Wearable Sensing and Telehealth Technology with Potential Applications in the Coronavirus Pandemic

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***Abstract*—Coronavirus disease 2019 (COVID-19) has emerged as a pandemic with serious clinical manifestations including death. A pandemic at the large-scale like COVID-19 places extraordinary demands on the world's health systems, dramatically devastates vulnerable populations, and critically threatens the global communities in an unprecedented way. While tremendous efforts at the frontline are placed on detecting the virus, providing treatments and developing vaccines, it is also critically important to examine the technologies and systems for tackling disease emergence, arresting its spread and especially the strategy for diseases prevention. The objective of this article is to review enabling technologies and systems with various application scenarios for handling the COVID-19 crisis. The article will focus specifically on 1) wearable devices suitable for monitoring the populations at risk and those in quarantine, both for evaluating the health status of caregivers and management personnel, and for facilitating triage processes for admission to hospitals; 2) unobtrusive sensing systems for detecting the disease and for monitoring patients with relatively mild symptoms whose clinical situation could suddenly worsen in improvised hospitals; and 3) telehealth technologies for the remote monitoring and diagnosis of COVID-19 and related diseases. Finally, further challenges and opportunities for future directions of development are highlighted.**

***Index Terms*—COVID-19, wearables, unobtrusive sensing, mobile health, cybercare, telemedicine, physiological monitoring.**

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I. Introduction

Coronavirus disease-2019 (COVID-19) has become a pandemic, affecting more than 210 countries throughout the world. COVID-19 is highly contagious, with reported average case-fatality rates ranging from 6.2% to 7.2% among the most-affected countries [1]–[3], and it is an acute public health issue. According to the latest data from the World Health Organization (WHO), the epidemic has infected more than 7.6 million people and caused the deaths of more than 427,000 globally [3]. As of 14 June 2020, the number of confirmed cases for COVID-19 is about 950 times more than the previous coronavirus-induced severe acute respiratory syndrome (SARS) outbreak in 2002-2003, and the numbers of those infected with COVID-19 are expected to grow. The COVID-19 outbreak not only threatens global public health but also impacts many other aspects of life, in particular the global economy.

Caused by the SARS coronavirus 2 (SARS-CoV-2), COVID-19 most frequently presents with respiratory symptoms that can progress to pneumonia and, in severe cases, acute respiratory distress syndrome (ARDS) along with cardiogenic or distributive shock. Though SARS-CoV-2 and SARS-CoV share some common clinical manifestations, a new study shows that SARS-CoV-2 is highly efficient in person-to-person transmission and frequently causes asymptomatic infections [4]. Clinical deterioration can occur rapidly, often during the second week of illness, which can lead to intensive care unit (ICU) admission and high mortality [8], [9]. Specifically, the severity of COVID-19 varies from asymptomatic, subclinical infection and mild illness to severe or fatal illness [8]. Cases of COVID-19 are generally categorized into five groups: asymptomatic, mild, moderate, severe, and critical. According to data from China, 15-20% of COVID-19 cases require hospitalization, with around 15% of cases presenting with severe symptoms and 5% requiring intensive care, including invasive mechanical ventilation [10]. In Italy and Spain, 40-50% of COVID-19 cases have been hospitalized, with 7–12% requiring admission to ICUs [11].

Given its severity and fast spread, the COVID-19 pandemic has raised huge challenges for global healthcare systems. COVID-19 can rapidly overwhelm health care systems, impairing their capacity to deliver services not only to patients infected with this epidemic disease but also to those with health problems that are not necessarily related with COVID-19. Lessons from epidemic centers such as China, Italy and United States show that COVID-19 can suppress the capacity of health care systems even in countries with extensive health resources and universal care [12]. Currently in most countries, to reduce the burden on health care systems, patients with COVID-19 are triaged based on the severity of the disease, *i.e.*, critically ill patients are admitted to the hospital while patients with mild symptoms and without underlying chronic conditions may be cared for at home, and mild cases will not require intervention unless rapid deterioration occurs [13], [14].

