IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 14, 2017, accepted July 26, 2017, date of publication August 4, 2017, date of current version August 29, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2735419

Monitoring of Cardiorespiratory Signal: Principles of Remote Measurements and Review of Methods

ALI AL-NAJI[1,2], KIM GIBSON[3], SANG-HEON LEE[1], (Member, IEEE), AND JAVAAN CHAHL[1,4], (Member, IEEE)
[1]School of Engineering, The University of South Australia at Mawson Lakes, Mawson Lakes, SA 5095, Australia
[2]Electrical Engineering Technical College, Middle Technical University, Baghdad 10022, Iraq
[3]School of Nursing and Midwifery, The University of South Australia, Adelaide, SA 5000, Australia
[4]Joint and Operations Analysis Division, Defence Science and Technology Group, Melbourne, VIC 3207, Australia

Corresponding author: Ali Al-Naji (ali_abdulelah_noori.al-naji@mymail.unisa.edu.au)

ABSTRACT Physiological signs can be remotely observed from the physiological and physical effects caused by a cardiorespiratory activity. A wide range of research on remote cardiorespiratory monitoring systems has been done using different methods, including methods based on Doppler effect, thermal imaging, and video camera imaging. The aim of this paper was to review and compare the newest and most promising of such remote measuring methods, introducing their merits and limitations under different circumstances. In addition, this paper summarizes the performance of these methods in a table regarding the noise artifacts, subject movement, the number of regions of interest, generalization to multiple subjects, detection range (distance), biological effects, and cost. This is a thorough general overview of the remote measurement of cardiorespiratory methods.

INDEX TERMS Cardiorespiratory signal, remote measurement methods, Doppler effect, thermal imaging, camera imaging, imaging photoplethysmography.

I. INTRODUCTION

Monitoring of human physiological signs, such as heart rate, heart rate variability, respiration rate, and blood oxygen saturation plays a role in diagnosis of health conditions and abnormal events, such as tachycardia, bradycardia, bradypnoea, tachypnoea, apnoea, and hypoxemia [5]–[7]. Conventionally, monitoring of cardiorespiratory activity is achieved by using adhesive sensors, electrodes, leads, wires and chest straps which may cause discomfort and constrain the patient if used for long periods of time. Also, these sensors may cause skin damage, infection or adverse reactions on people with sensitive skin (e.g., neonates or those suffering burns) [10]–[12]. There is also an element of cost involved since the monitoring leads and electrodes supposed to be for single use only and require disposal [17]. In addition, infants attached to monitors with leads and wires may be at risk of strangulation or entanglement [24]. The benefits of reducing the problems associated with contact monitoring systems has led to research using different alternative measurement methods for monitoring of physiological signs, such as the use of the radar Doppler effect, thermal imaging and camera imaging.

Many studies have reported that these remote methods could be alternative and effective methods in extracting physiological signs with adequate accuracy and reliability. The baseline of these remote methods relies on an observation of the physiological and physical effects resulting from the cardiorespiratory activity of both the cardiovascular and respiratory systems with different principles. Since these remote methods operate on different principles, each has its merits and limitations when applied under different scenarios, including noise artefacts, subject movement, the number of ROIs, generalisation to multiple subjects, detecting range, biological effects and cost.

This paper aims to provide a comparative review of recent studies in remote sensing of cardiorespiratory activity based on different technologies as well as to review their performance, advantages and disadvantages under various clinical scenarios. This review may provide the opportunity for researchers to evaluate the challenges and gaps of these methods and therefore enable further research opportunities.

II. BACKGROUND PHYSIOLOGY

A. CARDIOVASCULAR SYSTEM

The cardiovascular system is probably the most important human physiological system because it is responsible for transporting blood throughout the body. The cardiovascular system is composed of the heart, which pumps blood, and the circulatory system. The circulatory system is a network of the arteries, capillaries, and veins responsible for delivering blood, nutrients, oxygen and hormones to the body's organs as well as removing waste products from the body. There are two main loops in the blood circulatory system; the pulmonary circulation and the systemic circulation. Pulmonary circulation transports the blood from the heart to the lungs to absorb oxygen (O_2) and release carbon dioxide (CO_2) which then transports the oxygenated blood back to the heart [37]. The systemic circulation transports the oxygenated blood from the heart to the rest of the body, and returns the deoxygenated blood to the heart to begin the process again. The blood flow through the cardiovascular system is shown in Fig. 1.

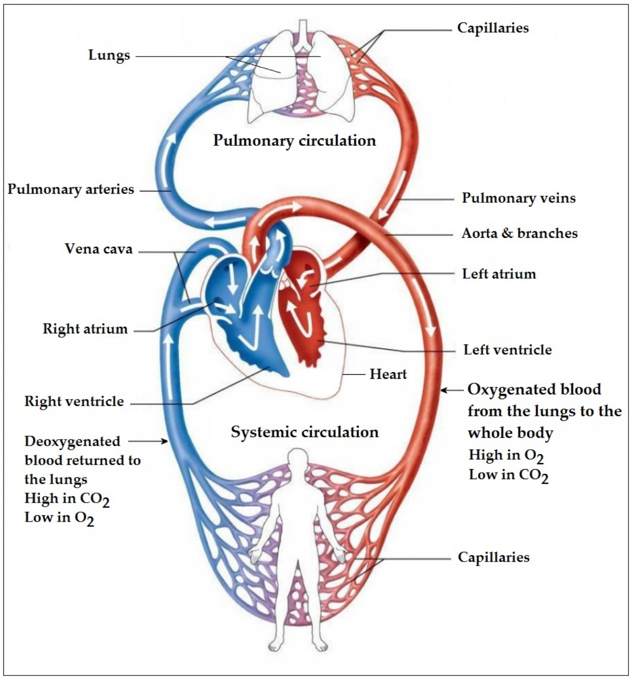

FIGURE 1. **The cardiovascular system of the human body (Adapted from Website: www.anatomybody-charts.us/circulatory-system-diagram/circulatory-system-diagram-heartdiagram6).**

B. RESPIRATORY SYSTEM

The respiratory system plays a major role by exchanging gases in the human body through inhalation of O_2 needed by the body's cells and exhalation of a waste product of cellular function (CO_2). The structure of the respiratory system is comprised of the upper and lower respiratory systems. The upper respiratory system consists of the mouth, nose, pharynx, and larynx which filters, moistens and warms the inhaled air before reaching the lower respiratory system. The lower respiratory system comprises of the trachea, bronchi, lungs and diaphragm. During inhalation, oxygen enters the lungs from the upper system via the trachea which branches into the left and right bronchi. The bronchi also branches many times throughout the lungs to form a network of tubes inside the lung called alveoli, which are responsible for gas exchange between the inhaled air and the blood. The O_2 travels across the walls of the alveoli into the blood, and the CO_2 crosses from the blood in the capillaries (small blood vessels) into the air in the alveoli and is then exhaled. The diaphragm is the main respiratory muscle which moves to support inhalation and exhalation of the air through the respiratory system [37].

The exhaled air has higher temperature and more humidity than the inhaled air which can be observed as temperature variations around the nostril area [28]. The respiratory system of the human body is shown in Fig. 2.

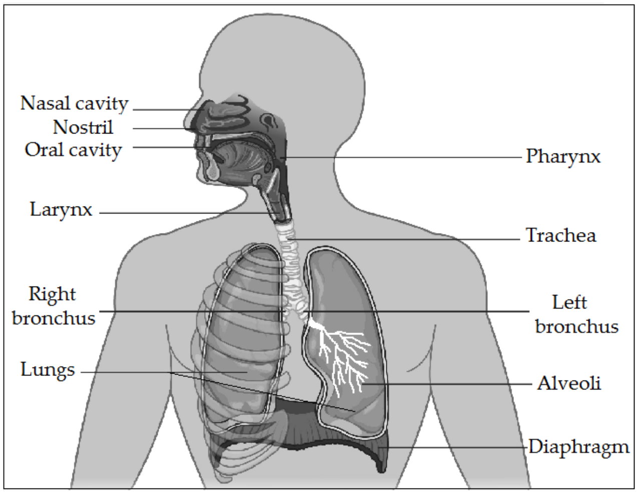

FIGURE 2. **The respiratory system of the human body (Adapted from Website: www.philschatz.com/anatomy-book/contents/m46548.html).**

III. PHYSIOLOGICAL EFFECTS OF CARDIORESPIRATORY ACTIVITY

Activity of the cardiovascular and respiratory systems causes physiological and physical effects on the human body. Although most of these effects are imperceptible to human operators due to limited spatiotemporal sensitivity of the human eye, they can be highly informative in biomedical and clinical settings [51]–[55]. The cardiorespiratory signal can be extracted based on the following mechanisms:

A. SKIN COLOR CHANGES

The color of blood varies due to the exchange of gases through cardiorespiratory action which affects the skin color. The blood cells appear red because of the dominating of the hemoglobin. The spectrum of light absorbed by hemoglobin in blood cells differs between the oxygenated and deoxygenated states, oxygenated blood appears lighter than the deoxygenated blood. Blood absorbs light more than surrounding tissue due to its dark and opaque appearance. In addition, the oxygenated blood appears lighter in color than the deoxygenated blood. Theoptical properties of the skin color changes due to cardiorespiratory activity can be described as photoplethysmographic (PPG) [59]–[61].

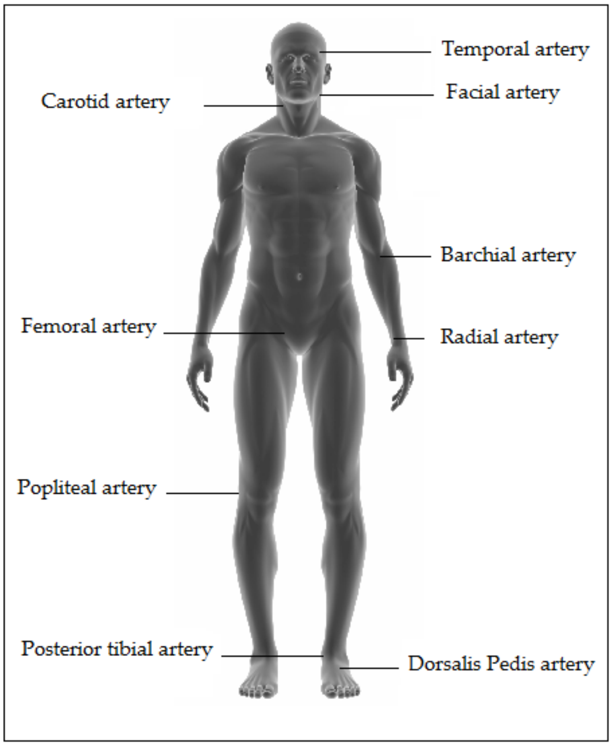

FIGURE 3. Anatomical locations of the arterial pulse.

