1

INTRODUCTION

Amy D. Droitcour[1], Olga Boric-Lubecke[2], Shuhei Yamada[2], and Victor M. Lubecke[2]

[1]*Wave 80 Biosciences, Inc., San Francisco, California, United States*
[2]*Department of Electrical Engineering, University of Hawaii at Manoa, Honolulu, Hawaii, United States*

COPYRIGHTED MATERIAL

Noncontact detection and monitoring of human cardiopulmonary activity is one of the most promising solutions for sleep monitoring, postsurgery monitoring, home health care, and search and rescue applications. Without contact or subject preparation (special clothing, attachments, etc.), this could facilitate health monitoring to the chronically ill, enable sleep monitoring outside of sleep laboratories, detect survivors under rubble, and deliver warnings of emergencies or changes in conditions of patients. Doppler radar remote sensing of physiological signatures has shown promise to this end. The development of Doppler radar for remote sensing of vital signs, with proof of concept demonstrated for various applications [Li et al., 2013], could offer a platform for unobtrusive, noncontact, yet continuous physiological monitoring systems.

Cardiopulmonary monitoring is typically carried out with contact sensors such as electrocardiogram (ECG) electrodes. The use of contact sensors is neither possible nor desirable in many situations, due to, for example, skin irritation, or simply lack of access for direct contact. The long-term, continuous use of contact sensors is also limited by degradation in contact quality over time. Some examples of long-term health-care monitoring that would benefit from noncontact sensing include monitoring postsurgery patients, chronic and elderly patients, and patients with sleep disorders. Premature infants and burn victims will also clearly benefit

Doppler Radar Physiological Sensing, First Edition.
Edited by Olga Boric-Lubecke, Victor M. Lubecke, Amy D. Droitcour, Byung-Kwon Park, and Aditya Singh.
© 2016 John Wiley & Sons, Inc. Published 2016 by John Wiley & Sons, Inc.

from noncontact sensing due to compromised skin integrity. A failure to respond to patient deterioration promptly and appropriately can lead to increased morbidity and mortality, increased requirement for intensive care, and elevated costs [Tarassenko et al., 2006]. Early identification of patient deterioration is important, as it can prevent subsequent cardiopulmonary arrest and reduce mortality. Early recognition of physiological abnormalities coupled with the rapid intervention of suitably trained staff may result in an improvement in the functional outcome or mortality rate. Early recognition relies on the physiological observations being measured accurately and at intervals appropriate to the condition of the patient. However, many patients are not monitored regularly, and some vital signs such as respiratory rate are measured significantly less frequently than other vital signs. There is a need for straightforward, automated, continuous physiological monitoring technology.

Noncontact physiological monitoring may make a significant impact beyond health-care applications, especially in situations where direct access to the subject is not available. Such situations include, for example, occupancy sensors for energy efficiency [Yavari et al., 2014], search and rescue operations for survivor detection under rubble [Chuang et al., 1990], and detection of adversaries through walls [Lubecke et al., 2007].

1.1 CURRENT METHODS OF PHYSIOLOGICAL MONITORING

Assessment of cardiopulmonary functions is most often performed with contact sensors when direct access to the subject is available. ECG is the gold standard for heart monitoring that is often used in hospital and ambulatory settings, whereas there is no equivalent gold standard for respiratory monitoring. There are many different approaches used for respiratory monitoring; however, none of them are easily applied. Even though respiratory rate is a key early indicator of physiological instability that may lead to a critical event, respiratory rate is measured significantly less frequently than other vital signs, such as blood pressure, pulse rate, and arterial oxygen saturation. Among the vital signs, respiratory rate is the only sign that is typically measured manually, via visual assessment, with a nurse counting chest excursions.

The current practices to measure respiration are divided into three categories: measurement of oxygen saturation, measurement of airflow, and measurement of respiratory effort/movement [Webster, 2010]. Pulse oximetry measures the percentage of hemoglobin (Hb) that is saturated with oxygen. A source of light originates from the probe at two wavelengths (650 and 805 nm). The light is partly absorbed by hemoglobin, at amounts which differ depending on whether it is saturated or desaturated with oxygen. Direct measurement of airflow typically uses a spirometer with a mouth piece or a face mask. It contains a precision differential pressure transducer for the measurements of respiration flow rates. The spirometer records the volume and rate of air that is breathed in and out over a specified time. These spirometers are rarely used continuously because they have large dead volumes and high resistance, which make them unpleasant to use. Indirect measurement of airflow, such as with a thermocouple or capnograph, has less adverse effects, but still requires the placement of sensors in front of the nose and/or mouth. Respiratory effort/movement measurement can be monitored by measuring body volume changes; transthoracic inductance and impedance plethysmographs, strain gauge measurement of thoracic circumference, pneumatic respiration transducers, and whole-body plethysmographs are examples of indirect techniques. Each respiratory measurement method has unique advantages and disadvantages. Pulse oximetry measurements indicate that a respiratory disturbance has occurred, but do not provide respiratory rate. Airflow measurements are the most accurate, but interfere with normal respiration. The whole-body plethysmograph can be highly accurate and does not interfere with respiration, but requires immobilization of the patient. The performance of commonly used transducers (belts or electrodes) for ambulatory respiration monitoring significantly degrades over time with wear and tear. Impedance plethysmography, performed through ECG electrodes, is the most common method of continuously measuring respiratory rate in the hospital.

The electrocardiograph (ECG) is traditionally considered the standard way to measure the cardiac activity. It records the electrical activity of the heart over time. Electrical waves cause the heart muscle to contract. These waves pass through the body and can be measured at electrodes attached to the skin. Electrodes on different sides of the heart measure the activity of different parts of the heart muscle. An ECG displays the voltage between pairs of these electrodes, and the muscle activity that they measure, from different directions. This display indicates the overall rhythm of the heart, and weaknesses in different parts of the heart muscle. The other approach is pulse measurement of changes in blood volume in the skin. Pulse measurements, such as a photoplethysmograph (PPG) or piezoresistance, use optical or pressure sensors to identify pulses of blood driven by heartbeats. These are less invasive and simpler than ECG, yet both of these methods require patients to be tethered to the sensing devices.