Responding to COVID-19 with the aim to contain the virus while maintaining essential health services requires the optimization of current healthcare service delivery approaches and the development of alternative delivery platforms to ensure that: **i)** the health status of isolated and quarantined individuals can be monitored continuously to intervene in a timely manner in case of rapid deterioration and to determine if individuals continue to require isolation or quarantine; **ii)** the health of caregivers and management personnel as one of the most important forces in caring for patients and fighting the pandemic; **iii)** the health status of vulnerable people who are at risk from coronavirus, *e.g.*, people who are aged over 60 years, and those with underlying conditions such as hypertension, diabetes, cardiovascular disease (CVD), chronic respiratory disease and cancer, are closely tracked; **iv)** patients with non-COVID-19-related health conditions can be monitored continuously while the health system shifts focus to the outbreak and patient contact is essentially minimized to reduce cross infection; and **v)** early screening and detection in the initial period of disease spread in public areas or in the community is critical to mitigate wide transmission.

To strengthen and reorganize the health care system, one important strategy is "forward-triage" or "virtual-triage", tracking the infection, screening and classifying each patient to determine priority of need and proper place of treatment based on the severity of their condition [15]. Advances in wearable health sensing and monitoring technologies is of very high potential for shifting the health care burden from hospital to improvised hospital or home, thereby securing established hospital resources for those in urgent need. The deployment of wearable and unobtrusive health monitoring technology that, together with advances in telehealth and mobile health (mHealth) technology that is empowering people to take control of their health and ultimately their lives, is a feasible and promising solution to help tackle the COVID-19 pandemic.

Being able to monitor a range of accessible physiological parameters including respiratory parameters, blood oxygen saturation (SpO2), heart rate (HR), blood pressure (BP), body temperature (amongst others), the mHealth technology enabled by wearable devices and unobtrusive sensing can also provide more accurate alerts to anomalous physiological changes, which can potentially identify deteriorating health or the onset of serious medical problems. It can be promisingly used for monitoring personal health continuously at either home, public places, residential care, or hospital, with application scenarios that include providing screening and real-time triage of patients with suspected infection, monitoring diagnosed patients with mild severity whilst in isolation, enabling real-time health surveillance of patients in improvised hospital and established hospital settings. A non-exhaustive depiction of application scenarios is shown in Fig. 1. During the COVID-19 pandemic, the wearable devices and unobtrusive sensing along with telehealth can monitor symptoms and warning signs of COVID-19 and allows health care providers to monitor a patient's health over time remotely. This will make it possible to further eliminate the need for face-to-face contact and enabling better management via early detection and monitoring of coronavirus symptoms. If symptoms develop, the data sent via the secure cloud platform can enable healthcare authorities to introduce effective general population triage such as placing patients under quarantine, transferring to care home facilities, or managing high-risk people in their own homes.

In particular, asymptomatic carriers of SARS-CoV-2 are highly prevalent during the explosive stage. A study about the virus transmission in a skilled nursing facility showed that the asymptomatic rate was as high as 56% (27 out of 57), about 90% of which subsequently developed symptoms [16]. That means the symptom-based screening could fail to detect approximately half the people with COVID-19. Furthermore, lack of available testing would make it very difficult to confirm if and when a subject has contracted COVID-19. Wearable health sensors and systems can potentially overcome this challenge, as their enabled continuous health recordings can possibly capture the complex variations of physiological system that are indicative of asymptomatic and presymptomatic cases, and enhance understanding of the development of COVID-19.

The aims of this paper are: to provide a comprehensive review of the wearable devices and unobtrusive sensing technologies that are able to monitor early symptoms of COVID-19 and common health conditions; to present the telehealth framework for remote screening and diagnosis of disease; and to highlight the most pressing directions for future research. In Section II, we present the wearable technologies that are for respiratory assessment and other physiological measurements. We also review unobtrusive sensing technologies that can be used in ubiquitous in-home and public domain monitoring. Section III

