heathy individuals, involving both adults and children. They found the highest temperature increase of 1107% ± 365% in 7 children, aged 3-8 years. There were 12 adolescents of age 13-18 years in which the increase in temperature was 33% ± 300% and in adults of age 35-58 years the temperature increase was 113% ± 195% [57]. It is to be noted that many publications suggest the use of thermal imaging in adults as an affective diagnostic tool but in the light of the findings of the above mentioned studies thermal imaging could prove to be more effective and accurate diagnostic tool in paediatrics [54].

3.2.2 Acute Undifferentiated Limp

Acute limp is a frequent problem in paediatric emergency departments [58]. A UK study reported that the possibility of a non-traumatic limp in every 1000 children is 1.8 but the actual paediatric population representing all kinds of limps is much more than this [59]. The precise and accurate diagnosis and effective management of patients is very important in situations such as an emergency department and thermal imaging could be the way forward in assessing acute limp especially in children, in which clinicians face difficulty in identifying the pathological region in case of an affected limb and thermal imaging might be helpful to identify the region of pathology allowing more room for thorough investigation [58].

Owen et al. [58] did a study on 30 children been treated for acute limb at Sheffield Children's NHS Foundation Trust (Sheffield Children's Hospital, Sheffield, U.K.) Emergency Department (ED) over a period of 1 year. The basic purpose of the study was to investigate the use of thermal imaging as an alternative tool for the diagnosis of acute limb in children presented to the emergency department with an acute non-specific limb. All the recruited paediatric patients had one limp affected leg to allow

the other healthy leg to be used as reference temperature. FLIR© T630sc thermal camera (FLIR Systems UK, West Malling) along with its corresponding software FLIR Research Max 4© were employed to capture the infrared thermographic videos. The participating children were recorded in 20 second videos rather than single images and the recordings were done at a frequency of 30 Hz, capturing 600 frames per recording of 20 seconds.

Five ROI's on the legs were considered for detailed analysis which were upper knee (front side), lower knee (front side), the knee (front side), ankle (front side), and hip. The thermal imaging videos were visually scanned for each ROI to select 20 best frames for processing and analysis. All the above mentioned ROI's were selected manually to ensure the presence of the affected region. The selection of the ROI and in terms of its size and coordinates was done by using Matlab graphic image processing user interface. This was achieved by displaying the image on the computer screen and then selecting the ROI by using the mouse to select a rectangle shape region. The region was then cropped by entering those coordinates in the Matlab function.

Once the ROI was cropped, the next step was to analyse the temperature of the ROI of the affected leg and compare it against the reference ROI from the healthy leg. This was achieved in three steps. The first step was of averaging the pixel values of a ROI to get a single averaged value of the temperature of the TOI in a frame. The second step was of repeating the first operation for the 20 selected frames from the recording of each participant. In the third step these 20 temperature values were further averaged to get a pair of averaged values representing the temperature of ROI's under consideration for the healthy and affected legs of each participant. These operations provided five pairs of mean temperature values for the five selected ROI's of the affected and healthy legs.

They reported that the median temperature of the relevant ROI of the affected leg was higher than that of the healthy leg which was in line with the findings of many previous studies, concluding that pathological affected regions showcase increased temperature and it is quantifiable using thermal imaging with increased temperatures associating with serious pathological conditions. Although the study showed

encouraging findings in favour of thermal imaging but still it was not enough to make conclusions at that point due to the short set of data and they highlighted the need of a larger and more focussed study to make solid conclusions for the application of limb in this area.

3.2.3 Fever Screening

The use of infrared thermal detecting systems (ITDSs) for fever screening had some success in the current outburst of some contagious diseases [60]. While the ITDS's are reasonably precise in fever screening in adults, their utility in children has not been explored well. To investigate the utilization of thermal imaging in children Selent et al. [60] did a study on mass screening of fever in children in a paediatric emergency department. They used three different ITDS's (OptoTherm Thermoscreen, FLIR ThermoVision 360 and Thermofocus 0800H3) for temperature measurement and then compared the results against the standard age-appropriate temperature measurements such as (confirmed fever defined as $\geq 38°C$[oral or rectal], $\geq 37°C$[axillary]). The results of the measured temperatures using ITDS's were compared with parental information of fever with the help of multivariate, descriptive and receiver operating characteristic analyses.

They reported a range of 76.4% - 83.7% for sensitivity which is approximately equal to the sensitivity of standard reported measurement of temperature which is 83.9%. Sensitivity could be explained as the probability of a test result to be positive when the disease is present and can be represented as $(a/a + b)$. For specificity they reported a range of 79.4%-86.3% greater than the standard reported value of 70.8%. Here specificity could be explained as the probability of a test to be negative if the disease is not present and can be represented as $(d/c + d)$. They observed that FLIR and OptoTherm were providing decent results in the accurate detection of fever in children when compared against the standard thermography. These results were in favour of ITDS's to be used as an non-invasive means of detecting fever in children.

In another study on the use of thermal imaging in medicine Ring and Ammer [61] reported a similar conclusion about the lack of evidence in the favour of thermal

imaging for fever screening of large population. They did a study of 352 afebrile children using thermography and found the and found the mean temperature of the inner corner of the eyes to be 36.48℃, on the other hand they also used 52 children with proven fever to compare the results. The results of the temperature measurements of the inner corner of the eyes with thermography for children with fever were a bit higher and they found the mean temperature to be 38.9℃ in children with fever. The results were very much in line with the results of standard thermography so they reported that the application of thermal imaging for fever screening in children in place of standard thermometry could produce more positive results due to its significant characteristics of detecting changes in facial temperature [61].

In a similar study of fever screening Chan et al. [62] recruited 176 subjects out of those 49 were hospital patients of suspected SARS, 99 of them were health clinic attendees and the remaining 28 were healthy volunteers. The subjects were sensed remotely using IRT from different parts of the front and side of the face from a distance of 0.5m and 1.5m. The results of IRT were compared against the results of the traditionally measured temperatures using thermometry of the same parts of the face. The data was then used for linear correlation, sensitivity and specificity analyses. They concluded the sensitivity and specificity of 83% and 88% respectively, similar to the findings of Selent *et al* [60]. These studies highlighted the accuracy of ITDSs over traditional methods in practice indistinguishing the patients without fever.

Fortuna et al. [63] did a study of non-contact infrared thermometry versus the rectal thermometry on two hundred patients of age 1 month to 4 years. They used a Welch Allen SureTemp thermometer of model 678 to measure the rectal temperatures of children. The thermometer was calibrated with the help of the calibration key supplied by the manufacturer. The thermometer was inserted into the rectum and the temperature was measured after 15 seconds of insertion. Once the rectal temperature was measured the next step was of measuring the temperature of the same skin area using infrared thermometery. Thermofocus non-contact infrared thermometer of model 1500 was plaed on the ceter of the forehead and the operator

placed the thermometer until a reliable measurement was taken and they reported a different conclusion from the above mentioned studies [63]. They criticized the efficacy of thermal systems by mentioning the problem of overestimation of the temperature in afebrile children and underestimation of temperature in febrile children by comparing the results of infrared thermometery against the rectal thermometery..

Despite the lack of widespread agreement on the use of thermal imaging for fever screening in paediatrics, the pros of using it for this purpose are its non-contact nature, ease and momentum at which the screening can be done for the paediatric patients [54]. Moreover with the on going improvements in the field of infrared thermal imaging it may have significant applications in the field of paediatric emergency for speedy and high-volume screening.

3.2.4 Haemangioma and Varicocele

Haemangioma or varicocele is another area where the use of thermal imaging could improve the diagnostic accuracy in monitoring and investigating their progression by assessing the asymmetrical pattern of the blood flow corresponding to their origination [54]. Saxena et al used thermal imaging in documenting and investigation of the trajectory of cutaneous haemangiomas and varicocele [64]. They employed a high performance thermal imager Talytherm® (Rank Taylor Hobson Ltd., Leicester, England) and operated in the 8-12μm band. The measurements were taken in standard conditions at a constant temperature of $20℃\pm2℃$. Before commencing the measurements it was ensured that no radiation was present and air convection was minimized. The subjects were present in the room 20 min before starting the measurements to thermally stabilize their bodies. Images were captured and stored for processing to analyse and interpret the results. They recorded 102 paediatric patients of haemangioma ageing from 1 month to 1 year. They reported a speedy progression of haemangiomas in 57 children with a temperature differential of 1.5 ± 0.3°C, whilst the patients who were monitored until complete resolution presented a decrease of <0.5°C in temperature differential. They also investigated 6 boys with varicoceles ageing between 13-15 years by employing thermal imaging. Thermal

imaging displayed an increase of 4.1 ± 0.3° C temperature differential in all the patients in comparison with the contralateral usual testis.

Mohammad et al. [65] also did a study on 42 infants to evaluate thermal imaging in assessing the proliferation and involution of infantile haemangiomas. Some validated and objective measures are being used to assess infantile haemangiomas. The standard procedure of measuring the extent of infantile haemangiomas is by using visual analogy scales. Infantile haemangiomas volume has been estimated through different mathematical formulas based on measured parameters but none of them proved to be ideal for all the different types. This study uses infrared thermography to measure the local temperature of infantile haemangiomas with the help TempTouch digital IRT device. Two measurements were taken, one at the start of examination and the second one after 30 minutes from the first measurement to check the reliability. The results of infrared thermography were then examined against the results of visual analogue scales to investigate the ability of infrared thermography in assessing the proliferation and involution of infantile haemangiomas.

The collected data was summarized using descriptive statistics. Temperature difference was calculated between the measurements from visual analogue scales and infrared thermography. Differential analysis was performed to compare the initial and 30 min temperature differences. Mohammad et al. [65] also outlined the decreasing temperature differential corresponding to the haemangioma resolution which was in line to the findings of Saxena et al. [64].

Garcia-Romero et al. [66] in their study on the role of thermal imaging in the evaluation of haemangiomas in 10 patients presenting haemangioma being treated with a systematic beta-blocker reported the effectiveness of thermal imaging in its treatment response. They measured the temperature of infantile haemangiomas in selected patients in the middle part of the affected region on weekly basis for six months. They used an infrared thermometer (TempTouch, Diabetica Solutions USA) and compared the results with the non-affected side. The correlation between the temperature difference of affected and non-affected side was performed using the investigation of treatment response from visual analogue scale and infrared thermometry.

Iwata et al. [67] also found a similar result to the findings of Saxena et al. [64] for varicocele, in case of a 12 year old boy displaying a varicocele on the left side [54] [67]. They also reported a close variation of temperature in the affected side. The boy with a left sided varicocele was examined before operating and was followed after the surgery using computer assisted infrared thermography. A temperature difference of 4 ℃ was observed between left and right scrotum before surgery. Once the varicocele was removed through surgery and the ligation of the left internal spermatic, the scrotal thermograms were normal after 12 months. In the light of the findings of the above mentioned studies for both haemangiomas and varicoceles, a prospective utilization of thermal imaging in monitoring and treatment of these diseases is very much attainable.

3.3 Thermal imaging in respiration monitoring

Respiration is a vital physiological procedure [9]. The accurate monitoring of respiration is of critical importance in sleep related disorders and studies, clinically serious patients, in diagnostic management of respiratory disorders and neonatal care. Most of the current in practice methods for respiration monitoring are contact based in nature i.e. the sensors need to be attached to patient's body for monitoring purposes causing irritation and soreness to the patients, disrupting the sleep and affecting respiration which is of critical importance in these kinds of sleep studies. These sensors can also be detached causing interruptions in real time monitoring [68]. These problems and the increasing practices of the utilization of thermal imaging in clinical diagnosis due to its non-contact nature have encouraged researchers to look for alternative non-contact methods for respiration monitoring.

Realizing the severity of the problem many researchers explored this area of respiration monitoring using thermal imaging but majority of the studies were done on a data set comprised of adults. We here will be discussing different studies done by researchers on both adult and paediatric patients in quest of a non-contact method for respiration monitoring and then in latter chapters of results and discussion we will highlight the contribution made by this study to the area of non-contact respiration monitoring.

Al-Khalidi et al. [68] did a study on monitoring respiration rate in 20 paediatric patients (Median age of 6.5 years) based on thermal imaging to investigate the possibility of a non-invasive alternative to current contact methods in practice. Out of these 20 patients only 16 patients breathing via nose were included in this study as the rest were breathing via mouth and this method had problems while the patients were breathing via mouth and they suggested detailed work is needed to overcome this issue. They reported an average respiration rate of 20.7 using thermal imaging across all patients while the average respiration rate measured using regular contact methods simultaneously was 21. They reported a correlation coefficient of 0.994 showing the efficacy of thermal imaging against the standard methods of monitoring respiration rate.

In a study of thermography based monitoring of respiration, Pereira et al. [49]worked on 11 healthy volunteers from 21 to 31 years of age and the volunteers were recorded in three different scenarios of 3 minutes each. The first scenario was of breathing normally without any head movements, second scenario was of breathing normally with some head movements (to check the robustness of the designed method) and the third scenario was of breathing with different instructed patterns. The movements and the breathing patterns in second and third scenarios respectively were to access the robustness and accuracy of the designed algorithm. They reported a correlation coefficient of 0.968, 0.840 and 0.974 for three scenarios respectively when compared against the standard practice of thoracic effort used in this method. They also observed the respiration rate errors of 0.33, 0.55 and 0.96 breathe per minute (bpm) respectively in the above mentioned scenarios showing the effectiveness of thermal imaging as an alternative method for respiration monitoring due to its efficacy and various extra ordinary advantages.

In a similar study of measuring respiration rate using thermal imaging Elphick et al. [69] reported a close conclusion in the favour of thermal imaging. They developed a new non-contact method of monitoring respiration rate with the help of a thermal camera. They evaluated the results of this newly developed method against five standard contact based methods which were used in clinical practice as standard procedures. Their data base included the recordings of 51 adults (Median age 35.7 years) and 20 paediatrics (Median age 6.4 years). They reported an average respiration rate of 14.8 bpm for thermal imaging. They found a correlation coefficient

of 0.88-0.998 in adults and 0.578-0.999 in children depending on the contact based method used for correlation. In a study of monitoring the breathing function by means of pattern recognition of thermal images, Al-Obaisi *et al* was able to develop a feature extraction method for thermal images based on the classification system of neural network that can be used as a part of the respiration monitoring framework [30]. This new neural network based framework has been generating positive classification results. In addition to that this new method is being used in calculating the respiration rate of all the subjects from the classification results.

Abbas et al. [70]did a study to evaluate the non-contact respiration monitoring based on thermal imaging in pre mature infants. They analysed seven premature new-borns with an average gestational age of 6 months and 23 days. All the patients were admitted to the department of neonatology while examined. The respiration signal was identified by applying the debauches wavelet function based continuous wavelet transformation in an image sequence. Successful non-contact respiration monitoring was achieved on the basis of 0.3C to 0.5C of temperature difference while inspiration and expiration episodes. This study is using this method for the first time in neonatal intensive care unit while it has been used in adults before. They believed further investigation was needed to validate the findings of this study as of right now depending on the patient population the proposed method is not ready for clinical setup.

In a similar study Alkali et al. [9] accessed the real time non-contact respiratory rate monitoring based on thermal imaging. They recorded around 55,000 images of 14 adult volunteers making head movements of different lengths to access the facial features detection framework. This was further evaluated by determining the respiration rate in comparison with the two existing contact based methods based on the tracking of thoracic and abdominal movements. This further assessment was executed on 15 adult volunteers (Median age of 36.6 years) in a hospital setting. In 12 subjects where the head movements were relatively small, they observed a correlation coefficient of 0.997 in the results of the thermal imaging against the values produced by the thoracic and abdominal bands. In the remaining 3 subjects where the head movements were relatively large the method made errors in detecting the ROI leading to inaccurate measurements for respiration signal and respiration rate.

3.4 Thermal Imaging in Apnoea Diagnosis

As explained earlier the diagnostic procedure for apnoea is PSG that involves several sensors to be attached to the patient's body especially the nasal airflow placed inside the nares and thermistor placed in the proximity of the nose affecting the sleep of the patient [49] [24]. These sensors are not tolerated by patients in many cases especially in children who try to remove the sensors resulting in important information being lost and making it difficult to score apnoea events. Both sensors are used in PSG and are considered a reliable source to identify reduction in airflow but the problem with both sensors is that the nasal cannula may not be as accurate to differentiate an apnoea event from hypopnoea and also as both sensors do not provide a quantitative measurement of airflow so they are not much reliable to detect hypopneas [48]. Thus significant developments in the field of thermal imaging that could lead to non-invasive and unobtrusive diagnosis of apnoea is worth exploring.

Researchers have been working in this field to achieve the aim of non-contact apnoea diagnosis but the majority of the researchers have worked on adults and only a few studies are available involving paediatric patients and even those studies are also based on recordings of small duration such as from some minutes to few hours which is not enough to accept the developed methods in clinical practice. To our knowledge this is the first time a study is being done on paediatric patients of apnoea with a data set of whole night recordings to investigate the findings of the previous studies and the framework developed in this work on a much larger scale.

Murthy et al. [71] worked in this area and came up with a novel method to monitor airflow during polysomnography. Their work included 14 adult participants of (18 years or older) with no prior history of apnoea diagnosis and also another 13 adult patients having a prior diagnostic history of OSA via PSG. They recorded each participant for at least an hour while asleep. They compared their results of thermal imaging with P_n (nasal pressure), thermistor, $P_E CO_2$ (expired carbon dioxide) and observed a good agreement between their results and each reference channel. They found a consensus of 99.6% between P_n and thermal imaging, 99.2% between thermistor and thermal imaging, 98% between $P_E CO_2$ and thermal imaging. They observed a better consensus between thermal imaging and all the reference

channels then the consensus among the reference channels. The authors of the study highlighted the limitations of this work with regards to short duration of collected data and sample size and they also suggested the evaluation of their work in a full night PSG.

A group of researchers applied the above work separately on another set of data as well and they named their study as thermal vision for sleep apnoea monitoring [72]. In this study they recorded 22 subjects (12 men, 10 women) age range (24 years-66 years) along with standard polysomnography measurements to compare their results against the reference channels. Out of the total 22 subjects, 10 subjects were with clinical diagnosis of apnoea and 12 subjects were without prior history of apnoea. This study evaluated the method's validity in the form of three benchmarks namely accuracy, precision and recall. They observed a 94.59%, 90.42% and 94.76% of accuracy, precision and recall respectively. The method showed high agreement between the results of thermal imaging and the ground truth results. The high performance indicators for thermal imaging validate its effectiveness in this area. This method was also limited in terms of its number of subjects recorded and the short duration and sample size of the recordings. To validate the findings of the study a larger study was required with thermal recordings of longer duration.

In another study, Al-Naji et al. [73] explored the possibility of apnoea monitoring in paediatrics by employing Microsoft Kinetic Sensor in detecting thorax and abdomen movements to observe the respiratory effort. Microsoft Kinetic v2 used in this study can produce an RGB image, IR image and depth image based on its optical sensors. Five healthy children (3 boys and 2 girls) of age 1 to 5 years with no prior history of sleep apnoea participated in this study. Participants were recorded for duration of 3 hours at different times (day and night), light quality (bright and dark) and participants with and without covering the body to investigate the data with all possibilities. All the participants in this study were asked to hold their breaths for 10 s, 18 s and 20 s, while recording to mimic the condition of apnoea. The results produced from all the participants were set in two scenarios. In first scenario the recordings were carried out in more lit environment and the frames acquired from the RGB sensor were processed via the suggested system and in the second scenario

the recordings were carried out in dark environment and the frames obtained from IR sensor were utilized.

They found that the subjects in the first scenario (bright conditions) give slightly better results than second scenario (dark conditions). The other point they observed was the subjects recorded without blankets were providing better results than those with blankets. This could be the result of problems in tracking of the suggested system due to its fully covered condition. The correlation coefficient of the measured data from the presented system in this study and the reference data for all the scenarios involved was 0.9812 which is satisfactory for clinical applications. The working nature of the proposed system with all the different scenarios and conditions shows its effectiveness in monitoring respiration and detecting apnoea. The proposed system could also be useful for detecting vital signs and sleep-disordered breathing in future. The authors of the study recommended further studies with more number of participants and recording of longer duration to validate the findings of their study. They also suggested the increase in the number of apnoea events in the recordings to investigate the accuracy and precision of the proposed framework.

Wang et al [74] explored this area in their study of unconstrained video monitoring of respiration and its utilization in diagnosing apnoea. In this study two datasets were used for evaluation of the proposed framework. In the simulated data set, 95.5% cases were identified correctly for both apnoea events and body movements on the other hand in case of clinical dataset 94% of the apnoea events and body movements were detected. This shows the effectiveness of the proposed framework on both clinical and simulated data. They suggested further investigation of the proposed framework by recording the data with improved range of cameras and also improving the cross validation of the clinical diagnosis to support clinical trials and interventions.

3.5 Summary

This chapter discusses different fields of medicine in which thermal imaging has been used with its pros and cons. Overall in most of the cases discussed above thermal imaging has been quite successful in producing the results when compared

against the standard methods in place for that particular disease. Especially in the case of respiration monitoring in general and apnoea monitoring specifically, thermal imaging proved very useful in monitoring respiration and detecting pauses induced in breathing due to sleep disordered breathing. The literature review proved to be quite helpful in this regard as it is directly related to this study as the study is also of respiration monitoring to detect apnoea induced pauses in breathing.

Chapter 4

Thermal Imaging and Image and Signal Processing Techniques

4.1 Thermal Infrared Imaging

Body temperature has been used for clinical diagnosis since 400 BC due to its good performance as a health indicator [75]. Hippocrates was the first person to use body heat to access the pathology [76]. Sir Williams Herschel discovered infrared radiation in1800 which led to more innovative ways in the area of temperature measurement [75] [77]. After the discovery of infrared radiation, it was Kalman Tihanyi, a Hungarian physicist who developed the first infrared camera in 1929 based on the principle of infrared radiation explained by Herschel that all objects emit a heat signal in the form of infrared radiation. The camera was able to detect infrared radiation just like the ordinary camera detected visible light. The proposition of human body emitting radiation was first described by Hardy in 1934 along with a suggestion of considering human skin as a blackbody radiator. He manifested the significance of temperature measurement by infrared methods that lead the way for infrared thermography utilization in clinical diagnosis. However due to the unavailability of high quality equipment and technical expertise the first known use of thermal imaging for diagnostic purposes didn't occur until 1960.

Rapid advancements in the field of thermal imaging resulted in decreasing equipment prices and improved the accessibility of latest IR technology in terms of IR-detectors and uncooled FPA (focal plane array) which explains why with time IR is being used more frequently in clinical diagnosis. Moreover the advanced techniques of digital image analysis also make it more accurate and precise [76]. Developments in this area have improved the performance to a large extent. In the latter half of the 20th century infrared detectors were in use for military applications and the IR imagers were scanning one to ten elements of detector units [61]. In 1984 for a target size of 50 cm², the process was carried out at 1 to 16 frames per second with a temperature resolution of 0.5˚C and spatial resolution of about 5mm. However, with advancements in the field, in 1995 higher temperature resolution (better than 0.1˚C) along with a spatial resolution (lower than 0.1mm) at 25 frames per second

was achieved. Fig 7 shows two infrared thermograms at different times to explain the difference in temperature distribution with improvements in technology. The thermogram on the left side was recorded in 1995 with 320×240 pixels and the thermogram on the right side was recorded in 2011 with improved infrared camera of 640×480 pixels. Fig 8 shows thermograms of dorsal hands recorded in 1990 and in 2011 with advanced focal plane array camera.
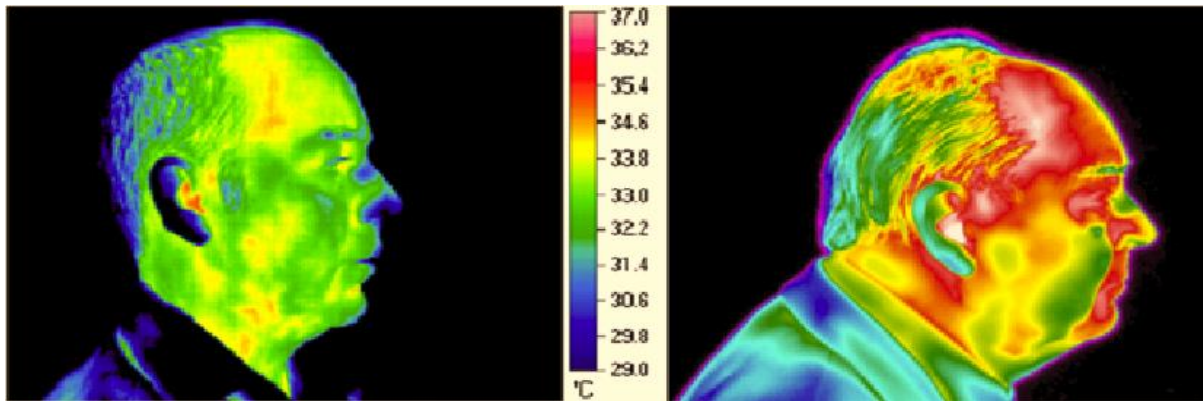
Figure 7 Left thermogram recorded in 1995 and right thermogram recorded in 2011 [61]
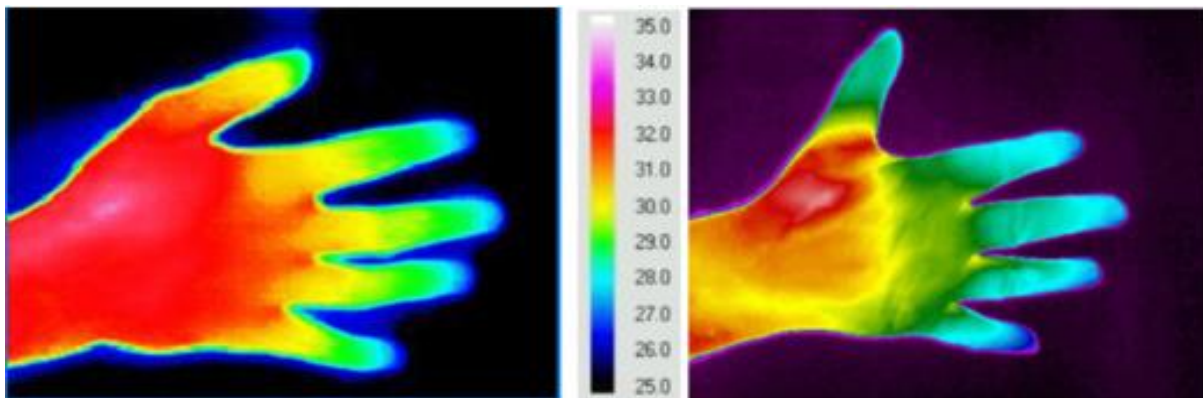
Figure 8 left thermogram of dorsal hand in 1990 thermogram in 2011and right [61]

4.2 Fundamentals of Infrared thermal imaging (IRTI)

Calopa and et al. [78] described IRTI in their studies of medical thermography as a process of measuring the radiated energy from a body due to its temperature. Hildebrandt et al. [79] described human skin with an emissivity factor of 0.98 as a black body radiator and hence an ideal infrared radiation emitter at room temperature. In both studies the features of infrared radiation emitted by an object were explained by Plank's law in the form of spectral radiant emittance. Both studies

mentioned Plank's law which is defined as any object with a temperature higher than zero Kelvin (0° K), emits radiation with a definite distribution of wavelengths:

$$\rho(T, \lambda)d\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda KT}} - 1} \, d\boldsymbol{\lambda} \qquad (4.1)$$

Where $\rho(T, \boldsymbol{\lambda})(W/m^3)$ is the density of energy emitted which is dependent on $T(K)$ and λm. Given variables are in correspondence with black body's temperature and wavelength of its radiation, respectively. More over $h(J \, . \, s)$ is the $Plank's$ constant, $K(J/K)$ represents the $Boltzmann's$ constant and $c(m/s)$ serve as the speed of light [78] [79].