1.2 NEED FOR NONCONTACT PHYSIOLOGICAL MONITORING

The ability to remotely detect vital signs such as heart beat and respiration is particularly useful in situations where direct contact with the subject is either impossible or unwanted. Avoidance of problems such as skin irritation, restriction of breathing, and electrode contacts is desirable in a number of health-care applications, including monitoring of patients with compromised skin, and sleep monitoring. Beyond health care, the potential applications that could benefit from remote sensing of physiological signals include fatigue monitoring, border crossing monitoring, occupancy sensors, sense through the wall, and search and rescue operations.

1.2.1 Patients with Compromised Skin

Development of reliable noninvasive physiological monitoring is an important goal in modern health-care research. Knowledge of routinely monitored heart and respiratory patterns would be clinically useful in many situations. In neonatal intensive care units, infants often suffer skin damage from adhesive tape, electrocardiogram electrodes, electroencephalogram electrodes, and transcutaneous probes, with some lesions leaving scars [Colditz et al., 1999]. Monitoring the cardiac state of burn victims can be challenging because it is sometimes difficult to find enough skin on which to apply an ECG electrode. Sometimes the electrode is stapled to the skin, or to an undebrided burn area [Loo et al., 2004]. Often an esophageal ECG must be used because adequate skin area cannot be located. A wireless heart and respiration rate monitor could fill the needs for both neonates and burn victims, by enabling the monitoring of these vital signs without contacting the skin with electrodes.

1.2.2 Sleep Monitoring

Cardiopulmonary activity is the main parameter used in the study of sleep disorders. Sleep is widely understood to play a key role in physical and mental health. The quality and quantity of sleep that an individual gets can have a significant impact on learning and memory, metabolism and weight, safety, mood, cardiovascular health, disease, and immune system function. Obstructive sleep apnea (OSA) is the most common sleep disorder with an estimated 12 million Americans suffering from it. Risk factors include gender, weight and age (being male, overweight, and over the age of 40), but sleep apnea can strike anyone at any age, even children. One of every five adults has at least mild OSA, and one of fifteen has at least moderate OSA [Young et al., 2002]. OSA has many negative effects, including excessive daytime sleepiness, increased risk of motor vehicle accidents, hypertension, psychological distress, and cognitive impairment. Apnea is the cessation of airflow for 10 s or longer, and OSA is apnea that occurs in spite of respiratory effort. To differentiate between central and obstructive apneic events, measurements of respiratory movement must be made in addition to measurements of airflow [Phillips et al., 1998]. Current laboratory polysomnography (PSG) is cumbersome, inconvenient, and expensive, causing considerable interest in portable monitoring of the condition. A Doppler radar monitoring system could identify respiratory movement, without the difficulties that accompany a full polysomnographic recording [Singh et al., 2013].

The gold standard for the clinical diagnosis of obstructive sleep apnea syndrome (OSAS) is PSG, consisting of simultaneous recordings of electrophysiological and respiratory signals, and overnight monitoring of the patient in a specially equipped sleep laboratory [Kryger et al., 2000]. However, the scarcity of sleep clinics and the expense associated with standard PSG allows treatment of small numbers of OSAS cases. The lack of awareness among the public and health-care professionals results in the vast majority of sufferers remaining undiagnosed and untreated, despite the fact that this serious disorder can have significant consequences. Untreated sleep apnea can cause high blood pressure and other cardiovascular disease, memory problems, depression, weight gain, and headaches. Moreover, untreated sleep apnea may be responsible for job impairment and motor vehicle collisions. A simple, less costly, noninvasive, reliable and ambulatory screening method for OSAS is desirable.

Sudden infant death syndrome (SIDS) is believed to be attributable to sleep apnea. Although rates of SIDS have declined sharply in the past 15 years, SIDS is still the third leading cause of infant mortality and the leading cause of postneonatal infant mortality [Arias et al., 2003; Hunt and Hauck, 2004]. In 2001, 8.1% of all infant deaths were caused by SIDS, affecting 55.5 of every 100,000 live births. Apparent life-threatening events (ALTEs), defined as an episode that is characterized by some combination of apnea, color change, marked change in muscle tone, choking, or gagging, are experienced by 2.46 of every 1000 infants [Kiechl-Kohlendorfer et al., 2005]. Although home electronic surveillance does not reduce the risk of SIDS at this time, this may be due to limits of current home-monitoring devices, or high false-negative rates. If obstructed breathing, central apnea, bradycardia, or oxygen saturation could be reliably detected, intervention could save infants' lives [Hunt and Hauck, 2004]. A Doppler radar device could detect central apneic events, where there is no respiratory motion, and bradycardia, where the heart rate slows. Doppler radar could be an integral part of a combination of sensors that could provide reliable home SIDS monitoring.

1.2.3 Elderly Monitoring

The population share of the elderly around the globe has been steadily increasing, due to improvements in health care and decrease in birth rates. The global percentage of people aged 60 years or above increased from 9.2% in 1990 to 11.7% in 2013 and will continue to grow as a proportion of the world population, projected to reach 21.1% by 2050 [United Nations, 2013]. This has resulted in an increasing need for health-care equipment specialized for routine in home monitoring of the elderly. With the reduced mobility, elderly adults may be at high risk of gait or balance disorders, which are the major causes of fall in this population and risk factors for increasing morbidity and mortality. Therefore, more specialized health-care equipment is needed for long-term monitoring of gait for the elderly.

The Doppler radar has demonstrated potential for human gait monitoring [Wang and Fathy, 2011]. A Doppler radar-based approach for gait monitoring and fall detection was proposed, with good accuracy in distinguishing common fall events from normal movements [Mercuri et al., 2013]. Such a system could be potentially linked to medical monitoring personnel to provide a prompt alert in the event of emergencies.

1.3 DOPPLER RADAR POTENTIAL FOR PHYSIOLOGICAL MONITORING

The development of Doppler radar for sensing of cardiopulmonary sensing, with proof of concept demonstrated for various applications [Li et al., 2013], could offer a platform to establish noncontact, continuous, physiological monitoring systems.