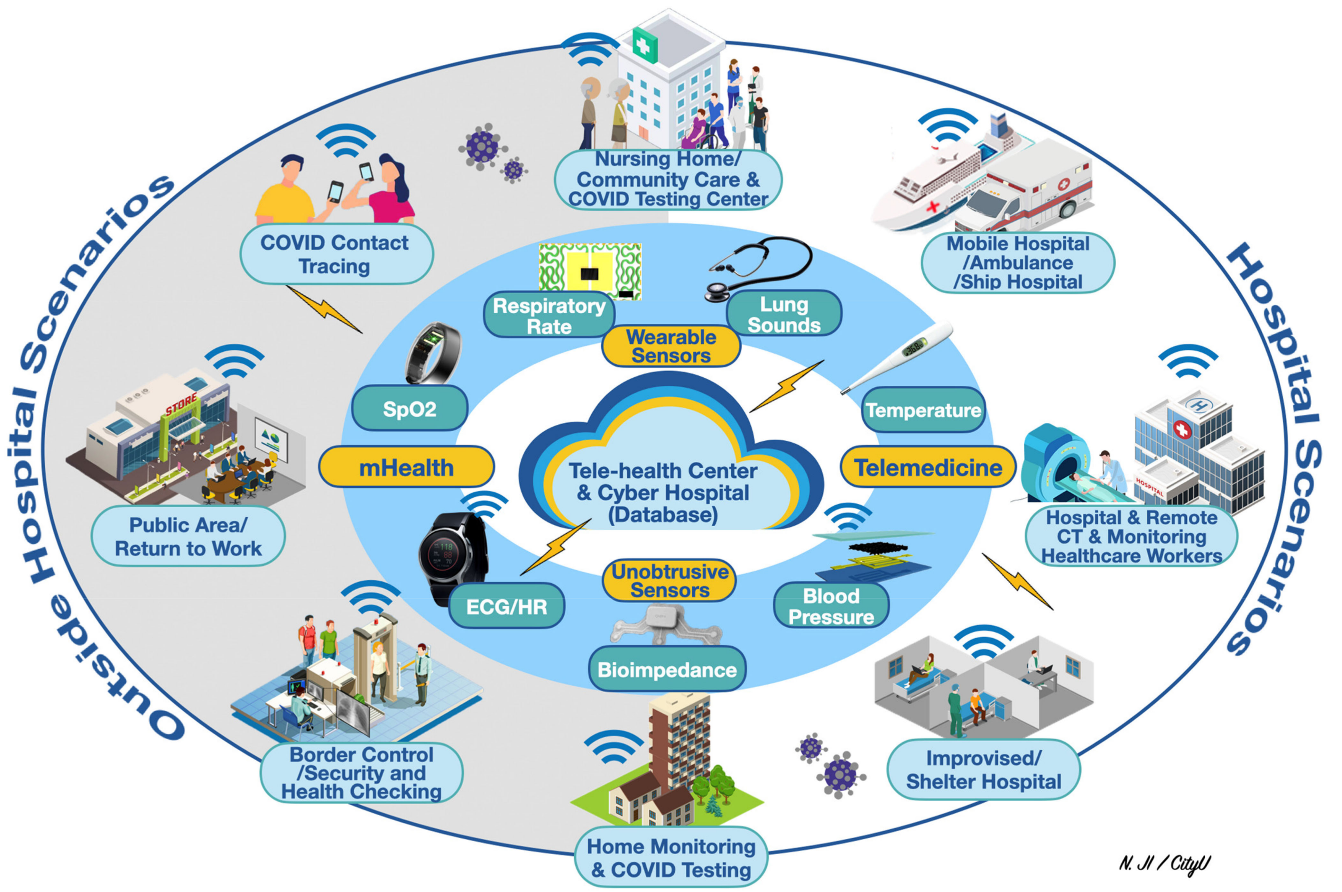

Fig. 1. Application scenarios of wearable devices, unobtrusive sensors and tele-health systems during pandemics (some of the original design concepts above are borrowed from Dr. R. Pettigrew's presentations at the IEEE Life Sciences Grand Challenge Conference held at National Academy of Sciences in 2012) [5]–[7].

provides a review of the mHealth and telemedicine technologies in managing COVID-19. Finally, in section IV, we highlight the most pressing directions for future research and development.

II. Wearable Technology for Health Monitoring of COVID-19

Wearables can play a vital role in early warning of COVID-19 infections by combining essential vital signs with clinical symptomology, to identify people who may be a more likely candidate for testing, to detect any sudden deterioration in people who are isolated, quarantined, or at a step down unit, in particular those who are asymptomatic, and to remotely monitor non-COVID-19-related patients for prioritizing the use and allocation of resources and reducing cross contamination.

Among all the clinical presentations of COVID-19, there are three primary coronavirus symptoms: i) respiratory distress in the form of shortness of breath, ii) fever, and iii) coughing [17]. Other complications such as cardiac injury may also occur in patients even without underlying heart conditions [15]. According to the National Institute for Health and Care Excellence (NICE) guidelines, where physical examination and other ways of making an objective diagnosis are not possible, clinical features could provide a rapid diagnosis of community-acquired pneumonia. These features are: i) respiratory rate (RR) $\geq$ 20 breaths per min (bpm), ii) temperature $\geq$38 °C, iii) pulse rate >100 beats per min with iv) crackles obtained via stethoscope [15], [18]. It is therefore crucial to conduct respiratory assessment, cardiovascular monitoring and other parameter or indicator evaluation such as temperature, and cough for the screening and detection of any suspected cases or deterioration.