B. ARTERIAL PULSE MOTION

The contractions of the heart muscle produce periodic dilatation waves travelling along the vascular tree at a speed of 4 m/s to 10 m/s, causing deflections in the surrounding tissues of the arterial walls [65]. Since the heart pumps blood via the arteries under high pressure and high velocity, the arterial pulse can be revealed in different anatomical locations on the human body as shown in Fig. 3. Furthermore, blood flowing through major superficial arteries also produces time-varying heat patterns which can also be observed in these locations providing useful information about the cardiorespiratory signal.

C. HEAD MOTION

The carotid arteries are major blood vessels that deliver oxygenated blood from the heart to the neck, face and brain. There are four carotid arteries; two on each side of the neck: right and left external carotid arteries and right and left internal carotid arteries. The external carotid arteries supply blood to the neck and face and the internal carotid arteries supply blood to the brain [37]. The physiology of the carotid arteries is shown in Fig. 4.

When the heart muscle pumps blood to the head via the carotid arteries, subtle head motions are generated as a result of pressure changes. The cardiac cycle of blood from the heart to the head via the carotid arteries causes a subtle head oscillation. This is caused by the Newtonian reaction to the influx of blood at each pulse. The head motion has been estimated to be around 5mm in amplitude and falls within a frequency band of 1-5 Hz [75].

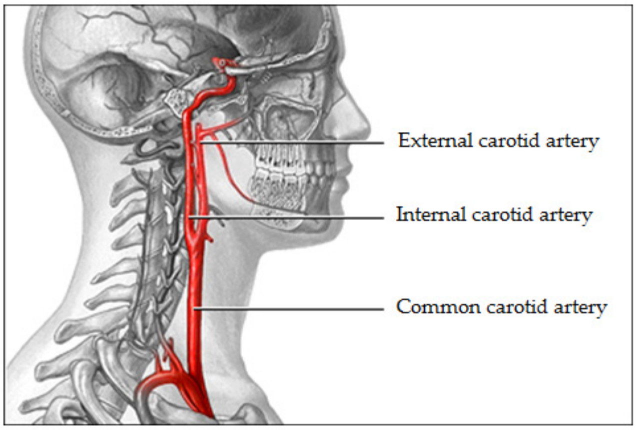

FIGURE 4. Blood flows from the heart to the head via the carotid arteries (Adapted from Website: https://medlineplus.gov/ency/presentations/100124_1.htm).

D. CHEST MOTION

The volumetric changes of the heart muscle due to pumping blood through the circulatory system can be transmitted to the chest leading to a subtle movement. This movement of the chest wall has an amplitude of 0.2 mm to 0.5 mm within a frequency band between 1 Hz and 2 Hz. The chest also moves as a result of movement of the diaphragm muscle from 4 mm to 12 mm with a different frequency band between 0.1 Hz and 0.3 Hz [54], [85].

IV. RELEVANCE OF PHYSIOLOGICAL SIGNS

The physiological effects of cardiorespiratory activity provide a signal which can be processed to extract physiological measures such as heart rate, heart rate variability, respiration rate, and blood oxygenation.

- Heart rate (HR) is one of most important signs and is defined as the number of cardiac beats per unit of time, typically expressed as beats per minute (beat/min). The normal range of HR for an adult varies from 60 to 100 beats/min [90]. The HR can be an indicator of developing hypertension, atherosclerosis [94] and cardiovascular events, such as tachycardia (a medical condition when the heart pulse exceeds the normal range) and bradycardia (a medical condition when the HR is under the normal range) [6].
- Heart rate variability (HRV) is defined as beat-to-beat variations or fluctuations of the heart rate period over time that occurs in the heart because of a complex internal dynamic balance.
- Respiratory rate (RR) is an important clinical sign that is defined as the number of breaths per unit of time, typically expressed as breaths per minute (breaths/min). Abnormal breathing patterns can be detected by measuring the RR such as tachypnea (a medical condition when respiration exceeds the normal range), bradypnea (a medical condition when respiration is under the normal range) and apnoea (a medical condition when there is no respiration) [7].

- Oxygen saturation (SpO_2) is another important clinical sign that is defined as the ratio of concentration of oxygenated hemoglobin carried by blood cells to the total concentration of hemoglobin. The normal range of SpO_2 varies from 94% – 100% and any abnormal values less than this range is called hypoxemia [5].

V. REMOTE MEASURING METHODS

A wide range of research has been done to extract physiological signs with several different methods, including methods based on Doppler Effect, thermal imaging and video camera imaging.

A. PHYSIOLOGICAL SIGNS EXTRACTION BASED ON DOPPLER EFFECT

The Doppler Effect is an active measurement technique capable of detecting subtle movement of the chest wall resulting from mechanical activity of the heart and lungs thereby revealing the cardiorespiratory signal. Also, it can detect the deflections in the skin due to arterial blood pressure.Physiological signs within the cardiorespiratory signal can be measured using Doppler radar and digital signal processing (DSP) techniquesby determining the frequency shift between the transmitted signals and the received radar signals reflected off a surface of interest. A time varying phase $\emptyset\,(t)$ between the radar and the surface of interest can be determined as [15], [27]

$$\emptyset\,(t) = \frac{4\pi}{\lambda} x(t) \tag{1}$$

where $x(t)$ is the displacement signal and λ is the wavelength of the signal. The radar sensor is an active measurement technique since it emits energy. It is therefore important to determine the power density level (D) to assess human exposure, which can be calculated as follows: [107]

$$D_{(mW/cm^2)} = \frac{PG}{40\pi r^2} \tag{2}$$

where P (mW) is an output radiating power of the radar sensor, G(dB) is the gain of radar antenna and r (cm) is the distance between the radar and the subject. 10 mW/cm^2 is the safe power density level for human exposure at operating frequencies from 10 to 300 GHz [107], [110].

The block diagram of Doppler Effect and main signal processing techniques are shown in Fig. 5.

There are two major methods using Doppler Effect:

1) ELECTROMAGNETIC RADAR-BASED METHODS

Measurement of human physiological signs based radar has been explored with three types of electromagnetic radar systems; continuous-wave, frequency-modulated (FM) and ultra-wide band (UWB). Many studies have focused on using Doppler radar at different frequencies, output powers, and distances. Various researches using Doppler radar are reviewed and summarized in Table 1, where the rating scale for removal of noise and artifacts from the cardiorespiratory signal ranging from '*' (least effective) to '*****' (most effective).

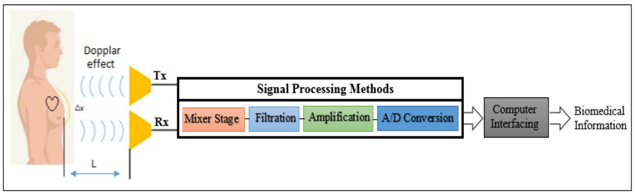

FIGURE 5. Using Doppler radar to extract physiological signs for human body.

Several advantages are associated with electromagnetic radar-based methods, which can be listed as follows:

- Promising results and reliability with stationary subjects.
- Possibility of extracting the cardiorespiratory signal even if there is some non-metal materials, such as wood, clothes, glass and water between the radar and the subject.
- Possibility of extracting of the cardiorespiratory signal from medium and long distances (up to 30m) [97], [114]. However, it is prone to motion artifacts and noise.

Most of the previous studies, however, have many limitations including:

- Radar-based methods are prone to motion artifacts and noise when movement of the surface of interest is very small (small Doppler shifts) or superposed on other movements (e.g.of the subject's head and arms).
- Radar-based methods restrict subject movement and need an exposed ROI to analyse, which is inappropriate for long-term monitoring [54].
- At distances of greater than 1 meter, radar-based methods are prone to degradation due to the motion artifacts and noise caused by the increased free space loss. For example, SNR decreases to about 50% as the distance of the subject from the electromagnetic radar sensor increases from 0.25m to 2.5m [58].
- Radar-based methods are limited to extracting the cardiorespiratory signal of one subject at a time.
- Radar-based methods need specialized hardware to produce radio frequencies and process return signals with low noise.
- Achieving a high displacement resolution and sensitivity at different distances requires the use of a radar sensor with high frequency and output power. This may lead to biological effects on humans [54], [56].

2) LASER RADAR-BASED METHODS

Based on the Doppler Effect, laser Doppler velocimetry (LDV) is an optical vibrocardiography technique that uses a laser radar instead of radio-frequency radar to extract the shift in laser frequency caused by the movement of the surface of interest [115], [116]. The LDV emits a laser with high spatial resolution and temporal coherence, making the beam able to measure the smallest Doppler shifts with a displacement resolution of about 8 nm [54], [117].

TABLE 1. **A research review of the electromagnetic radar-based methods.**

	Vital signs	Radar freq.	ROIs	Motion artifact	Subject movement	Detection range (m)	No. of subjects at a time	Signal power
Greneker [1]	HR and respiratory	24 GHz	Chest region	*	*	10	1	30mW
Matthews, Sudduth & Burrow [8]	HR and respiratory	35 GHz	Chest region	*	*	Short distance	1	0.017 mW
Droitcour et al. [15]	HR and respiratory	1.09 - 1.99 GHz	Chest region	*	*	1	1	5mW
Lubecke, Ong & Lubecke [21]	HR and respiratory	10 GHz	Chest region	*	*	0.5	1	19.95 mW
Lohman et al. [27]	HR and respiratory	2.4 GHz 850 MHz	Chest region	*	*	1-2	1	Low power
Yamada et al. [30]	HR	2.4 GHz	Chest region	*	*	1	1	2mW 0.2μW 20nW
Droitcour et al. [35]	Respiratory	2.4 GHz	Chest region	*	*	1	1	Low power
Vasu et al. [40]	Cardiac activity	5.8 GHz	Chest region	**	**	0.5-1.5	1	8mW
Vasu et al. [43]	Cardiac activity	5.8 GHz	Chest region	**	**	0.5-1.5	1	8mW
Min et al. [49]	Respiratory activity	240 KHz	Chest region	*	*	1	1	Low power
Scalise et al. [58]	Respiratory activity	6 GHz	Chest region	*	*	0.25-2.5	1	1mW
Lie et al. [64]	HR and respiratory	2.4 GHz	Chest region	**	*	0.5-1.5	1	Low power
Birsan & Munteanu [67]	HR and respiratory	24 GHz	Chest region	*	*	0.5-1	1	39mW
Tan, Qiao & Li [70]	HR and respiratory	24 GHz	Chest region	*	*	0.5	1	Low power
Kao et al. [74]	HR and respiratory	60 GHz	Chest region	*	*	0.3	1	Low power
Hu et al. [78]	HR, HRV and respiratory	5.8 GHz	Chest region	**	**	0.5	1	5.62 mW
Wang et al. [81]	HR and respiratory	5.88 GHz	Chest region	**	**	0.91-3.65	1	Low power
Ren et al. [86]	HR and respiratory	3.3 GHz	Chest and back region	**	**	1	1	Low power
Adib et al. [89]	HR and respiratory	5.46 GHz	Chest region	**	*	1-8	1	0.75mW
Huang et al. [93]	HR and respiratory	5.8 GHz	Chest region	**	*	<2	1	0.1 mW
Dalal, Basu & Abegaonkar [97]	HR and respiratory	10 GHz	Chest region	**	**	1	1	Low power
Mercuri et al. [100]	HR and respiratory	2.4 GHz	Chest region	**	**	0.5-2	1	Low power