Doppler radar systems can perform noncontact sensing of respiratory and cardiac signatures at a distance, through clothing, walls, or debris. A particular advantage of Doppler radar is its ability to detect both heart and respiratory signals simultaneously, but independently, and without contact with the subject. This may be particularly useful in chronic disease management, sleep studies, heart rate variability (HRV) and energy balance studies, and for obtaining biometric signatures for security applications.

1.3.1 Principle of Operation and Power Budget

Radar, an acronym for RAdio Detection And Ranging, describes a system that transmits an electromagnetic signal and senses the echo from reflecting objects, thereby gaining information about those objects. The time delay between the transmitted and received signals indicates the distance to the target; the frequency shift of the received signal due to Doppler effect enables calculation of the target's velocity; and the strength of the signal gives information about the target's radar cross section, which provides information about its size, geometry, and composition. A major advantage of radio and microwave frequency radar systems is that these waves can penetrate through some objects that light cannot penetrate, allowing detection of objects that cannot be seen. However, radar systems developed for different applications may operate at many different frequencies, varying from a few megahertz to optical frequencies.

The Doppler effect can be observed as the change of frequency or pitch when a wave source moves either toward or away from the observer. This principle was discovered by the Austrian physicist Christian Doppler in 1842, and it applies to all wave motion. Doppler radar uses this principle to measure target velocity from the frequency shift between the transmitted electromagnetic wave and the wave reflected from the moving object.

Radar systems were originally developed for military applications including surveillance and weapon control. Radar now has many civil applications, including navigation of aircraft, ships, and spacecraft, remote sensing of the environment (including weather), and law enforcement. Depending on the radar system hardware and the type of signal sent, it may be possible to detect the range and/or angle to the target, the size and shape of the target, and the linear and/or rotational velocity of the target [Skolnik, 1990]. Depending on which of these parameters is most important to sense, as well as the range to and the nature of the target, different radar topologies may be used. A pure continuous-wave (CW) system can readily detect moving targets via the Doppler shift of the received signal, although it cannot detect the range. Frequency-modulated continuous-wave (FMCW) radar systems can detect both the range to and the velocity of the target. Altimeters and Doppler navigation devices use FMCW radar systems [Saunders, 1990]. Pulsed radar allows transmitting and receiving to occur at different times, and it is used when the return signal is much smaller than the transmitted signal and, therefore, difficult to sense the received signal in the presence of the transmitted signal [Skolnik, 1990]. Different types of Doppler radar and their applications are discussed in more detail in Chapter 2.

A low-power Doppler radar system can be used to sense physiological movement, enabling the monitoring of vital signs parameters without contact, and through clothing and bedding [Li et al., 2013]. A low-power radio frequency (RF) signal is transmitted, and as it reflects from the patient's body, the echo is modulated by physiological motion. The Doppler shift theory states that a reflected signal from an object with periodic movement but zero net velocity is phase modulated. This phase is proportional to the displacement of the subject. If the subject is the human body, the reflected signal will contain information on the positional variations on the surface due to cardiopulmonary activity. A combination of hardware and software compares the echo signal with the transmitted signal, and extracts a physiological motion signal.

CW, FMWC, and pulsed Doppler radar can be used to sense physiological movement. A CW radar topology is the simplest radar topology for two reasons: a single oscillator can be used for both the transmitter and the receiver, and the extremely narrow signal bandwidth avoids interference and rejects stationary clutter. A pure CW radar system can measure targets at any range (subject to the signal-to-noise ratio (SNR)) that are moving at any velocity (subject to the receiver bandwidth) without ambiguity, unlike pulsed or modulated systems that have limited velocity resolution. However, CW radar systems cannot detect range without modulation, and when modulated, the same range ambiguities found in pulsed radar systems are present.

When the goal of the measurement is target motion rather than distance to the target, a pure CW radar system is very effective. When the CW signal is directed at a target, it is reflected and frequency-modulated by the target motion. According to Doppler theory, a target with a time-varying position but no net velocity will reflect the signal, modulating its phase in proportion to the time-varying position of the target. A stationary person's chest has a periodic movement with no net velocity, and a CW radar with the chest as the target will, therefore, receive a signal similar to the transmitted signal, with its phase modulated by the time-varying chest position. Demodulating the phase will then provide a signal directly proportional to the chest position, which contains information about movement due to heartbeat and respiration, from which heart and respiration rates can be determined. Noncontact heart and respiration monitors have been developed based on this principle [Lin, 1992].

The most significant issues with CW radar are linked to its nature of constantly transmitting and receiving, which results in the inability to separate reflections temporally. A portion of the transmitted signal leaks from the transmitter to the receiver, either through coupling between the transmit and receive circuitry, or directly through the antenna(s). In addition, clutter reflects some of the signal and its noise sidebands back to the receiver, adding to the signal power at the transmit frequency due to leakage. These unwanted signals result in a DC offset and low-frequency noise if they are not eliminated before the signal is detected.

1.3.1.1 Frequency and Power Considerations The peak-to-peak chest motion due to respiration in adults ranges from 4 to 12 mm [DeGroote et al., 1997; Kondo et al, 1997], while the peak-to-peak motion due to the heartbeat is about 0.5 mm [Ramachandran and Singh, 1989]. The amount of phase modulation due to chest motion will be proportional to displacement and the operating frequency. At 2.4 GHz, 1 cm of displacement corresponds to about 1 rad of phase change, and the phase change increases proportionally to increasing frequency. The ability of the system to discern changes in phase will depend on the overall SNR that is determined by the size of the moving surface, displacement amplitude, range to target, and electrical properties of the radar system.

The electrical properties of biological tissue affect the amount of signal that is reflected and transmitted, both at the skin–air interface and at interfaces between different tissues within the body. The electric properties of biological tissue depend on frequency of operation, and are largely governed by the percentage of water content. Tissues with high water content, such as skin, muscle, and blood, are more lossy and more readily absorb electromagnetic waves. As the frequency of operation increases, the losses increase, whereas tissues with low water content, such as bone and fat, are largely transparent to electromagnetic waves. The tissue contrast based on different absorption and propagation characteristics has been used for microwave imaging.