The object referred to as black body here is an ideal body that is capable of absorbing all the energy it receives and also radiating the energy corresponding to its temperature at the same time [78]. That means:

$$\alpha(T) = \varepsilon(T) = 1 \qquad (4.2)$$

Here $\alpha(T)$ is the absorption coefficient and $\varepsilon(T)$ is the coefficient for emission. Nonetheless, real objects and bodies are not ideal (black) and a body emitting similar amount of energy in all wavelengths $(0 < \varepsilon(T) = constant < 1)$, is known as a grey body. On the other hand a body emitting different portion of energy depending upon the wavelength $(0 \leq \varepsilon(\lambda, T) \leq 1)$ is referred to as a selective radiator [78].

Therefore the authors explained that the emission of energy is dependent on the spectral emissivity of an object. Fig 9 shows the spectral emissivity of different materials.
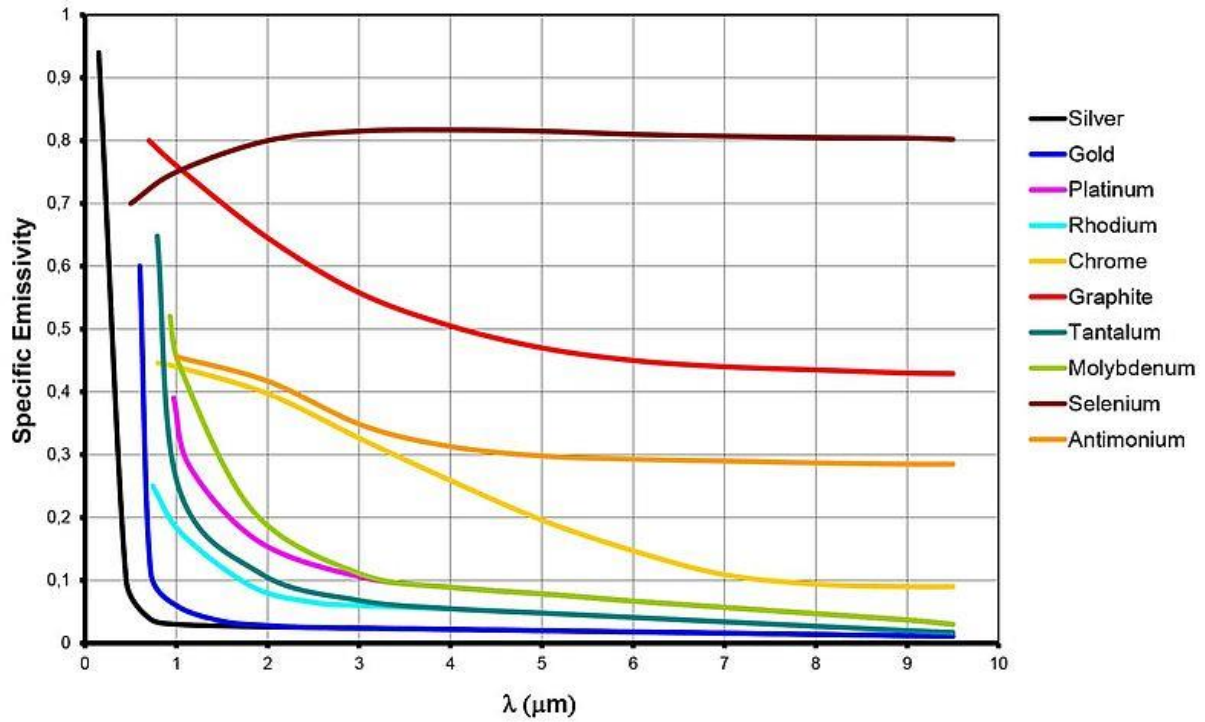
Figure 9 Spectral emittance of some metals and materials corresponding to the wavelength of the signal [78]

Hence, the complete radiation power of an object $(\Phi)(W)$ is dependent on both the temperature and emissivity of the material as explained by Calopa [78]. It can be calculated by using Stefan-Boltzmann's law:

$$\frac{\Phi}{A} = \varepsilon\sigma(T^4 - T_C^4), \tag{4.3}$$

Here $A(m^2)$ represents the surface area of the object, σ is the Stefan-Boltzmann constant and its value is given as $\frac{2\pi^4 K^4}{15C^2 h^3} = 5.669 \times 10^{-12} W cm^{-2} K^{-4}$ and $T_C(K)$ represents surrounding temperature of the object [78]. In addition to this equation 4.3 presents the total radiation power as a function of the fourth power of temperature:

$$\int_0^\infty \varepsilon(\lambda, T)\rho(\lambda, T)d\rho \propto T^4 \tag{4.4}$$

Calopa [78] also explains that the radiation emitting black body has a maximum value that changes with varying temperature, which can be described by Wien's law:

38

$$T\lambda_{max} = 2898\ \mu mK \qquad\qquad (4.5)$$

It shows temperature is directly proportional to frequency and inversely proportional to wavelength. At room temperature the wavelength of emittance is $10\mu m$.

The wavelength of the radiation emitted from a body, above absolute zero temperature lies within a range of $(0.75\mu m - 1000\mu m)$, i.e in-between the visible light and microwaves [75] [78]. As shown in Fig 10 this infrared spectrum could be further divided into 5 bands: (1) near infrared ($NIR - 0.74\mu m\ to\ 1\ \mu m$), (2) short wave infrared($SWIR - 1\mu m\ to\ 3\mu m\ approximately$), (3) middle wave infrared ($MWIR - 3\mu m\ to\ 5\mu m$), (4) long wave infrared ($LWIR - 8\mu m\ to 14\mu m$) and (5) very long wave infrared ($VLWIR - 14\mu m\ to\ 1mm$).
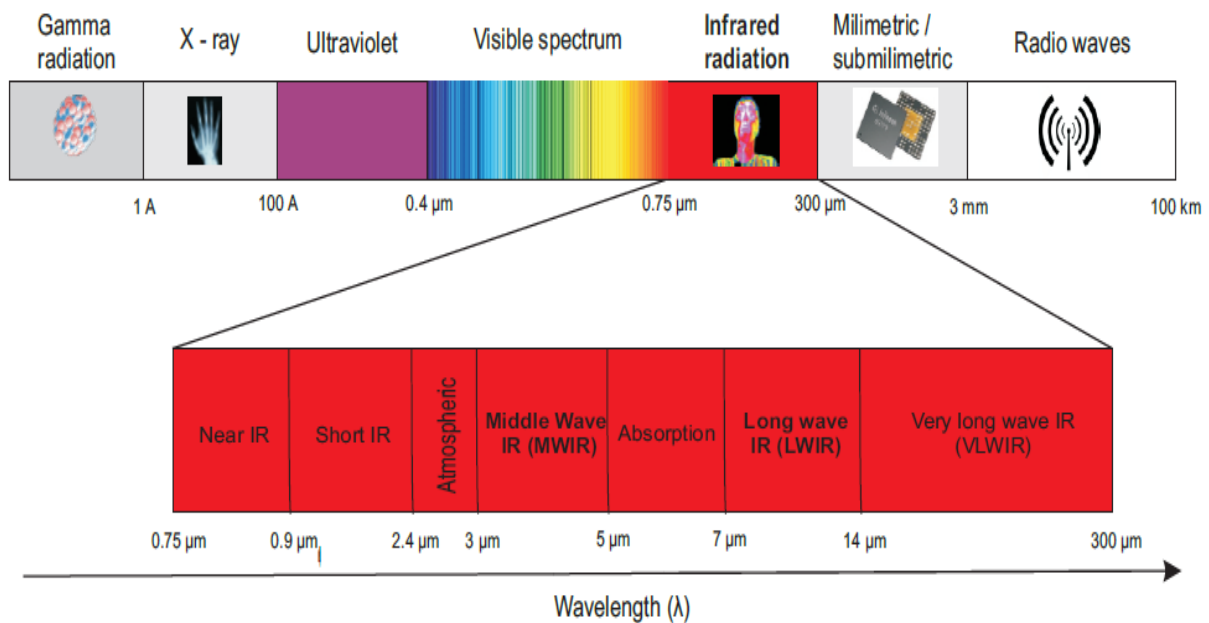
Figure 10 Detailed classification of infrared spectrum in the electromagnetic spectrum [78].

4.3 Heat Emission in Humans

The same study of thermal imaging by Calopa [78] explains that our body produces heat as a result of metabolism and some of the heat is lost to the outer environment and the remaining heat in the body is referred to as body temperature. The study mentions the core temperature (within deep tissues) of the body ranging between 36 to 38℃ is nearly stable irrespective of any physical activities. However, the outer temperature or the skin temperature of the body is slightly lower and averages around 33℃. The study also suggested that this temperature is dependent of part of

the skin and varies with the heat flow in the body. Energy emitted by a body corresponding to its temperature is shown in Figure 11 with the help of its spectrum of energy. The human body emits energy only in two bands of the earlier shown spectrum of infrared radiation which provide sufficient thermal sensitivity and those bands are MWIR and LWIR. Out of these two bands, LWIR is utilized more often due to its relatively cheaper sensor technology [78].
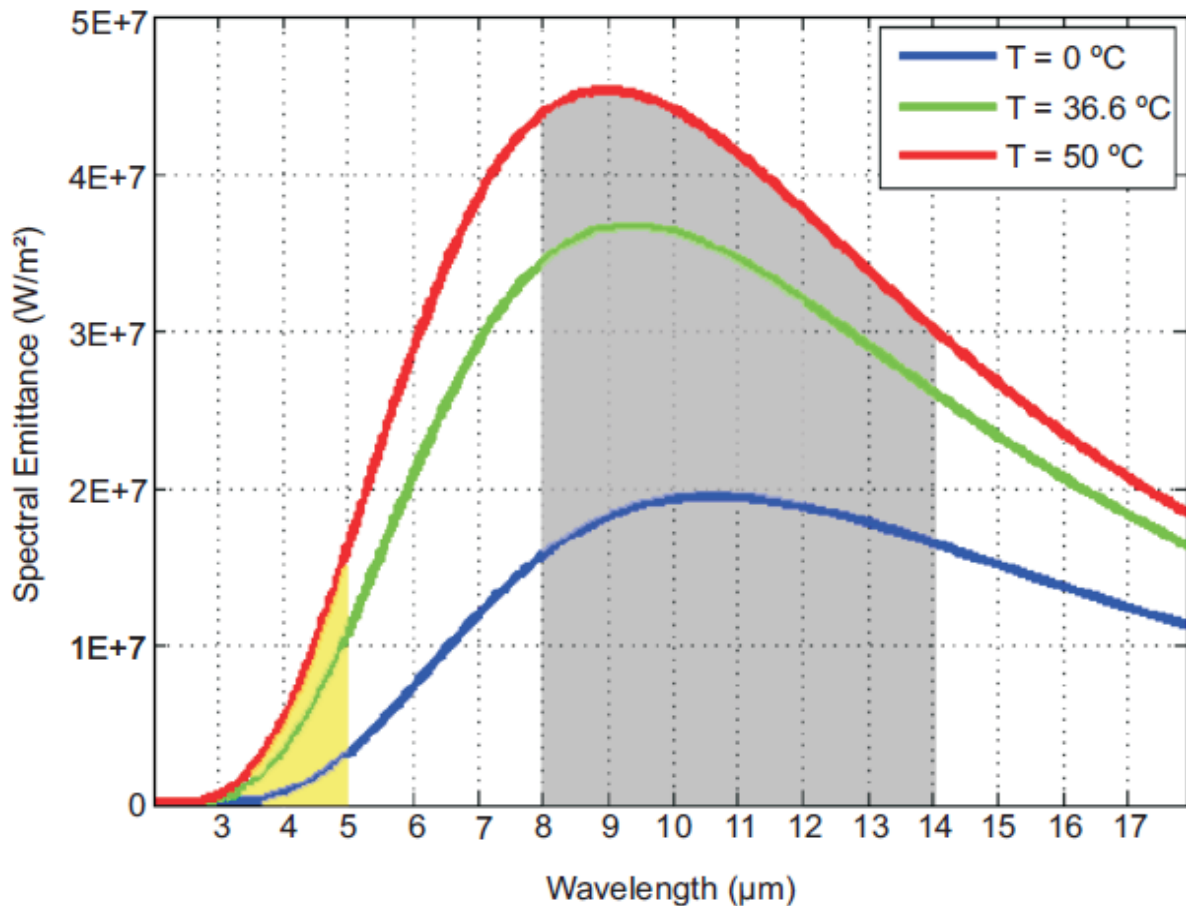
Figure 11 Spectral emittance (heat energy) at temperatures close to the temperature of the human body [78].

4.4 Digital Signal Processing

Signal processing is a term used to explain any physical or automatic mechanism that is used for examining, modifying or influencing any information involved in a signal [80].

4.4.1 Multirate Signal Processing

 Apolinari and Diniz [81]in their book of introduction to signal processing theory describes that systems having various sampling rates are known as multirate system.

They explain that in digital signal processing we have to deal with signals of distinct sampling rates quite often. The book referees this technique as very useful in such cases as it is easy to make adjustments in sampling rates by a proportion of integer values. They encouraged the use of this technique especially when we have to merge information of different systems having distinct sampling rates but it is necessary for sampling rates to be made compatible in such cases. Figure 12 demonstrate decimation and interpolation of a discrete-time signal. Figure 12 (a) shows the widening of the spectrum by a decimation factor of 2 while comparing against the new sampling rate. Figure 12 (b) illustrate the result of interpolation when the sampling rate of a sequence is increased by a factor of 2.

(a) Signal decimation with M = 2.

(b) Signal interpolation with L = 2.
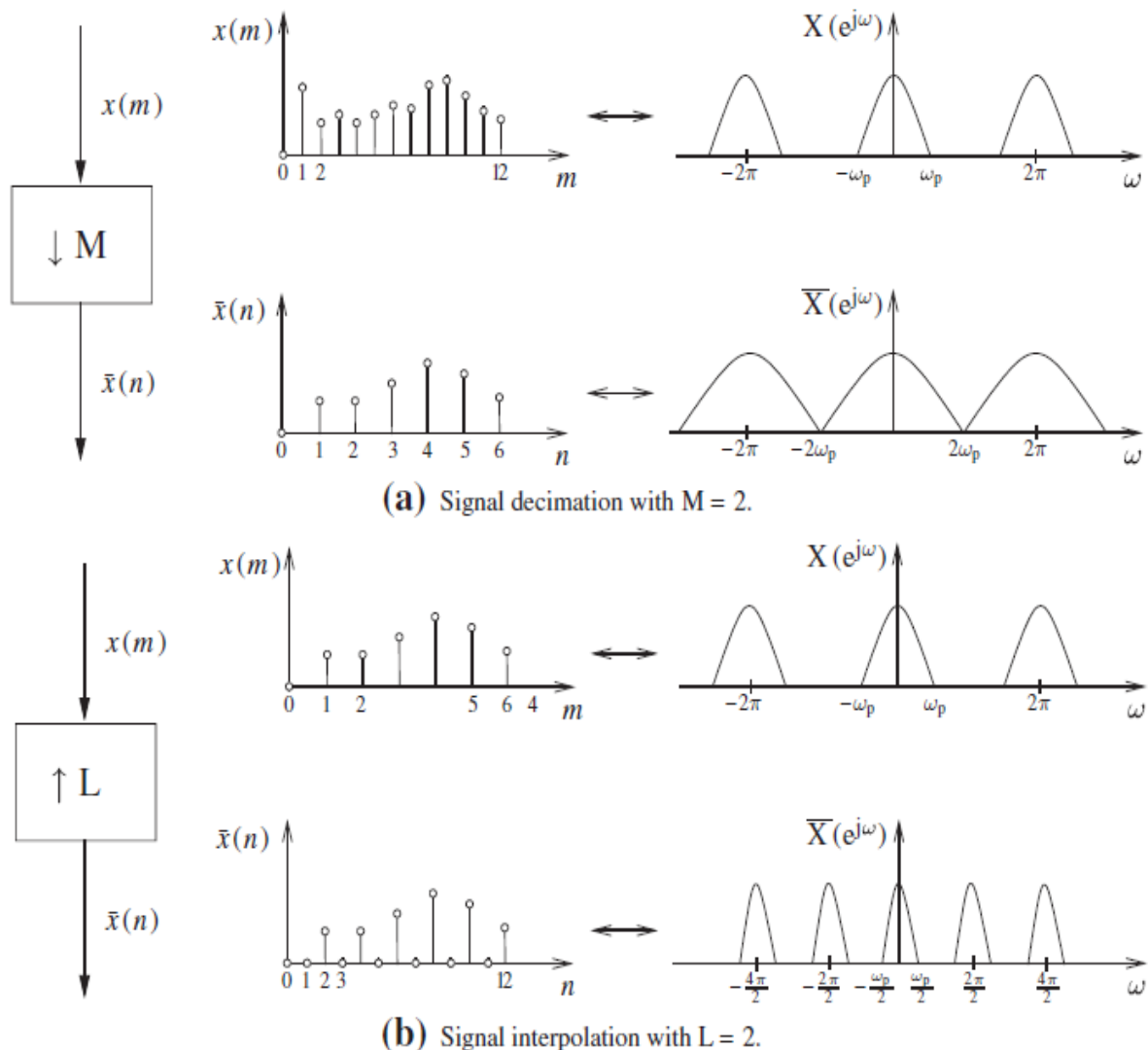
Figure 12 (a) Signal decimation with M=2. (b) Signal interpolation with L=2 [81].

4.4.2 Discrete Fourier Transform

Discrete Fourier Transform (DFT) is an efficient way of switching from time domain to frequency domain of signal [80] [82]. Petrou and Petrou [82] explained that every sine or cosine function of a Fourier Transform has a given frequency and respective amplitude. They said that both of these parameters are utilized in building the frequency spectrum of the actual time signal. A 1D DFT of a function $f(k)$, at discrete points $k = 0,1 ....., N-1$, is described as:

$$F(m) = \frac{1}{N} \sum_{k=0}^{N-1} f(k) e^{-j\frac{2\pi mk}{N}}$$ (4.6)

Here $f(k)$ represents the input of the signal at time k, $F(m)$ is the mth output frequency and N is the number of samples.

4.4.3 Fast Fourier Transform

With all the advantages of DFT, it also has a disadvantage of long computation time. In 1965 Cooley and Tukey came up with an algorithm which basically changed the landscape of digital signal processing [83]. This new algorithm reduced the running time of DFTs from $O(n^2)$ to $O(nlogn)$. They termed FFT as an efficient way of implementing DFT without its long computation time. They pointed out that the time-frequency information of both DFT and FFT is not simultaneous. Figure 13 shows the comparison of the processing time for both DFT and FFT for an input vector of length 50. Due to this significant superiority of FFT was used for respiration rate computations.
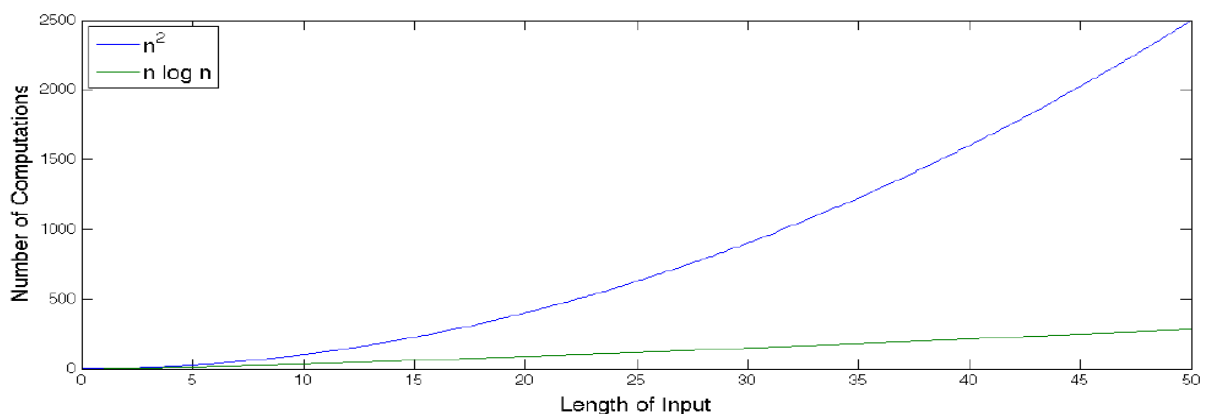
Figure 13 Comparison of O(n^2) and O(nlogn) processing speed [83].

4.4.4 Time Frequency Analysis

In a study of recent advances in time-frequency analysis methods for machinery fault diagnosis, Feng and Chu [84] explained time frequency analysis as an important tool in signal processing to study the varying nature of frequency of a signal over a given period of time. The study explained that time frequency analysis can determine the frequency components of a signal at any specified time. The study also referred to time frequency analysis as a useful approach in identifying the time variant characteristics of a signal. This feature is particularly useful where non-stationary signals are under consideration in many technical and scientific projects especially in this study of respiration signal. The study explains different time-frequency analysis techniques suggested for machinery fault diagnosis such as wavelet transform and Short time Fourier transform (STFT) which are discussed below.

4.4.4.1 Short Time Fourier Transform

In a study of Fourier analysis with applications to music, Lenssen and Needell [83] noted that computation of FFT on the whole signal or a small section may not give enough required information. The study suggests the problem could be solved by taking DFT of sequential sections of the signal under consideration. This technique is known as short-time Fourier transform (STFT). This technique is used to identify changes in frequency over time simultaneously [85]. STFT is achieved by taking both the time and frequency into consideration, i.e

$$X_{STFT}(e^{j\theta}, m) \quad = \sum_{n=-\infty}^{n=+\infty} x(n)w(n-m)e^{-jn\theta} \quad , \quad -\pi \leq \theta < \pi$$

(4.7)

Here centre (m) of window function $w(n)$ represents the time. The agreement between time resolution and frequency localization is given by the width of $w(n)$ in STFT. The uncertainty principle describes the widening of $w(n)$ as improving the frequency localization and reducing the time resolution at the same time. The frequency resolution for all the components of the signal remains unchanged as $w(n)$ is constant [85].

4.4.4.2 Wavelet Transform

Mustafa $et\ al$ in their study of medical image de-noising schemes using wavelet transform with fixed form thresholding, explained wavelet transform is similar to a windowed Fourier transform (WFT), but their merit function is completely different [86]. The study explained the main difference lies in their way of analysing a signal, Fourier transform decomposes the signal into sine and cosine i.e. functions are localized in Fourier space. However, the functions used in wavelet transform are localized in both Fourier and real space. Wavelets are combinations of different functions originated from base function(t), known as mother wavelet, by the course of scaling and translating operations [87]:

$$\psi_{a,\tau}(t) = \frac{1}{\sqrt{a}}\psi(\frac{t-\tau}{a}) \qquad a>0 \qquad\qquad (4.8)$$

Here $\psi(t)$ is the scaling parameter and τ is the parameter of translation. Alkali described that τ is large at low frequency components which results in expansion of the width of mother wavelet, on the contrary it reverses at higher frequency components [85]. The study also suggest that this adaptability of wavelet transform in scale adjustments makes it an efficient tool in nonstationary signals such as the respiration signal in this study.