A. Wearable Devices for Respiratory Assessment

COVID-19 is primarily considered a respiratory disease. Through attachment of its spiky surface protein to angiotensin-converting enzyme 2 (ACE2) receptors to healthy cells, the SARS-CoV-2 targets the respiratory tract, especially the lower airways that have more ACE2 receptors than the rest of the respiratory tract. The lungs may be inflamed, causing dyspnea and leading to rapidly progressive ARDS; furthermore it can lead to pneumonia, an infection of the alveoli inside the lungs where the blood exchanges oxygen and carbon dioxide [19].

Wearable devices are able to provide noninvasive and continuous assessment and monitoring of respiratory functions or parameters of a patient including SpO2, RR and lung sounds.

1) Oxygen Saturation: Oxygen saturation (SpO2), a measure of the percentage of hemoglobin saturated with oxygen, is an indication of respiratory function and the overall physiological condition of the human body. As COVID-19 develops, the lungs can become filled with inflammatory material and fluid with the air sacs becoming inflamed, hindering their ability to pass oxygen from the air into the bloodstream, potentially leading to hypoxia and impending organ damage [20]. A normal healthy person is able to achieve SpO2 at levels of 95%–100%, but the level may decrease in patients with a health issue or respiratory distress. SpO2 is an important indicator for triage of COVID-19 patients. The WHO guideline suggests patients with an SpO2 greater than 94% can be cared at home [21]. SpO2 levels are also predictive of outcome; levels below 93% indicate a severe case of COVID-19, which should be transferred to an ICU [17], and patients with an SpO2 lower than 90% during admission are more likely to die [22]. Hence continuous monitoring of SpO2 levels is crucial to track the progression of the disease and identify any deterioration, in particular in severe cases. The application of a wearable finger pulse oximeter on patients with chronic obstructive pulmonary disease allows continuous SpO2 measurements to capture significant SpO2 fluctuations over long periods of time that can help determine the clinical relevance of such fluctuations [23]. This may shed light on the application of wearable pulse oximeter for home care of patients with mild symptoms or convalescent patients. In addition, the pulse oximeters have the major benefits of being usable within the homes of mildly ill and convalescent patients. It can also save many lives by making oximetry widely available, in particular in less well-resourced countries [24], [25].

Pulse oximetry devices are based on photoplethysmography (PPG), the measurement of light-absorption change due to the changes in arterial blood volume. It consists of a dual light-emitting diode (LED), usually red and infrared, and a detector. By illuminating lights from the dual LED to a portion of the body (*e.g.*, fingertips or earlobe), the detector can detect the different wavelengths of lights that have passed through or been reflected from the body part. SpO2 is then calculated based on the difference in the absorption of the two wavelengths of light by oxygenated haemoglobin (O2Hb) and deoxygenated haemoglobin (HHb).

Compared with other wearable health monitors, the technology underpinning wearable pulse oximeters has been maturing and there are a number of products available. Fig. 2 shows a schematic diagram of several commercially available wearable pulse oximeters. These devices are either reflectance-type or transmission-type and can be worn on different places of the body. Traditionally, the devices are worn on the fingertip or earlobe. Recent advances in wearables technology including device miniaturization makes it possible to wear the oximetry device on the wrist, chest or other areas. The wristwatch or band is the most common wearable form. The commercially available products include the Oxitone 1000M [26], Checkme O2 (Viatom, Shenzhen, China) [27], Wavelet Health Wristband (Wavelet, California, USA), Loop (SpryHealth, California, USA). Of note, most of these wearables are consumer-grade rather than clinical-grade. Among them, Oxitone 1000M was claimed as the world's first FDA-cleared wrist-sensor pulse oximetry monitor, with SpO2 measurement error within 3% [26]. Devices can also be worn on the head or attached to the chest area as a patch.

Fig. 2. Commercially available wearable pulse oximeters, Oxitone 1000M (Oxitone, Hartford, USA) [26], Checkme O2 (Viatom, Shenzhen, China) [27], Timesco CN130, Loop (SpryHealth, California, USA), WristOx2 (Nonin Medical Inc, Plymouth, United Kingdom), Wellue O2Ring (Wellue Health, Shenzhen, China), Biostrap (Biostrap, California, USA), and Wavelet Health Wristband (Wavelet, California, USA).