Doppler radar detects all motion in the radar field of view. If the antenna is placed in contact with the skin, internal organ motion may be measured, assuming that there is enough penetration for the electromagnetic wave to reach the internal organs, and propagate back to the receiver after the reflection. If the Doppler radar is placed at some standoff distance from a subject, at frequencies of 2.4 GHz and above, about 50% of the incident power will be reflected at the air–skin interface, and more than 90% of the reflected power will come from the surface reflection. Thus, in this case, for all practical purposes, we can assume that noncontact Doppler radar physiological measurements are measurements of skin surface motion.

1.3.2 History of Doppler Radar in Physiological Monitoring

Physiological motion detection with CW Doppler radar has been known since the 1970s [Lin, 1975], and with FMCW [Sharpe, 1990] and ultra-wideband (UWB) [Staderini, 2002] Doppler radar since the 1980s. Understanding of microwave noninvasive physiological sensing has advanced tremendously in the past few decades, and recent advances in wireless technology have enabled further progress in medical radar, culminating with recent FDA approvals. Widespread use of microwave technology and digital processors in common household communications devices has driven down costs, making it possible to develop practical radar monitors that cost significantly less than conventional cardiopulmonary assessment instruments.

Microwave Doppler radar monitoring of respiratory and cardiac movements was first demonstrated in the late 1970s, when respiration [Lin, 1975; Lin et al., 1977] and heart beats [Lin et al., 1979] were measured separately, with a breath-hold required for the heart measurement [Lin et al., 1979]. X-band sweep oscillators were used, with horn antennas directing the microwave energy toward the upper torso of the subjects. A nonanesthetized rabbit's respiration was measured from a distance of 30 cm [Lin, 1975]. In [Lin et al., 1977], the same system was used with an apnea-detector circuit, and was tested on a rabbit and two cats, all of which were anesthetized and intubated. Both hyperventilation and apnea were induced in the animals, and both states were clearly detected by the microwave monitor. Microwave apexcardiography was demonstrated by using a continuous-wave 2-GHz microwave signal with an antenna placed 3 cm above the apex, and the precordial motions were easily detected [Lin et al., 1979].

From the mid-1980s through the late 1990s, radar transceivers were developed that incorporated analog and digital signal processing to separate the small heart signal from the much larger respiration signal, so the subject did not need to hold his/her breath for the heart rate to be measured, and heart and respiration could be measured simultaneously [Chan and Lin, 1987; Chen et al., 2000; Chuang et al., 1990; Greneker, 1997; Seals et al., 1986]. These transceivers were used for the detection of heart and respiration rates of persons in rubble, persons behind walls, and Olympic athletes. An analog amplification and filtering for separation of heart and respiration signatures was combined with 8-bit digitization and digital signal processing to detect heart and respiration rates [Chan and Lin, 1987]. An automatic clutter-cancellation circuit was developed to facilitate measurement of the heart and respiration signatures through seven layers of brick [Chuang et al., 1990] and through 10 ft of rubble [Chen et al., 2000]. Heart and respiration rates of athletes were successfully detected at ranges exceeding 10 m [Greneker, 1997]. At 100 m standoff distance, the limit was moving background clutter, not the system sensitivity. A quadrature receiver was used to avoid phase-demodulation null points [Seals et al., 1986].

More recently, Doppler radar vital signs monitoring was explored to detect hypovolemic states and shock in persons under rubble or in biochemical hazard conditions that could pose danger to health-care providers [Matsui et al., 2004a, 2004b]. Hypovolemic rabbits and rabbits in shock could be reliably distinguished from the control rabbits based on the Doppler radar information by using linear discriminant analysis on the heart and respiration rates. The hypovolemic rabbits have higher heart and respiration rates. Doppler radar was also used to estimate arterial blood pH without contact using heart and respiration rate monitoring coupled with an infrared thermographic temperature measurement and an exhaled gas (CO and CO_2) analyzer [Matsui et al., 2006]. This measurement was successful at estimating blood pH using linear regression analysis on hypovolemic rabbits.

The connection of this technology to the existing wireless communications infrastructure was also investigated [Boric-Lubecke and Lubecke, 2002; Lubecke et al., 2002; Boric-Lubecke et al., 2003]. A modified wireless LAN PCMCIA card was used to detect heart and respiration [Boric-Lubecke et al., 2003], and a module that combines the transmitted and reflected signals from any wireless communication device, such as a cordless telephone, was used to detect heart and respiration [Lubecke et al., 2002]. Using this technology to directly connect Doppler measurement of heart and respiration rate to health-care providers has been proposed [Boric-Lubecke and Lubecke, 2002].

In addition, UWB radar has been used for the measurement of heart and respiration rates. Using 0.4-W pulses and a 1-GHz central frequency, heart rates were detected through 1 m of air and a 0.4-m brick wall [Immoreev and Samkov, 2005] and respiration was measured at up to 5 m [Ossberger et al., 2004].

Research efforts in the last decade have been moving the technology development toward lower power, lighter weight, smaller form factor, better accuracy, longer detection range, and more robust operation for practical portable and handheld applications. Among many possible applications this technology can be used for, health care seems to be drawing the most interest. As an example, a baby monitor using this technology was demonstrated to monitor SIDS [Hafner et al., 2007; Li et al., 2009]. The Doppler radar embedded into the baby monitor detects tiny baby movements induced by breathing. If no movement is detected within 20 s, an alarm goes off to warn the parents. Operating in similar ways, biomedical Doppler radar is also being investigated as a cost-effective solution for long-term monitoring of sleep apnea [Singh et al., 2013]. Human studies in clinical environment have validated this technology as a potential substitute for conventional respiratory monitors [Droitcour et al., 2009; Massagram et al., 2009] and a useful tool for precise assessment of key parameters relating to cardiopulmonary activity including body orientation [Kiriazi et al., 2012]. Furthermore, recent studies have demonstrated that Doppler radar could help a medical linear accelerator to track the location of a mobile tumor during radiotherapy with the help of advanced signal-processing algorithms [Li et al., 2011; Gu et al., 2012]. Doppler radar has also been applied to monitor the health and behavior of land and sea animals including lizards and fish [Singh et al., 2012b, 2012a; Hafner et al., 2012].