4.5 Image Processing Techniques

In a study of digital image processing in nuclear medicine Cherry and Sorenson [88] described image processing as a combination of various techniques used for enhancing the output information of a picture. The study highlights that with various developments in technology, it is quite easy to enhance contrast, compute intensity, detect edges and apply different mathematical operations such as image acquisition, segmentation and tracking with small investment. Arena et al. [89] in their study of image processing in medical diagnosis analyse that clinical diagnoses is one of the different areas in which image processing techniques are vastly utilized in improving diagnostic approaches and surgical operations. The study suggested that the desired results of the above-mentioned image processing techniques could be achieved by removing unnecessary information like noise or by manipulating the image to extract further information by using signal processing techniques like Fourier transform.4.5.1 Image Acquisition

In a study of image acquisition Mishra [90]described the basic purpose of image acquisition is to convert a visual image (Real World Data) into an array of numerical data that could be modified on a computer. They explained that before proceeding with any form of video or image processing it is necessary to capture an image and transform that into an adjustable entity. Their work described that this process of image acquisition involves three steps:

- An optical system with energy as focal point
- Reflected energy from the subject under consideration (Object of interest)
- A sensor measuring quantity of energy.

The study highlighted the importance for selection of an appropriate camera for image acquisition and it explains that the selection of the camera depends upon the application we need it for. For example, in case of x-ray images, the camera

sensitive to x-rays will be used. Similarly, for capturing infrared images, a camera sensitive to infrared radiation will be used. Figure 14 shows that; image acquisition is the building block in any form of image processing system.
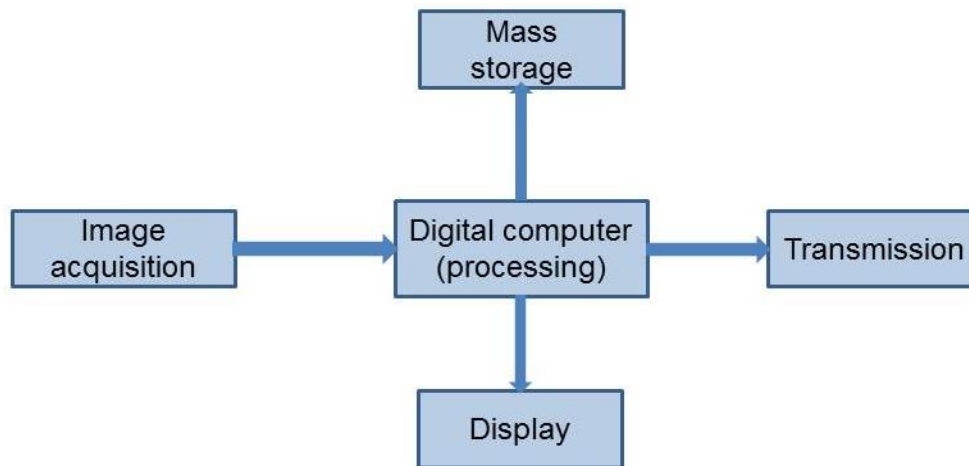
Figure 14 Image processing

4.5.2 Image Enhancement

Petrou and Petrou [82] in their book of image processing; the fundamentals, explained image enhancement as a process by which we intend to reform an image in such a way that it provides more relevant information then it was providing before. It also explains that, in image enhancement we cannot really predict the outcome instead we can judge whether or not it has been improved. They suggested that this can be achieved by analysing the output to assess that whether it shows any further information, or whether any unnecessary brightness has been separated or the contrast is superior. The book refers to different techniques used for these improvements such as low pass, high pass filtering, histogram adjustments or employing algorithms to remove noise without blurring the image.

4.5.3 Image Restoration

Image Processing; the fundamentals by Petrou and Petrou [82]defines image restoration as a process which is used to improve an image for a specific purpose and with advance knowledge that how should the image look like. The book explained that the image restoration is done in cases where the image quality has been degraded because of the alteration of the grey values of individual pixels or due to the distortion created by the movement of individual pixels from their original position.

4.5.4 Image Segmentation and Edge Detection

Petrou and Petrou [82]analysed that there are several techniques which are applied to an image before it is ready as an input to an electronic vison system. They described image segmentation and edge detection are some of the basics from those techniques and their basic aim is of extracting the required information in a fashion that the resulting image possesses far less information than the actual image but that less information is much more pertinent to the different segments of an electronic vision system than abandoned information. The book suggests that these techniques are applied in such a way that they select the contours of distinct regions of the image to split the image into parts involving pixels having something familiar. For example, the image may possess close brightness or colour specifying that they are from the same entity or surface of the entity. Figure 15 shows an example.

Figure 15 An original image, its segmentation and its edge map [82].

4.6 Detection and Tracking

Balaji and Karthikeyan [91]describes computer vision as an extensive area and object tracking performs an essential role in this area. They did a survey on tracking moving objects using image processing and noted that with recent developments in this area, object tracking has come to the forefront because of the easy access to really sophisticated electronic equipment like computers and high-quality cameras in affordable range. In another survey on tracking of moving objects, Ojha and Sakhare [92] describes the operation of tracking involves identifying a moving object

with the help of a video camera. In other words, they explained tracking is an association of target objects in successive video frames. They described the overall tracking process involves three basic operations, which are moving object detection, its classification and tracking of the detected and classified object in subsequent frames. These operations are elaborated here:

4.6.1 Object Detection

In a process of investigating a video the first step is detection of the moving object. Balaji and Karthikeyan [91] noted that, this could be done at the start of the video when the object first comes into the picture or can be done in each and every frame of the video. According to their study this operation also involves the removal of the stationary objects in the background of the moving object of interest. They explained that this could be achieved by frame difference method, background subtraction method and object flow method.

4.6.2 Object Classification

The study also described that the process of classifying the objects is achieved on the basis of the shape characteristics of the moving region [91]. They demonstrated that there are different techniques of classifying objects such as texture-based classification in which inclination of the moving object is assessed in an image. It was then evaluated by the help of overlapping local contrast normalization over a thick grid of evenly separated cells in order to improve accuracy. They suggested other techniques which could be used in object classification are motion based, shape based and colour-based classifications.

4.6.3 Object Tracking

The survey proposed that once the object is detected and classified then the operation of its tracking to monitor a moving object in a video sequence can commence [91]. They explained it as a framework used to track the detected object in successive frames to monitor the traveling direction of the moving objects. The survey highlighted the commonly used form of tracking is point tracking as objects are shown by their feature points while in motion. The survey observed that this approach can result in wrong detection and incidence of occlusions due to the reason of false detection of points especially in case of longer displacements. They suggested that this problem could be solved by making the recognition process

straightforward with the help of thresholding while identifying the points. Their findings showed that other than the point based tracking approach, the field of object tracking has various other methods as well, such as kernel tracking and silhouette tracking including several sub branches.

4.7 Summary

This chapter explains the working nature of thermal imaging with respect to human body as this study is based on thermal recordings of the subjects. It further describes different signal and image processing techniques that can be utilized to achieve the desired results from the kind of data recorded in this study. Several signal processing techniques were used in this study such as, Fourier Transform, Short Time Fourier Transform and Wavelet Transform for signal analysis. The different image processing techniques used in this study are image acquisition, image enhancement, image segmentation and edge detection. At last the chapter briefly explains different approaches for object detection and tracking. In this study KLT algorithm and template matching were used for detecting and tracking of the head movements of the subjects.

Chapter 5
Methodology

5.1 Introduction

This study was to develop thermal imaging-based respiration monitoring to assist with detection and diagnosing apnoea. The study involves human participants so it was necessary to undergo strict rules and regulations before commencing the study. This study was registered at Sheffield Hallam University and was done in collaboration with Sheffield Children's Hospital (SCH) NHS Foundation Trust. The study required research approval from both bodies before getting started. University's research clearance was subjected to their Ethics and Risk Assessment regulations, while SCH had their own set of ethics, health assessments and criminal record checks for research clearance. The work has both Sheffield Hallam University and NHS ethics approval.

5.2 Ethics

Sheffield Hallam University's Research Ethics Policy states that:

"Any research undertaken by staff or students (undergraduate or post graduate) of the University which involves direct contact with human participants, whether clinical, biomedical or social research, or the secondary use of human and animal materials or specimens, or where there may be any other ethical issues, should be subject to ethical review." [93]

In compliance with university's Research Ethics Policy, Ethics approval was obtained from SHU's Research Ethics Committee given in (appendix J). In addition to this, as mentioned earlier the study is in collaboration with Sheffield Children's Hospital and involves recording paediatric patients so NHS ethics approval was also obtained to carry out the research on hospital patients. The recorded data both at university with volunteers and at hospital involving actual patients were secured in university's password protected drive and was only available to the authors of this study. All of the patient data was coded and the identities of the paediatric patients remained confidential to the hospital staff only.

As per the guidelines of the University and NHS ethics policy, consent forms were prepared for subjects willing to participate in the study (Appendix G). In addition to

the consent forms, information sheets were also prepared for volunteers, explaining the basic purpose of the study, why they were asked to take part in the study, how they are going to be monitored, What if they did want to take part, how their identities were kept anonymous and what happened to the data once they were recorded.

Information sheets prepared for adults were more detailed to answer all the possible questions they might ask conversely simpler, age appropriate versions of the information sheets were designed for children and young people along with assent forms for the under 16 year age group. Both patient assent forms and parental consent forms were completed for the hospital participants. Subjects were free to ask questions and to make them comfortable before giving consent to take part in the study. Subjects were also free to leave the study at any time if they felt like doing so.

Information sheets for the age groups of 0-5, 6-10, 11-15 years and also for parents or legal guardians and adult participants are provided in the appendices A-D. An anonymous data collection form, assent form and consent forms are also attached as appendices E-G. Sleep unit staff evaluation form and parent/carer/child evaluation form, for PSG and thermal imaging are given as appendices H and I respectively. A copy of each signed form was kept by researcher and a copy was provided to the participant in case of adult participants recorded at university. Copies of signed forms were retained by hospital in the research site file and a copy was provided to the parent or carer of the child participant recorded at hospital.

5.3 Selection of Participants

This study was carried out in two stages. The first stage involved the recordings of healthy participants at Sheffield Hallam University, with and without gold standard sensors attached. Subjects were asked to breathe with different types of breathing patterns to mimic different types of apnoea to test the developed algorithms and make any changes if necessary. The second stage was based on using the recorded thermal videos of paediatric patients during overnight PSG at Sheffield Children Hospital. Three children were included in this part of the study.

5.3.1 Adult participants

In the first stage of the study 11 healthy individuals were recruited from SHU's staff and students. Out of these 11 participants, 8 were males and 3 were females. Their age ranged from 24 to 62 years, with an average age of 36 years and 4 months. These recordings were done to test the results of the framework against the gold standard values of nasal airflow sensor, thorax and abdominal (respiratory effort) bands. The results and findings of these tests were used to improve the effectiveness and accuracy of the developed framework in the monitoring of respiration airflow and diagnosing the pauses in breathing mimicked by the participants of the study.

In the recordings performed at the university including healthy adult participants, every participant was recorded in two Quiet Breathing scenarios named Quiet Breathing 1 (QB1), Quiet Breathing 2 (QB2) and also two irregular breathing scenarios named as Irregular Breathing 1 (IB1) and Irregular Breathing 2 (IB2). The scenarios QB1 and IB1 included thorax and abdominal respiratory induction bands attached to the body of the participant as the gold standard sensors and acted as reference signals for comparison with the respiration signal extracted by this method using thermal recordings. The scenarios QB2 and IB2 included the nasal airflow sensor as well in addition to the thorax and abdominal inductance bands. The device used for this purpose was SOMNOtouch^{TM} RESP that is a portable cardiorespiratory polysomnography recording device which records respiration for nasal air flow and respiratory effort (thorax and abdomen) bands. The signal sample rate for the device was 32 samples per second for respiratory effort bands and 256 samples per second for nasal airflow. Figure 16 shows the SOMNOtouch^{TM} RESP device used in the research for recording the respiration signals from the sensors attached to the body of the patient. This method was compared to the thermal imaging method.

The sum of the thoracic and abdominal respiratory inductance plethysmography bands was also used as a reference for comparison with the results of this method. Table 2 shows the four scenarios with respective sensors attached in recording with adult participants.

Figure 16 Showing SOMNOtouchTM RESP® with flow, thorax and abdomen signals.

Each of the above mentioned scenarios included 5 minutes of thermal video recording with the respective sensors attached to the participant. In case of QB1 and QB2 the participants sat on a chair, breathing normally for five minutes. In case of IB1 and IB2 the subjects sat on the chair and were asked to breathe in three different breathing patterns and paused in breathing for about 10 seconds to mimic different types of apnoea such as central apnoea, obstructive apnoea and hypopnoea. So altogether 44 videos (22 Quiet Breathings and 22 Irregular Breathings) of five minutes duration, with sensors attached according to the breathing scenario and participants mimicking the types of apnoea were recorded.

Table 2 Four scenarios with respective sensors attached in recordings with adult participants

QB1	• Thorax band attached • Abdomen band attached
QB2	• Flow sensor attached • Abdomen band attached • Thorax band attached
IB1	• Thorax band attached • Abdomen band attached
IB2	• Flow sensor attached • Thorax band attached • Abdomen band attached

5.3.2 Paediatric Patients

The data from three children patients were used in part two of this study. These patients had been recruited from Sheffield Children's Hospital (SCH) Sleep Unit undergoing overnight PSG monitoring for SDB. All cases had confirmed apnoea by medical staff.

5.4 Data Collection

The data recorded at the university including healthy participants was secured in a password protected drive at the university and was only accessible to the authors of the study. While in the case of participating children, they were given a unique number to compare their results against their hospitable information. The thermal imaging information recorded at the hospital were provided to the authors of the study and was kept in a password protected secured drive which was again only accessible to the authors of this study. The airflow channels from the PSG data were anonymously extracted by the hospital staff and were shared with the researchers at the University for allow comparison between methods.

5.5 Thermal Camera

Two cameras were used in this study, first in the university with adult volunteers and second in the hospital for paediatric patients. FLIR A655sc with its operating software (ResearchIR) was used for the recordings done in the University with adult volunteers. This camera was able to capture thermal images at a maximum rate of 50 frames per second at a full frame 640×480 resolution. ResearchIR software saved the images that can be used at a later time when required. Table 3 shows FLIR A655sc specifications.

Table 3 FLIR A655sc Camera Specification

Parameter	Specification
Spectral Range	7.5-14.0 μm
Image Resolution	640×480
NETD	<30mK
Maximum Frame Rate	50 frames per second
Standard Temperature Range	-40℃ to 150℃ 100℃ to 650℃
Operating Temperature Range	-15℃ to +50℃
Accuracy	$\pm$2℃ or $\pm$2% of reading
Focus	Automatic or Manual
Digital Data	Via PC Using ResearchIR Software
Power	12/24 VDC, 24W Absolute Max

FLIR T650sc was used for the recording of paediatric patients undergoing PSG at SCH. FLIR T650sc can capture the data directly into Matlab software for advanced image analysis and enhancement. It has an increased accuracy range of 1% of reading. Table 4 shows FLIR T650sc specifications.

Table 4 FLIR T650sc Camera Specification

Parameter	Specification
Spectral Range	7.5-13.0 μm
Image Resolution	640×480
NETD	<20mK
Maximum Frame Rate	30 frames per second
Standard Temperature Range	-40℃ to 2000℃
Operating Temperature Range	-15℃ to 50℃
Accuracy	$\pm$1℃ or $\pm$1% of reading
Focus	Continuous Automatic or Manual
Digital Data	Via PC Using ResearchIR Software
Power AC Adapter	AC Adapter 90-260 VAC Max

5.6 Camera Setup

The Camera FLIR A655sc was mounted on a tripod stand, at about 1m distance from the subject sitting comfortably on a chair in case of recordings at the university with adult volunteers. The camera was placed at such an angle that its field of view (FOV) should capture the images from shoulder to head only. The FOV was set in this way to ensure the presence of the ROI most affected by respiration. The emissivity of the camera was kept at 0.98 according to the standard requirement of skin temperature measurement. Figure 17 shows a typical camera setup in recordings with adults where thermal recordings are done simultaneously along with nasal airflow and thorax and abdomen bands attached and connected to SOMNOtouch device. These recordings were done along with contact sensors to compare the findings of thermal imaging with these standard sensors. Each volunteer was recorded 4 times with different scenarios of 5 minutes each as explained in chapter 6. The frame rate was 50 frames per second. These recordings were done at room temperature.

Figure 17 Thermal camera setup along with ground truth sensors.

In case of recordings at the hospital the camera was mounted on a similar tripod at distance of about 1 m on one side of the bed on which the child undergoing PSG was sleeping. These recordings were performed using FLIR T650sc at a frame rate of 10 frames per second. In these recordings individual images were saved throughout the recording, otherwise the file size would have been too excessive.

5.7 Summary

The regulatory codes of conducts for Ethics were followed both at University and hospital for recording all the recruited subjects. Subject's recruitment details and the recording procedures with both adults and children were discussed in this chapter. For 11 adult participants recorded at the university, a total of 44 videos of 5 minutes each were recorded. Each video was comprised of around 7 to 8 MB of data. So altogether a total of around 350MB of data was recorded at university with adult participants. While 3 paediatric patients were recruited from SCH, undergoing overnight PSG monitoring. Each overnight recording was comprised of approximately 1GB of data.

Chapter 6
Results and Discussions of Testing the Method on Adults

6.1 Introduction

The results of this study for adult volunteers are presented in this chapter. They are comprised of the results for different breathing scenarios with different sensors attached. This chapter will discuss different techniques and approaches used in processing the recorded thermal videos to extract respiratory signal and then compare the findings with the results of the existing contact sensors such as nasal airflow sensor and respiratory inductance plethysmography bands (thorax and abdomen). A comparison of the algorithm for cases where nasal prongs were attached or missing are performed to demonstrate the efficacy of thermal imaging in different scenarios.

Initially some common terms used in chapter are explained.

- **Images:** Gonzalez and Woods [94] described a digital image as a two dimensional signal similar to a matrix which has rows and columns. They explained it mathematically as a function $f(x, y)$ whereby x and y here represents the two co-ordinates horizontally rows and vertically columns and the pixel or intensity value at any point of an image is given by the value of function $f(x, y)$ at that point.

- **Temperature image:** Gonzalez and Woods [94] explained that image processing can be of coloured or grey scale image. They described temperature images are the ones in which the function $f(x, y)$ indicates the temperature value of the image at that point (x, y).

- **Video:** Digital image processing by Gonzalez and Woods [94]describes a video as a collection of individual images appearing one after the other in a short interval in such a way that it forms a continuous sequence of images representing a continuous video instead of individual still images.

6.2 Tracking Operation

Initially, a video was acquired by recording an adult volunteer for five minutes with the aim of processing it to extract the temperature related information from the respiration region of the face, i.e. the nostrils region i.e. the respiratory region of interest (ROI). Figure 18 shows thermal images of subject from this study and the changing behaviour of the nostrils due to inhalation and exhalation could be seen. The next step was the selection of the co-ordinates of the ROI in the first frame of the video. This was required for continuous tracking of the ROI throughout subsequent frames of the entire video. This was achieved by employing KLT feature points tracking algorithm. After tracking the ROI in each frame the ROI was cropped from the individual images for resizing the image to standard dimension. Suitable thresholds were applied to convert the grayscale image to a binary image for differentiating foreground from the background. This was performed to get the foreground which in this case are the black pixels representing the inhalation phase of respiration. These black pixels were counted and smoothening of the back pixels count was achieved by applying Daubechies filter of suitable order to get the respiration signal. This whole procedure of the algorithm will be explained step by step in this chapter.

Figure 18 Images showing the changing behaviour of nostril region due to inhalation and exhalation.

6.3 Co-ordinate selection for ROI

 In order to track any object, the location of the region of interest location of the ROI needs to be specified. In this study the ROI was the nostril region. A rectangular ROI with coordinates $[x_1, y_1, width, height]$ which was selected from the area around the top of the eyebrows on the forehead to the area under the nose and above the upper lip was selected. This rectangular region was selected by taking the spatial co-

ordinates (x_1, y_1) representing top left corner of the rectangle on the image where x for columns and y for rows. For the width and height of the rectangle two more points were selected, one on the top right corner and the other on the bottom right corner of the rectangle with pixel co-ordinates of (x_2, y_2) and (x_3, y_3) representing columns and rows of the selected points respectively. The width and height of the rectangle were then calculated as:

$$width = x_2 - x_1, \tag{6.1}$$

$$height = y_3 - y_2, \tag{6.2}$$

Figure 19 shows the images of a subject with and without nasal airflow sensor attached from this study with selected rectangular region for tracking the ROI.

Figure 19 Images of a subject from this study with selected rectangular region for tracking the ROI.

6.4 Tracking

A number of tracking algorithms were reported that were primarily for visual images but could also be applied to thermal imaging. Infrared thermography is a continuously evolving process due to its nature of changes in temperature and it is this behaviour that results in a modelling problem to tracking [72]. Coalitional tracking based on partial filter trackers has been used by Murthy *et al* in a novel method for monitoring airflow during polysomnography, to handle the dynamics of facial temperature changes [71]. In addition to this there are other tracking algorithms for object tracking, based on different approaches such as sparse representation [95] , and KLT [96] and histogram based CAMShift algorithm [97].

6.4.1 Histogram Based Tracking (CAMShift Algorithm)

In this study a method used for tracking was histogram-based CAMShift (continuously adaptive mean-shift algorithm) tracking. Gonzalez and Woods described a histogram of an image as a graphical representation of the total number of pixels in an image at every distinct intensity value found in that image [94]. They explained that in the case of a grayscale image of 8-bit unsigned data type, there are 256 distinct possible grayscale intensity levels, and the histogram of an image will graphically represents 256 grayscale values in one axis and the other axis will speaks for the distribution of pixels in the corresponding grayscale values.

CAMShift is generally being used in the field of security surveillance, artificial intelligence, medical diagnosis and military applications [98]. In this work CAMShift algorithm used the histogram of the pixel values to identify the tracked object from the image sequence. The problems observed for tracking the nose region are listed below:

i.   The tracking algorithm was not good enough to track the nose region in subsequent frames of the images.
ii.   The location of the ROI changed as the tracking progresses.
iii. In some videos the tracked area of the ROI was expanded as the tracking process progressed.

The above issues occurred due to the continuous changing behaviour of the histogram of the nose region in the exhalation and inhalation phases. When the subject inhales the black pixels were highly present whereas, during exhalation phase the black pixels were absent. So due to the changing behaviour of ROI due to the effect of respiration, the performance of the histogram based tracker was not good enough to track the ROI effectively.

6.4.2 Kanade-Lucas-Tomasi (KLT) Tracking Algorithm

The KLT feature tracker has been applied in this study to track the head movements and the ROI which is the nostril region in the current study as it is most affected by the respiration through nose. KLT has been applied in a number of studies because of its efficiency with respect to the feature points being tracked and good performance against other tracking methods [99]. Fassold *etal* used KLT in real time feature tracking of high definition videos and described that KLT feature tracker is an

approach to feature extraction and tracking. They further explained that the exact locations of feature points are pre-defined and play an important role for the algorithm's operation. Their study referred KLT as a tracking algorithm that works on the principle of feature points tracking and these feature points are points that are dissimilar to their neighbours such as L-corner, T-junction or a white dot on a black background etc. KLT algorithm looks for unique feature points in a frame and then tracks for these feature points in subsequent frames in an image sequence [100].

Barnes *etal* [96] described the process of feature tracking in KLT as having three integral components which are explained here:

Feature Detector: The first component in feature tracking is feature detector. The function of feature detector is to identify salient points in each frame that have the highest possibility of being selected in subsequent frames. They described its output to be in the form of array of points, and each point is represented by its pixels co-ordinate [96].

Feature tracker: They refer to the second component as feature tracker and its task is to take the array of points (output of feature detector) and try to identify the exact location of each feature point in the image sequence. It was reported that some of the feature points may get lost in the progression of image sequence which could be due to the feature point shifting out of the camera's field of view or its transformed in such a fashion that the tracker can no longer identify any similarity with the last frame [96].

Feature Manager: The study termed the last component of the process as feature manager and its basic function is to ensure the set of feature points being tracked stays above a given threshold. It was explained that in case the tracked feature points are lost (e.g. moving out of camera's field of view) in the subsequent frames, the feature manager employs the detector to identify new feature points to replace the lost feature points. It was also explained in the study that the feature manager also ensures that there is an even distribution of feature points across the image to enhance the uniqueness of tracked features [96].