Although the use of commercially available pulse oximetry is widespread, this wearable technology still suffers from common issues such as motion artefact and high power consumption, which are crucial challenges for long-term telehealth applications. In recent decades, there have been continuous efforts attempting to resolve these challenges. Aiming to mitigate the effects of motion artefacts, Yan and Zhang developed and algorithm using a minimum correlation discrete saturation transform to estimate SpO2, which can achieve a better performance than the clinically verified motion-resistant algorithm – discrete saturate transform – when signal quality is low [28]. Mendelson *et al.* investigated a multi-channel reflectance pulse oximeter that proved to be efficient for robust noise cancellation with PPG signal acquired concurrently from each channel [29]. Chacon *et al.* reported a wireless wearable pulse oximeter that was integrated with a novel data-dependent motion artefact tailoring algorithm, which demonstrated to be an efficient method for continuous monitoring of SpO2 [30]. Another recent study by Harvey *et al* developed an algorithm based on the time-frequency components of a PPG, which was demonstrated to have an accuracy of 96.76% for SpO2 measurements with motion artefacts and at low oxygen level [31]. Potential solutions have also been studied for improving the energy efficiency of pulse oximetry. A study by Haahr *et al.* presented a patch SpO2 monitor that used an annular backside silicon photodiode can decrease the power consumption of the oximeter sensor [32]. While Kim

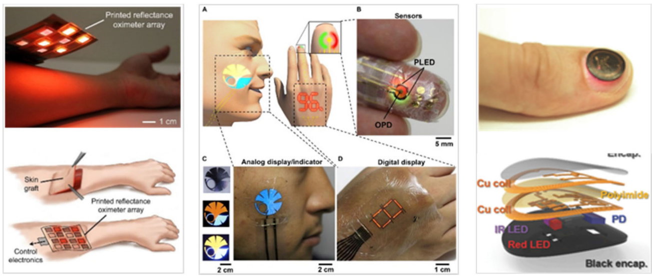

Fig. 3. Flexible sensing for pulse oximetry. Left column: flexible organic reflectance oximeter array [35]; middle column: ultra-flexible organic photonic skin [36]; right column: miniaturized battery-free wireless systems for wearable pulse oximetry [33].

et al. reported flexible wearable battery-free pulse oximetry that employed novel material with near-field communication technology for power supply [33]. Recently, Lee *et al.* designed a reflective patch-type oximeter with a flexible organic LED and organic photodiodes that has ultralow power consumption compared with typical LEDs and detectors [34]. With the issues of motion artefact and energy saving adequately addressed, robust wearable pulse oximeters with very low power consumption would be of great potential for mHealth applications in pandemics like COVID-19.

With rapid advances in novel sensing materials and fabrication techniques, the newly emerging technology of oximetry based on flexible sensing via organic optoelectronics could revolutionize the conventional oximeter by measuring SpO2 levels at any place on the body (Fig. 3). As examples, Yokata *et al.* demonstrated an ultraflexible pulse oximeter with polymer LEDs and organic photodetectors [36], and using design similar to Yokata *et al.*, a flexible and printed reflectance oximeter array was designed by Kan *et al.*, which gives a 2D mapping of the oxygen level over the sensing place [35] (Fig. 3).

2) Respiratory Rate: Respiratory rate (RR) is an important vital sign for monitoring illness progression. Changes and anomalies in RR are not only associated with respiratory conditions, but also have implications for patients with difficulty in maintaining homeostatic control. Being an early, measurable indicator of physiological conditions such as hypoxia (low levels of oxygen) and hypercapnia (high levels of carbon dioxide in the bloodstream), it has also showed to be a strong predictor of acute events such as cardiac arrest and unplanned intensive care admission [37]. Together with SpO2, HR and body temperature, RR is one of the clinical features for evaluating the severity of respiratory disease, *e.g.*, a patient with severe respiratory distress has an RR greater than 30 breaths/min that can develop into ARDS [9], [38]. Moreover, RR may be a vital prognostic factor for COVID-19. A retrospective cohort study of adult inpatients with COVID-19 in Wuhan showed that 63% (34 out of 54) of the patients who died from the disease had a RR higher than 24 breaths per min, compared with that of 16% (22 out of 137) of survivors [39]. Measuring RR with wearable devices and unobtrusive sensing systems in a real-time and continuous manner is therefore extremely important for monitoring the progression of COVID-19, allowing identification of any deterioration, assessment of response to treatment, and evaluation of whether a change of clinical care is required.