With growing interests in health and life sciences in the engineering community, many researchers have been contributing to the technology advancement in this field. This has led to various radar front-end architectures including the conventional homodyne/heterodyne [Xiao et al., 2006], self-/mutual-injection locking [Wang et al., 2011], and coherent low-IF [Mostafanezhad and Boric-Lubecke, 2014]. Each of these architectures shows its specific advantage in certain environments. Signal conditioning and processing methods such as adaptive DC calibration [Vergara et al., 2008b; Gu and Li, 2012], arctangent demodulation [Park et al., 2007], and noise cancellation [Li and Lin, 2008; Oum et al., 2008; Fletcher and Jing, 2009; Wiesner, 2009] have been proposed to enable practical applications of the biomedical radar. Various techniques, including blind source separation (BSS) and the use of passive RF tags, have been applied to isolate multiple targets and clutter noise [Vergara et al., 2008a; Singh and Lubecke, 2013]. Hardware implementations from benchtop fast prototyping using fundamental RF/microwave instruments [Gu et al., 2010] to radar-on-chip application-specific integrated circuits (ASICs) [Droitcour et al., 2002, 2004; Li et al., 2008, 2010] have been demonstrated to make this technology available to both researchers and general users.

The selection of published works outlining Doppler radar physiological monitoring history from 1975 to date are described briefly in Table 1.1 with the year of publication, reference, description, and results.

TABLE 1.1 Doppler Radar Physiological Monitoring from 1975 to 2014

References	Description	Results
Lin [1975]	X-band sweep oscillator, rectangular horn antenna	Respiration measured on rabbit and human at 30-cm range
Lin et al. [1977]	Microwave apnea detector proposed for low-birth-weight infants 3-mW at 30-cm, 3-cm by 3-cm horn	Respiration measured on cats and rabbit at 30-cm range Detection of apnea and hyperventilation
Lin et al. [1979]	"Apexcardiography" heart measurements made while breath held Signal amplitude and phase vary with antenna location	Heart measurement made 3-cm from apex
Seals et al. [1986]	Analog signal processing separates heart and respiration signs Digital rate detection algorithm 10- and 3-GHz quadrature radar systems	Measured heart and respiration simultaneously with digital rate detection algorithm
Chen et al. [2000]	An X-band microwave life-detection system has been developed for vital signs	Measured heartbeat and breathing of human subjects lying on the ground at a distance of about 30 m or located behind a cinder block wall
Chan and Lin [1987]	Heart and respiration separated with analog and digital signal processing: amplification, filtering, 8-bit ADC sampled at 80 Hz 10.5-GHz, 10-mW, horn antenna a few centimeter from subject	Heart and respiration obtained simultaneously at 5–7-cm range
Chuang et al. [1990]	Heart and respiration for detecting victims in clutter 10-GHz system does not penetrate wet bricks, but 2-GHz system does Automatic clutter cancellation algorithm introduced	Successful measurement with subject both faceup and facedown, through 4–7 layers of brick, with 2- and 10-GHz radar systems

(*Continued*)

TABLE 1.1 **(*Continued*)**

References	Description	Results
Greneker [1997]	0.6-m dish aimed at subject's thorax 24-GHz, 30-mW output signal, 40-dB antenna gain	Heartbeat and respiration measured at ranges exceeding 10 m
Chen et al. [2000]	Life-detection system for victims under rubble or behind barriers including 6 in. of steel, bricks, and cylinder blocks Heart and respiration were measured	450-MHz signal penetrates deepest into concrete rubble without metal 1150-MHz signal penetrates rubble with metallic wire mesh
Droitcour et al. [2002]	The first CMOS and BiCMOS Doppler radar chips	A fully integrated direct conversion Doppler radar that detects heart and respiration movement at a distance of 50 cm. The 1.6 GHz transceiver is implemented in both CMOS and BiCMOS technologies
Lubecke et al. [2002]	Add-on module uses signals from existing wireless devices to measure heart and respiration rates	Heart and respiration were measured with a 2.4-GHz cordless phone and a 2.4-GHz signal generator
Boric-Lubecke et al. [2003]	Modified wireless LAN PCMCIA cards are used to sense heart and respiration rates	Heart and respiration were obtained successfully at 40-cm
Droitcour et al. [2004]	Range correlations and I/Q performance benefits in single-chip Doppler radars	The range-correlation effect on residual phase noise is a critical factor when detecting small phase fluctuations with a high-phase-noise on-chip oscillator. Phase-noise reduction due to range correlation was experimentally evaluated
Matsui et al. [2004a]	Determining hypovolemic and shock states using linear discriminant analysis Heart and respiration rates of hypovolemic rabbits 1215 MHz, 70-mW output power	Linear discriminant analysis effectively predicted hypovolemic state of 10 rabbits
Ossberger et al. [2004]	Ultra-wideband pulse radar Wavelet signal processing	Respiration measured at 1–5-m and through a wall at 85-cm

Immoreev and Samkov [2005]	Ultra-wideband radar, 1-GHz central frequency	Measured respiration through 1-m air and 0.4-m brick wall on one subject
Matsui et al. [2006]	Used 1215-MHz radar, infrared thermography, and exhaled CO/CO_2 analyzer to estimate blood pH	Significant correlation of measured and calculated blood pH on rabbits
Xiao et al. [2006]	Heterodyne Ka-band radar	Double-sideband transmission is used for avoiding null detection point
Park et al. [2007]	Used 2.4-GHz quadrature receiver. Arctangent demodulation with DC offset compensation to detect heart and respiration rate	Robust and accurate output data obtained from arctangent demodulation. Unwanted DC offset was successfully eliminated
Hafner et al. [2007]	Vital signs sensing using a baby monitor and a passive sensor node	Signal from a baby monitor, with an addition of a passive sensor is used to detect vital signs
Li and Lin [2008]	4–7-GHz quadrature transceiver with the complex and arctangent demodulation for random movement cancellation	The complex signal demodulation is more favorable for random body movement cancellation. The arctangent demodulation has the advantage of eliminating the harmonic and intermodulation interference at high frequencies using high gain antennas
Li et al. [2008]	A 5 GHz double-sideband radar sensor chip	The differential architecture has the advantage of reducing local oscillation leakage. The 5 GHz double-sideband system can avoid null detection point by frequency tuning
Vergara et al. [2008b]	DC offset cancellation and DC information preservation	Digitally controlled voltage feedback and center finding preserves the important DC information for optimal extraction of phase information in the quadrature system
Vergara et al. [2008a]	Blind source separation of human motion	The successful separation of cardiopulmonary motion and hand motion for a single subject