In this study KLT makes use of spatial intensity information to direct the search for the position that yields the best match in subsequent frames of a video. It is faster

than the traditional practices for observing less potentially correct matches between two images. Figure 20 shows the flow chart explaining the functionality of KLT tracking algorithm in this study.
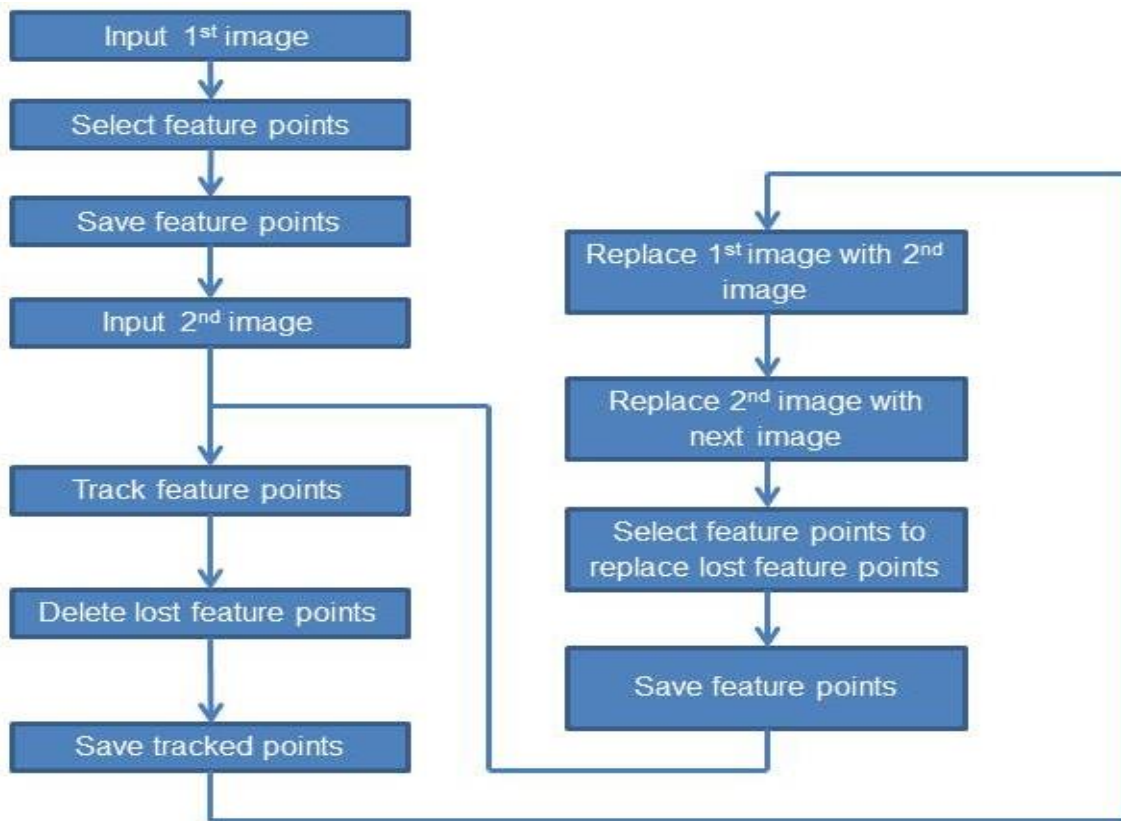
Figure 20 Flow chart explaining functionality of KLT algorithm

6.5 Cropping and Resizing the Nose Region

After tracking the nose region then the next step was to crop and resize the tracked region. The tracker continuously tracks the nose region with the specified rectangular co-ordinates (*x, y, w, h*) and returns the enclosed bounding box of the nose region. This tracked nose region was then cropped from each image in the sequence. The size of the black pixels in the nostrils continuously changed due to inhalation and exhalation. So the cropped image was resized to 120×120 pixel that proved effective.

6.6 Grayscale to Binary Conversion through Suitable Thresholding

In order to differentiate foreground (black pixels) from the background, we needed to convert the resized nose image from grayscale to binary image. Gonzalez and Wood described a binary image in their book on digital signal processing. They explained that a binary image consists of only two possible values for each pixel [94] and the two colours present in the binary image are black and white. They explained the colour used for the object in the image is the foreground while the rest of the image is the background colour. In our case the nostril region in inhalation phase with black pixels is our foreground and the white region in exhalation phase is the unwanted background region. Binary images are also called bi-level or two-level, so each pixel in the binary image can have only a single bit either '0' or '1'.

We converted the grayscale image to a binary image by applying suitable thresholds. The grayscale intensity values for black pixels in each frame above the threshold values were considered 1 and the grayscale intensity values for black pixels in the same frame below the threshold values were considered 0.

$$F(x, y) > threshold = 1 \qquad (6.3)$$

$$F(x, y) < threshold = 0 \qquad (6.4)$$

The appropriate threshold selection was imperative to get the black pixels in each frame as in the cases where an inappropriate threshold value was selected; it resulted in over segmentation or down segmentation in terms of the black pixel count for each frame and affected the respiration signal. So through experimentations, most appropriate threshold values were selected and they depended on different parameters such as the breathing behaviour of the subjects as the number of black pixels in a subject breathing heavily and a subject breathing normally varied due to temperature changes in the nostril region.

6.7 Counting the Black Pixel Region for the Respiration Signal

After the conversion of grayscale image to a binary, it displayed the respiration in black and white pixels representing inhalation and exhalation phases. When the

subject inhaled, the temperature of the nose decreased (an increase in the number of black pixels). Black region could be seen highly at that point but when the subject was exhaling the black pixels disappeared and the nostrils turned into a brighter region. By counting the total black pixels with a suitable threshold applied in each frame over an image sequence the black pixel count signal was obtained. This represented the respiratory signal.

The presence of the nasal airflow pressure sensor along with the nose temperature of the subject affected the threshold value. The nose skin temperature was affected in such a way that in some cases the detected nose of the subject remained cold throughout the recording irrespective of the fact that whether the subject was inhaling or exhaling so the nose pixels remained black. In some other cases the nose of the person remained warm throughout the recording and the black pixels were observed only from the nostrils. Figure 21 shows the images of such a scenario, where the first image shows a cold nose making the threshold value to be less for differentiating the nose black pixels from the black pixels of the nostrils on the basis of grey scale intensity On the other hand the second image in Figure 21 shows the nose of the subject brighter throughout the video irrespective of inhaling or exhaling and showing the black pixels just at the nostril. In this case a higher threshold value was required in picking up black pixels of the nostrils as in this case there were reduced number of black pixels present so higher value of threshold meant the black pixels with even smaller grey value intensity would be picked to obtain as much respiratory information as possible. So an appropriate threshold was necessary to differentiate the nose black pixels from the black pixels of the nostrils depending on the intensity values so that only the black pixels of the nostril reflecting inhalation phase gets selected.
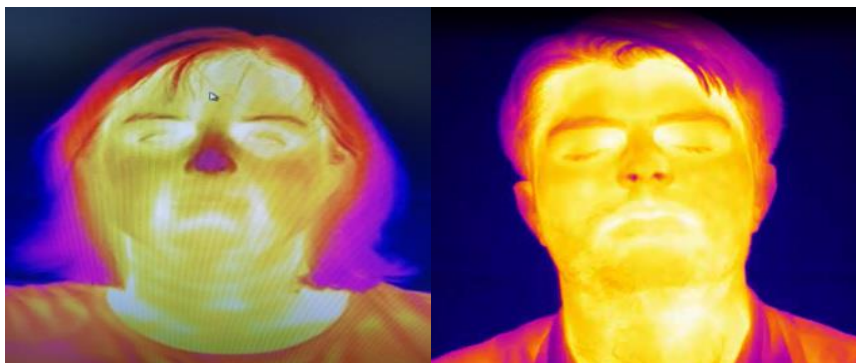
Figure 21 Images of subjects showing different nose temperature.

The cases in which the nasal airflow pressure sensor was attached, the sensor also affected the threshold value making its value to increase due to the additional black pixels present. So it was necessary in such cases to differentiate the black pixels of the nostrils from the additional black pixels of either nose skin or nasal airflow pressure sensor. Figure 22 shows such a case with and without nasal airflow pressure sensor attached and their binary images showing the extracted black pixels. A significant increase in the black region could be seen in the second image where the nasal airflow pressure sensor is attached. The black pixel count signal was filtered to obtain the respiration signal.
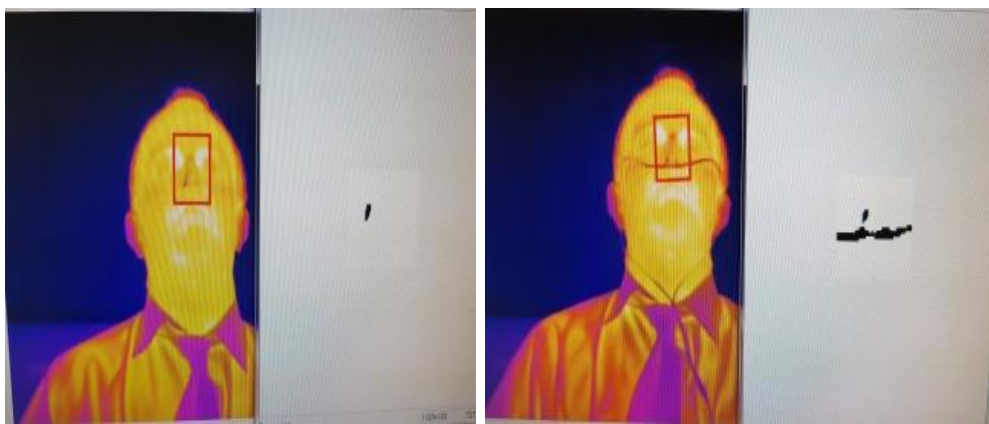
Figure 22 Binary images of a subject showing a significant increase in the number of black pixels in the 2nd image when airflow sensor was attached

6.8 Results and Discussions

In this section the results obtained by using the above explained approach are discussed in detail. Here the results of the adult volunteers recorded at the University are in discussion. As explained earlier in section 5.2.1 the adult subjects were recorded in four different scenarios of QB1, QB2, IB1, and IB2. So here one case of each scenario are discussed and the results obtained through the designed approach using thermal imaging will be compared with the results of nasal airflow pressure sensor for QB2 and IB2 as it was in place in these two scenarios while in case of QB1 and IB1 as there was no airflow pressure sensor attached to the subject, the sum of respiratory effort (thorax and abdomen) was used for comparison of the results. In case of irregular breathing IB1 and IB2, the designed approach was judged on the basis of its performance in detecting the breathing pauses performed

by subjects to mimic different forms of apnoea such as obstructive apnoea, central apnoea and hypopnoea.

The first scenario is of Quiet Breathing QB1 and therefore and no airflow sensor was attached so sum of respiratory effort channels (the sum of thoracic and abdominal bands) was used for comparison. Immediately after recording of the thermal camera and recording from the SOMNOtouch device were commenced, the subjects were asked to hold their breath for about 10 seconds to allow the timings for the SOMNOtouch™ RESP device and the thermal imaging to be synchronised. The pause in breathing can be seen in the respiration signal shown in Figure 23 (bottom) similar to the pause in the sum of respiratory effort shown in Figure 23 (top). More over the number of respiration cycles are very much similar in both the signals and a particular incident in the middle of the signal where the subject's breathing goes down considerably as shown in sum signal is also detected by thermal imaging indicating the sensitivity of thermal imaging in this case.

Figure 23 Respiratory signal from sum of Respiratory bands and respiratory signal from thermal imaging

The second scenario to be discussed is of Quiet Breathing QB2 from the same subject. The airflow nasal pressure sensor is attached in QB2 scenarios so this will be used for comparing respiration signal of thermal imaging against the gold standard used in normal practice of PSG. Figure 24 shows the starting pause in

breathing for the subject in the reference signal from the airflow nasal pressure sensor and the pause in the respiration signal shown at the bottom part of Figure 24 obtained by thermal imaging are similar. Moreover after the pause, the flow signal shows an increase in the respiration activity of the subject at the start of the signal and then it shows a varying behaviour until at the end where it again show an increase in the respiration activity. The respiration signal obtained through this method using thermal imaging shows a similar pattern.
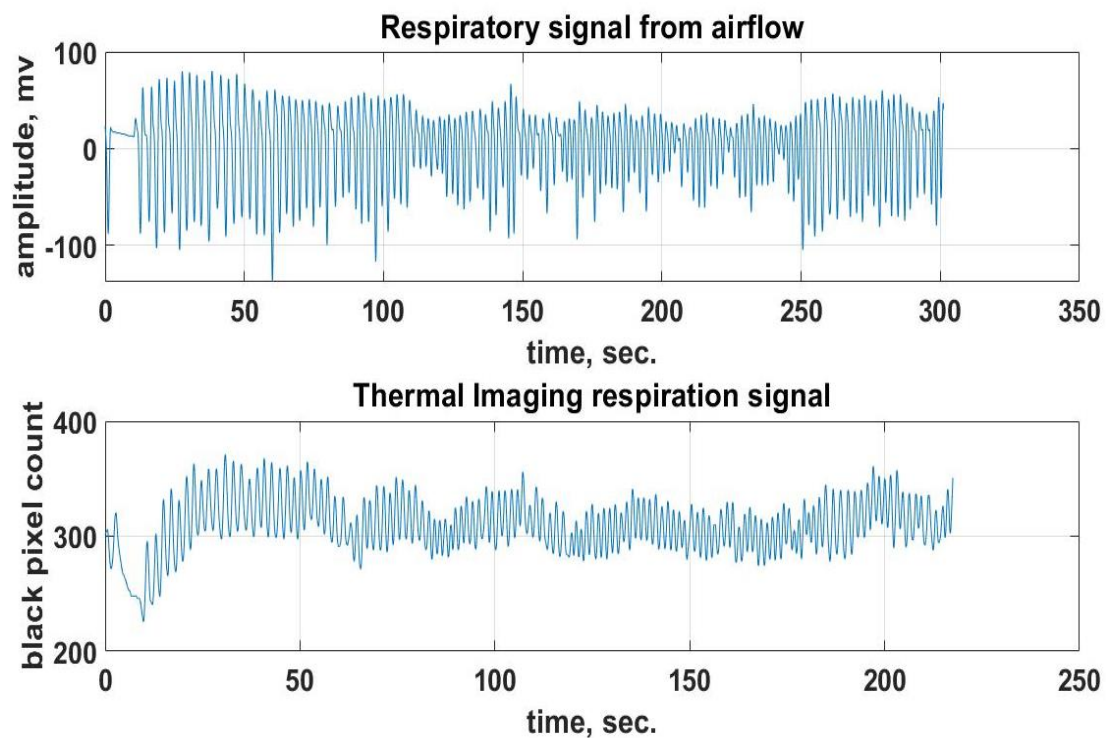
Figure 24 Respiratory signal from airflow and respiratory signal from thermal imaging.

The third scenario to be discussed is of irregular breathing IB1 of a subject and again as airflow nasal pressure sensor is not attached in this scenario so the sum of respiratory effort bands was used as a reference signal for comparison. Figure 25 shows the sum of the respiratory effort band signals and a respiration signal obtained using thermal imaging. The starting pause of the respiration and then the first three pauses in the respiratory signal obtained from the bands are shown. These pauses are mimicking central apnoeas as there is cessation in respiratory effort in the respiratory effort bands during these apnoeas and similar pauses are present in the respiratory signal from thermal imaging as there is a cessation of breathing at the nostrils. The next 3 pauses are mimicking obstructive apnoeas and the final three

pauses are mimicking hypopnoeas and match the pauses seen in the reference signal.
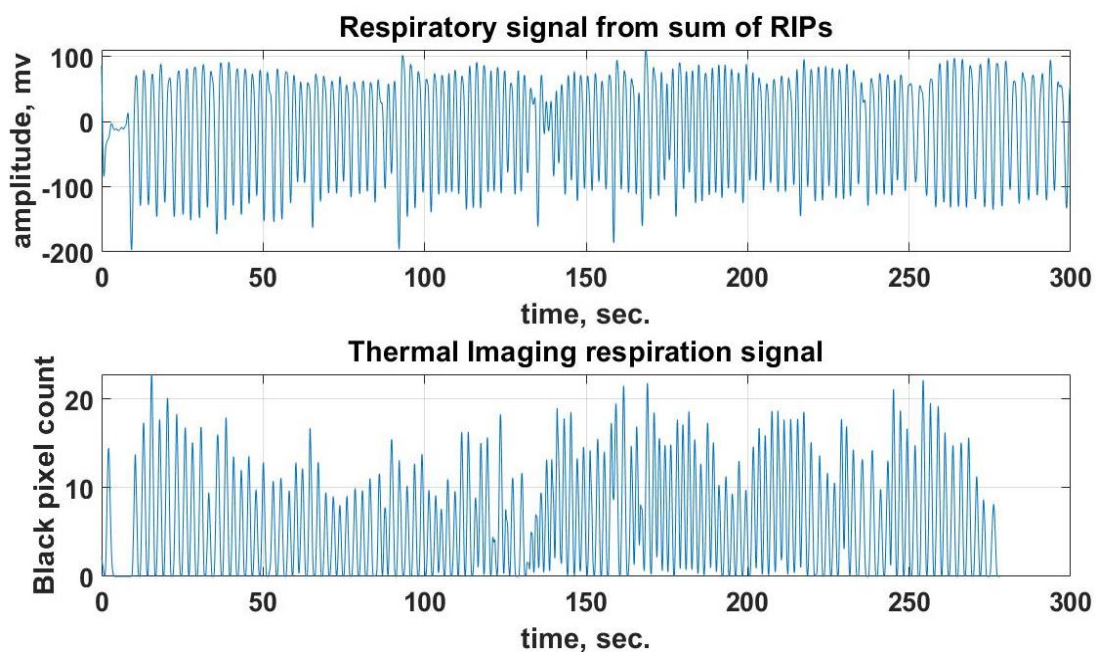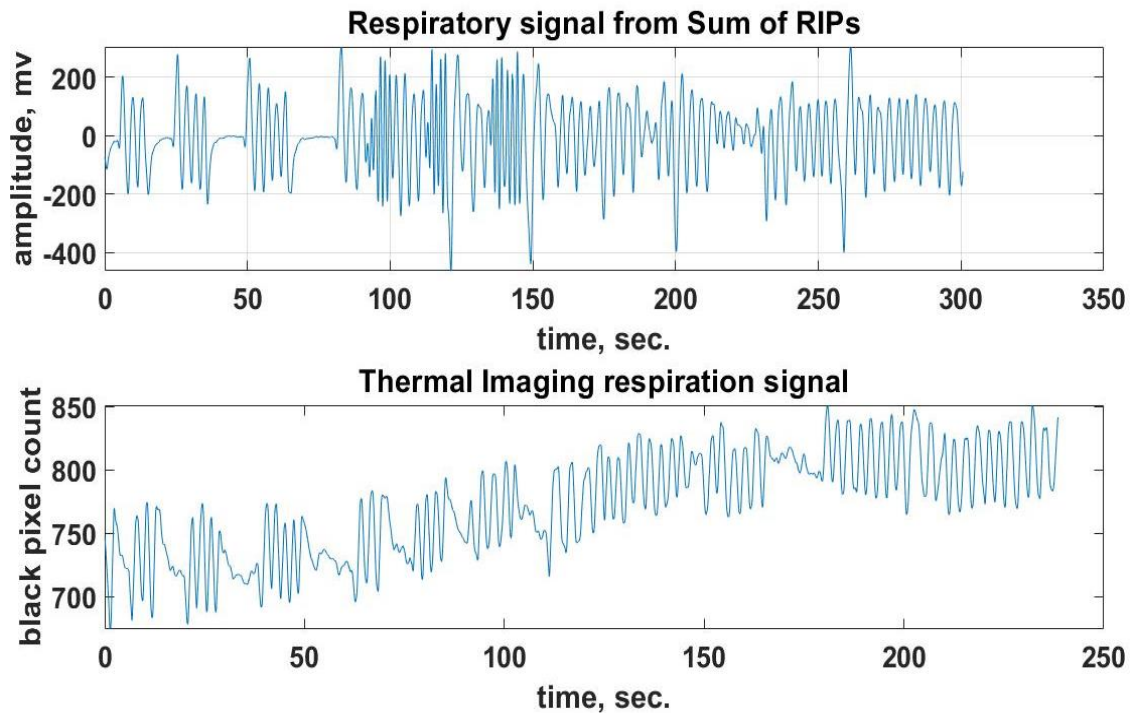

Figure 25 Respiratory signal of sum of Respiratory bands and respiratory signal from thermal imaging.

The fourth and the last scenario to be discussed is the most important scenario as the nasal airflow pressure signal is present in this scenario for comparison and also the scenario is of irregular breathing so we have the opportunity for comparing the result of this method in terms of apnoea detection and comparing it against the gold standard methods of apnoea detection in terms of the nasal airflow pressure sensor and the sum of the respiratory band channels. Figure 26 shows the starting pause in the respiration signal from the airflow nasal pressure sensor and a similar pause is also present in the respiration signal obtained from the thermal imaging method. Then there are three pauses representing central apnoea, then three pauses representing obstructive apnoeas and finally three pauses representing hypopnoeas and the thermal imaging method successfully detected all the apnoea types mimicked by the subject.
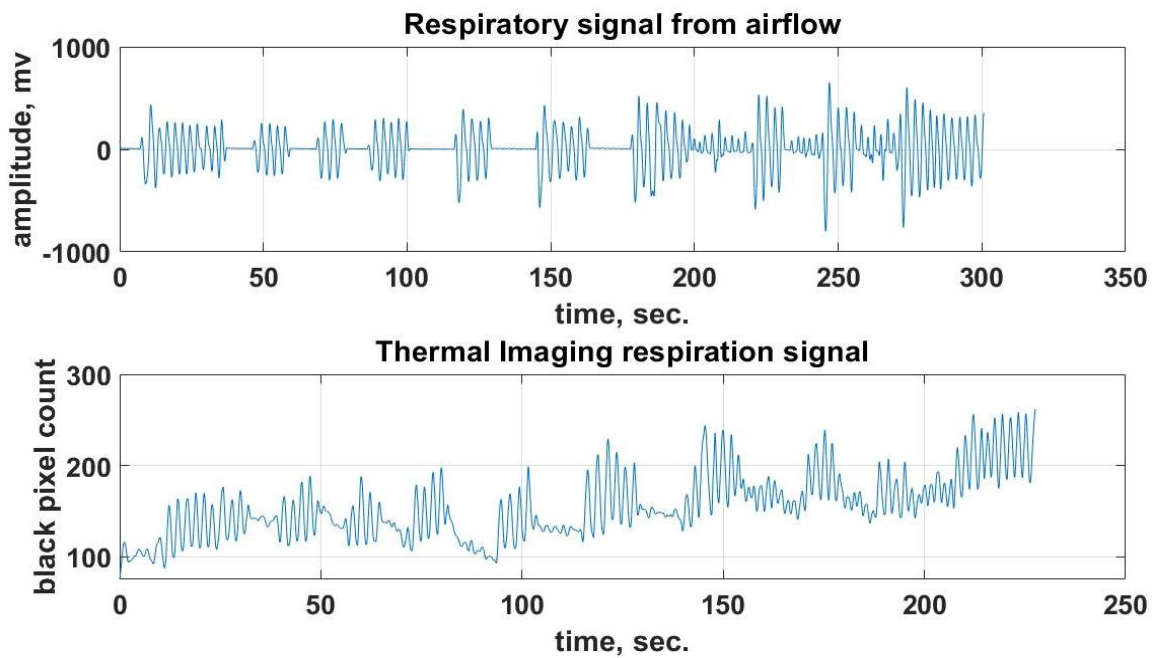
Figure 26 Respiratory signal from airflow and respiratory signal from thermal imaging.

Table 5 shows the results for QB1 and IB1. These two scenarios were combined because both scenarios did not have the airflow sensor attached during recording and sum of respiratory effort (thorax and abdomen) bands was used as a reference signal for comparison. Such cases where the airflow nasal pressure sensor was not attached, obstructive apnoeas and hypopnoeas could not be distinguished because the respiratory effort in both cases was very similar so the thorax and abdomen bands were not reliable in such cases. Therefore they were combined in one column but considered two separate events and were counted as such. The respiration signal obtained by using the developed algorithm is categorized as matched, partially matched and ROI not available (N/A). ROI (N/A) means the subject's face was in such a posture that his/her nostril region was not visible to the camera's field of view.

The cases in which the respiration signals obtained were partially matched with the reference signal were due to two different reasons. The first reason is the same as in case of ROI (N/A). Other problems were, the nose skin temperature was too cold resulting in extra black pixel count as even with variation in threshold the problem was not avoided. As there were 11 subjects, the total events in this table are 44, 11 for QB1 as it was a Quiet Breathing signal so considered as 1 event per subject and in case of IB1 there were a total of 33 events: 11 central, 22 for obstructive and hypopnoea.

Table 5 indicates that out of total 44 events from QB1 and IB1, 20 events were matched, 9 partially matched and in 15 cases ROI was (N/A).

Table 5 Thermal imaging results for QB1 and IB1.