A number of studies for extracting the cardiorespiratory signal based on LDV have been undertaken. For example, a study by Morbiducci *et al.* [117] used LDV as an optical remote approach for extracting cardiac activity at a distance of 1.5m based on the measurement of chest wall movements. The study by Scalise and Morbiducci [118] used LDV to monitor cardiac activity at a distance of 1.5m by sensing the skin surface vibrations in the neck caused by the vascular wall motion in the carotid artery. Others studies detected chest wall movements (velocity and displacement) by the LDV to measure respiratory activity of adults [119] and infants inside an incubator [120] at a distance of 1.5m. A study by Kaplan *et al.* [121] used LDV to detect movements of the skin overlaying the carotid artery by sensing the dynamics of the skin caused by the blood pressure pulse. In their study they were also able to detect the respiration phase and show how the cardiac signal shape was affected by the state of the subject. A proposed non-contact method based on LDV was also proposed by Marchionni *et al.* [122] to detect the cardiorespiratory signal of an infant inside an incubator at a detection range of 1m– 2m.

There are several advantages of laser Doppler-based methods that are as follows:

- High sensitivity even with very small Doppler shifts (high displacement resolution).
- Possibility of extracting the cardiorespiratory signal at long operative distances (tens of meters) [117], [118].
- No biological effects on human as a low power density is required (less than 1mW),although it is recommended to avoid directing the laser beam at the eye [120].

Laser Doppler-based methods suffer some disadvantages, such as:

- High cost [54].
- The method is highly affected by motion artifacts and subject movement and can only be applied when the ROIs are distinct. The high displacement resolution (8nm) is directly related to deformation of the cardiorespiratory signal despite superposed small movement of the human body making it inappropriate for long-term use [54]. Furthermore, LDV cannot distinguish between movement resulting from cardiorespiratory activity and

some unexpected movements that correspond to other physiological dynamics [121].
- Limited to one subject at a time.

B. PHYSIOLOGICAL SIGNS EXTRACTION BASED ON THERMAL IMAGING

Thermal imaging is a passive measurement technique (does not emit energy), which can be used to detect the emitted radiation from certain locations of the human body in the infrared (IR) range of the electromagnetic spectrum to extract the cardiorespiratory signal. The spectral range of thermal imaging systems typically involve four IR bands: near IR (0.75-3 μm), middle IR (3-6μm), far IR (6-15 μm) and extreme IR (15-100 μm) [13], [123]. Two physiological effects as a result of cardiorespiratory activity can be sensed by thermal imaging techniques. The first effect related to cardiac activity, is the slight heat variations caused by pulsating blood flow in the major superficial arteries at certain anatomical locations (see Fig. 3). This can be detected by a thermal camera to reveal the cardiac signal. The heat variations due to the pulsating blood flow is estimated at approximately 0.08 Kelvin (-273.07 C^o), which is far less than normal skin temperature (310 Kelvin) [38]. The second effect is related to respiratory activity, where the thermal camera can be applied to extract the respiratory signal by detecting small temperature variations around the nostril area of approximately 0.1C^o [28]. A simple diagram of the thermal imaging system for extracting and measuring physiological signs is shown in Fig. 6.

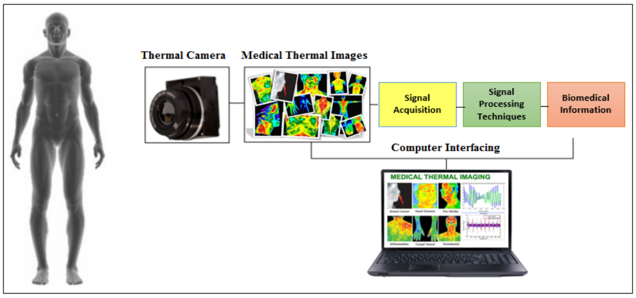

FIGURE 6. Using thermal imaging to extract physiological signs for the human body.

In the last two decades many researchers have conducted studies of IR thermographic imaging for monitoring a wide range of physiological signs for subjects both in clinical and non-clinical environments. The research undertook analysis, synthesis, development and performance of thermographic imaging for monitoring and measuring physiological signs. The major studies using thermal imaging are reviewed and summarized in Table 2.

Thermal imaging-based methods are very appealing for non-contact measurement methods that can use several ROIs to extract cardiorespiratory signal as well as being robust to motion artifact, subject movement and noise. In addition, they have an advantage under conditions of varying illumination, especially when the ambient illumination is dim. However, they still have many limitations:

- Thermal imaging-based methods are affected by small heat variations and several other complex interactions, including motion artifacts and head rotation. The small heat variations mean that the techniques are also affected by ambient environmental thermal noise due to the variation of background temperature.
- Thermal imaging-based methods cannot be applied to the subject when the ROIs are unclear to analyze or the subject is moving (i.e. the ROI cannot be covered by a blanket, intubation equipment or face masks).
- Thermal imaging-based methods are limited to short distances and low depth of field.
- Thermal imaging-based methods need specialized hardware and are thus expensive [54].

C. PHYSIOLOGICAL SIGNS EXTRACTION BASED ON CAMERA IMAGING

1) COLOR-BASED METHODS

The optical properties of light passing through or reflecting from the skin due to blood volume variations can be described as PPG [59]–[61]. PPG is an optical monitoring technology that can provide valuable information about cardiorespiratory activity in biomedical and clinical environments [124]. The principle of PPG is that blood absorbs light more than the surrounding tissue which causes macroscopic changes in the optical properties of the skin due to the hemoglobin associated with blood flow. PPG technology needs a dedicated illumination source to illuminate a part of the body and a photo-detector (attached to the skin) to detect the optical properties of the skin. Non-contact camera-based PPG is called imaging photoplethysmography (iPPG). The basic principle of iPPG is shown in Fig. 7.

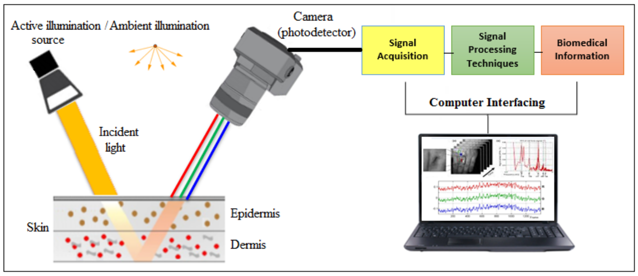

FIGURE 7. Principle of iPPG. A digital camera is used to detect the optical properties of the skin tissue either with dedicated illumination or ambient light.

Recently, many studies have used a video camera as a photodetector either with a dedicated illumination source or ambient light to detect PPG data without any physical contact with the skin. In a light-controlled environment, some research has succeeded in extracting PPG data based on analysis of the red, green and blue (RGB) channels captured by a video camera with a dedicated illumination source at different wavelengths (530–940 nm) and considered the ambient

TABLE 2. A research review of the thermal imaging-based methods.

	Vital signs	Thermal range	ROIs	Motion artifact	Subject movement	Detection range (m)	No. of subjects at a time	Long/Short term monitoring
Murthy, Pavlidis & Tsiamyrtzis [3]	Respiratory activity	Mid-wave IR	Nose	*	*	1.83-2.44	1	Short term
Chekmenev, Rara & Farag [13]	Cardiac and respiratory	Far-wave IR	Nose and neck	*	*	1	1	Short term
Sun et al. [16]	Cardiac activity	Far-wave IR	Forehead, neck and wrist	*	*	1.83	1	Short term
Fei & Pavlidis [23]	Respiratory activity	Mid-wave IR	Nose	*	*	1.83-2.44	1	Short term
Murthy & Pavlidis [28]	Respiratory activity	Mid-wave IR	Nose	**	*	1.83-2.44	1	Short term
Pavlidis et al. [32]	Cardiac and respiratory	Mid-wave IR	Forehead, neck wrist and nose	**	*	3	1	Short term
Garbey et al. [36]	Cardiac activity	Mid-wave IR	Forehead, neck and wrist	**	**	0.91-3	1	Short term
Yang et al. [38]	Cardiac and respiratory	Mid-wave IR	Neck and noise	**	**	~1	1	Short term
Chekmenev et al. [45]	Cardiac activity	Far-wave IR	Forehead	**	*	1.2	1	Short term
Fei & Pavlidis [48]	Respiratory activity	Mid-wave IR	Nose	**	*	1.83	1	Short term
Abbas et al. [56]	Respiratory activity	Far-wave IR	Nose	**	*	1-1.3	1	Long term
Abbas et al. [62]	Respiratory activity	Far-wave IR	Nose	**	**	1.5	1	Long term
Lewis, Gatto & Porges [66]	Respiratory activity	Far-wave IR	Nose	**	*	~1	1	Short term
Blanik et al. [71]	Respiratory activity	Far-wave IR + RGB	Nose	**	**	~1	1	Long-term
Klaessens et al. [76]	Cardiac activity	Far-wave IR+ RGB	Forehead and nose	**	**	~1	1	Long-term
Nakayama et al. [79]	Cardiac and respiratory	Far-wave IR+ RGB	Face and nose	**	**	0.5	1	Long-term
Bennett, Goubran & Knoefel [82]	Cardiac activity	Far-wave IR	Forehead, cheek, chest and arm	**	*	~1	1	Short term

visible light (e.g. green) as a source of noise [125]–[133]. However, a dedicated illumination source may annoy the subject, especially infants and may increase the experimental hardware setup [69].