(*Continued*)

TABLE 1.1 (*Continued*)

References	Description	Results
Wiesner [2009]	CW vital sign radar with enhanced target detection probability in a highly cluttered environment with range and angle-of-arrival estimation	A respiration signature around 0.2 Hz and higher harmonics along with heartbeat signature around 1.3 Hz are clearly discernible
Massagram et al. [2009]	2.4-GHz quadrature system with linear demodulation method to detect heart rate variability (HRV) and respiratory sinus arrhythmia (RSA)	The data were obtained from 12 human subjects in seated and supine positions. High accuracy in extracting the HRV and RSA indices was achieved
Droitcour et al. [2009]	The first clinical validation of the respiratory rate accuracy	A human study in a clinical environment validated Doppler radar technology as a potential substitute for conventional respiratory monitors
Li et al. [2009]	Infant vital sign monitor	The Doppler radar embedded into the baby monitor detects tiny baby movements induced by breathing. If no movement is detected within 20 s, an alarm goes off to warn the parents
Fletcher and Jing, 2009	Dual-antenna differential radar front-end system for short-range heart rate and background motion noise removal	Designed two helical directional antennas at 2.46-GHz and 2.510-GHz to detect heart rate at 0.5-m distance with motion noise cancellation
Li et al. [2010]	A direct-conversion 5.8-GHz radar sensor chip with 1-GHz bandwidth	Analyses on sensitivity and link budget guide the design of high-sensitivity noncontact vital sign detector. This radar sensor chip is software configurable to set the operation point and detection range for optimal performance
Gu et al. [2010]	Fast prototyping using fundamental RF/microwave instruments	Heterodyne digital quadrature demodulation architecture that helps mitigate quadrature channel imbalance and eliminate the complicated DC offset calibration required for arctangent demodulation

Wang et al. [2011]	Single antenna self-injection-locked (SIL) radar presented to detect vital signs with random body motion cancellation	Two-radar array placed 2-m away at 2.4 GHz is implemented with random body motion cancellation for monitoring subject jogging on treadmill. Provided theoretical basis for determining signal-to-noise spectral density ratio
Gu et al. [2012]	DC-coupled adaptive tuning radar sensor to precisely measure respiratory movement in motion-adaptive radiotherapy	Submillimeter accuracy was achieved in measurement for respiratory gating and has potential tumor tracking
Kiriazi et al. [2012]	Dual-frequency (2.4 and 5.8-GHz) radar for cardiopulmonary effective radar cross section (ERCS) and displacement in the direction of incidence	Results showed that an ERCS is larger for the back of the torso and smaller for the side than to the front, while the respiration depth is smaller in the prone position than in supine
Singh et al. [2012a]	Lizard activity monitoring and motion classification	Lizard monitoring in a nonconfined laboratory environment and uses multiple Doppler radars operating at 10.525 GHz
Hafner et al. [2012]	Fish heart rate monitoring	The heart rate detected by the body contact radar matched the heart rate detected by ECG
Singh et al. [2013]	Doppler radar for clinical sleep monitoring	Doppler radar is being investigated as a cost-effective solution for long-term monitoring of sleep apnea
Singh and Lubecke [2013]	2.45-GHz system with a frequency doubling passive planar harmonic tag	The harmonic radar system isolates the respiration of a tagged human subject from an untagged large scattering object
Mostafanezhad and Boric-Lubecke [2014]	Coherent low-IF receiver architecture	Measurements on a mechanical target and a human subject demonstrate a signal-to-noise ratio improvement of 7 dB, which can increase the range of operation by 50%

REFERENCES

Arias E, MacDorman MF, Strobino DM, Guyer B. Annual summary of vital statistics – 2002. Pediatrics 2003;112(6):1215–1230.

Boric-Lubecke O, Atwater G, Lubecke VM. Wireless LAN PC card sensing of vital signs. Proceedings of IEEE Topical Conference on Wireless Communications Technology; 2003. p 206–207.

Boric-Lubecke O, Lubecke VM. Wireless house calls: using communications technology for health care monitoring. IEEE Microwave Mag 2002;3(3):43–48.

Chan KH, Lin JC. Microprocessor-based cardiopulmonary rate monitor. Med Biol Eng Comput 1987;25(9):41–44.

Chen K-M, Huang Y, Zhang J, Norman A. Microwave life-detection systems for searching human subjects under earthquake rubble or behind barrier. IEEE Trans Biomed Eng 2000;47(1):105–114.

Chuang H-R, Chen Y-F, and Chen K-M. Microprocessor-controlled automatic clutter-cancellation circuits for microwave systems to sense physiological movements remotely through the rubble. Proceedings of the Instrumentation and Measurement Technology Conference; 1990. p 177–181.

Colditz PB, Dunster KR, Joy GJ, Robertson IM. Anetoderma of prematurity in association with electrocardiographic electrodes. J Am Acad Dermatol 1999;41(3):479–481.

DeGroote A, Wantier M, Cheron G, Estenne M, Pavia M. Chest wall motion during tidal breathing. J Appl Physiol 1997;83(5):1531–1537.

Droitcour AD, Boric-Lubecke, O, Lubecke VM, Lin, J. 0.25 μm CMOS and BiCMOS single-chip direct-conversion Doppler radars for remote sensing of vital signs. IEEE International Solid-State Circuits Conference 2002, ISSCC 2002. Digest of Technical Papers; 2002. Vol. 1, p 348–349.