	QB1	IB1		Respiration Event Detection		
		Central	Obstructive and Hypopnoea	Matched	Partially Matched	ROI N/A
Subject 1	Yes	Yes	Yes	4	0	0
Subject 2	ROI N/A	ROI N/A	ROI N/A	0	0	4
Subject 3	Partially	Yes	Yes	3	1	0
Subject 4	Partially	Partially	Partially	0	4	0
Subject 5	Partially	Yes	Partially	1	3	0
Subject 6	ROI N/A	ROI N/A	ROI N/A	0	0	4
Subject 7	Yes	Yes	Yes	4	0	0
Subject 8	ROI N/A	ROI N/A	ROI N/A	0	0	4
Subject 9	Partially	ROI N/A	ROI N/A	0	1	3
Subject 10	Yes	Yes	Yes	4	0	0
Subject 11	Yes	Yes	Yes	4	0	0
Total events	44			20	9	15

Table 6 shows the results of QB2 and IB2 and these scenarios have been combined because in both scenarios the airflow nasal pressure sensor was in place during recording the adult participants. In this table obstructive and hypopneas are placed in separate columns because the airflow sensor was present for distinguishing them from each other. The respiration signal obtained by this developed method using thermal imaging was categorized as matched and not matched only as the problem of ROI (N/A) did not arose in these scenarios due to the presence of the airflow nasal pressure sensor in the recording and providing us the respiration related information of interest. This table also had 44 events in total, as there were 11 subjects and so 11 for QB2 and 11 each for central apnoea, obstructive apnoea and hypopnoea scenarios.

Table 6 shows out of total 44 events for QB2 and IB2, 43 were matched and 1 did not matched.

Table 6 Thermal imaging results for QB2 and IB2.

Subjects	QB2	IB2			Respiration Signal	
		Central	Obstructive	Hypopnoea	Matched	Not Matched
Subject 1	Yes	Yes	Yes	NO	3	1
Subject 2	Yes	Yes	Yes	Yes	4	0
Subject 3	Yes	Yes	Yes	Yes	4	0
Subject 4	Yes	Yes	Yes	Yes	4	0
Subject 5	Yes	Yes	Yes	Yes	4	0
Subject 6	Yes	Yes	Yes	Yes	4	0
Subject 7	Yes	Yes	Yes	Yes	4	0
Subject 8	Yes	Yes	Yes	Yes	4	0
Subject 9	Yes	Yes	Yes	Yes	4	0
Subject 10	Yes	Yes	Yes	Yes	4	0
Subject 11	Yes	Yes	Yes	Yes	4	0
Total Events	44				43	1

Considering the results of both Tables 5 and 6, there were a total of 88 events. Out of these in 63 cases the results of thermal imaging matched the standard sensor in place. In 9 cases the results of thermal imaging partially matched with the standard sensors in place while 15 cases were found where the ROI was not available. One event in IB2 (hypopnoea) was not picked by thermal imaging.

The results of Table 6 are considerably better then Table 5 and the reason is the unavailability of ROI in15 cases for Table 5. The second point is the presence of the nasal airflow pressure sensor in Table 6 has assisted in such scenarios where the nostril region was not visible to the camera and the black pixels of the nasal airflow pressure sensor representing the necessary information of respiration phases of inhalation and exhalation were available to extract the respiration signal and apnoea related pauses mimicked by adult volunteers. This does not mean that the method is dependent on airflow for its performance, because all it relies on is the respiration information from the nostrils. The results show the performance of thermal imaging in respiration monitoring and detecting apnoea based on KLT tracking approach. Furthermore the effectiveness of this new approach was very promising before commencing data collection on children undergoing PSG.

6.9 Summary

This chapter is comprised of the results obtained by processing the data recorded at the university involving 11 adult participants. They were recorded in four scenarios of 5 minutes each. Each 5 min video was of around 7 to 8 MB of data so altogether it was around 350MB of data to process in case of adult participants. It explains the tracking algorithms such as camshift and KLT in detail and advantages of KLT over camshift due to the problems faced by camshift in processing. In addition to tracking it also explains different techniques such as cropping and resizing the nose region, grayscale to binary conversion using thresholds and counting the black pixel region to obtain the respiration signal. Finally the chapter discusses one scenario from each of the four scenarios (QB1, QB2, IB1,& IB2) recorded from different participants. As discussed above there were total of 88 events in 44 videos of 11 participants. Out of these 88 events, in 63 thermal imaging matched the results of contact sensors, In 9 cases thermal imaging partially matched the results of the contact sensors in place, In 15 cases ROI was not available for thermal imaging to work on and in 1 case thermal imaging did not detected the event under consideration.

Chapter 7
Results and Discussions of Testing the Method on Paediatric Patients

7.1 Introduction

After processing the data recorded at the University with adult participants and obtaining satisfactory results for the designed approach, the next step was to test the approaches on thermal recordings of paediatric patients undergoing PSG in a hospital environment. Thermal recordings were performed simultaneously along with the standard practice of respiration monitoring in PSG without interfering with the routine diagnostic measurements. The procedure for measuring respiration airflow for HRTI is non-invasive therefore; no adverse safety issues were anticipated. There was no risk associated with the use of the camera in performing HRTI, furthermore the camera does not emit any harmful radiation.

The recordings were performed at a frame rate of 10 frames per second and the images were saved as individual files. In addition to KLT and template matching methods for tracking were utilised and their performance compared. In order to reduce the noise from the extracted respiration signal, wavelet multiresolution analysis (MRA) decomposition was performed, and the respiration airflow information signal was then reconstructed using MRA to get an enhanced version of the respiration signal through thermal imaging. Three cases are included as examples in this study.

The recorded data of paediatric patients was first processed using the approach previously described in Chapter 6. The feature tracking, cropping and resizing of the nose region, grayscale to binary conversion through suitable thresholding and counting the black pixels in the cropped region to extract the airflow information for the respiration signal described in sections 6.4.2, 6.5 , 6.6 and 6.7 respectively were used and resulted in a respiration signal.

The second approach used for tracking and in the extraction of airflow information was the improved template matching method which is described below.

7.2 Template Matching

In an overview of template matching methodologies and their applications, Perveen *et al* described it as a high-level machine vision approach, which helps in identifying the sections of an image or images which matches the given image configuration [101]. Mei and Ling in their study of robust visual tracking explains template matching as the process of the object under consideration being tracked in the image sequence or video by taking a template frame from the first image and searching for its best possible match in the subsequent images [102]. They explained that a template with fixed appearance may not be adequate enough to tackle recent changes in the image sequence; on the other hand a continuously changing model using a best patch of interest from the previous frame is vulnerable to drift. The study also highlighted that, if the object being tracked appears differently in an image, for example by being partially visible or no loner visible, the method will fail.

7.2.1 Template Matching Approaches

The choice of matching is highly dependable on the tracking objectives and nature of the images. In an overview of template matching methodologies and applications, Perveen *et al* classified template matching based on two approaches which are feature-based approaches and template or area based approaches [101].

i. **Template-based approach:** The study described the template based approaches as the ones in which a patch of area, region or template is used for matching and in cases where the template does not provide a straight match, Eigen spaces are employed that provides the description of the image under consideration in different conditions such as colour contrast, illumination or admissible matching poses [101]. The prefix eigen is acquired from a German word meaning proper or characteristic. So eigen spaces are distinct spaces with sharp characteristics in an image, used in template based approach where the template fails to provide a straight match.

ii. **Feature-based approaches:** The study deemed this approach more suitable in cases where both the reference and template images possess more similarity in terms of features and control points [101]. Features were

described in the study as points, surface model or curves that need to be matched. The aim of feature based matching in the study is mentioned as identifying the pair wise association among the template and the reference by using their description of features or spatial relation. The study mentioned the further classification of feature based matching as invariant descriptors, relaxation methods, spatial relations and pyramids and wavelets.

7.3 Template Matching Operation in this Study

In this study, the existing template matching approach was applied for identifying a predefined template (which was a small area under the tip of the nose most affected by respiration changes) within each successive frame proved to be ineffective. It was observed that when the template was selected to represent the respiratory region under consideration, i.e. a small area under the tip of the nose, the tracking operation missed the desired region repeatedly resulting in failure of tracking. On the other hand with selection of a larger region the tracking was successful but the region was too large to accurately express the respiratory region of the interest. Representation of this region by a feature such as averaged pixel values gave poor outcomes as the target region was diffused into a much larger selected region.

To overcome the limitation of template matching, a novel approach was adapted. This approach was based on two stage tracking. The first stage involved the selection of a larger area as a template with the tip of the nose and mouth at the centre of the chosen area. The algorithm tracked and saved this region successfully. In the second stage, the selected region was used instead of the original images to improve the tracking. A new template with a much smaller region and focused under the tip of the nose was selected and template matching was again applied. With this new method the tracking proved successful and the ROI was tracked effectively in all subjects.

7.4 Respiration Signal from Template Matching

Once the tracking of ROI was achieved successfully, the region was represented by its average pixel value and by repetition of the process over successive images resulted in respiration signal. It was noted that the signal contained unwanted

components representing noise and other unrelated respiratory effects. MRA was used to select the component associated with respiratory airflow. It was also useful to obtain the respiration rate of the subjects as this has clinical information and clinical value. This was achieved by plotting the magnitude frequency spectrum of the extracted respiration signal and considering the dominant peak in the spectrum. The frequency associated with this peak was multiplied by 60 to obtain the respiration rate in breaths per minute.

7.5 Results and Discussion

In this section the results of both the developed techniques are discussed when employed for processing the thermal imaging data for paediatric patients undergoing PSG.

7.5.1 Analysis of Patient Number 28

The first subject is male child of 1.81 years old. The child went through PSG monitoring along with thermal recordings for investigation of central apnoea. Table 7 provides the patient details. He had undergone previous PSG monitoring in the past. The child did not tolerate wearing either of the nasal sensors required during the PSG (i.e. oronasal thermistor or nasal pressure airflow).

Table 7 Patient detail (number 28)

Parameter	Value
Recording date	2018
Age	1.81 years
Gender	Male
Reason for PSG	Central apnoeas
Room temperature at the time of recording	21.4℃
Room humidity at the time of recording	32
Has the child worn nasal sensors for any significant length of time	No

Figure 27 shows a section of the sum of respiratory effort (thoracic and abdominal) bands (RIPs) and its corresponding magnitude frequency spectrum. The sample rate for RIPs was 32 per second, so the signal shown in the figure is from the start of the RIPs till 54530th sample that corresponds to 1704 seconds approximately as shown in the figure.

As the child had not worn nasal sensors (i.e. thermistor or nasal pressure airflow), the respiratory signal from RIPs has been used as a reference signal for comparison with the results of thermal imaging. The respiratory signal in Figure 27 does not drift and its dc (average) component is zero. Its magnitude frequency spectrum peaks at frequency 0.3 Hz. This corresponds to a RR of 0.3×60=18 bpm. For an infant of 1.81 years of age, RR of 18 bpm could be on the low side.

Four events of disruption in the respiration can be observed at times 344, 534, 1020 and 1656 seconds.
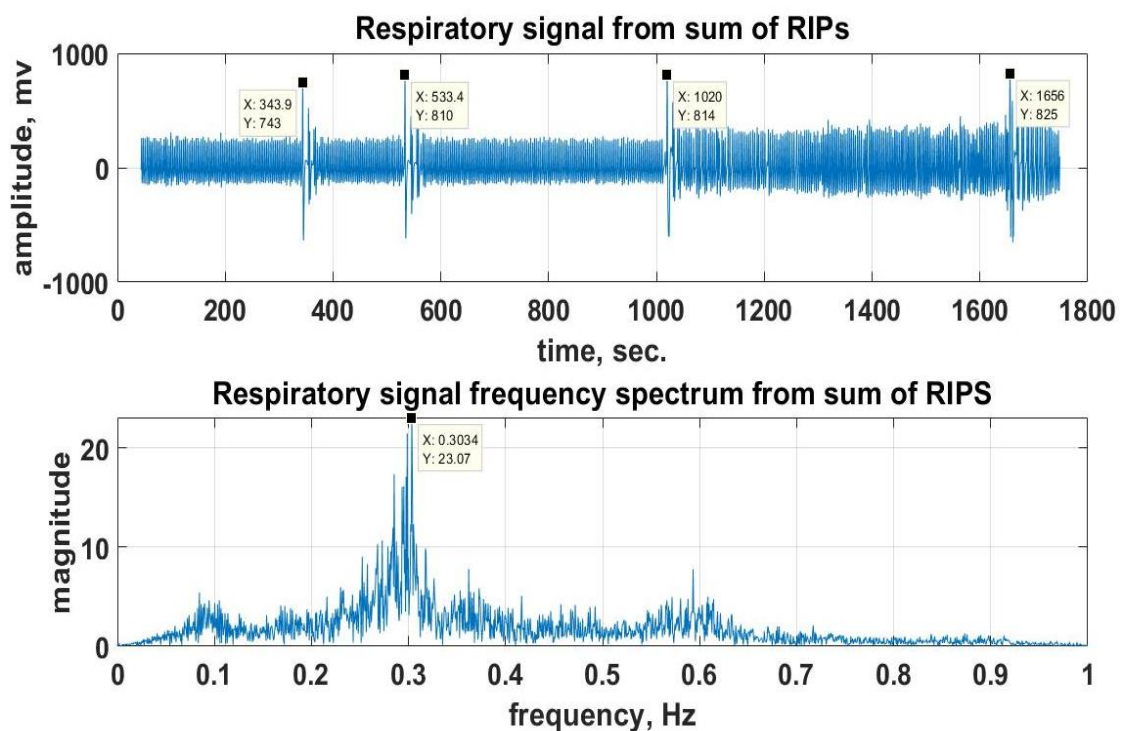
Figure 27 Respiratory signal obtained from sum of RIPs and its corresponding frequency spectrum.

Figure 28 shows a zoomed in version of Figure 27 for signal analysis. In Figure 28 the respiratory signal from the sum of the thoracic and abdominal bands (RIPs) is replotted with the first event occurring at 533.4 seconds. The sum is used rather than individual signal as in some patients respiration results in thoracic and in others abdominal movements. The event is representing a central apnoea at that time (during the onset of central apnoea there is no chest movement). The duration of this apnoea occurrence is approximately 10 seconds (i.e. 533.4 to 543.3). The subject then has 2 breaths and has a second respiratory pause lasted for about 7 seconds

(548.1 to 554.9 seconds). The respiratory cycle thereafter briefly becomes atypical of the infant respiratory norm and then recovers to a normal breathing pattern.
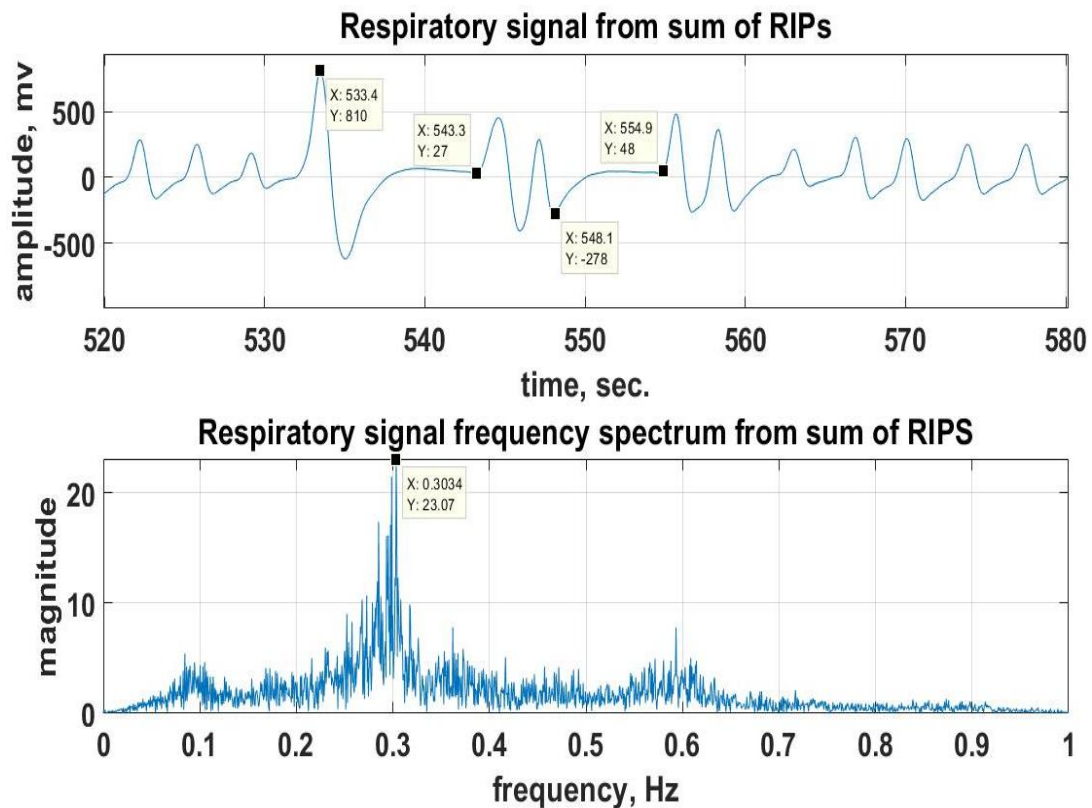
Figure 28 A replot of figure 27 with an apnoea onset occurrence zoomed in.

Figures 29 and 30 show the template matching tracking operation for thermal imaging based respiration monitoring. Template matching tracking was performed in two stages as explained earlier in section 7.3. In the first stage a large area covering of the nose and around the mouth was tracked and segmented. In the second stage the nostril region was tracked from the segmented region obtained in stage 1. Single stage tracking was not suitable as tracking the nostril region directly from the original images resulted in the identification of incorrect regions. In the two-stage tracking approach, the region matched is reduced for the second stage involving the nostrils. Figure 29 shows the first stage of tracking where a large area centred on the nose is initially tracked. The blue boxes show the areas being tracked over time. The shifts in the blue box are due to subject's body movements, primarily as a result of respiration, as respiration causes some head movements for an infant. The tracking algorithm readjusts to the new location to match the originally selected template region in an optimum manner.
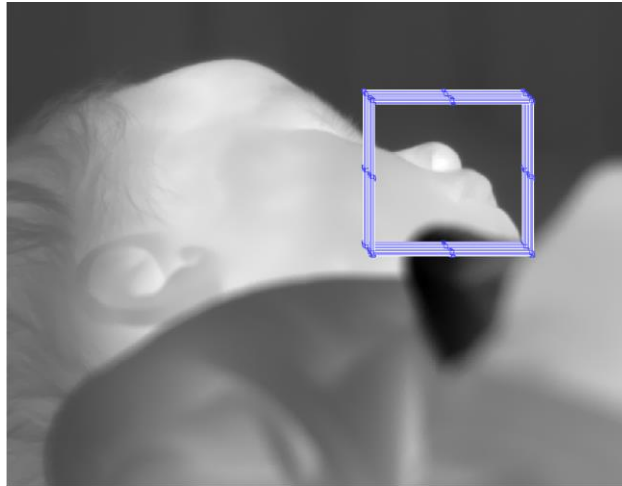
Figure 29 Tracking stage 1 for a larger region.

Figure 30 shows the second stage of tracking where a smaller region centred on the nostril is tracked. The blue boxes show the areas being tracked over time. Again, the shifts in the blue boxes are more noticeable are due to subject's body movements primarily caused by respiration. The boxes visually appear to be moving by a larger amount but this is because the area is zoomed in.
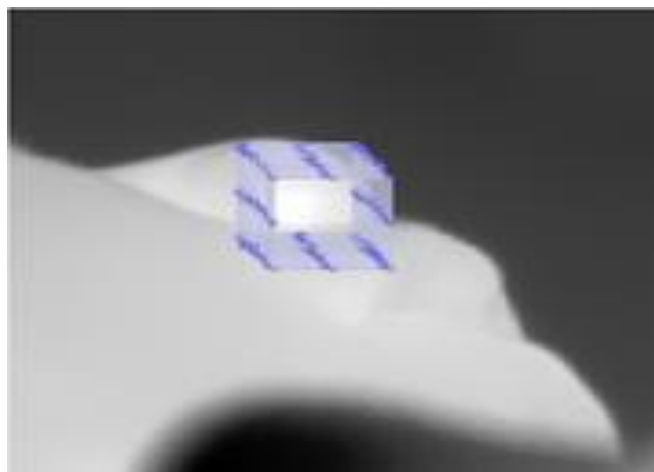
Figure 30 Tracking stage 2 where the nostril region is tracked.

Figure 31 shows a section of the respiratory signal obtained by thermal imaging (from the same section as was the respiratory signal from RIPs in Figure 27) prior to any processing. The signal duration is 820 seconds or about 13 minutes and 40 seconds. A drift of 2 ℃ is visible in the signal baseline (ranging from about 31.4℃ to 33.4℃). Given the short duration of the signal, the drift is unlikely to have been caused by either the environmental factor (e.g. room temperature changes) or camera operation. The more likely cause of this temperature drift is changes in

temperature of the nostril region caused by irregular or inconsistent breathing. This information may have the diagnostic information and this may allow the consistency of breathing over time to be monitored. The respiratory signal obtained from sum of RIPs (shown in Figure 27) does not contain this information and this could be one of its limitations.
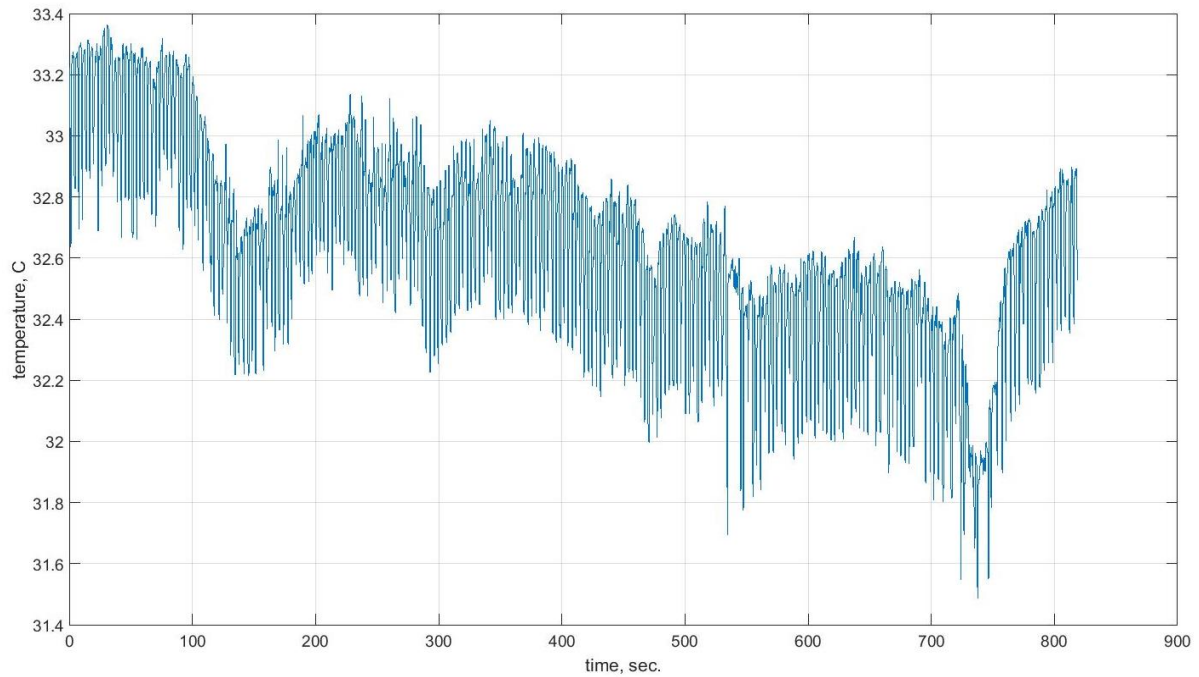
Figure 31 A section of respiratory signal obtained using thermal imaging.

Figure 32 shows a replot of (respiration signal obtained by thermal imaging in Figure 31) for duration of 45 seconds (from 520 to 565 seconds) with central apnoea events zoomed in. The signal is in its original form without any processing being performed on it.
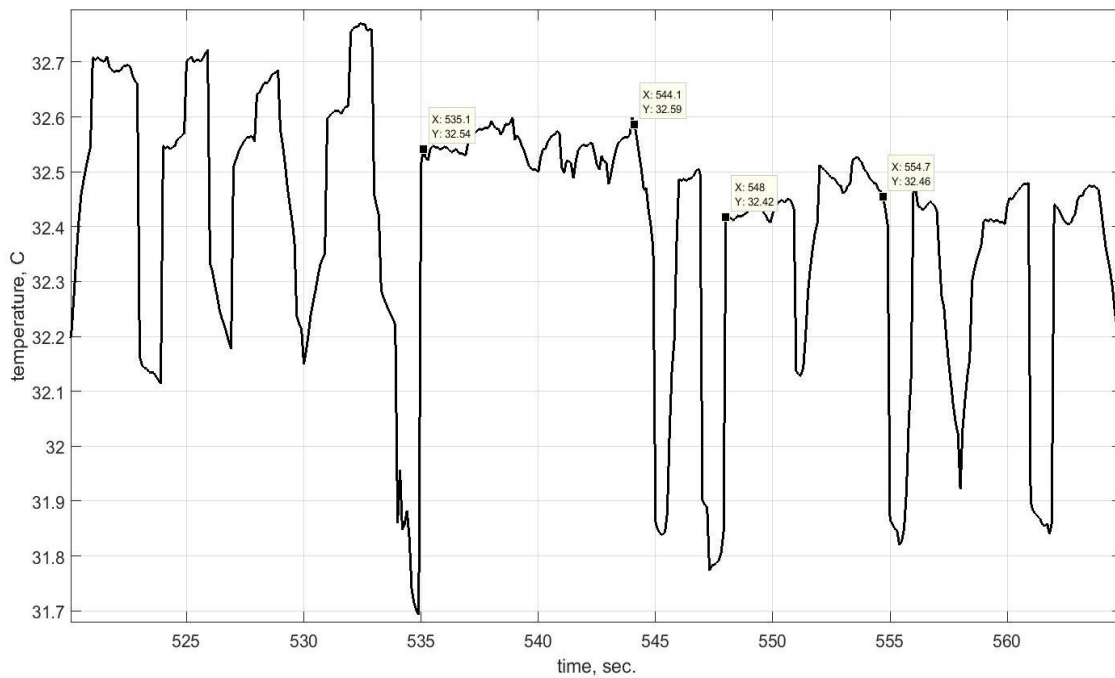
Figure 32 A section of respiratory signal obtained by using thermal imaging with apnoea events zoomed in

The Figure 32 indicates a large drop of (1℃) in temperature, a result of more than average inhalation just prior to significant reduction in airflow. The apnoea event lasts for 9 seconds (from 535 to 544 seconds) and then the infant briefly recovers for two respiratory cycles and then a second apnoea event occurs lasting for about 6 seconds (from 548 to 554 seconds). During each apnoea event some respiratory activities are taking place but severely reduced.