Other researches have shown that the PPG data can be remotely acquired from RGB channels using only the ambient light for illumination. Extraction of PPG data with ambient illumination was first proposed by Takano and Ohta [2]. Their methodology used the average pixel value of the ROI of a single channel followed by an autoregressive (AR) spectral analysis to extract frequency bands of interest. Another study used multiple channel analysis to extract PPG data followed by Fast Fourier transform (FFT) to extract frequency bands of interest [9]. Many algorithmic image processing techniques can be used with single/multiple channel analysis to improve the extracted signal. For example, Bousefsaf *et al.* [50] used spectral skin analysis based on skin detection to isolate skin pixels that contain PPG information and reduce the influence of illumination variations. Another example, Tarassenko *et al.* [96] used AR modelling and pole cancellation to remove frequency components caused by artificial illumination variations. A study by Feng *et al.* [102] used an adaptive green/red difference (GRD) to enhance the signal from moving subjects. Chen *et al.* [103] used a reflectance decomposition method on the green channel and ensemble empirical mode decomposition (EEMD) to extract the cardiac signal from the environmental illumination noise in the PPG data. Qi *et al.* [104] proposed an improved remote measurementsystem to enhance the PPG signal by incorporating facial sub-regions landmark localization andusing a joint blind source separation (JBSS) methodto recover thePPG signal. Another study by Cheng *et al.* [108] demonstrated the feasibility of removing the illumination variation noise from the PPG data using JBSS and EEMD. Other researchers used blind source separation (BSS) methods to enhance the PPG data under motion artifact assumptions, such as principle component analysis (PCA) [25] to separate temporal RGB channel waveforms into uncorrelated signal sources and independent component analysis (ICA) [10], [19], [20], [29], [33], [41], [46], [91] to separate temporal RGB channel waveforms into independent signal sources, in order to retrieve the cardiorespiratory signal. A motion robustness method based on chrominance (CHRO) signals was proposed by de Haan and Jeanne [73] to linearly combine the color difference signals using the standardized skin-tone assumption. A later study by Hsu *et al.* [99] proved that the PPG data extracted from ICA or by analyzing chrominance-based model can be improved by leveraging the mid-level PPG based features using support vector regression (SVR). Another motion robustness method based on blood volume pulse signature was also proposed by De Haan and Van Leest [11], which used the blood volume pulse vector (PBV) as a signature for different skin-reflection spectrums to explicitly separate the cardiorespiratory signal from motion noise. A study by Wang *et al.* [109] proposed a new iPPG method based on spatial subspace rotation (2SR), which estimated a spatial subspace of skin-pixels and determined its temporal rotation in the image domain to extract the cardiorespiratory signal. A plane orthogonal to skin based-method was proposed by Wang *et al.* [111] to define a plane orthogonal to the skin [114] in the temporally normalized color space based on physiological reasoning. Later, Wang *et al.* [112] improved the robustness of PPG signal over the POS method using subband decomposition to enable the independent suppression of multiple motion frequencies in fitness applications.A novel remote measuring system based on partial least squares (PLS) and multivariate empirical mode decomposition (MEMD) was recently proposed by Xu *et al.* [113] to effectively extract PPG signalunderchanging illumination conditions. A summary of these representative iPPG studies is presented in Table 3.

Several advantages are associated with the color-based methods mentioned in Table 3 and can be listed as follows:

- Promising results and reliability with stationary and non-stationary subjects.
- Possibility of extracting the cardiorespiratory signal from multiple subjects at the same time [20].
- Many anatomical ROIs can be applied to extract the cardiorespiratory signal.
- No biological effects on human.
- Low cost [54], [134].

However, it can be seen from Table 3 that color-based methods have some challenges:

- Color-based methods need clear ROIs to extract the cardiorespiratory signal.
- Color-based methods are limited to short distances and depth of field may impact image focus.
- PPG waveforms vary due to different ROIs, artificial illumination variations and skin tone.

2) MOTION-BASED METHODS

Small-amplitude motion in different ROIs captured by a video camera may also contain useful information about cardiorespiratory activity. Many researchers have analyzed video and image sequences to detect these motions and extract physiological signs either with a dedicated illumination source or ambient light. For example, earlier studies used a CCD camera as a non-contact sensor to extract the respiratory activity by detecting optical flow of the body surface movement resulting from respiratory rhythms [4], [14]. Another study by Parra and Da Costa [18] proposed a non-contact method based on a video camera to detect the skin displacement caused by mechanical deflection caused by arterial blood pressure at different ROIs. In the work of Frigola *et al.* [22], the video camera provided a respiratory monitoring system based on image processing through analysis of the visual movement of the subject's chest based on optical flow analysis. However, optical flow based methods are affected by artificial noise due to subject movement, lighting conditions and unclear ROIs. A study by Sato and Nakajima [26] developed a remote monitoring system to detect respiratory activity and related sleep disorders using two CCD cameras and two fiber grating (FG) 3D vision sensors by detecting the volume change in the location caused by respiratory rhythms. Another study by Wiesner and Yaniv [31] used a Webcam to track the motion of colorful markers attached to the subject's abdomen in the epigastric region to extract respiratory rate based on PCA. Other studies [34], [39], [44], [47], [57], [63], [68] proposed remote respiratory monitory systems using a depth image sensing camera (e.g. time of flight (ToF) sensor, and Kinect sensor) without the use of markers to track 2D/3D surface information of the subject's chest and abdomen based on average depth information within the ROI. However, depth image sensing cameras are limited to short detection ranges [135]–[137]. A study by Bartula *et al.* [72] used a monochrome camera to track the raw respiratory signal and non-respiratory motion, followed by a classifier to select only the valid breath measurements. Some research [75], [77], [80], [92] used head motion as a result of the systolic pressure in the carotid arteries to reveal the cardiac signal based on ICA [77], PCA [75], [80] and a frame subtraction method [92]. The arterial pulse in different ROIs (e.g. wrist, hand neck and leg) was extracted by He *et al.* [87] and Al-Naji and Chahl [95] based on video magnification techniques. Recently, Prathosh *et al.* [98] proposed a new generic blind deconvolution system to estimate periodic respiration signals from videos by modeling every pixel in the abdominal-thoracic region as the output of a linear time-invariant (LTI) channel connected in parallel with an unknown dynamics response. Various research describing the applications of camera imaging with motion based-methods are reviewed and summarized in Table 4.

The motion-based methods have two advantages over the color-based methods. The first advantage is that they are effective even when skin is not visible or even when the ROI is unclear for analysis (e.g. covered by a blanket or a mask. The second advantage is that they are not affected by artificial illumination variations or skin tone as they rely on motion detection rather than skin color analysis. However, there are still some disadvantages for moving subjects and when measuring from larger distances which results in noise dominating the signal.

VI. DISCUSSION

All of the reviewed remote measuring methods are promising for extracting physiological signs within the cardiorespiratory

TABLE 3. A research review of the iPPG-based methods.

	Vital signs	Sensor type	The used technique	ROIs	Motion artifact	Subject movement	Detection range (m)	No. of subjects at a time
Takano & Ohta [2]	Cardiac and respiratory	CCD	Single channel analysis	cheek	*	*	~1	1
Verkruysse, Svaasand & Nelson [9]	Cardiac and respiratory	CCD	Single/Multiple channel analysis	face & forehead	*	*	1-2	1
Poh, McDuff, & Picard [19, 20]	Cardiac and respiratory	Webcam	ICA	Face	**	**	0.5	1, 3
Lewandowska et al. [25]	Cardiac activity	Webcam	PCA	face & forehead	*	*	1	1
Pursche, Krajewski & Moeller [29]	Cardiac activity	Webcam	ICA	forehead, nose & mouth	**	**	0.5	1
Scalise et al. [33]	Cardiac activity	Webcam	ICA	forehead	**	**	0.2	1
Sun et al. [41, 42]	Cardiac and respiratory	CMOS+ Webcam	ICA	face, forehead & hand	**	**	0.35- 0.4	1
Kwon, Kim & Park [46]	Cardiac activity	Cell phone	ICA	face	**	**	0.3	1
Bousefsaf, Maaoui & Pruski [50]	Cardiac activity	Webcam	Single channel analysis + skin detections	face	***	**	1	1
Aarts et al [69]	Cardiac activity	CMOS	Single channel analysis	face & check	**	*	1	1
Zhao et al. [10]	Cardiac and respiratory	CMOS	ICA	face & chest	**	**	1	1
De Haan & Jeanne [73]	Cardiac activity	CCD	CHROM	face	***	***	~1	1
De Haan & Van Leest [11]	Cardiac activity	CCD	PBV	face	***	***	~1	1
Blanik et al. [71]	Cardiac and respiratory	CCD + thermal camera	Single channel analysis	forehead	**	**	~1	1
Li et al. [83]	Cardiac activity	iSight camera	Single channel analysis	face	***	***	0.35, 0.5	1
McDuff, Gontarek, Picard [88]	Cardiac and respiratory	Digital camera	Single/Multiple channel analysis	Face, forehead	**	**	3	1
Feng et al. [91]	Cardiac activity	Webcam	ICA	forehead	**	***	0.75	1
Tarassenko et al. [96]	Cardiac and respiratory	CCD	RGB channel analysis +auto-regressive (AR) model	forehead or check	**	**	1	1
Hsu, Lin & Hsu [99]	Cardiac activity	CMOS	SVR ICA/ CHRO	face	***	***	~1	1
Bal [101]	Cardiac activity	Webcam	RGB channel analysis + skin detections	face	***	**	~0.5	1
Feng et al. [102]	Cardiac activity	Webcam	Multiple channel analysis + GRD	face, forehead & check	***	***	0.75	1
Chen et al. [103]	Cardiac activity	Digital camera	Single channel analysis +EEMD	forehead	***	**	0.1-0.25	1
Qi et al. [104]	Cardiac activity	Digital camera	JBSS	face	**	*	~1	1
Lin et al. [105]	Cardiac activity	Digital camera	Single channel analysis +EEMD	forehead	***	**	~0.1	1
Wiede, Richter & Gangolf [106]	Cardiac activity	CCD	ICA/PCA	face & forehead	**	**	0.5-2	1
Cheng et al. [108]	Cardiac activity	Webcam	JBSS + EEMD	face	***	***	0.5	1
Wang, Stuijk & de Haan [109]	Cardiac activity	CCD	2SR	face & forehead	***	***	1.5	1
Wang et al. [111]	Cardiac activity	CCD	POS	face	***	***	~1.5	1
Wang et al. [112]	Cardiac activity	CCD	Sub-band decomposition	face	***	***	2	1
Xu et al. [113]	Cardiac activity	Webcam	PLS + MEMD	face	***	***	0.5	1

Note: CCD= charge-coupled device, CMOS= complementary metal-oxide-semiconductor.

TABLE 4. A research review of the MOTION-based methods.