Droitcour AD, Boric-Lubecke O, Lubecke VM, Lin J, Kovacs GTA. Range correlation and I/Q performance benefits in single-chip silicon Doppler radars for noncontact cardiopulmonary monitoring. IEEE Trans Microwave Theory Tech 2004;52:838–848.

Droitcour AD, Seto TB, Byung-Kwon P, Yamada S, Vergara A, El Hourani C, Shing T, et al., Non-contact respiratory rate measurement validation for hospitalized patients. Engineering in Medicine and Biology Society, 2009, EMBC 2009. Annual International Conference of the IEEE; 2009. p 4812–4815.

Fletcher R, Jing H. Low-cost differential front-end for Doppler radar vital sign monitoring. IEEE MTT-S International Microwave Symposium Digest, 2009, MTT'09; 2009. p 1325–1328.

Greneker EF. Radar sensing of heartbeat and respiration at a distance with applications of the technology. Radar 97 Conference Proceedings; 1997. p 150–154.

Gu C, Li C. DC coupled CW radar sensor using fine-tuning adaptive feedback loop. Electron Lett 2012;48:344–345.

Gu C, Li C, Lin J, Long J, Huangfu J, Ran L. Instrument-based noncontact Doppler radar vital sign detection system using heterodyne digital quadrature demodulation architecture. IEEE Trans Instrum Meas 2010;59:1580–1588.

Gu C, Li R, Zhang H, Fung A, Torres C, Jiang S, Li C. Accurate respiration measurement using DC-coupled continuous-wave radar sensor for motion-adaptive cancer radiotherapy. IEEE Trans Biomed Eng 2012;59:3117–3123.

Hafner N, Drazen JC, Lubecke VM. Fish heart rate monitoring by body-contact Doppler radar. IEEE Sensors J 2012;13:408–414.

Hafner N, Mostafanezhad I, Lubecke VM, Boric-Lubecke O, Host-Madsen A. Non-contact cardiopulmonary sensing with a baby monitor. Engineering in Medicine and Biology Society, 2007, EMBS 2007. 29th Annual International Conference of the IEEE; 2007. p 2300–2302.

Hunt CE, Hauck FR. Sudden infant death syndrome. In: Behrman RE, Kliegman RM, Jenson HB, editors. Nelson Textbook of Pediatrics. 17th ed. Philadelphia: Saunders; 2004. p 1380–1385.

Immoreev IY, Samkov S. Short-distance ultrawideband radars. IEEE Aerospace Electron Syst Mag 2005;20(6):9–14.

Kiechl-Kohlendorfer U, Hof D, Peglow UP, Traweger-Ravanelli B, Kiechl S. Epidemiology of apparent life threatening events. Am Acad Pediatr Grand Rounds 2005;90(3):297–300.

Kiriazi JE, Boric-Lubecke O, Lubecke VM. Dual-frequency technique for assessment of cardiopulmonary effective RCS and displacement. IEEE Sensors J 2012;12:574–582.

Kondo T, Uhlig T, Pemberton P, Sly PD. Laser monitoring of chest wall displacement. Eur Resp J 1997;10:1865–1869.

Kryger MH, Roth T, Dement WC. Principles and Practice of Sleep Medicine. 3rd ed. Philadelphia: W.B. Sunders Co.; 2000. p 869.

Li C, Cummings J, Lam J, Graves J, Wu W. Radar remote monitoring of vital signs. IEEE Microwave Mag 2009;10(1):47–56.

Li C, Gu C, Li R, Jiang SB. Radar motion sensing for accurate tumor tracking in radiation therapy. 12th Annual IEEE Wireless and Microwave Technology Conference, Clearwater, FL; 2011.

Li C, Lin J. Random body movement cancellation in Doppler radar vital sign detection. IEEE Trans Microwave Theory Tech 2008;56:3143–3152.

Li C, Lubecke VM, Boric-Lubecke O, Lin J. A review on recent advances in Doppler radar sensors for noncontact healthcare monitoring. IEEE Trans Microwave Theory Tech 2013;61(5):2046–2060.

Li C, Xiao Y, Lin J. A 5 GHz double-sideband radar sensor chip in 0.18 μm CMOS for non-contact vital sign detection. IEEE Microwave Wireless Compon Lett 2008;18:494–496.

Li C, Yu X, Lee C-M, Li D, Ran L, Lin J. High-sensitivity software-configurable 5.8-GHz radar sensor receiver chip in 0.13-μm CMOS for noncontact vital sign detection. IEEE Trans Microwave Theory Tech 2010;58:1410–1419.

Lin JC. Non-invasive microwave measurement of respiration. Proc IEEE 1975;63(10):1530.

Lin JC. Microwave sensing of physiological movement and volume change: a review. Bioelectromagnetics 1992;13(6):557–565.

Lin JC, Dawe E, Majcherek J. A noninvasive microwave apnea detector. Proceedings of the San Diego Biomedical Symposium; 1977. p 441–443.

Lin JC, Kiernicki J, Kiernicki M, Wollschlaeger PB. Microwave apexcardiography. IEEE Trans Microwave Theory Tech 1979;27(6):618–620.

Loo S, Kuo T, Waters G, Muller M, Brown TLH. A mobile electrode for ECG monitoring. Burns 2004;30(2):203.

Lubecke VM, Boric-Lubecke O, Beck E. A compact low-cost add-on module for Doppler radar sensing of vital signs using a wireless communications terminal. The IEEE Microwave Theory and Techniques Symposium Digest; 2002. p 1767–1770.

Lubecke VM, Boric-Lubecke O, Host-Madsen A, Fathy AE. Through-the-wall radar life detection and monitoring. IEEE/MTT-S International Microwave Symposium, 2007; 3–8 June 2007. p 769–772.

Massagram W, Lubecke VM, Host-Madsen A, Boric-Lubecke O. Assessment of heart rate variability and respiratory sinus arrhythmia via Doppler radar. IEEE Trans Microwave Theory Tech 2009;57(10):2542–2549.

Matsui T, Hagisawa K, Ishizuka T, Takase B, Ishihara M, Kikuchi M. A novel method to prevent secondary exposure of medical and rescue personnel to toxic materials under biochemical hazard conditions using microwave radar and infrared thermography. IEEE Trans Biomed Eng 2004b;51(12):2184–2188.