In order to extract the respiratory component from the recorded thermal imaging based respiratory signal MRA was performed. The Daubechies wavelets with order 24 were used for this purpose as they provide a robust filtering. This filter order and type were chosen after a number of tests with different filters and orders and the best was chosen. Daubechies wavelet is shown in Figure 33
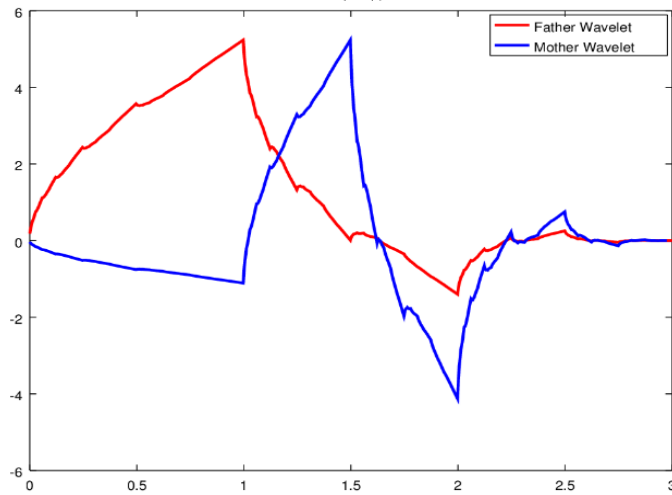
Figure 33 Daubechies wavelet.

The respiratory signal was decomposed to level 7. Level 7 provided a sufficiently high level of details. The resulting components are shown in Figure 34.
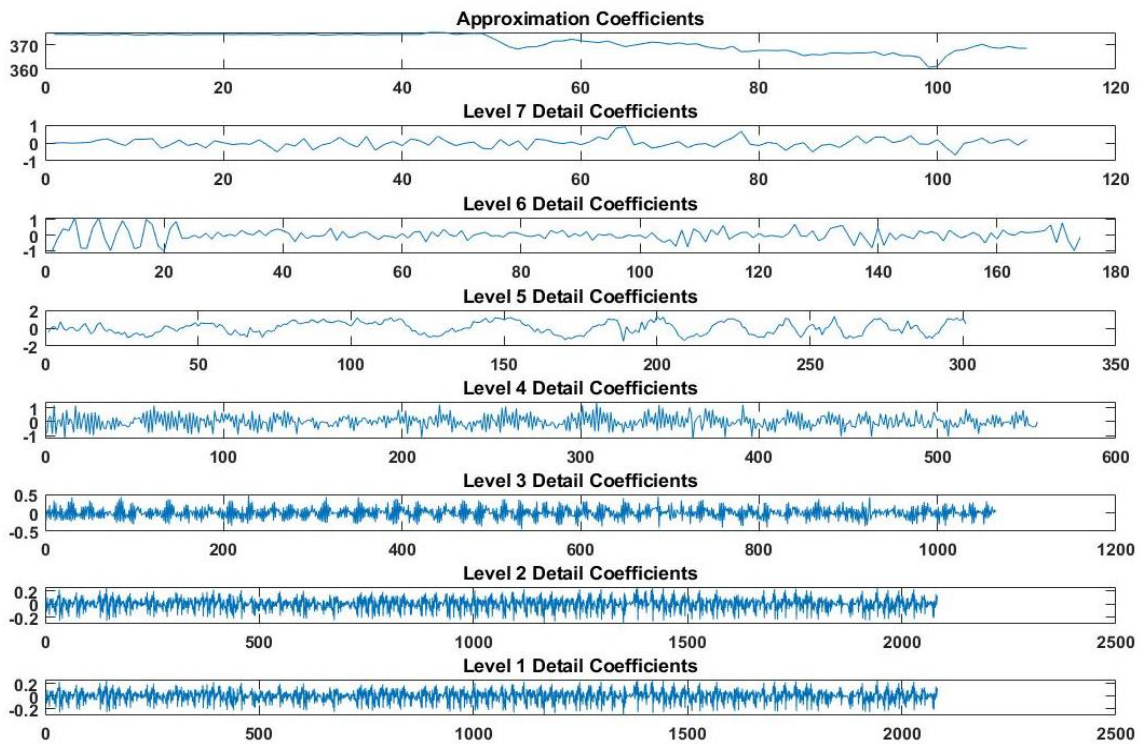
Figure 34 Multiresolution analysis of the respiratory signal using thermal imaging, here vertical axes representing amplitudes of coefficients and horizontal axes representing coefficient number

The respiratory signal was then reconstructed from the MRA components, leaving out the high frequency details, i.e. details from levels 1 to 3. The reconstructed respiratory signal together with its magnitude frequency spectrum is shown in Figure 35.
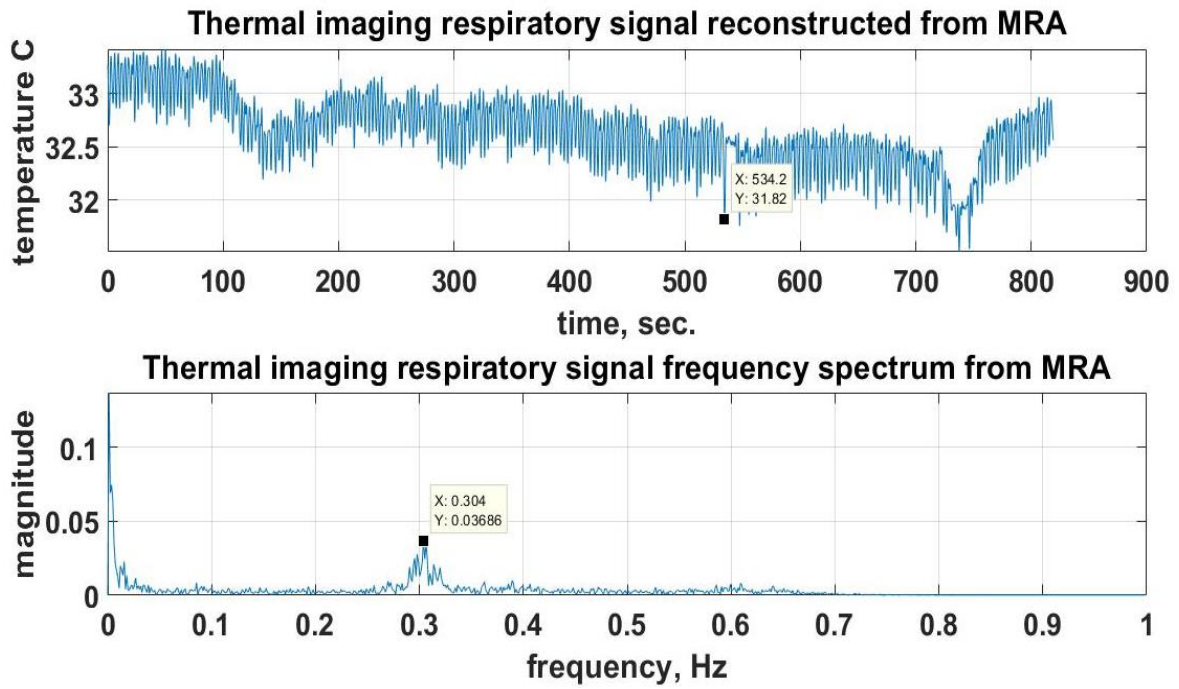
Figure 35 Thermal imaging based respiratory signal filtered using multiresolution analysis.

Figure 36 shows a replot of Figure 35 with two apnoea events zoomed in. The signal as compared to Figure 32 prior to processing has less noise and events are more evident.
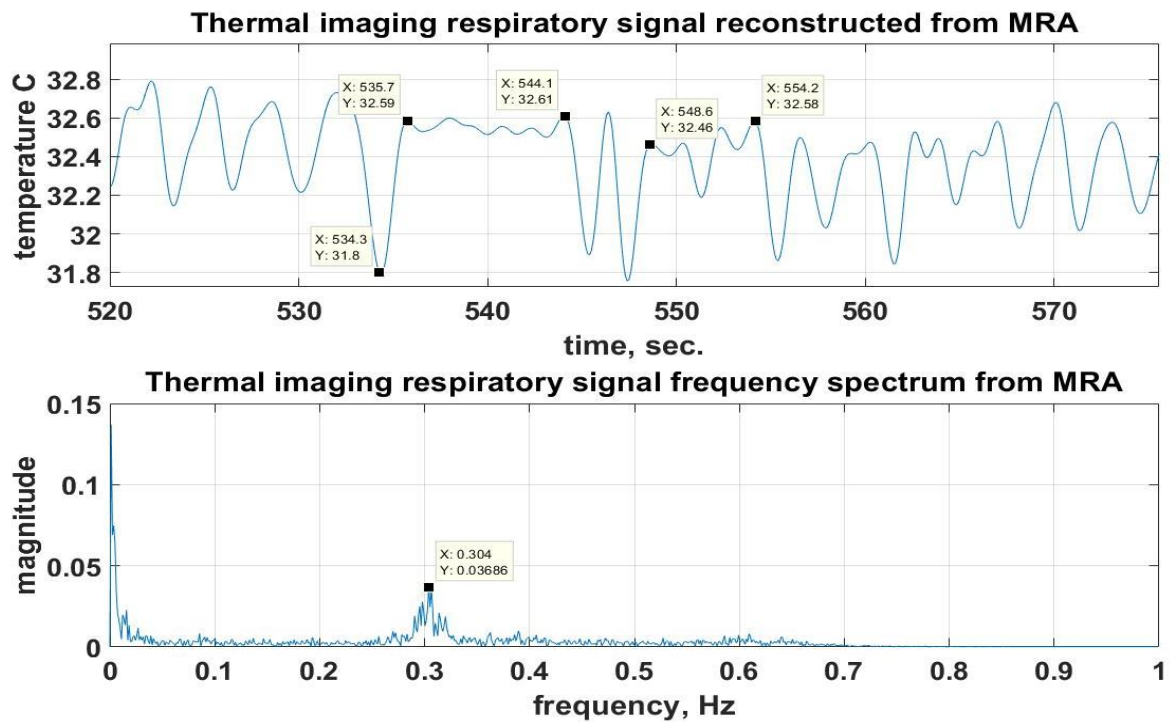
Figure 36 Replot of figure 35 with apnoea events zoomed in along with its magnitude frequency spectrum.

Comparing Figure 36, with the respiration signal obtained from the sum of respiratory effort (thorax and abdomen) bands shown in Figure 28, the following points were observed.

- The thermal imaging based respiratory signal has more details than the one obtained from the sum of respiratory effort bands. For example, it indicates that there are respiratory activities during the apnoea events while the respiratory effort bands based signal shows no activity. This also signifies that the thermal imaging based method is more sensitive and can quantify respiration airflow more accurately as compared to respiratory effort bands.

- The thermal imaging based signal drifts in relation with the respiratory pattern. The analysis of this drift may have valuable diagnostic information. The respiratory signal from the respiratory effort bands does not show any drift.

- The respiratory rate obtained from the magnitude spectra of both signals (thermal and respiratory effort) show the same value, i.e. 18 breaths per minute, confirming they both accurately determine the respiratory rate.

Figure 37 shows the zoomed in respiration signal of the same section using thermal imaging by KLT approach as in Chapter 6 along with its magnitude frequency spectrum. The respiration signal shows two apnoea events confirming the working nature of thermal imaging with both methods. The magnitude frequency spectrum also peaked at the same frequency of 0.3 Hz approximately, giving the same respiration rate of 18 bpm as found with template matching, when compared with the respiration rate from RIPs bands in Figure 28.
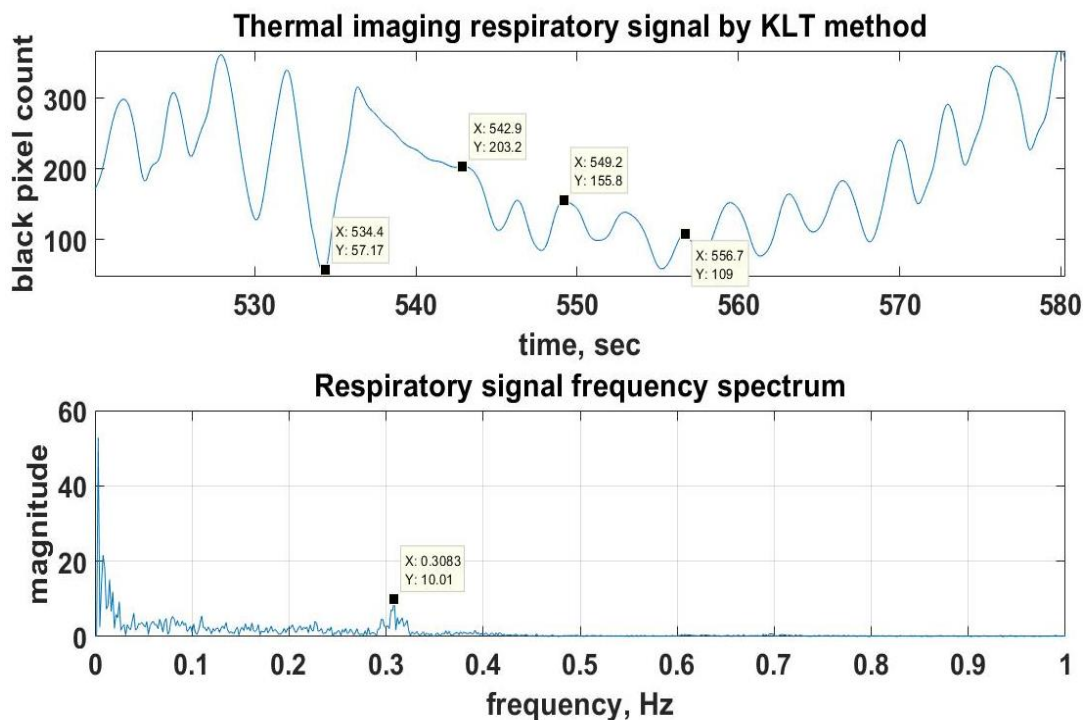
Figure 37 Thermal imaging respiration signal and its frequency spectrum by KLT approach.

Figure 38 shows the short-time Fourier transform (STFT) or spectrogram together with the continuous wavelet transform of the signal in Figure 35 (thermal imaging based respiratory signal). The spectrogram indicates the respiratory rate to remain around 18 breaths per minute for the duration of the signal however it fluctuates by a small value. Its value is slightly reduced at time=10 minutes as compared to its initial parts. Spectrogram is valuable for monitoring fluctuations in respiratory rate. The continuous wavelet transform (bottom of Figure 38) provides consistent result to that obtained from the spectrogram but the respiratory rate is defined in a more well-defined manner (i.e. narrower band).
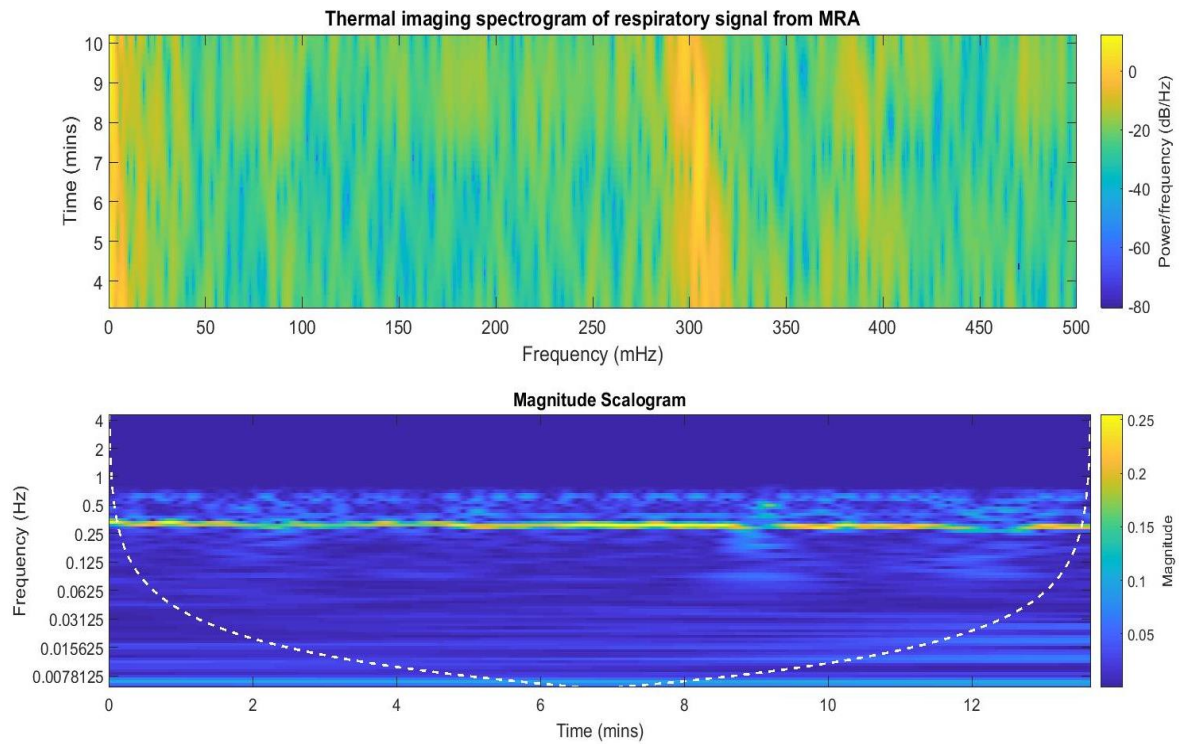
Figure 38 The spectrogram and continuous wavelet transform of the signal shown in Figure 35.

7.5.2 Analysis of Patient Number 1

The second subject to discuss in this work is a female child of 3.72 years old. She went through PSG monitoring along with thermal recordings in 2017 for suspected mild OSA and snoring. Table 8 shows the patient details at the time of recording.

Table 8 Patient detail (number 1)

Parameter	Value
Recording date	2017
Age	3.72 years
Gender	Female
Reason for PSG	Mild OSA and snoring
Room temperature at the time of recording	21.4℃
Room humidity at the time of recording	32
Have the child worn nasal sensors for any significant length of time.	No

Figure 39 shows the respiratory signal along with its magnitude frequency spectrum from a section of sum of respiratory effort (thorax and abdomen) RIPs bands which are used as a reference signal in this case as the patient did not tolerate nasal sensors during the monitoring. Frequency spectrum allowed the respiration rate of the subject to be determined by considering its dominant peak. Frequency spectrum of the respiration signal from RIPs peaks at 0.25 Hz. This corresponds to RR of 0.25×60= 15 breath per minute (bpm).
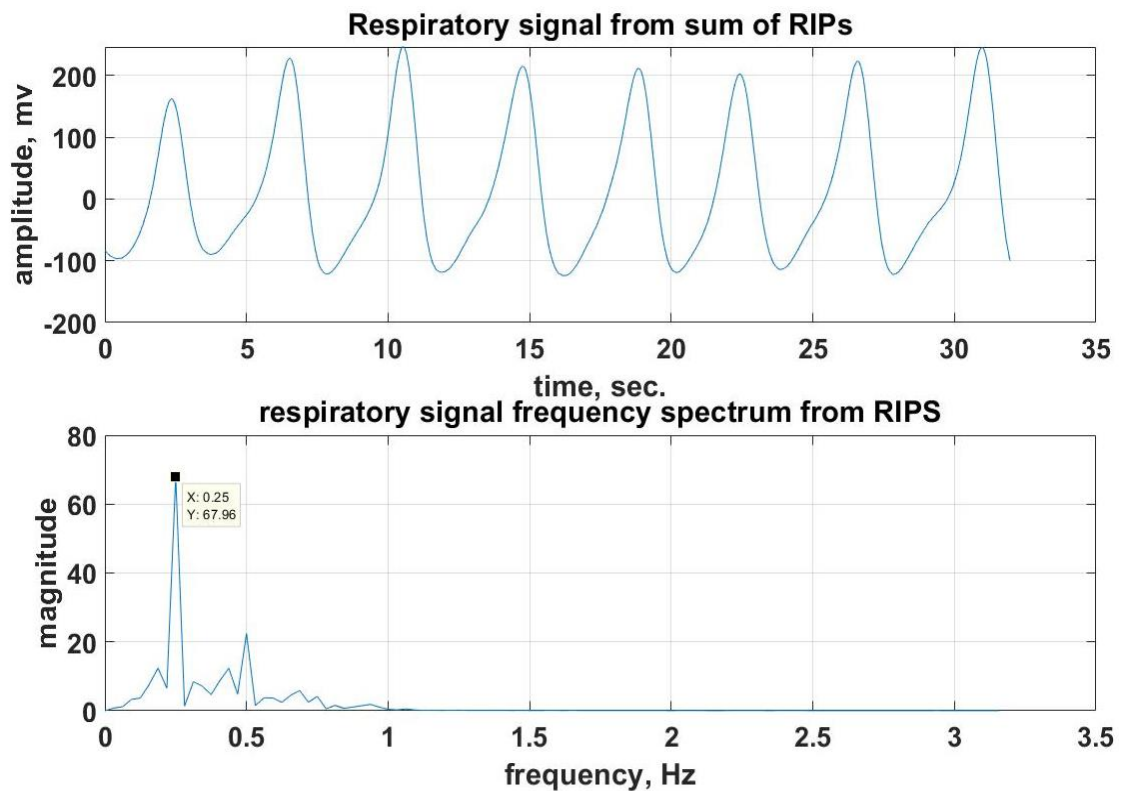
Figure 39 Respiratory signal from sum of RIPs along with its frequency spectrum.

Figure 40 shows thermal imaging respiratory signal of the patient from exactly the same time duration as the respiratory signal of the RIPs in Figure 39, obtained by employing template matching algorithm. The frequency spectrum of the respiratory signal obtained by template matching via thermal imaging in Figure 40 peaks at 0.2441 Hz. This corresponds to a respiration rate of 0.2441×60=14.646 bpm which is approximately equal to the respiration rate of the RIPs bands in Figure 39. This confirms the working nature of thermal imaging with hospital settings.
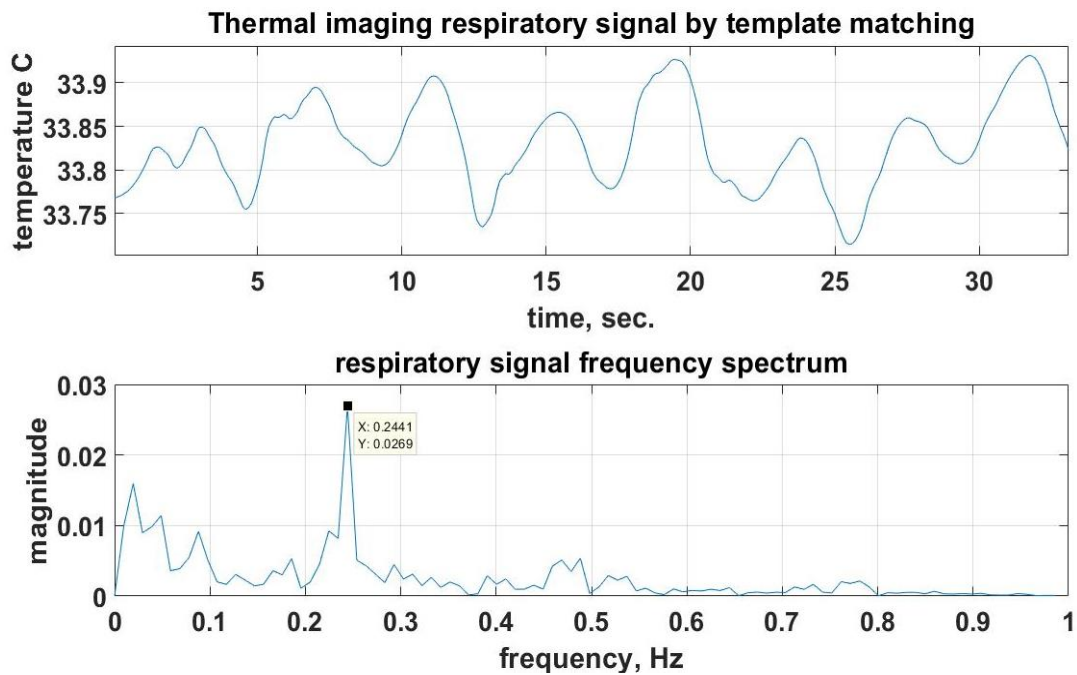
Figure 40 Thermal imaging respiratory signal from template matching and its frequency spectrum.