	Vital signs	Sensor type	The used technique	ROIs	Motion artifact	Subject movement	Detection range (m)	No. of subjects at a time	Illumination source
Nakajima, Osa, & Miike [4]	Cardiac and respiratory	CCD	Optical flow	Entire body	*	*	2	1	near-infrared lamp
Nakajima, Matsumoto & Tamura [14]	Respiratory activity	CCD	Optical flow	Chest	*	*	2	1	Near-infrared lamp
Parra & Da Costa [18]	Cardiac activity	Video camera		Arm, wrist & neck	*	*	~1	1	Laser beam
Frigola, Amat & Pagès [22]	Respiratory activity	Video camera	Optical flow	Chest	*	*	~2	1	Ambient light
Sato & Nakajima [26]	Respiratory activity	CCD and FG	Optical 3D analysis	thoracic and abdominal area	*	*	~2	1	laser light source
Wiesner and Yaniv [31]	Respiratory activity	Webcam	PCA	thoracic and abdominal area	**	**	~1	1	Ambient light
Schaller, Penne & Hornegger [34]	Respiratory activity	ToF camera	Depth image sequence analysis	thoracic and abdominal area	**	**	~2	1	LED
Penne et al. [39]	Respiratory activity	ToF camera	Depth image sequence analysis	thoracic and abdominal area	**	**	0.6-1	1	LED
Falie, David & Ichim [44]	Respiratory activity	ToF camera	Depth image sequence analysis	thoracic and abdominal area	**	**	1	1	LED
Yu et al [47]	Respiratory activity	ToF camera	Depth image sequence analysis	thoracic and abdominal area	***	***	1.25	1	LED
Yu et al [57]	Respiratory activity	Kinect	Depth image sequence analysis	thoracic and abdominal area	***	***	1.4	1	Ambient light
Xia, & Siochi [63]	Respiratory activity	Kinect	Depth image sequence analysis	thoracic and abdominal area	***	***	2	1	Ambient light
Bernacchia et al. [68]	Cardiac and respiratory	Kinect	Depth info + ICA	Neck, chest and abdomen	***	***	1.2	1	Ambient light
Bartula, Tigges & Muehlsteff [72]	Respiratory activity	monochrome camera	Single channel analysis	thoracic and abdominal area	**	**	~2	1	Ambient light
Balakrishnan, Durand & Guttag [75]	Cardiac activity	Digital camera	Feature extraction + PCA	head	*	*	~1	1	Ambient light
Shan & Yu [77]	Cardiac activity	Cell phone	Feature extraction + ICA	head	*	*	0.4	1	Ambient light
Irani, Nasrollahi & Moeslund [80]	Cardiac activity	Webcam	Feature extraction + PCA	head	**	**	~1	1	Ambient light
Alnaji & Chahl [84]	Respiratory activity	CMOS	Video magnification + Frame subtraction	thoracic and abdominal area	**	**	1	1	Ambient light
He, Goubran & Liu [87]	Cardiac activity	Digital camera	Video magnification	Wrist	*	*	~0.5	1	Ambient light
Alnaji & Chahl [92]	Cardiac activity	CMOS	Video magnification + Frame subtraction	Head	**	**	0.5	1	Ambient light
Alnaji & Chahl [95]	Cardiac activity	CMOS	Video magnification + Frame subtraction	Wrist, arm, neck and leg	*	*	0.5	1	Ambient light
Prathosh et al. [98]	Respiratory activity	CMOS	Selective ensemble aggregation	thoracic and abdominal	**	*	~2	1	Ambient light

Note: LED= light-emitting diode.

signal from different ROIs. Each remote measuring method, however, has its advantages and disadvantages under different assumptions, leading to a number of challenges to consider. The advantages and disadvantages of each remote sensing method based on several influencing challenges are presented in Table 5, where symbol '*' indicates the minimum value and symbol '*****' indicates the maximum value.

The first influencing challenge is the noise artifacts against which the immunity of the reviewed remote measuring methods is compared. Noise artifacts can be classified in this

TABLE 5. The merits and demerits of reviewed underlying remote measuring methods.

Influencing challenges		Doppler Effect based methods		Thermal Imaging based methods	Camera Imaging based methods	
		Electromagnetic Radar	LDV		Color	Motion
Noise artifacts immunity	Motion artifacts	*	*	**	***	**
	Ambient enviro.	*****	****	****	**	****
Subject movement immunity		*	*	**	***	**
ROIs		*	*	**	***	***
Multiple subject		*	*	*	**	**
Detecting range		***	***	*	*	*
Active/passive		A	A	P	P	P
Biological effects		*****	**	*	*	*
Cost		***	****	****	*	*
Short*/Long***** term		*	**	****	*****	*****

review paper into two types. The first type is motion artifact noise acquired by minor motion in the ROI that are generated even with a stationary subject (e.g. facial expressions, talking, eye blinking or other minor unexpected movements). The second type is ambient environment condition noise (e.g. light conditions, ambient temperature and skin tone). Generally, all remote measurement methods that rely on motion to extract cardiorespiratory signals may be affected by motion artifact noise of the first type, while they present robust performance for the noise of the second type. In contrast, color based-methods are robust to motion artifact noise of the first type and highly affected by ambient environment conditions noise (light conditions and skin tone) as shown in Table 5.

The second significant challenge which may impact the reviewed remote measuring methods is subject movement (e.g. walking, excising, head rotation or sleeping with different postures) which may yield an unclear ROI. Radar-based methods are most affected by subject movement and any uncontrolled movement of the subject during the measurement. The reason returns to difficulty tracking a particular ROI in the field of view of the radar in addition to mixing the radar signal with other unexpected movements. On the other hand, vision systems have a greater possibility and flexibility for using many tracking algorithms to track single or multiple ROIs in the field of view. However, further study is still needed to overcome the significant challenge posed by variations in posture.

The next challenge is the number of ROIs that can be applied to extract physiological signs. As shown in Table 1, radar based methods rely greatly on the chest area in extracting the cardiorespiratory signal, although some other locations where the arterial pulse can be observed have proved to be feasible with laser radar. Thermal imaging-based methods are also restricted to limited ROIs located around the nasal area and certain locations of major superficial arteries close to the skin. Camera imaging-based methods have more flexibility in extracting physiological signs from multiple ROIs as shown in Table 3 and 4.

Generally, remote measuring methods can detect physiological signs from a single subject. Still, another challenge facing these methods is monitoring of physiological signs for a number of subjects at a time. While it is a difficult problem with radar-based methods and thermal imaging-based methods (both have been reported to be able to successfully extract physiological signs from a single subject), high resolution vision systems seem to be a promising approach to tracking physiological signs for a number of subjects at the same time. There was one study by Poh *et al.* [20] based oncamera imaging that succeeded in extracting the cardiorespiratory signal from three subjects simultaneously under a single scenario (stationary subjects), this may provide opportunity for further study to monitor physiological signs for a number of subjects at a time using camera imaging.

Detection range is another challenge facing the reviewed methods. It is clear from Table 5 that both laser and radio frequency radar-based methods can detect physiological signs at ranges of several meters (up to 30m). However, radar is prone to motion artifacts and noise as well as being constrained in the amount of emitted power. As imaging-based methods (thermal imaging and camera imaging) are currently limited to short distances (less than 3 m), further study is required with these methods to extend their detection range and extract physiological signs at long distances (up to tens of meters).

The biological effects associated with active measuring methods can be considered a disadvantage in contrast to the passive measuring methods. Although most of the radar-based methods (active methods) operate at safe power levels (<10 mW/cm2) for human exposure, the radiated energy that is focused in specific circumstances may be harmful to individuals' health and may cause effects on human biological tissue. In comparison, there are no biological effects on humans when the passive imaging methods are used, which should give priority to the image based methods.

Another important challenge in the reviewed remote measurement methods is the cost of the hardware. Radar methods and thermal imaging methods need high resolution hardware that will be expensive compared to mass produced cameras.

The issues caused by motion artifact sensitivity, subject movement sensitivity and possible biological effects make the radar-based method unsuitable for long term monitoring. Imaging-based methods on the other hand may be more appropriate for long-term monitoring.

Each reviewed method has its advantages and disadvantages and may outperform in some challenges but be inferior for others, a computer vision based system has high potential in being a robust and feasible method in terms of the noise artifacts, subject movement, number of ROIs, multiple subjects, detection range, possible biological effects and cost.

VII. CONCLUSION

In conclusion, it is evident that all reviewed remote measurementmethods, including the Doppler effect, thermographic imaging and video camera imaging could be successful alternative methods to conventional contact measurement methods used in biomedical and clinical environments. However, it can be seen from this review paper that these remote measurement methods have some advantages and disadvantages when they are applied under different assumptions, including noise artifacts, subject movement, number of ROIs, multiple subjects, detection range, possible biological effects and cost. We believe that a computer vision based system using visible light video (camera imagery) offers benefits where the subjects' safety, system cost, multiple subject detection, long distance and long-term monitoring are main considerations.

REFERENCES

[1] E. Greneker, "Radar sensing of heartbeat and respiration at a distance with applications of the technology," in *Proc. Radar*, 1997, pp. 150–154.

[2] C. Takano and Y. Ohta, "Heart rate measurement based on a time-lapse image," *Med. Eng. Phys.*, vol. 29, no. 8, pp. 853–857, 2007.

[3] R. Murthy, I. Pavlidis, and P. Tsiamyrtzis, "Touchless monitoring of breathing function," in *Proc. 26th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Sep. 2004, pp. 1196–1199.

[4] K. Nakajima, A. Osa, and H. Miike, "A method for measuring respiration and physical activity in bed by optical flow analysis," in *Proc. 19th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Nov. 1997, pp. 2054–2057.

[5] C. Rotariu and V. Manta, "Wireless system for remote monitoring of oxygen saturation and heart rate," in *Proc. Federated Conf. Comput. Sci. Inf. Syst.*, 2012, pp. 193–196.

[6] M. T. I. Papon, I. Ahmad, N. Saquib, and A. Rahman, "Non-invasive heart rate measuring smartphone applications using on-board cameras: A short survey," in *Proc. NSysS*, 2015, pp. 1–6.

[7] A. Alonso, J. Sasin, and N. Bottini, "Signs of respiratory disease," *apoptosis*, vol. 85, no. 8, pp. 721–726, 2006.

[8] G. Matthews, B. Sudduth, and M. Burrow, "A non-contact vital signs monitor," *Critical Rev. Biomed. Eng.*, vol. 28, nos. 1–2, pp. 173–178, 2000.

[9] W. Verkruysse, L. O. Svaasand, and J. S. Nelson, "Remote plethysmographic imaging using ambient light," *Opt. Exp.*, vol. 16, no. 26, pp. 21434–21445, 2008.

[10] F. Zhao, M. Li, Y. Qian, and J. Z. Tsien, "Remote measurements of heart and respiration rates for telemedicine," *PLoS ONE*, vol. 8, no. 10, p. e71384, 2013.

[11] G. De Haan and A. van Leest, "Improved motion robustness of remote-PPG by using the blood volume pulse signature," *Physiol. Meas.*, vol. 35, no. 9, p. 1913, 2014.

[12] M. Butler, J. Crowe, B. Hayes-Gill, and P. Rodmell, "Motion limitations of non-contact photoplethysmography due to the optical and topological properties of skin," *Physiol. Meas.*, vol. 37, no. 5, p. N27, 2016.