Matsui T, Hattori H, Takase B, Ishihara M. Non-invasive estimation of arterial blood pH using exhaled CO/CO_2 analyzer, microwave radar, and infrared thermography for patients after massive hemorrhage. J Med Eng Technol 2006;20(2):97–101.

Matsui T, Ishizuka T, Takase B, Ishihara M, Kikuchi M. Non-contact determination of vital sign alterations in hypovolemic states induced by massive hemorrhage: an experimental attempt to monitor the condition of injured persons behind barriers or under disaster rubble. Med Biol Eng Comput 2004a;42(6):807–811.

Mercuri M, Soh PI, Pandey G, Karsmakers P, Vandenbosch GAE, Leroux P, Schreurs D. Analysis of an indoor biomedical radar-based system for health monitoring. IEEE Trans Microwave Theory Tech 2013;61(5):2061–2068.

Mostafanezhad I, Boric-Lubecke O. Benefits of coherent low-IF for vital signs monitoring using Doppler radar. IEEE Trans Microwave Theory Tech 2014;62(10):2481–2487.

Ossberger G, Buchegger T, Schimback E, Stetzler A, Weigel R. Non-invasive respiratory movement detection and monitoring of hidden humans using ultra wideband pulse radar. Proceedings of the International Workshop on Ultrawideband Technologies; 2004. p 395–399.

Oum JH, Kim D-W, Hong S. Two frequency radar sensor for non-contact vital signal monitor. 2008 IEEE MTT-S International Microwave Symposium Digest; 2008. p 919–922.

Park BK, Boric-Lubecke O, Lubecke VM. Arctangent demodulation with DC offset compensation in quadrature Doppler radar receiver systems. IEEE Trans Microwave Theory Tech 2007;55:1073–1079.

Phillips BA, Anstead MI, Gottlieb DJ. Monitoring sleep and breathing: methodology; Part I: Monitoring breathing. Clin Chest Med 1998;19(1):203–212.

Ramachandran G, Singh M. Three-dimensional reconstruction of cardiac displacement patterns on the chest wall during the P, QRS, and T-segments of the ECG by laser speckle interferometry. Med Biol Eng Comput 1989;27(5):525–530.

Saunders WK. CW and FM radar. In: Skolnik MI, editor. Radar Handbook. 2nd ed. San Francisco: McGraw-Hill, Inc.; 1990. p 14.1–14.45.

Seals J, Crowgey SR, Sharpe SM. Electromagnetic vital signs monitor. Georgia Tech Research Institute Biomedical Division, Atlanta, GA, Final Report Project A-3529-060; 1986.

Sharpe S, Seals J, MacDonald A, Crowgey S. Non-contact vital signs monitor. US patent# 4,958,638. 1990.

Singh A, Baboli M, Gao X, Yavari E, Padasdao B, Soll B, Boric-Lubecke O, Lubecke VM. Considerations for integration of a physiological radar monitoring system with gold standard clinical sleep monitoring systems. 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2013, 3–7 July 2013. p 2120–2123.

Singh A, Hafner N, Butler M, Lubecke VM. A data efficient method for characterization of Chameleon Tongue motion using Doppler radar. Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2012, EMBC 2012; 2012b.

Singh A, Lee S, Butler M, Lubecke VM. Activity monitoring and motion classification of the Lizard Chamaeleo Jacksonii using multiple Doppler radars. Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2012, EMBC 2012; 2012a.

Singh A, Lubecke VM. Adaptive noise cancellation for two frequency radar using frequency doubling passive RF tags. IEEE Trans Microwave Theory Tech 2013;61(8):2975–2981.

Skolnik MI. An introduction to radar. In: Skolnik MI, editor. Radar Handbook. 2nd ed. San Francisco: McGraw-Hill, Inc.; 1990. p 1.1–1.21.

Staderini EM. UWB radars in medicine. IEEE Aerospace Electron Syst Mag 2002;17(1):13–18.

Tarassenko L, Hann A, Yound D. Integrated monitoring and analysis for early warning of patient deterioration. Br J Anaesth 2006;97(1):64–68.

United Nations. World Population Ageing. New York, NY: Department of Economic and Social Affairs, Population Division; 2013.

Vergara A, Boric-Lubecke O, Lubecke VM. DC information preservation for cardiopulmonary monitor utilizing CW Doppler radar. 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2008, EMBS 2008; 20–25 August 2008b. p 1246–1249.

Vergara A, Petrochilos N, Boric-Lubecke O, Host-Madsen A, Lubecke V. Blind source separation of human body motion using direct conversion Doppler radar. IEEE MTT-S International Microwave Symposium Digest; 2008a. p 1321–1324.

Wang Y, Fathy AE. Micro-Doppler signatures for intelligent human gait recognition using a UWB impulse radar. 2011 IEEE International Symposium on Antennas and Propagation (APSURSI); 3–8 July 2011. p 2103–2106.

Wang F-K, Horng T-S, Peng K-C, Jau J-K, Li J-Y, Chen C-C. Single-antenna Doppler radars using self and mutual injection locking for vital sign detection with random body movement cancellation. IEEE Trans Microwave Theory Tech 2011;59(12):3577–3587.

Webster J. Medical Instrumentation. Wiley; 2010.

Wiesner A. A multifrequency interferometric CW radar for vital signs detection. 2009 IEEE Radar Conference; 2009. p 1–4.

Xiao Y, Lin J, Boric-Lubecke O, Lubecke VM. Frequency-tuning technique for remote detection of heartbeat and respiration using low-power double-sideband transmission in the Ka-band. IEEE Trans Microwave Theory Tech 2006;54(5):2023–2032.

Yavari E, Song C, Lubecke VM, Boric-Lubecke O. Is there anybody in there?: Intelligent radar occupancy sensors. IEEE Microwave Mag 2014;15(2):57–64.

Young T, Peppard PE, Gottlieb DJ. Epidemiology of obstructive sleep apnea: a population health perspective. Am J Respir Crit Care Med 2002;165(9):1217–1239.