Comparing Figures 39 and 40, the respiration signal from sum of RIPs shows an easily identifiable inhalation and exhalation cycles. On the other hand the respiratory cycles are not as clearly defined in the thermal imaging based respiratory signal shown in Figure 40. The temperature change in Figure 40 is only of about $0.1℃$. There are several possible causes for such a low temperature variation. A possibility could be that the air flow to the lungs is quite low although there is a respiratory event and the chest/abdomen moves. In this case thermal imaging is providing a valuable insight to the diagnosis for apnoea. Another possibility is that the thermal camera is not adequately positioned to be able detected the respiratory airflow in an optimal manner. If so this points to the need for a standardisation in camera positioning. Comparison of Figure 40 with Figure 36 where there is a 1 ℃ temperature variation during the respiratory cycle indicate the nasal area for subject in Figure 40 to be significantly warmer (by about 1 ℃). The warmer nose may have masked the temperature variations for the subject in Figure 40. Again, this is an issue that needs to be considered for further development of the method.

For further analysis another section of recording was considered, starting from image number 3001 till 4241 which is approximately 2 minutes as the sample rate was set at 10 samples per second. Figure 41 shows the respiration signal from sum of RIPs used as reference signal as the child did not wear nasal sensors. The frequency

spectrum of RIPs peaked at 0.2338 Hz which corresponds to RR of 0.2338×60=14.0 bpm. For a child of this age this rate could be on the low side.
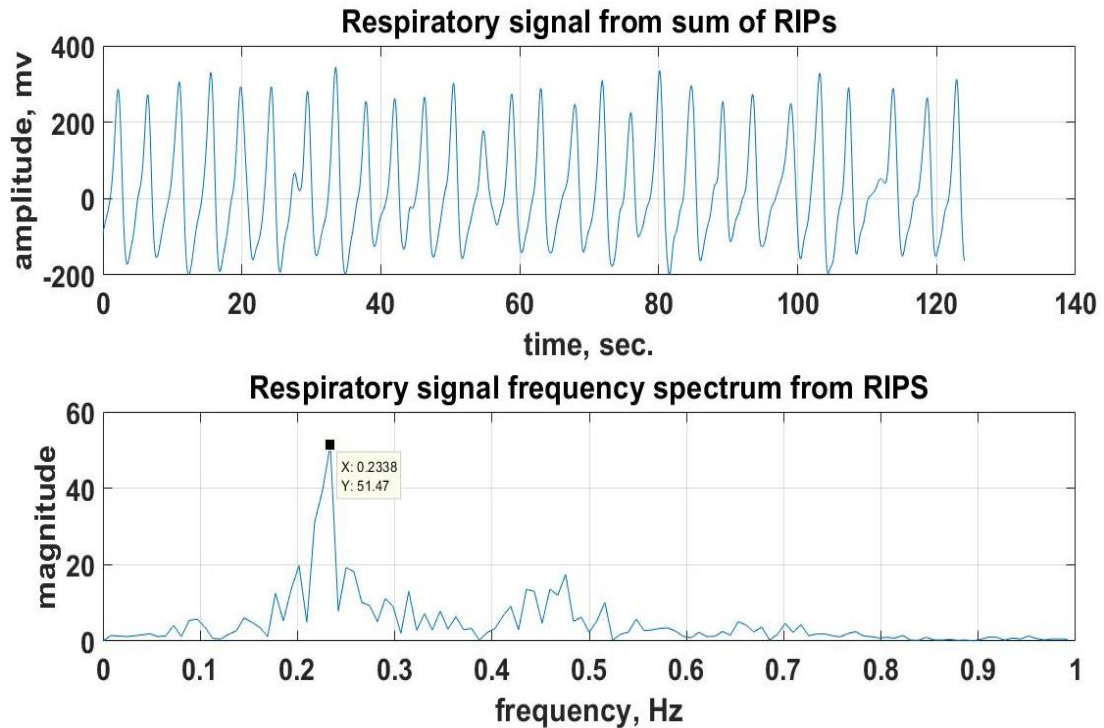
Figure 41 Respiratory signal from sum of RIPs and its magnitude frequency spectrum.

Figure 42 shows thermal imaging respiration signal by template matching of the same section as shown in Figure 41. Its frequency spectrum peaks at 0.2539 Hz which corresponds to a respiration rate of 0.2539×60=15.234 bpm. The respiratory rate here is higher in comparison to the respiratory rate of RIPs in Figure 41.
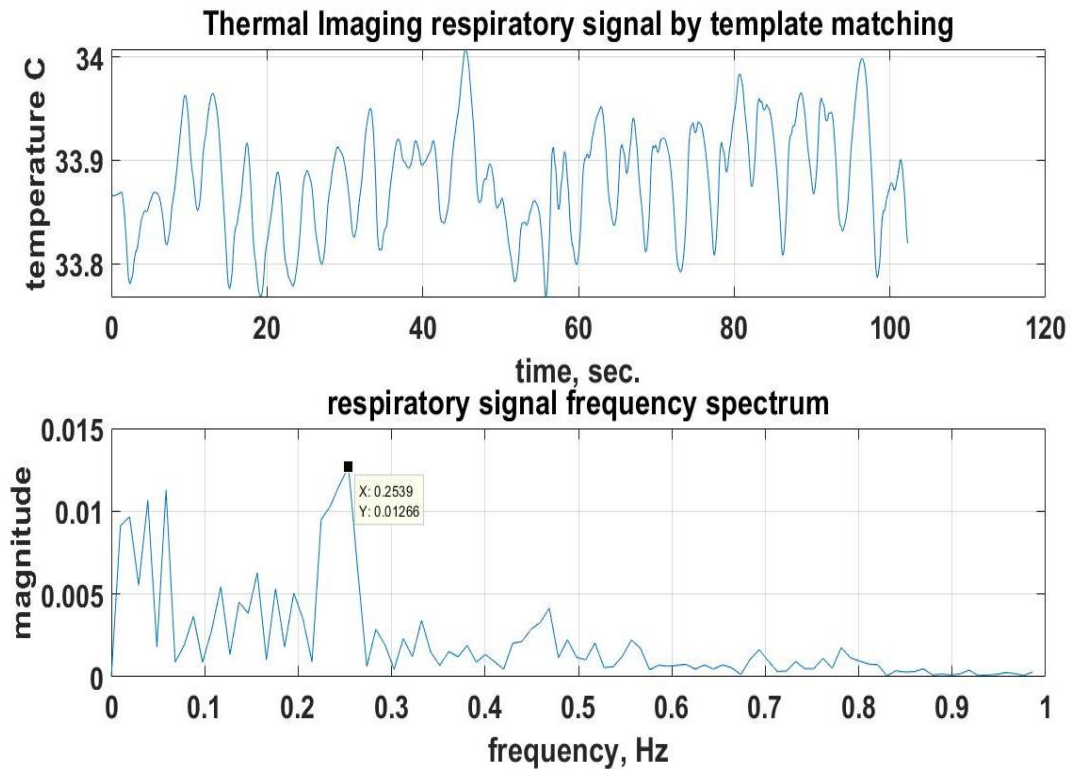
Figure 42 Thermal imaging respiratory signal from template matching and its magnitude frequency spectrum.

7.5.1 Analysis of Patient Number 12

The third subject we are discussing here is a female child of 5.08 years old. She went through PSG monitoring along with thermal recordings in 2018 due to suspected breathing issues during sleep. The room temperature and humidity at the time recording were 21.4℃ and 32 respectively. This child did not wear nasal pressure airflow throughout the PSG and thermal recording, therefore thermistor and the sum of respiratory effort bands have been used as reference signals for comparison with the results of thermal imaging. Table 9 shows the details of the patient at the time of recording.

Table 9 Patient detail (number 12)

Parameter	Value
Recording date	2018
Age	5.08 years
Gender	Female
Reason for PSG	Breathing issues during sleep
Room temperature at the time of recording	21.4℃
Room humidity at the time of recording	32
Have the child worn nasal sensors for any significant length of time.	Only thermistor (No nasal pressure airflow)

Figure 43 shows the respiratory signal of the patient for duration of around 140 seconds along with its magnitude frequency spectrum. The frequency spectrum of the respiratory signal from the thermistor peaks at 0.2371 Hz. This corresponds to a respiration rate of 0.2371×60=14.226 bpm.
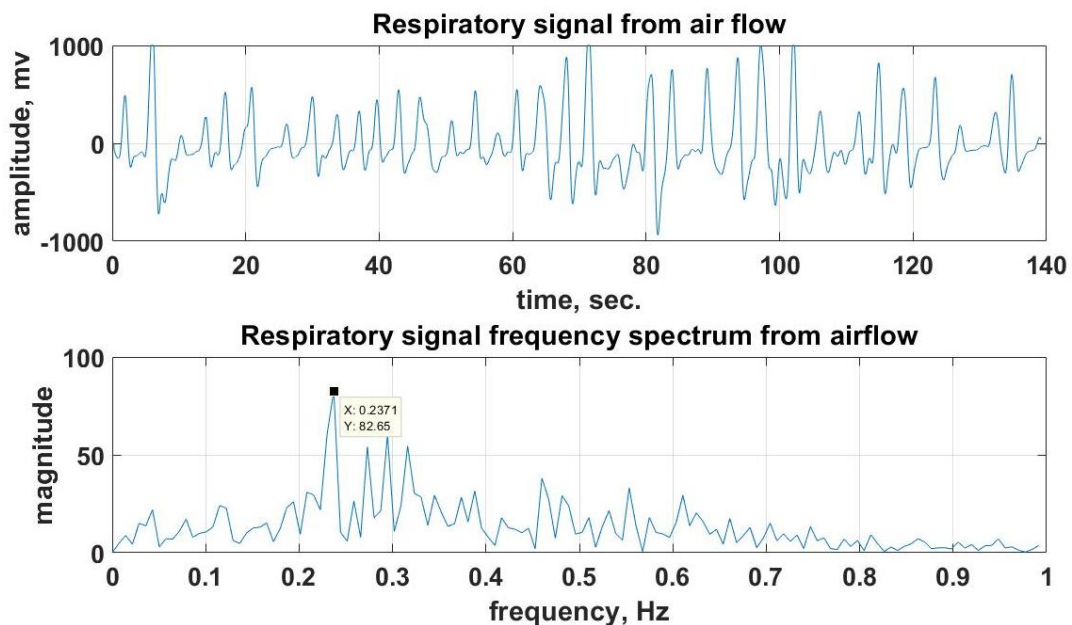
Figure 43 Respiratory signal from air flow and its magnitude frequency spectrum.

Figure 44 shows the respiratory signal of the patient from the same time duration of 140 seconds as in figure 43 along with its frequency spectrum. The frequency spectrum of the respiratory signal from RIPs peaks at 0.2357 Hz. This corresponds to respiration rate (RR) of 0.2357×60=14.142 breathe per minute (bpm).
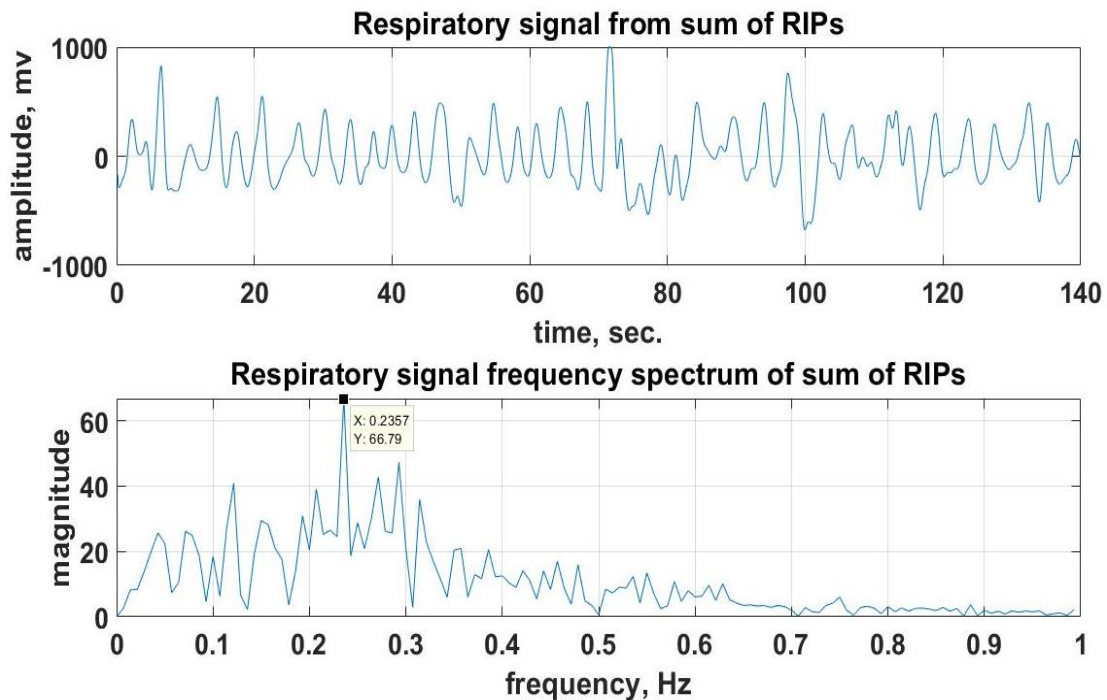
Figure 44 Respiratory signal from sum of respiratory effort bands and its frequency spectrum.

Figure 45 shows thermal imaging respiratory signal of the patient starting from exactly the same time duration as the respiratory signal from airflow and sum of RIPs in Figures 43 and 44 respectively, obtained by employing template matching algorithm. Figure 45 shows a better version of the respiration signal from thermal imaging with a smoother respiratory signal as compared to the respiratory signal from thermistor and sum of RIPs shown in Figures 43 and 44 respectively. This may highlight that the respiratory signal from airflow sensor and respiratory effort bands are not as accurate as the airflow information extracted by thermal imaging. The frequency spectrum of the respiratory signal obtained by template matching via thermal imaging shown in Figure 45 peaks at 0.2344 Hz. This corresponds to a respiration rate of 0.2344×60=14.064 bpm which is approximately equal to the RRs of the thermistor and sum of RIPs bands. This confirms the working nature of thermal imaging in hospital environment.
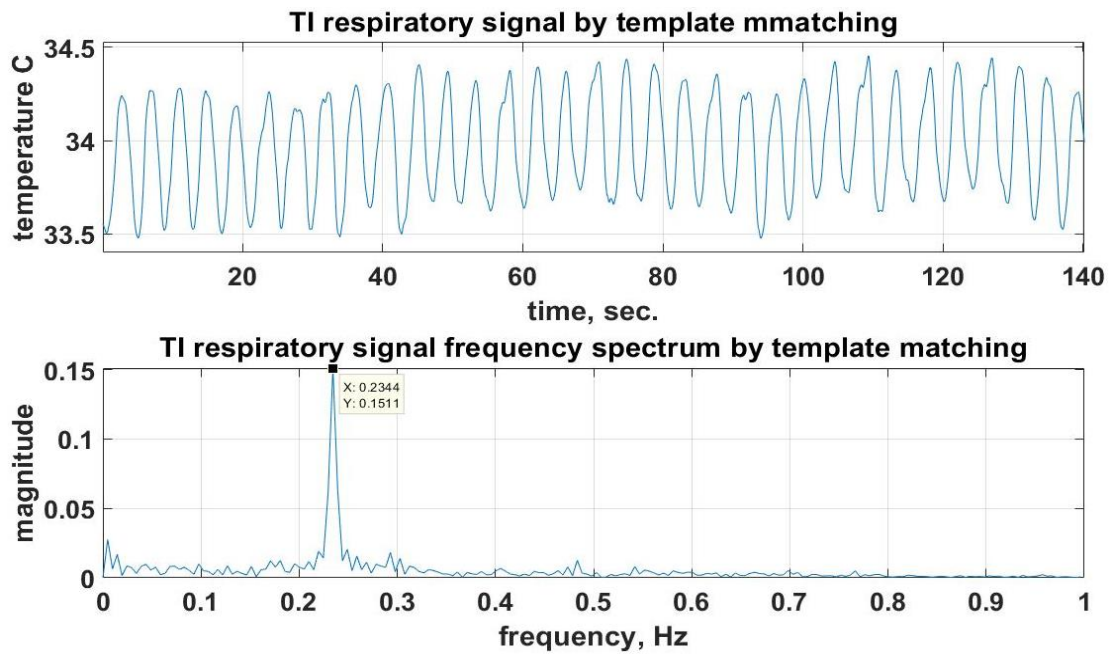
Figure 45 Thermal imaging respiratory signal by template matching along with its frequency spectrum.

Figure 46 shows the thermal imaging respiratory signal of the patient from the same time duration and length of 140 seconds as in figures 43, 44 of the PSG recording. The thermal imaging respiratory signal in Figure 46 was obtained by the employing KLT algorithm and the approach described in chapter 6 for the extraction of respiratory signal. The respiratory signal in this figure is very much similar to the respiratory signal obtained by template matching. The frequency spectrum in Figure 46 peaks at the similar frequency of 0.2391 Hz. This corresponds to a respiration rate of 0.2391×60=14.5 bpm which is approximately equal to the RR's obtained from the nasal pressure airflow sensor in figure 43 and sum of RIPs in figure 44.
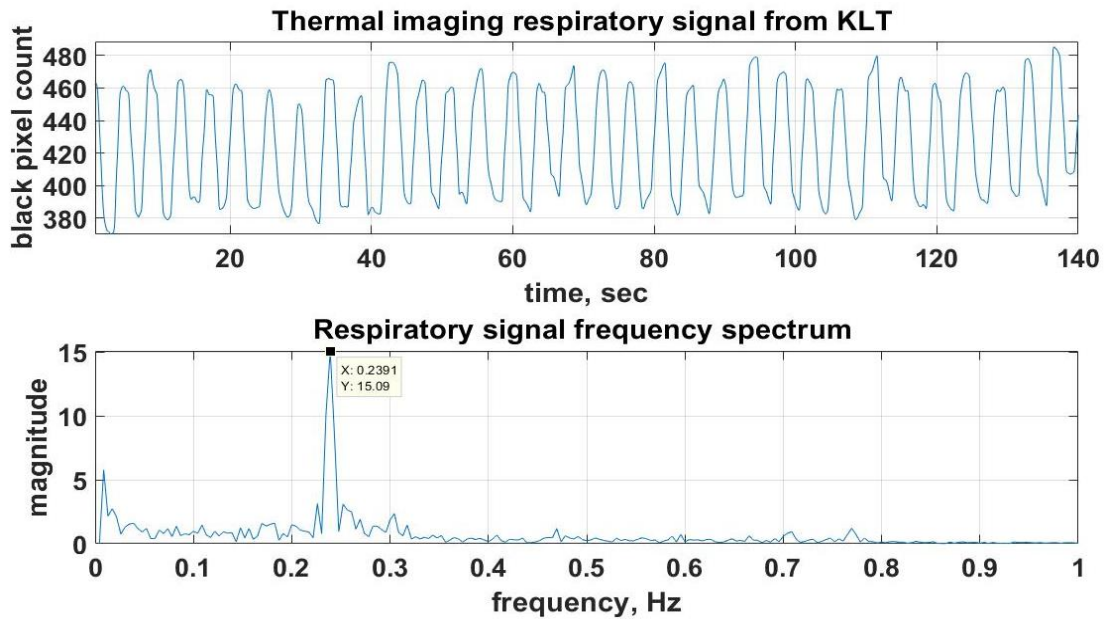
Figure 46 Thermal imaging respiratory signal by KLT algorithm along with its frequency spectrum.

Thermal imaging worked well in extracting the respiration signal with both template matching and KLT. Both approaches determined the respiration rate correctly in relation to the respiration rate obtained from the thermistor and sum of respiratory effort bands.

Thermal imaging was successful in detecting the apnoea, however we currently have some difficulties time synchronising the thermal video recordings with those of thermistor, nasal pressure airflow and RIP sensors. This will require further development and can be resolved in further work. Time synchronisation was in place for the first patient discussed in this study (patient 28) but for the second and third subjects (patient 1 and 12) time synchronization for the reference signals and thermal imaging was not in place.

7.6 Limitation of Thermal Imaging

The main limitation of the thermal imaging based respiratory monitoring in comparison with contact based methods is that once the person faces away from the camera, monitoring will not be successful. More work need to be done to improve the tracking in thermal imaging based respiratory monitoring.

7.7 Summary

This chapter discusses in detail the process of analysing the data recorded at hospital with paediatric patients. Thermal recordings of 3 paediatric patients undergoing overnight PSG monitoring were processed and analyzed in this study. Each overnight recording was of around 1GB of data so altogether in case of 3 child patients a total data of 3GB was processed and analyzed In addition to the already used approach of KLT tracking the subjects are also analyzed in this chapter by newly developed approach based on template matching. So template matching with its different types is described and the problems faced in this study in extracting the desired results through the standard approach of template matching are discussed. It further explains the newly developed 2 stage tracking based on template matching which rectifies the problems we were facing and help in improving the precision and accuracy of the results. Altogether 3 patients recorded at SCH for overnight PSG monitoring are discussed here along with detailed procedure of employing different signal and image processing techniques to obtain the desired results. The data has been processed using both KLT and template matching to compare the accuracy of both the methods in comparison with the contact sensors in place while recording. Both techniques successfully detected the under consideration types of apnoea in all three cases.

Chapter 8

Conclusion

8.1 Conclusion

Thermal imaging to measure respiratory airflow to assist with diagnosing apnoea was investigated and further developed. As head and body movements constrain thermal imaging, two tracking approached were utilised. One operated based on Kanade-Lucas-Tomasi (KLT) tracking algorithm and the other template matching. Template matching in its original form failed to track movements in the recorded respiratory thermal videos and so it was further developed to operate in two stages. The new approach proved successful. Thermal imaging was evaluated on 11 adult healthy volunteers and 3 children patients undergoing investigation for suspected sleep-disordered breathing.

8.2 Background

The gold standard practice of respiration monitoring in PSG is through nasal airflow and thermistor sensors for apnoea diagnosis. These two sensors are placed in the vicinity of nose making it difficult for children to sleep. Due to their contact nature, children often try to remove them during PSG and their percentage tolerance throughout the sleep study is not satisfactory. In cases where the child does not tolerate these sensors, clinicians have to rely on respiratory effort (thorax and abdomen movement) bands for respiration monitoring and apnoea diagnosis. These respiratory effort bands are less reliable especially in differentiating various apnoea conditions.

The developed technique of non-contact respiration monitoring is based on two separate approaches, which were KLT based tracking and template matching based tracking of the ROI to extract the respiratory signal and detecting pauses in breathing (different conditions of apnoea). The results from these methods were judged against the results of standard contact based sensors in place along with thermal recordings, which are nasal pressure air flow sensor, thermistor and respiratory effort (thorax and abdomen) bands

8.2 Testing of KLT Based Method on Adults

In the first step the KLT based tracking approach for tracking the ROI to extract the respiratory signal was developed and tested on 11 healthy volunteers recorded at Sheffield Hallam University. Each adult participant was recorded in four different scenarios for duration of five minutes each. There were two Quiet Breathing scenarios QB1, QB2 and two irregular breathing scenarios IB1, IB2. Respiratory effort bands were used as a reference signal in QB1 and IB1, while in case of QB2 and IB2 a nasal pressure airflow signal was also used in addition to the respiratory effort bands as a reference signal in thermal recordings.

While compiling results QB1 and QB2 were referred as a single event as it was normal breathing and was judged against the reference contact based sensor as matched, partially matched, not matched or ROI not available (cases where ROI was not present). In case of irregular breathings, as the irregular breathings involved different patterns of apnoea, so each apnoea type in a signal was referred as an individual event. So in case of IB1 and IB2 the signal had 3 events each (central, obstructive and hypopnoea) and these events were judged against the reference signal as individual events as matched, partially matched, not matched and ROI not available.

In the case of QB1 out of eleven subjects, the respiration signal obtained by thermal imaging was compared against the sum of respiratory effort bands and matched in 4 cases, partially matched in 4 cases and in case of 3 participants, the ROI was not available. On the other hand in QB2 the respiration signal obtained using thermal imaging was compared against the nasal pressure airflow sensor and matched in all 11 subjects. The differences in results were due to the condition of ROI not available in case of QB1, which did not happen in QB2.

In the case of IB1, the eleven subjects had a total of 33 events as each participant had three sets of central, obstructive and hypopnoeic events. Out of the total 33 events, the results obtained by thermal imaging matched in 16 events, partially matched in 5 events and in 12 events the ROI were not available. On the other hand in the case of IB2 the results of thermal imaging were compared against the nasal pressure airflow sensor and were matched in 32 events and in 1 event the results of thermal imaging did not matched.

Summarizing the results, there were a total of 88 events in 44 recordings of 11 subjects (4 recording each). QB1 and QB2 had 11 events each and IB1 and IB2 had 33 events each. Out of these 88 events, in 63 events the results of thermal imaging matched the results of contact sensors, in case of 9 events the results of thermal imaging partially matched with those of the results of contact sensors, in 15 events the ROI was not available in the recordings and in case of 1 event the approach failed to match the results of the contact sensors in place.