[13] S. Y. Chekmenev, H. Rara, and A. A. Farag, "Non-contact, wavelet-based measurement of vital signs using thermal imaging," in *Proc. 1st Int. Conf. Graph., Vis., Image Process.*, Cairo, Egypt, 2005, pp. 107–112.

[14] K. Nakajima, Y. Matsumoto, and T. Tamura, "Development of real-time image sequence analysis for evaluating posture change and respiratory rate of a subject in bed," *Physiol. Meas.*, vol. 22, pp. 21–28, Aug. 2001.

[15] A. Droitcour, V. Lubecke, J. Lin, and O. Boric-Lubecke, "A microwave radio for Doppler radar sensing of vital signs," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2001, pp. 175–178.

[16] N. Sun, M. Garbey, A. Merla, and I. Pavlidis, "Imaging the cardiovascular pulse," in *Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recogn.*, Jun. 2005, pp. 416–421.

[17] A. Al-Naji, K. Gibson, and J. Chahl, "Remote sensing of physiological signs using a machine vision system," *J. Med. Eng. Technol.*, vol. 41, no. 5, pp. 396–405, 2017.

[18] J. E. Parra and G. Da Costa, "Optical remote sensing of heartbeats," *Proc. SPIE*, vol. 4368, p. 113, Aug. 2001.

[19] M.-Z. Poh, D. J. McDuff, and R. W. Picard, "Advancements in noncontact, multiparameter physiological measurements using a webcam," *IEEE Trans. Biomed. Eng.*, vol. 58, no. 1, pp. 7–11, Jan. 2011.

[20] M.-Z. Poh, D. J. McDuff, and R. W. Picard, "Non-contact, automated cardiac pulse measurements using video imaging and blind source separation," *Opt. Exp.*, vol. 18, no. 10, pp. 10762–10774, 2010.

[21] O. B. Lubecke, P.-W. Ong, and V. Lubecke, "10 GHz Doppler radar sensing of respiration and heart movement," in *Proc. IEEE 28th Annu. Northeast Bioeng. Conf.*, Apr. 2002, pp. 55–56.

[22] M. Frigola, J. Amat, and J. Pagès, "Vision based respiratory monitoring system," in *Proc. 10th Med. Conf. Control Autom.*, 2002, pp. 9–12.

[23] J. Fei and I. Pavlidis, "Analysis of breathing air flow patterns in thermal imaging," in *Proc. 28th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Jun. 2006, pp. 946–952.

[24] I. Sheppard, L. Morris, and D. Blackstock, "Medication safety alerts," *Can. J. Hospital Pharmacy*, vol. 57, no. 3, pp. 176–179, 2004.

[25] M. Lewandowska, J. Rumi?ski, T. Kocejko, and J. Nowak, "Measuring pulse rate with a webcam—A non-contact method for evaluating cardiac activity," in *Proc. Federated Conf. Comput. Sci. Inf. Syst.*, 2011, pp. 405–410.

[26] I. Sato and M. Nakajima, "Non-contact Breath Motion Monitor ing System in Full Automation," in *Proc. IEEE 27th Annu. Int. Conf. Eng. Med. Biol. Soc.*, Jan. 2005, pp. 3448–3451.

[27] B. Lohman, O. Boric-Lubecke, V. M. Lubecke, P. W. Ong, and M. M. Sondhi, "A digital signal processor for Doppler radar sensing of vital signs," *IEEE Eng. Med. Biol. Mag.*, vol. 21, no. 5, pp. 161–164, Sep. 2002.

[28] R. Murthy and I. Pavlidis, "Noncontact measurement of breathing function," *IEEE Eng. Med. Biol. Mag.*, vol. 25, no. 3, pp. 57–67, May 2006.

[29] T. Pursche, J. Krajewski, and R. Moeller, "Video-based heart rate measurement from human faces," in *Proc. IEEE Int. Conf. Consum. Electron.*, Jan. 2012, pp. 544–545.

[30] S. Yamada, M. Chen, and V. Lubecke, "Sub-μW signal power Doppler radar heart rate detection," in *Proc. Asia–Pacific Microw. Conf.*, Dec. 2006, pp. 51–54.

[31] S. Wiesner and Z. Yaniv, "Monitoring patient respiration using a single optical camera," in *Proc. 29th Annu. Int. Conf. Eng. Med. Biol. Soc.*, 2007, pp. 2740–2743.

[32] I. Pavlidis, J. Dowdall, N. Sun, C. Puri, J. Fei, and M. Garbey, "Interacting with human physiology," *Comput. Vis. Image Understand.*, vol. 108, no. 1, pp. 150–170, 2007.

[33] L. Scalise, N. Bernacchia, I. Ercoli, and P. Marchionni, "Heart rate measurement in neonatal patients using a webcamera," in *Proc. IEEE Int. Symp. Med. Meas. Appl.*, May 2012, pp. 1–4.

[34] S. Christian, P. Jochen, and H. Joachim, "Time-of-flight sensor for respiratory motion gating," *Med. Phys.*, vol. 35, no. 7, pp. 3090–3093, 2008.

[35] A. D. Droitcour *et al.*, "Non-contact respiratory rate measurement validation for hospitalized patients," in *Proc. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Sep. 2009, pp. 4812–4815.

[36] M. Garbey, N. Sun, A. Merla, and I. Pavlidis, "Contact-free measurement of cardiac pulse based on the analysis of thermal imagery," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 8, pp. 1418–1426, Aug. 2007.

[37] K. Saladin, *Anatomy & Physiology: The Unity of Form and Function*, vol. 31, 4th ed. New York, NY, USA: McGraw-Hill, 2007, p. 75.

[38] M. Yang, Q. Liu, T. Turner, and Y. Wu, "Vital sign estimation from passive thermal video," in *Proc. IEEE Conf. Comput. Vis. Pattern Recogn.*, Jun. 2008, pp. 1–8.

[39] J. Penne, C. Schaller, J. Hornegger, and T. Kuwert, "Robust real-time 3D respiratory motion detection using time-of-flight cameras," *Int. J. Comput. Assist. Radiol. Surgery*, vol. 3, no. 5, pp. 427–431, 2008.

[40] V. Vasu, N. Fox, T. Brabetz, M. Wren, C. Heneghan, and S. Sezer, "Detection of cardiac activity using a 5.8 GHz radio frequency sensor," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Sep. 2009, pp. 4682–4686.

[41] Y. Sun, C. Papin, V. Azorin-Peris, R. Kalawsky, S. Greenwald, and S. Hu, "Use of ambient light in remote photoplethysmographic systems: Comparison between a high-performance camera and a low-cost webcam," *J. Biomed. Opt.*, vol. 17, no. 3, p. 0370051, 2012.

[42] Y. Sun, S. Hu, V. Azorin-Peris, S. Greenwald, J. Chambers, and Y. Zhu, "Motion-compensated noncontact imaging photoplethysmography to monitor cardiorespiratory status during exercise," *J. Biomed. Opt.*, vol. 16, no. 7, p. 077010, 2011.

[43] V. Vasu, C. Heneghan, T. Arumugam, and S. Sezer, "Signal processing methods for non-contact cardiac detection using Doppler radar," in *Proc. IEEE Workshop Signal Process. Syst.*, Oct. 2010, pp. 368–373.

[44] D. Falie, L. David, and M. Ichim, "Statistical algorithm for detection and screening sleep apnea," in *Proc. Int. Symp. Signals, Circuits Syst.*, Jul. 2009, pp. 1–4.

[45] S. Y. Chekmenev, A. A. Farag, W. M. Miller, E. A. Essock, and A. Bhatnagar, "Multiresolution approach for noncontact measurements of arterial pulse using thermal imaging," in *Augmented Vision Perception in Infrared*. London, U.K.: Springer, 2009, pp. 87–112.

[46] S. Kwon, H. Kim, and K. S. Park, "Validation of heart rate extraction using video imaging on a built-in camera system of a smartphone," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, San Diego, CA, USA, Aug. 2012, pp. 2174–2177.

[47] M.-C. Yu, H. Wu, J.-L. Liou, M.-S. Lee, and Y.-P. Hung, "Breath and position monitoring during sleeping with a depth camera," in *Proc. Int. Conf. Health Inf.*, 2012, pp. 12–22.

[48] J. Fei and I. Pavlidis, "Thermistor at a distance: Unobtrusive measurement of breathing," *IEEE Trans. Biomed. Eng.*, vol. 57, no. 4, pp. 988–998, Apr. 2010.

[49] S. D. Min, J. K. Kim, H. S. Shin, Y. H. Yun, C. K. Lee, and J.-H. Lee, "Noncontact respiration rate measurement system using an ultrasonic proximity sensor," *IEEE Sensors J.*, vol. 10, no. 11, pp. 1732–1739, Nov. 2010.

[50] F. Bousefsaf, C. Maaoui, and A. Pruski, "Continuous wavelet filtering on webcam photoplethysmographic signals to remotely assess the instantaneous heart rate," *Biomed. Signal Process. Control*, vol. 8, no. 6, pp. 568–574, 2013.

[51] D. Teichmann, C. Brüser, B. Eilebrecht, A. Abbas, N. Blanik, and S. Leonhardt, "Non-contact monitoring techniques - Principles and applications," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Sep. 2012, pp. 1302–1305.

[52] Y. Sun and N. Thakor, "Photoplethysmography revisited: From contact to noncontact, from point to imaging," *IEEE Trans. Biomed. Eng.*, vol. 63, no. 3, pp. 463–477, Mar. 2016.

[53] Y. G. Lim *et al.*, "Monitoring physiological signals using nonintrusive sensors installed in daily life equipment," *Biomed. Eng. Lett.*, vol. 1, no. 1, pp. 11–20, 2011.

[54] J. Kranjec, S. Beguš, G. Geršak, and J. Drnovšek, "Non-contact heart rate and heart rate variability measurements: A review," *Biomed. Signal Process. Control*, vol. 13, pp. 102–112, Sep. 2014.

[55] M. J. Gregoski *et al.*, "Development and validation of a smartphone heart rate acquisition application for health promotion and wellness telehealth applications," *Int. J. Telemed. Appl.*, vol. 2012, p. 1, Jan. 2012.

[56] A. K. Abbas, K. Heiman, T. Orlikowsky, and S. Leonhardt, "Non-contact respiratory monitoring based on real-time IR-thermography," in *Proc. World Congr. Med. Phys. Biomed. Eng.*, Munich, Germany, Sep. 2009, pp. 1306–1309.

[57] M.-C. Yu, J.-L. Liou, S.-W. Kuo, M.-S. Lee, and Y.-P. Hung, "Noncontact respiratory measurement of volume change using depth camera," in *Proc. Eng. Med. Biol. Soc.*, 2012, pp. 2371–2374.