Wearable RR monitoring is usually performed in three ways: 1) by detecting respiratory airflow by measuring parameters such as temperature, humidity, and CO_2, 2) by sensing breathing-related mechanical effort such as respiratory sound, and respiratory related chest or abdominal movements, and 3) by extracting respiratory component from other cardiovascular signals such as electrocardiogram (ECG) and PPG based on the modulating effect of breathing on these signals as caused by respiratory sinus arrhythmia (RSA). The sensor technologies include thermal, humidity, acoustic, pressure, resistive, inductive, acceleration, electromyography, and impedance. A wearable device with these sensors can be mounted into chest belts [40]–[43], or applied to the skin [44], [45], amongst other modes of attachment.

The airflow-based method relies on the fact that the exhaled air is warmer with higher humidity and more CO_2 than the inhaled air. Accordingly, RR can be measured by detecting changes in temperature, humidity and CO_2. The airflow-sensing method usually needs a sensor that attaches to the airways. The sensor can be a nasal or oronasal thermistor, humidity sensor or a CO_2 sensor which detects the temperature/humidity/CO_2 changes between the inhaled and exhaled air. For example, Liu *et al.* devised a flexible epidermal respiratory sensor based on the thermal convection effect which had high thermal sensitivity and could well capture various breathing patterns via mounting the sensor above the upper lip [45]. Dai *et al.* developed a polyelectrolyte humidity sensor that can be integrated into a facial mask, as is widely used during the current pandemic [46]. But monitoring with a face mask can still be intrusive to users, and the displacement of the sensor may affect the accuracy.

Wearable strain gauge sensors, triboelectric sensors and accelerometers have been extensively studied to detect respiratory movement in the thorax or abdomen area caused by respiratory volumetric changes. In one study by AI-Halhouli *et al.*, a wearable inkjet-printed strain gauge sensor was developed, and its performance was comprehensively evaluated against a reference nasal airflow sensor at different locations (umbilicus, upper abdomen, xiphoid process, upper thorax, and diagonal). The results indicate a high RR estimation accuracy ($<0.07 \pm 0.54$ bpm) at these places without significant difference, but the upper thorax was shown to be the most comfortable location [41]. Zhang *et al.* developed a triboelectric nanogenerator based waist-wearable wireless respiratory monitoring device, and it was demonstrated to be highly accurate and sensitive for real-time respiratory monitoring [40]. Another study by Liu *et al.* reported a body sensor network (BSN) enabled three-dimensional accelerator to track inclination changes due to breathing. By extracting breathing information with principal component analysis, dynamic RR estimation can be obtained during various activities such as walking, running and sleeping [42].

RR can also be obtained by extracting the RSA component from other vital signs that can be acquired by wearable devices, such as ECG and PPG. The derivation of RR from cardiac signals mainly consists of extraction of respiratory signals via different modulations (baseline wander, amplitude, and frequency) from

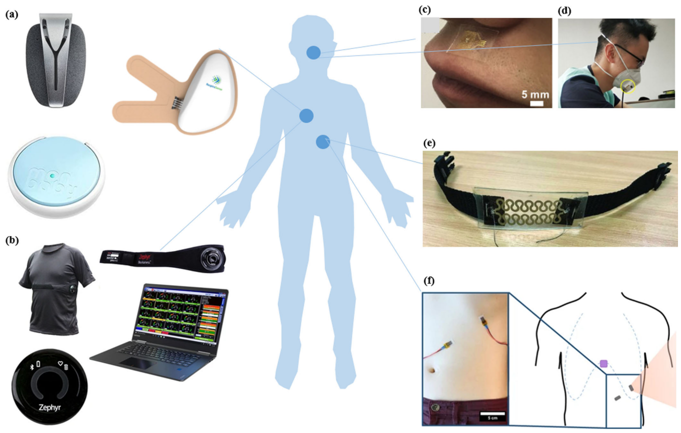

Fig. 4. Wearable RR monitor products: (a) Spire medical health tag (Spire Health, USA) [47], RespiraSense$^{\mathrm{TM}}$ patch (PMD Solutions, Ireland) [48], and MonBaby clip (MonBaby, New York, USA) [49], (b) Zephyr$^{\mathrm{TM}}$ garment (Zephyr Technology, Auckland, New Zealand) [50], and state-of-the-art research, (c) an epidermal thermal sensor [45], (d) humidity sensor [46], (e) wearable strain gauge [41], and (f) a BandAid like respiratory monitor [44].

the signal and estimation of RR from the extracted respiratory signal [51]. With a fusion algorithm at the stage of respiratory extraction with estimations from multiple signals, it is possible to improve robustness against motion artefact hence increase estimation accuracy. Further technical details are provided in the article by Charlton *et al.* that reviews the RR estimation from ECG and PPG [51]. The advantage of indirect estimation of RR is that these techniques can be easily integrated into commercially existing wearable devices, adding the value of RR monitoring to the existing functionality.