8.3 Testing of KLT Based and Template Based Tracking methods on Paediatrics

The next step was the testing of the two tracking on paediatric patients from Sheffield Children's Hospital. Three patients were included. A novel technique based on template matching was developed for this purpose for testing and analysis of thermal imaging with two different approaches in the hospital setting. The findings of both the approaches were similar, providing the same results in terms of respiration rate and detection of apnoea related pauses in breathing.

Data from the whole night thermal recordings of PSG monitoring of three paediatric patients were processed and analysed with both approaches. Both approaches provided robust respiration monitoring. They indicated the respiration rate correctly as compared to the contact sensors. In the first case the respiration rate of sum of respiratory bands provided a respiration rate of 14.34 breaths per minute (bpm). This value was matched by the respiration rate of 14.06 bpm and 14.35 bpm obtained by using thermal imaging with template matching and KLT based approach respectively. In another case the respiration rate of 18 bpm for a paediatric patient was also matched by both the template matching and KLT based approaches for tracking ROI to extract the respiration signal.

Furthermore different apnoea events shown by the respiration signal of contact sensors were also correctly identified and picked in the respiration signal obtained by thermal imaging using both the developed approaches. A unique characteristic of thermal imaging signal was noted that it provided respiration related information during the apnoea events in finer details than the respiration signal of the contact sensors, proving the edge of thermal imaging over contact sensors in terms of

sensitivity. Thermal imaging indicated reduced respiratory airflow in central apnoea of the cases examined while the contact sensors did not indicate this issue clearly. The analysis of thermal imaging respiration signals also showed drift in relation to respiratory pattern, while the respiratory signal from contact sensors did not. This analysis of the drift in thermal imaging respiratory signal may have significant diagnosis related information as it points to changes in the respiratory pattern over time.

8.4 Further Work

Thermal imaging is a novel method in the field of respiration monitoring and apnoea detection and diagnosis because of its non-contact nature meaning sensors are not attached during monitoring. Along with its advantages, it also has some issues that need opportunities for improvements in the area. The main difficulty with thermal imaging method based respiration monitoring is dealing with very large head and body movements. Currently the camera is fixed on a tripod in front of the patient and if the patient's face moves out of the camera's field of view, the monitoring fail. This problem could be countered with further improvements in tracking for example by allowing a feedback to the camera to reorient to the new position. This is a major research flaw, but its successful implementation could make thermal imaging an important tool for monitoring sleep disordered breathing.

Thermal cameras are expensive devices. Although their cost over time is reducing, nevertheless developing a cost effective customised thermal imaging device dedicated for respiratory monitoring will be valuable.

The recorded respiratory related thermal videos were processed off-line. It will be advantageous to implement a real-time processing of the data.

Currently the scoring of the apnoea type from the recorded data are performed by an experienced clinician offline. This is time consuming. It will be helpful to devise an approach to assist with the apnoea scoring.

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Appendix A: Participant Information Sheet for Young Children (0-5 years)

<u>**PARTICIPANT INFORMATION SHEET**</u>

<u>**FOR YOUNG CHILDREN**</u>

Study title: Using a camera to measure breathing

This information is to be shown and read by a parent/carer

I am a researcher who is studying how we breathe

I would like to find out if a special camera can measure

your breathing

To help us find out more, I would like to measure your
breathing

I would also like to ask you and your mummy and daddy some
questions

If you don't want to do this – just say no thank you !

Thanks for reading this

Appendix B: Participant Information Sheet for Children Aged (6-10 years)

To be shown and read by parent/carer if required

Study title: **Using a heat sensitive camera to measure breathing**

1. What is research?

Research is a way we try to find out the answers to questions.

2. Why is this project being done?

We want to try and find out if our new test that uses a heat detecting camera (called a thermal camera) can measure the amount of air you breathe in and out. This may help us measure breathing during sleep.

3. Why have I been asked to take part?

You have been chosen because your doctor has said you should have a sleep study at the hospital to measure your breathing. We are asking 30 children to take part in the study.

4. Did anyone else check the study is OK to do?

Before any research is allowed to happen, it has to be checked by a group of people called a Research Ethics Committee. They make sure that the research is fair. Your project has been checked by the Research Ethics Committee.

5. Do I have to take part?

No you do not! It is up to you. We would like you to read this information sheet. If you agree to take part, we would like you to write your name, if you can, on two forms. We will also ask your mum, dad or carer to write their name on the forms and give one back to us. You can still change your mind later. If you don't want to take part, just say no!

6. What will happen to me if I take part in the research?

If you are happy to take part in the research study, then pictures of your face will be taken with a heat sensitive camera that can measure your breathing overnight. You can see the pictures of yourself if you want to. We have used the same camera on other children in the hospital before. We will also ask your grown up to complete a questionnaire. Then the research study will be over.

7. Will joining in help me?

No, but it may help us to know more about how to measure breathing during sleep in the future.

8. What happens when the research stops?

We will collect all the information together and we will decide if it is useful in telling us if the doctors can use heat sensitive cameras in the future to measure breathing.

9. What if something goes wrong during the project?

We do not think anything will go wrong, but if it does, your mum, dad or carer will be able to talk to someone who will be able to tell them what they need to do about it.

Will my medical details be kept private if I take part? Will anyone else know I'm doing this?

The people in our research team will know you are taking part. The doctor looking after you while you are in hospital will also know. No one else will know because we will not use your name or address. You will get a number which will be used instead.
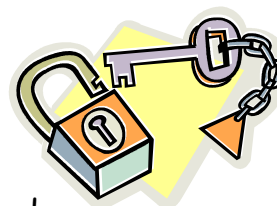
10.   What if I don't want to do the research anymore?

If at any time you don't want to do the research any more, just tell your parents, carer, doctor or nurse. They will not be cross with you. You will still have the same care whilst you are in hospital.

11.   What happens to what the researchers find out?

When we collect your information we will make sure it is stored in a safe place and only the people doing the research study can look at it.
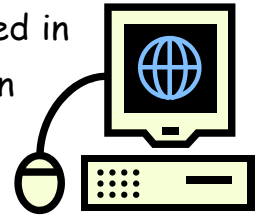
We will use the information to teach doctors about how to measure breathing more easily, and we will put it in medical magazines and on websites that doctors read.

A short summary will also be on the hospital's and Sheffield Hallam University research websites. No-one will know you were in the study.

12.   How can I find out more about this study?

Your mum, dad, carer or other grown up you trust may be able to answer your questions. The doctors and nurses looking after you can also help you find out more about the study.

Thank you for taking the time to read this – please ask any questions if you need to.

Appendix C: Participant Information Sheet for Children/Young People Aged (11-15 years)

PARTICIPANT INFORMATION SHEET

FOR CHILDREN/YOUNG PEOPLE AGED 11 TO 15

Study title: Measuring Breathing Airflow Using a Heat Sensitive Camera

We are asking if you would join in a research project to find the answer to the question 'Can a heat sensitive camera measure breathing?' Before you decide if you want to join in, it's important to understand why the research is being done and what it will involve for you. So please consider this leaflet carefully. Talk to your family, friends, doctor or nurse if you want to.

Part 1 – to give you first thoughts about the project

1.   Why are we doing this research?
We want to try and find out if a heat measuring camera (called a thermal camera) is helpful in measuring breathing airflow. When you breathe out your nose becomes slightly warmer and when you breathe in it becomes slightly cooler. The thermal camera produces a video of these heat changes from which we can measure airflow. We are specifically interested in the breathing patterns seen during sleep and how this new method compares with the nasal sensors that are currently used in a sleep study to measure breathing airflow.

2.   Why have I been invited to take part?
You have been chosen because your doctor has decided that you are coming into the hospital for an overnight sleep study recording. We would like to do the thermal camera video recording during your planned overnight sleep study. We are asking 30 children to take part.

3.   Do I have to take part?

No! It is up to you. We will ask you for your assent and then ask if you would sign a form. We will give you a copy of this information sheet and your signed form to keep. You are free to stop taking part at <u>any time during the research</u> without giving a reason. If you decide to stop, this will not affect the care you receive.

4.   What will happen to me if I take part?

Your overnight sleep study will go ahead as planned. As part of the research we would also measure your breathing using the thermal camera. This camera will be positioned in your sleep study bedroom near to your bed. This camera will be set up to record your face and will measure the heat coming from your face as you breathe in and out. It can record the video in complete darkness and so normal lighting will not be altered for the research. The camera is completely harmless and will not disturb your sleep (for example it does not make any noise). We have used the camera on other studies in the hospital and the sleep unit before without problem. The researchers will set the camera up whilst you are awake and being set up for your sleep study. Before recording begins you can see the camera for yourself and ask the researchers to demonstrate it for you. After the recording, the thermal video will be analysed by the researchers to compare your breathing with the usual nasal sensors used in a sleep study, to see if the new thermal imaging camera is as good as traditional sensors in measuring breathing. In the morning your parent/carer will be asked to complete a short questionnaire on how you found the thermal camera compared to the nasal sensors. Then the research is completed.

5.   What will I be asked to do?

You will be asked if you want to take part in the research study. If you are happy to take part then one of the researchers will give you an assent form to sign. You will not be asked to do anything else for the purposes of the research study.

6.   Is there anything else to be worried about if I take part?

There is nothing to worry about for this study. The research test (thermal imaging camera) will not be uncomfortable in any way.

7.   What are the possible benefits of taking part?

We cannot promise the study will help you but the information we get might help treat children and young people who have to have an overnight sleep study.

8.   Contact for further information

If you would like any further information about this study you could contact:

Name: Professor Heather Elphick

Designation: Consultant Paediatrician in Sleep and Respiratory Medicine

Hospital/Department: Dept of Sleep and Respiratory Medicine

Sheffield Children's NHS Foundation Trust

Tel: 0114 2717585

Thank you for reading so far - if you are still interested, please go to Part 2:

Part 2 - more detail – information you need to know if you want to take part.

9. What happens when the research project stops?

We will collect all the information together and we will decide if it is useful in telling us if the doctors can manage breathing during sleep better in the future.

10. What if there is a problem or something goes wrong?

Tell us if there is a problem and we will try and sort it out straight away. You and your mum, dad or carer can either contact the project co-ordinator:

Name: Prof Heather Elphick

Designation: Consultant Paediatrician in Sleep and Respiratory Medicine

Hospital/Department: Sheffield Children's NHS Foundation Trust

Tel: 0114 2717585

or the hospital complaints co-ordinator:

Patient Advice & Liaison Co-ordinator

Sheffield Children's NHS Foundation Trust

Tel: 0114 271 7594

11. Will anyone else know I'm doing this?

The people in our research team will know that you are taking part. The nurse looking after you whilst in hospital will also know. Your medical notes may also be looked at by staff working at the hospital to check that the study is being carried out correctly. We will keep your information in confidence. This means

we will only tell those who have a need or right to know. You will be given a unique number which we will use instead of your personal details. Any information about you that leaves the hospital will have your name, date of birth and address removed so that you cannot be recognised from them.

12.   Who is organising and funding the research?

Researchers at Children's NHS Foundation Trust are organising this study. They will not get any extra money for doing this research. The research is being funded by The Children's Hospital Charity Research Fund. The research is supported by Sheffield Hallam University.

13.   Who has reviewed the study?

Before any research goes ahead it has to be checked by a Research Ethics Committee. They make sure that the research is fair. This study has been checked by Sheffield Hallam University's Research Ethics Committee. It has also been checked by the Research Department at this hospital and has been approved by the Research Ethics Committee of Sheffield Hallam University.

Thank you for reading this – please ask any questions if you need to.

Appendix D: Parent/Legal Guardian Information Sheet

<u>**PARENT/LEGAL GUARDIAN INFORMATION SHEET**</u>

Study title: Measuring Breathing Airflow Using a Heat Sensitive Camera

*We would like to invite you and your child to take part in our research study. Before you decide we would like you to understand why the research is being done and what it would involve. **One of our team will go through the information sheet with you and answer any questions you have.** Talk to others about the study if you wish.*

Part 1 tells you the purpose of this study and what will happen to you and your child if you take part.
Part 2 gives you more detailed information about the conduct of the study.

Ask us if there is anything that is not clear.

Part 1 – to give you first thoughts about the project

1. **What is the purpose of the study?**

During a sleep study sensors are attached to the face and body to measure sleep and breathing patterns. One of the purposes of a sleep study is to look for changes in your child's breathing pattern by measuring airflow using two sensors positioned at the nose. These sensors are often poorly tolerated by children overnight. Breathing produces temperature changes around the nose and the mouth which can also be measured using a high resolution thermal imaging camera. The non-invasive technique of thermal imaging holds promise as a better technique to measure airflow. The aim of the study is to investigate thermal imaging to measure airflow. We would like to test the accuracy of this new method on 30 children. The method does not involve any direct contact of the thermal imaging equipment with the child.

2. Why have we been invited?

We want to compare the new method of thermal imaging with the existing method of nasal sensors in children and young people who are already attending the sleep unit for assessment of their breathing during sleep. We are choosing children who are attending the hospital for an overnight sleep study. This research study will not in any way affect the quality of your child's sleep study. We will recruit 30 children in the study.

3. Do we have to take part?

It is up to you and your child (wherever possible) to decide to join the study. We will describe the study and go through this information sheet. If you agree to take part, we will then ask you to sign a consent form. If your child is able to understand the research and is happy to take part and can write their name, they will be asked to sign an assent form with you, if they want to.

You will be given a copy of the information sheets and the signed consent and assent forms to keep for your records. You are free to withdraw at any time, without giving a reason. This would not affect the standard of care your child receives.

4. What will happen to my child if we agree take part?

Your child will be set up for their sleep study as planned. Therefore, this study has no bearing on the manner in which your child is medically treated. If you take part in the research study, you will be asked for permission for a thermal camera to be in the room where your child's sleep study is taking place. The thermal camera will also be set up whilst your child is still awake and takes images from a distance to determine the amount of heat emitted from the nose and mouth during breathing. Later on, the research team will process the images to investigate whether this approach can be used instead of nasal sensors to measure airflow during a sleep study. The camera will not be in direct contact with your child and will not cause any harm. The thermal imaging camera will record overnight. The camera's images are thermal

rather than visual and so the child cannot be identified from them. The camera is completely safe and will not disturb your child's sleep overnight. It is quiet and operates in the dark. After the overnight recording, you will be asked to complete a short questionnaire seeking feedback on the thermal imaging camera, in addition to the age, gender and reason for having the sleep study being recorded by the research team. After this you and your child will have no further involvement in the research study. You will be able to stay with your child throughout the sleep study and the research study.

5. Expenses and payments

There are no expenses or payments for taking part in this research. This has been decided because you and your child are already attending the overnight sleep study for clinical purposes.

6. What happens to the recorded videos and the research questionnaire?

If you and your child agree to take part in the research, your child will be issued with a research ID number rather than using their name. The thermal image recording and the questionnaire will be stored with a research ID number (anonymously) onto the research laptop. Later on, the research team will compare the results from the sleep study to those from the thermal imaging data.

7. What are the possible disadvantages and risks of taking part?

The research staff will visit your sleep unit bedroom to discuss the study and consent. They will also enter the room to switch the thermal imaging camera on and off. The research questionnaire will take 10 minutes extra of your time. If at any time you or your child feels unable to continue with the research, please don't hesitate to tell a member of the sleep unit staff and the thermal imaging recording will stop.

8. What are the possible benefits of taking part?

Your child will not benefit from by taking part in this study and the results of the study will not affect his/her medical treatment.   However the information we collect may help us to treat future patients better.

9. What happens when the research study stops?

We will collect all the information together and we will decide if the thermal imaging camera is a useful alternative to nasal sensors in detecting airflow in sleep studies.

10. What if there is a problem?

Any complaint about the way you or your child have been dealt with during the study or any possible harm you or your child might suffer will be addressed. The detailed information on this is given in Part 2.

11. Will my child's taking part in the study be kept confidential?

Yes. We will follow ethical and legal practice and all information about your child will be handled in confidence. The details are included in Part 2.

This completes Part 1.

If the information in Part 1 has interested you and you are considering your child's participation, please read the additional information in Part 2 before making any decision.

Part 2 of the information sheet

12. What will happen if we don't want to carry on with the study?

If you withdraw from the study, we will destroy all your child's thermal imaging data relating to the study if you wish, but we will need to use the data collected up to their withdrawal.

13. What if there is a problem?

Complaints: If you have a concern about any aspect of this study, you should ask to speak to the researchers who will do their best to answer your questions.

Name: Professor Heather Elphick

Designation: Consultant Paediatrician in Sleep & Respiratory Medicine

Hospital/Department: Dept of Sleep and Respiratory Medicine

Sheffield Children's NHS Foundation Trust

Tel: 0114 271 7585

If you remain unhappy and wish to complain formally, you can do this by contacting:

Patient Advice & Liaison Co-ordinator

Sheffield Children's NHS Foundation Trust

Tel: 0114 271 7594

Harm

In the event that something does go wrong and your child is harmed during the research and this is due to someone's negligence then you may have grounds

for a legal action for compensation, but you may have to pay your legal costs. The normal NHS complaints mechanisms will still be available to you.

14. Will my taking part in this study be kept confidential?

All information which is collected about your child during the course of the research will be kept strictly confidential. Any information about your child which leaves the hospital will have their name, date of birth and address removed so that they cannot be recognised from it. Once the study is complete all information will be kept for 5 years in a secure location and then destroyed in accordance with standard operating procedures. Our procedures for handling, processing, storage and destruction of data are compliant with the Data Protection Act 1998. The thermal imaging videos will be stored on an encrypted laptop. The data will be coded and only authorised people involved in the research study will have access. Your child's medical notes may also be looked at by other staff within the hospital involved in the running and supervision of the study to check that it is being carried out correctly.

15. What will happen to the results of the research study?

When the study has finished we will present our findings to other researchers, doctors and health professionals at professional events, and we may put the results in medical magazines and websites that researchers read. We would also like to put a brief summary on the hospital research website so that you will be able to read about our results too. This will be available at the end of the study, on www.sheffieldchildrens.nhs.uk/research-and-innovation.htm. The results will also be included as part of an MPhil/PhD student's educational qualification. They will be anonymous, which means that your child will not be able to be identified from them.

16.Who is organising and funding the research?

The research is being organised by Sheffield Children's NHS Foundation Trust and is funded by The Children's Hospital Charity Research Fund. The research is supported by Sheffield Hallam University.

17.Who has reviewed the study?

All research in the NHS is looked at by an independent group of people, called a Research Ethics Committee, to protect your interests. This study has been reviewed and given a favourable opinion by *Sheffield Hallam University's* Research Ethics Committee. It has also been approved by the Research Department at this hospital.

18.How can I find out more?

If you would like to know more about research in general, the Clinical Research Facility at this hospital has an **Information for families** section on its website www.sheffieldchildrens.nhs.uk/research-and-innovation.htm or you could contact the hospital Clinical Research Facility:

Ms Wendy Swann

R&D Manager

Sheffield Children's NHS Foundation Trust

Tel: 0114 3053478

If you would like to know more specific information about this research project, please contact the project co-ordinator:

Name: Professor Heather Elphick

Designation: Consultant Paediatrician in Sleep & Respiratory Medicine

Hospital/Department: Dept of Sleep and Respiratory Medicine

Sheffield Children's NHS Foundation Trust

Tel: 0114 271 7585

If you would like advice as to whether your child should participate you could contact the project team, or one of your child's health care professionals.

If you have any concerns during the study, you should contact the project team.

If you and your child decide to take part in this study, you will be given this information sheet and signed consent and assent forms to keep.

Thank you for taking the time to read this information sheet.

Appendix E: Anonymous Data Collection Form

Sheffield Children's **NHS**
NHS Foundation Trust

Study ID: _ _ _ _ _ _ _

ThermFlow Data Collection Form

Variable	Value
Date of PSG	
Age (2dp) at time of PSG (yrs)	
Gender	
Reason for PSG	
Co-morbidities	
Is this their first PSG?	
Have the child worn nasal sensors for any significant length of time?	

Appendix F: Assent Form Children & Young People

ASSENT FORM FOR CHILDREN & YOUNG PEOPLE

(To be completed by the child/young person and their parent/carer)

Title of project: Measuring Breathing Airflow Using a Heat Sensitive Camera
Participant study number:

Child (or if unable, parent on their behalf)/young person to circle all they agree with:

Has somebody else explained this project to you?   Yes / No

Do you understand what this project is about?   Yes
/ No

Have you asked all the questions you want?   Yes
/ No

Have you had your questions answered in a way you understand?   Yes / No

Do you understand it's OK to stop taking part at any time?   Yes / No

Are you happy to take part?   Yes / No

If any answers are 'no' or you don't want to take part, don't sign your name!

If you do want to take part, you can write your name below

Your name _____   Date
_____

The person who explained this project to you needs to sign too:

_____   _____

Name of Researcher   Signature   Date

Thank you for your help.

1 for participant; 1 for researcher site file; 1 to be kept with hospital notes

Appendix G: Consent Form Parent/Carer

Participant study number:

PARENT / CARER CONSENT FORM

Title of project: Measuring Breathing Airflow Using a Heat Sensitive Camera

Researchers: Prof Heather Elphick, Dr Ruth Kingshott, Prof Reza Saatchi and Muhammad Usman.

Please initial box

1. I confirm that I have read and understand the information sheet dated 21/04/2017 (version 1.0) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand that my child's participation is voluntary and that I am free to withdraw my child at any time, without giving any reason, without my medical care or legal rights being affected.	
3. I understand that relevant sections of any of my child's medical notes and the data collected during the study, may be looked at by researchers and those involved in running and supervising the study from Sheffield Children's NHS Foundation Trust or from the regulatory authorities, where it is relevant to my taking part in research. I give permission for these individuals to have access to my records.	
4. I understand that as part of my child's involvement in the study, thermal imaging video will be taken of the face. The images / videos taken will be completely anonymised.	
5. I agree to my child taking part in the above study	
OPTIONAL 6. I agree that anonymous images of my child's face may be reproduced at a later date for medical publications, presentations or press releases	

_____   _____

_____

Name of Parent/ Guardian   Signature   Date

_____   _____

Name of Child   Relationship to Child

_____   _____

_____

Name of Person taking consent   Signature   Date

When completed: 1 for participant; 1 (original) for researcher site file; 1 to be kept with hospital notes

Appendix H: Staff Evaluation Questionnaire

Study ID: _ _ _ _ _ _ _

ThermFlow Sleep Unit Staff Evaluation Questionnaire

1. Did the patient tolerate the nasal pressure flow sensor? ☐ yes   ☐ no

If not, please give reasons why:

………

………

………

2. Did the patient tolerate the nasal thermistor sensor? ☐ yes   ☐ no

If not, please give reasons why:

………

………

………

3. Did the patient tolerate the thermal imaging system? ☐ yes   ☐ no

If not, please give reasons why:

………

………

………

4. Please write down any further anonymous comments /feedback to the research team about the overnight study:

………

………

………

Many thanks for your help and feedback on this questionnaire

Appendix I: Parent/Carer/Child Evaluation Questionnaire

<u>Evaluation Questionnaire – Parent/Carer/Child</u>

Sheffield Children's **NHS**
NHS Foundation Trust

Study ID: _ _ _ _ _ _ _

ThermFlow Evaluation Questionnaire

<u>Falling off to Sleep</u>

1) Was your sleep/your child's sleep onset delayed by the nasal sensors?
Please rate on a scale of 1 to 10 (1 being very delayed to 10 being not delayed at all)

☹ 😐 ☺

(Very delayed)   1   2   3   4   5   6   7   8   9   10   (Not delayed at all)

2) Was your sleep/your child's sleep onset delayed by the thermal imaging system?
Please rate on a scale of 1 to 10 (1 being very delayed to 10 being not delayed at all)

☹ 😐 ☺

(Very delayed)   1   2   3   4   5   6   7   8   9   10   (Not delayed at all)

<u>Sleep Disturbance</u>

3) Was your sleep/your child's disturbed by the nasal sensors?

Please rate on a scale of 1 to 10 (1 being very disturbed to 10 being not disturbed at all)

☹ 😐 ☺

(Very disturbed)   1   2   3   4   5   6   7   8   9   10   (Not disturbed at all)

4) Was your sleep / your child's sleep disturbed by the thermal imaging system?
Please rate on a scale of 1 to 10 (1 being very disturbed to 10 being not disturbed at all)

☹ 😐 ☺

(Very disturbed)   1   2   3   4   5   6   7   8   9   10   (Not disturbed at all)

5) In a future sleep study, would you prefer to just have the nasal sensors or the thermal imaging system? (please choose 1)

☐   Nasal sensors   ☐   Thermal Imaging System

6) **Please write down any further comments and feedback about the nasal sensors or the thermal imaging system**

……

……

Many thanks for your help and feedback on this questionnaire

Appendix J: SHU Ethics Approval

Your study's ethics application   Inbox x

Saatchi, Reza <engrs@exchange.shu.ac.uk>   9 Jun 2017, 11:58
to me

Dear Usman

Your study's ethics application to carry out evaluation thermal imaging tests (as explained in the attached shurec2a) on healthy people at Sheffield Hallam University was approved by the Faculty Ethics Committee yesterday. The related ethics application documents are attached.

Best wishes

Reza

From: Saatchi, Reza
Sent: 09 June 2017 11:53
To: Bows, Andrea
Cc: ! ACES Research Ethics Committee (FREC)
Subject: Muhammad Usman

Dear Andrea

Would you mind please archiving the approved ethics application from Muhammad Usman. It was considered and approved by FREC yesterday.

Many thanks

Best wishes