[58] L. Scalise, A. De Leo, V. M. Primiani, P. Russo, D. Shahu, and G. Cerri, "Non contact monitoring of the respiration activity by electromagnetic sensing," in *Proc. IEEE Int. Workshop Med. Meas. Appl.*, May 2011, pp. 418–422.

[59] D. J. Meredith, D. Clifton, P. Charlton, J. Brooks, C. W. Pugh, and L. Tarassenko, "Photoplethysmographic derivation of respiratory rate: A review of relevant physiology," *J. Med. Eng. Technol.*, vol. 36, no. 1, pp. 1–7, 2012.

[60] Y. Mendelson and B. D. Ochs, "Noninvasive pulse oximetry utilizing skin reflectance photoplethysmography," *IEEE Trans. Biomed. Eng.*, vol. 35, no. 10, pp. 798–805, Oct. 1988.

[61] A. Kamal, J. Harness, G. Irving, and A. Mearns, "Skin photoplethysmography-a review," *Comput. Methods Programs Biomed.*, vol. 28, no. 4, pp. 257–269, 1989.

[62] A. K. Abbas, K. Heimann, K. Jergus, T. Orlikowsky, and S. Leonhardt, "Neonatal non-contact respiratory monitoring based on real-time infrared thermography," *Biomed. Eng. Online*, vol. 10, no. 1, p. 93, 2011.

[63] J. Xia and R. A. Siochi, "A real-time respiratory motion monitoring system using KINECT: Proof of concept," *Med. Phys.*, vol. 39, no. 5, pp. 2682–2685, 2012.

[64] D. Lie *et al.*, "A 2.4 GHz non-contact biosensor system for continuous monitoring of vital-signs," in *Telemedicine Techniques and Applications*. Rijeka, Croatia: InTech, 2011, pp. 211–238.

[65] G. Da Costa, "Optical remote sensing of heartbeats," *Opt. Commun.*, vol. 117, nos. 5–6, pp. 395–398, 1995.

[66] G. F. Lewis, R. G. Gatto, and S. W. Porges, "A novel method for extracting respiration rate and relative tidal volume from infrared thermography," *Psychophysiology*, vol. 48, no. 7, pp. 877–887, 2011.

[67] N. Birsan and D.-P. Munteanu, "Non-contact cardiopulmonary monitoring algorithm for a 24 GHz Doppler radar," in *Proc. Annu. Int. Conf. Eng. Med. Biol. Soc.*, 2012, pp. 3227–3230.

[68] N. Bernacchia, L. Scalise, L. Casacanditella, I. Ercoli, P. Marchionni, and E. P. Tomasini, "Non contact measurement of heart and respiration rates based on Kinect," in *Proc. IEEE Int. Symp. Med. Meas. Appl.*, Jun. 2014, pp. 1–5.

[69] L. A. Aarts *et al.*, "Non-contact heart rate monitoring utilizing camera photoplethysmography in the neonatal intensive care unit—A pilot study," *Early Hum. Dev.*, vol. 89, no. 12, pp. 943–948, Dec. 2013.

[70] H. Tan, D. Qiao, and Y. Li, "Non-contact heart rate tracking using Doppler radar," in *Proc. Int. Conf. Syst. Informat.*, 2012, pp. 1711–1714.

[71] N. Blanik, A. K. Abbas, B. Venema, V. Blazek, and S. Leonhardt, "Hybrid optical imaging technology for long-term remote monitoring of skin perfusion and temperature behavior," *J. Biomed. Opt.*, vol. 19, no. 1, p. 016012, 2014.

[72] M. Bartula, T. Tigges, and J. Muehlsteff, "Camera-based system for contactless monitoring of respiration," in *Proc. 35th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Jul. 2013, pp. 2672–2675.

[73] G. de Haan and V. Jeanne, "Robust pulse rate from chrominance-based rPPG," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 10, pp. 2878–2886, Oct. 2013.

[74] T.-Y. J. Kao, Y. Yan, T.-M. Shen, A. Y.-K. Chen, and J. Lin, "Design and analysis of a 60-GHz CMOS Doppler micro-radar system-in-package for vital-sign and vibration detection," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 4, pp. 1649–1659, Apr. 2013.

[75] G. Balakrishnan, F. Durand, and J. Guttag, "Detecting pulse from head motions in video," in *Proc. IEEE Conf. Comput. Vis. Pattern Recogn.*, Jun. 2013, pp. 3430–3437.

[76] J. H. Klaessens, M. Born, A. Veen, J. Sikkens Kraats, F. A. Dungen, and R. M. Verdaasdonk, "Development of a baby friendly non-contact method for measuring vital signs: First results of clinical measurements in an open incubator at a neonatal intensive care unit," *Proc. SPIE*, vol. 8935, p. 89351P, Feb. 2014.

[77] L. Shan and M. Yu, "Video-based heart rate measurement using head motion tracking and ICA," in *Proc. 6th Int. Congr. Image Signal Process.*, 2013, pp. 160–164.

[78] W. Hu, Z. Zhao, Y. Wang, H. Zhang, and F. Lin, "Noncontact accurate measurement of cardiopulmonary activity using a compact quadrature Doppler radar sensor," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 3, pp. 725–735, Mar. 2014.

[79] Y. Nakayama, G. Sun, S. Abe, and T. Matsui, "Non-contact measurement of respiratory and heart rates using a CMOS camera-equipped infrared camera for prompt infection screening at airport quarantine stations," in *Proc. Comput. Intell. Virtual Environ. Meas. Syst. Appl.*, 2015, pp. 1–4.

[80] R. Irani, K. Nasrollahi, and T. B. Moeslund, "Improved pulse detection from head motions using DCT," in *Proc. Int. Conf. Comput. Vis. Theory Appl.*, 2014, pp. 118–124.

[81] G. Wang, J.-M. Munoz-Ferreras, C. Gu, C. Li, and R. Gomez-Garcia, "Application of linear-frequency-modulated continuous-wave (LFMCW) radars for tracking of vital signs," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 6, pp. 1387–1399, Jun. 2014.

[82] S. L. Bennett, R. Goubran, and F. Knoefel, "Adaptive eulerian video magnification methods to extract heart rate from thermal video," in *Proc. IEEE Int. Symp. Med. Meas. Appl.*, May 2016, pp. 1–5.

[83] X. Li, J. Chen, G. Zhao, and M. Pietikainen, "Remote heart rate measurement from face videos under realistic situations," in *Proc. CVPR*, Jun. 2014, pp. 4264–4271.

[84] A. Al-Naji and J. Chahl, "Remote respiratory monitoring system based on developing motion magnification technique," *Biomed. Signal Process. Control*, vol. 29, pp. 1–10, Aug. 2016.

[85] D. Obeid, S. Sadek, G. Zaharia, and G. El Zein, "Multitunable microwave system for touchless heartbeat detection and heart rate variability extraction," *Microw. Opt. Technol. Lett.*, vol. 52, no. 1, pp. 192–198, 2010.

[86] L. Ren, H. Wang, K. Naishadham, Q. Liu, and A. E. Fathy, "Non-invasive detection of cardiac and respiratory rates from stepped frequency continuous wave radar measurements using the state space method," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2015, pp. 1–4.

[87] X. He, R. A. Goubran, and X. P. Liu, "Wrist pulse measurement and analysis using Eulerian video magnification," in *Proc. IEEE-EMBS Int. Conf. Biomed. Health Inf.*, Las Vegas, NV, USA, Feb. 2016, pp. 41–44.

[88] D. McDuff, S. Gontarek, and R. W. Picard, "Improvements in remote cardiopulmonary measurement using a five band digital camera," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 10, pp. 2593–2601, Oct. 2014.

[89] F. Adib, H. Mao, Z. Kabelac, D. Katabi, and R. C. Miller, "Smart homes that monitor breathing and heart rate," in *Proc. 33rd Annu. ACM Conf. Human Factors Comput. Syst.*, 2015, pp. 837–846.

[90] W. K. Lei, B. N. Li, M. C. Dong, and M. I. Vai, "AFC-ECG: An adaptive fuzzy ECG classifier," *Soft Computing in Industrial Applications*. Berlin, Germany: Springer, 2007, pp. 189–199.

[91] L. Feng, L.-M. Po, X. Xu, and Y. Li, "Motion artifacts suppression for remote imaging photoplethysmography," in *Proc. 19th Int. Conf. Digit. Signal Process.*, 2014, pp. 18–23.

[92] A. Al-Naji and J. Chahl, "Contactless cardiac activity detection based on head motion magnification," *Int. J. Image Graph.*, vol. 17, no. 1, p. 1750001, 2017.

[93] M.-C. Huang, J. J. Liu, W. Xu, C. Gu, C. Li, and M. Sarrafzadeh, "A self-calibrating radar sensor system for measuring vital signs," *IEEE Trans. Biomed. Circuits Syst.*, vol. 10, no. 2, pp. 352–363, Feb. 2016.

[94] p. Palatini and S. Julius, "elevated heart rate: A major risk factor for cardiovascular disease," *Clin. Experim. Hypertension*, vol. 26, nos. 7–8, pp. 637–644, 2004.

[95] A. Al-Naji and J. Chahl, "Non-contact heart activity measurement system based on video imaging analysis," *Int. J. Pattern Recogn. Artif. Intell.*, vol. 31, no. 2, pp. 1–21, 2017.

[96] L. Tarassenko, M. Villarroel, A. Guazzi, J. Jorge, D. Clifton, and C. Pugh, "Non-contact video-based vital sign monitoring using ambient light and auto-regressive models," *Physiol. Meas.*, vol. 35, no. 5, p. 807, 2014.

[97] H. Dalal, A. Basu, and M. P. Abegaonkar, "Remote sensing of vital sign of human body with radio frequency," *CSI Trans. ICT*, vol. 5, no. 2, pp. 161–166, 2017.

[98] A. Prathosh, P. Praveena, L. K. Mestha, and S. Bharadwaj, "Estimation of respiratory pattern from video using selective ensemble aggregation," *IEEE Trans. Signal Process.*, vol. 65, no. 11, pp. 2902–2916, Nov. 2017.

[99] Y. Hsu, Y.-L. Lin, and W. Hsu, "Learning-based heart rate detection from remote photoplethysmography features," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process.*, May 2014, pp. 4433–4437.

[100] M. Mercuri, Y.-H. Liu, I. Lorato, T. Torfs, A. Bourdoux, and C. van Hoof, "Frequency-tracking CW Doppler radar solving small-angle approximation and null point issues in non-contact vital signs monitoring," *IEEE Trans. Biomed. Circuits Syst.*, vol. 11, no. 3, pp. 671–680, Mar. 2017.