Some of the technologies for respiratory monitoring have been commercialized, such as Spire medical health tag (Spire Health) [47], a wearable RR monitor by motion sensors, MonBaby, a clip-on device for breath monitoring of babies based on a MEMS accelerometer [49], and RespiraSense$^{\mathrm{TM}}$, a patch-like wearable that uses piezoelectric sensor array to detect deformations in the relative angles of the thoracic and abdominal surfaces thus measuring the RR [48]. Fig. 4 lists these products as well as the technologies that are at the prototype stage.

3) Lung Sounds: Both infectious and non-infectious diseases can lead to abnormal levels of air and fluid in the lungs. Structural changes induced by disease cause alterations in acoustic transmission of frequencies through the thoracic cavity [52], [53]. Adventitious respiratory sounds have been classified into several different types, depending on their spectral-temporal characteristics and their location. The common types include crackles, wheezes, rhonchi, stridor, and squawks. A variety of lung pathologies and injuries result in adventitious respiratory sounds and/or alter sound transmission pathways, with both spectrally and regionally differing effects that, if properly quantified, may provide additional information about the severity and location of the trauma or disease [54]. For COVID-19, where there is currently an overall lack of clinical studies on respiratory sounds, a study has investigated lung sounds on patients with confirmed COVID-19 by lung auscultation, and shown that all patients ($n = 10$) were found to have abnormal respiratory sounds [55]. This indicates that lung sounds can potentially be used as a simple screening method for suspected and asymptomatic patients.

Auscultation of the lungs is an important part of the respiratory examination. It is noninvasive, safe, easy to perform, low cost and commonly used by a physician to diagnose various cardiopulmonary diseases [56]. The lung sounds obtained by auscultation enables assessment of the airflow through the trachea and bronchial tubes, and it is able to distinguish normal breath sound from abnormal ones, thus aiding diagnosis of pulmonary disorders or evaluation of ventilation [57].

Traditionally, auscultation is performed with a stethoscope, which consists of a small disc-shaped resonator and two tubes connected to earpieces. With the analogue stethoscope, contacts with infected or suspected patients would increase risk of infection for physicians. A wearable digital stethoscope allows a health worker to check the lung sounds as well as cardiac sounds continuously and remotely and is therefore very important for baseline assessment of patients during the pandemic. Wearable acoustic sensing technology has emerged for auscultation. Gupta *et al.* have developed a wearable solution that integrates an accelerometer and a microphone via a nano-gap transducer for longitudinal monitoring of heart and lung sounds as well as relevant parameters including HR, RR, and body motion [58]. Klum *et al.* have reported a wearable stethoscope patch that combines sensing modalities like a MEMS stethoscope, ambient noise sensing, ECG, impedance pneumography and 9-axis actigraphy. The system is able to monitor auscultation continuously without requiring the distribution of sensors over different places of the body [59], [60]. To detect wheezing or potentially other adventitious respiratory sounds, Shkel *et al.* implemented a resonant microphone array that could counteract the interference from the heart and external noise sources, thus reducing the digital processing of the acquired signals, reducing power consumption and improving the detection accuracy [61]. With transducers and signal recognition algorithms specifically designed, the wearable digital stethoscope can be used for continuous monitoring of lung sounds and assessing respiratory function of patients with COVID-19.

B. Wearable Devices for Cardiovascular Evaluation

Although the most frequent clinical presentation of COVID-19 are dominated by respiratory symptoms, COVID-19 can significantly affect heart function and lead to myocardial injury and possibly cause chronic damage to the cardiovascular system [62]. One cohort study reports that 19.7% of patients ($n = 416$) with COVID-19 had cardiac injury during hospitalization [63]; another study found that 27.8% of patient has myocardial injury, which resulted in cardiac dysfunction and arrhythmias [64]. The mechanisms of cardiovascular damage caused by SARS-CoV-2 are not clear yet, but may involve increased cardiac stress due to respiratory failure and hypoxemia, direct myocardial infection resulting from the virus attack of the lining of the heart and blood vessels that are rich in ACE2 receptors [65], indirect injury from the systemic inflammatory response that can trigger a “cytokine storm”, or a combination of all three factors [66].