[101] U. Bal, "Non-contact estimation of heart rate and oxygen saturation using ambient light," *Biomed. Opt. Exp.*, vol. 6, no. 1, pp. 86–97, 2015.

[102] L. Feng, L. M. Po, X. Xu, Y. Li, and R. Ma, "Motion-resistant remote imaging photoplethysmography based on the optical properties of skin," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 25, no. 5, pp. 879–891, May 2015.

[103] D.-Y. Chen *et al.*, "Image sensor-based heart rate evaluation from face reflectance using Hilbert-Huang transform," *IEEE Sensors J.*, vol. 15, no. 1, pp. 618–627, Jan. 2015.

[104] H. Qi, Z. Guo, X. Chen, Z. Shen, and Z. J. Wang, "Video-based human heart rate measurement using joint blind source separation," *Biomed. Signal Process. Control*, vol. 31, pp. 309–320, Jan. 2017.

[105] K.-Y. Lin, D.-Y. Chen, and W.-J. Tsai, "Face-based heart rate signal decomposition and evaluation using multiple linear regression," *IEEE Sensors J.*, vol. 16, no. 5, pp. 1351–1360, May 2016.

[106] C. Wiede, J. Richter, and G. Hirtz, "Signal fusion based on intensity and motion variations for remote heart rate determination," in *Proc. IEEE Int. Conf. Imag. Syst. Techn.*, Oct. 2016, pp. 526–531.

[107] G. Lu, F. Yang, Y. Tian, X. Jing, and J. Wang, "Contact-free measurement of heart rate variability via a microwave sensor," *Sensors*, vol. 9, no. 12, pp. 9572–9581, 2009.

[108] J. Cheng, X. Chen, L. Xu, and Z. J. Wang, "Illumination variation-resistant video-based heart rate measurement using joint blind source separation and ensemble empirical mode decomposition," *IEEE J. Biomed. Health Inform.*, 2016, doi: 10.1109/JBHI.2016.2615472.

[109] W. Wang, S. Stuijk, and G. De Haan, "A novel algorithm for remote photoplethysmography: Spatial subspace rotation," *IEEE Trans. Biomed. Eng.*, vol. 63, no. 9, pp. 1974–1984, Sep. 2016.

[110] J. C. Lin, "A new IEEE standard for safety levels with respect to human exposure to radio-frequency radiation," *IEEE Antennas Propag. Mag.*, vol. 48, no. 1, pp. 157–159, Feb. 2006.

[111] W. Wang, A. den Brinker, S. Stuijk, and G. de Haan, "Algorithmic principles of remote-PPG," *IEEE Trans. Biomed. Eng.*, vol. 64, no. 7, pp. 1479–1491, Jul. 2016.

[112] W. Wang, A. C. den Brinker, S. Stuijk, and G. de Haan, "Robust heart rate from fitness videos," *Physiol. Meas.*, vol. 38, no. 6, p. 1023, 2017.

[113] L. Xu, J. Cheng, and X. Chen, "Illumination variation interference suppression in remote PPG using PLS and MEMD," *Electron. Lett.*, vol. 53, no. 4, pp. 216–218, Apr. 2017.

[114] K.-M. Chen, D. Misra, H. Wang, H.-R. Chuang, and E. Postow, "An X-band microwave life-detection system," *IEEE Trans. Biomed. Eng.*, vol. BME-33, no. 7, pp. 697–701, Jul. 1986.

[115] C. P. Wang, "Laser doppler velocimetry," *J. Quant. Spectrosc. Radiat. Transf.*, vol. 40, no. 3, pp. 309–319, 1988.

[116] R. Beauvais, "Laser-Doppler velocimetry (LDV)," *Optical Measurements*. Berlin, Germany: Springer, 1994, pp. 179–193.

[117] U. Morbiducci, L. Scalise, M. De Melis, and M. Grigioni, "Optical vibrocardiography: A novel tool for the optical monitoring of cardiac activity," *Ann. Biomed. Eng.*, vol. 35, no. 1, pp. 45–58, Jan. 2007.

[118] L. Scalise and U. Morbiducci, "Non-contact cardiac monitoring from carotid artery using optical vibrocardiography," *Med. Eng. Phys.*, vol. 30, no. 4, pp. 490–497, 2008.

[119] L. Scalise, P. Marchionni, and I. Ercoli, "Optical method for measurement of respiration rate," in *Proc. IEEE Int. Workshop Med. Meas. Appl.*, May 2010, pp. 19–22.

[120] L. Scalise, I. Ercoli, P. Marchionni, and E. P. Tomasini, "Measurement of respiration rate in preterm infants by laser Doppler vibrometry," in *Proc. IEEE Int. Workshop Med. Meas. Appl.*, May 2011, pp. 657–661.

[121] A. D. Kaplan, J. A. OrSullivan, E. J. Sirevaag, P.-H. Lai, and J. W. Rohrbaugh, "Hidden state models for noncontact measurements of the carotid pulse using a laser Doppler vibrometer," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 3, pp. 744–753, Mar. 2012.

[122] P. Marchionni, L. Scalise, I. Ercoli, and E. Tomasini, "An optical measurement method for the simultaneous assessment of respiration and heart rates in preterm infants," *Rev. Sci. Instrum.*, vol. 84, no. 12, p. 121705, 2013.

[123] Q.-L. Yan, Z.-W. Song, X.-B. Shi, Z.-Y. Yang, and X.-H. Zhang, "Combustion mechanism of double-base propellant containing nitrogen heterocyclic nitroamines (II): The temperature distribution of the flame and its chemical structure," *Acta Astron.*, vol. 64, no. 5, pp. 602–614, 2009.

[124] J. Allen, "Photoplethysmography and its application in clinical physiological measurement," *Physiol. Meas.*, vol. 28, no. 3, pp. R1–R39, 2007.

[125] J. Zheng and S. Hu, "The preliminary investigation of imaging photoplethysmographic system," *J. Phys., Conf. Ser.*, vol. 85, no. 85, p. 012031, 2007.

[126] F. P. Wieringa, F. Mastik, and A. F. V. D. Steen, "Contactless multiple wavelength photoplethysmographic imaging: A first step toward 'SpO$_2$ camera' technology," *Ann. Biomed. Eng.*, vol. 33, no. 8, pp. 1034–1041, 2005.

[127] S. Dangdang, Y. Yuting, L. Chenbin, T. Francis, Y. Hui, and T. Nongjian, "Noncontact monitoring breathing pattern, exhalation flow rate and pulse transit time," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 11, pp. 2760–2767, Nov. 2014.

[128] G. Lempe, S. Zaunseder, T. Wirthgen, S. Zipser, and H. Malberg, "ROI selection for remote photoplethysmography," *Bildverarbeitung für die Medizin*. Berlin, Germany: Springer, 2013, pp. 99–103.

[129] A. A. Kamshilin, S. Miridonov, V. Teplov, R. Saarenheimo, and E. Nippolainen, "Photoplethysmographic imaging of high spatial resolution," *Biomed. Opt. Exp.*, vol. 2, no. 4, pp. 996–1006, 2011.

[130] K. Humphreys, T. Ward, and C. Markham, "Noncontact simultaneous dual wavelength photoplethysmography: A further step toward noncontact pulse oximetry," *Rev. Sci. Instrum.*, vol. 78, no. 4, p. 044304, 2007.

[131] S. Hu, J. Zheng, V. Chouliaras, and R. Summers, "Feasibility of imaging photoplethysmography," in *Proc. BMEI*, May 2008, pp. 72–75.

[132] S. Hu, V. A. Peris, A. Echiadis, J. Zheng, and P. Shi, "Development of effective photoplethysmographic measurement techniques: From contact to non-contact and from point to imaging," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Sep. 2009, pp. 6550–6553.

[133] E. B. Blackford and J. R. Estepp, "Effects of frame rate and image resolution on pulse rate measured using multiple camera imaging photoplethysmography," *Proc. SPIE*, vol. 9417, p. 94172D, Mar. 2015.

[134] C. Brüser, C. H. Antink, T. Wartzek, M. Walter, and S. Leonhardt, "Ambient and unobtrusive cardiorespiratory monitoring techniques," *IEEE Rev. Biomed. Eng.*, vol. 8, pp. 30–43, 2015.

[135] T.-S. Nguyen, T.-H. Tran, and H. Vu, "Accurate object localization using RFID and Microsoft Kinect sensor," in *Proc. 8th Int. Conf. Knowl. Syst. Eng.*, 2016, pp. 345–350.

[136] F. Negin and F. Bremond, "Human action recognition in videos: A survey," Route de Lucioles, Sophia Antipolis, France, INRIA Tech. Rep., p. 47. 2004.

[137] A. Ali, G. Kim, L. Sang-Heon, and C. Javaan, "Real time apnoea monitoring of children using the microsoft Kinect sensor: A pilot study," *Sensors*, vol. 17, no. 2, p. 286, 2017.

ALI AL-NAJI received the bachelor's degree in medical instrumentation engineering techniques from the Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq, in 2005, and the M.S. degree from the Electrical and Electronic Engineering Department, Technology University, Baghdad, in 2008. He is currently pursuing Ph.D. degree with the School of Engineering, Electrical and Information Engineering, The University of South Australia. His research interests include biomedical engineering, computer vision systems, and microcontroller applications.

KIM GIBSON received the bachelor's degree in nursing from Flinders University in 2003 and the master's degree in neonataology from Flinders University. She has been a Neonatal Critical Care Nurse since 2006, where she was with the Neonatal Intensive Care Unit as a Senior Member of Staff. She was part of the Neonatal Emergency Transport Service with Flinders Medical Centre, South Australia, where she would retrieve premature or unwell newborns from metropolitan and country hospitals. She is currently a Lecturer with the School of Nursing and Midwifery, The University of South Australia, and teaches nursing and midwifery programs.

SANG-HEON LEE received the B.E.Sc. degree in aeronautical engineering from Inha University, South Korea, and the M.E.Sc. degree in mechatronics from the University of New South Wales, and the Ph.D. degree in system engineering from Australian National University. He is currently a Program Director and a Senior Lecturer with the School of Engineering, The University of South Australia. He has published over 100 papers in academic journals and conferences. His current research focus is on the development of an efficient algorithm for green supply chain and digital image processing in agricultural and medical applications, and discrete-event systems, fuzzy logic control, and neural networks.

JAVAAN CHAHL (M'11) received the Ph.D. degree from Australian National University. He joined the Defence Science and Technology Group (DST Group) as a Research Scientist in 1999. In 2011, he joined RMIT University as a founding Professor of unmanned aerial vehicles. In 2012, he became the Chair of Sensor Systems with a joint appointment between DST Group and The University of South Australia. Prof. Chahl is a member of the Institute of Engineers Australia. He was an elected Fellow of the Royal Aeronautical Society in 2014.