In addition, patients with pre-existing CVD have a significantly increased risk of developing severe symptoms and higher risk of poor outcome including death if infected with SARS-CoV-2 [9], [67], [68]. Among adult patients, CVD and hypertension were the most common comorbidities [69]. One study showed that among the patients with severe symptoms of COVID-19, 58% were hypertensive, 25% with heart disease and 44% with arrhythmia [70]. Moreover, those with cardiovascular comorbid conditions are more at risk of infections, as underlying health conditions are a clear risk factor for COVID-19 and CVD is one of the most common conditions in global population, in particular in the elderly population. For these reasons, continuous monitoring of cardiovascular conditions by measuring key indicators such as ECG, HR, and arterial BP would be beneficial for the following reasons: i) to evaluate those who are more susceptible to the SARS-CoV-2, ii) to triage patients with COVID-19 according to the presence of underlying CVD, and iii) to provide early warning of any cardiac dysfunction to those confirmed with COVID-19 but without a cardiac condition thus to prioritize clinical services and treatment.

In this section, we will review the wearable and unobtrusive technologies for monitoring the two key cardiovascular function evaluation parameters *i.e.*, ECG, and BP.

1) Electrocardiogram for Monitoring CVD and COVID-19 Patients: The ECG is a diagnostic tool routinely used to evaluate the electrical and muscular function of the cardiac system by recording the rhythm and activity of the heart. ECG and its derived HR can provide valuable information in screening asymptomatic individuals with CVD, diagnosis of CVD, and risk assessment of COVID-19 treatment. COVID-19 complicated by cardiovascular injury may indirectly be reflected by ECG changes. ECG abnormalities including ST-segment elevation and multifocal ventricular tachycardia have been reported in patients with COVID-19 [71]. Also, medications are currently used empirically to treat COVID-19 may have side effects and drug interactions, *e.g.,* chloroquine and hydroxychloroquine are known to prolong the QT interval which can potentially lead to fatal side effects [72]. Close monitoring of ECG is therefore required for COVID-19 patients with QT prolonging medications [73]. Furthermore, wearable based tele-ECG monitoring instead of standard vital sign checks by medical staff can potentially reduce cross-infections through reducing staff to patient contact.

Adhesive ECG patches are one of the most common wearable ECG monitoring approaches. Compared with the traditional wearable Holter monitor, the wearable continuous ECG monitoring patch is small in size, wireless with miniaturized electronics, and easy and comfortable to use. It can record ECG for many days for the detection of intermittent arrhythmia. The ECG patch device typically consists of a sensor system, a microelectronic circuit with recorder and memory storage, and an internal embedded battery. Depending on the devices, they are for medium-term use ranging from days to several weeks.

There are a number of products that have been approved by the FDA and that are used in monitoring COVID-19. For example, the MCOT patch (BioTelemetry, Pennsylvania, USA) was used to monitor the ECG changes of patients treated with hydroxychloroquine and azithromycin [74]. After the administration of the drugs, atrial fibrillation (AF) was identified a few hours later, and a timely intervention by appropriate therapy for AF caused reversion to sinus rhythm. Similarly, the CAM^{TM} Patch has been announced for use in monitoring QT interval in patients who have been treated with hydroxychloroquine [75], [76]. Other ECG patch products with a similar function have been used in clinical studies including Zio^{XT} (iRhythm, California, USA), NUVANT (Corventis, California, USA), Savvy monitor (Ljubljana, Slovenia) [77], and the SEEQ MCT patch (Medtronic, Inc) [78], VitalPatch wearable sensor (VitalConnect, California, USA) [79] (Fig. 5). Some of them have been demonstrated to have superior performance in identifying hidden arrhythmias than traditional Holter monitors [80], [81]. One example is the iRhythm Zio^{XT} that was used in one study to improve the diagnosis rate of AF for patients at home with a randomized clinical trial of 2569 individuals, and showing that a continuous ECG monitoring patch improved the rate of AF diagnosis to four times higher compared with regular ECG check [80].

Fig. 5. Commercial ECG patches used in clinical trials and in COVID-19, (a) MCOT (BioTelemetry, Pennsylvania, USA), (b) Zio^{XT} (iRhythm, California, USA), (c) NUVANT (Corventis, California, USA), (d) SEEQ MCT patch (Medtronic, Dublin, Ireland), (e) Savvy (Ljubljana, Slovenia), (f) CAM (BardyDx, Washington, USA), and (g) VitalPatch (VitalConnect, California, USA).

However, the main disadvantages of the patch ECG monitor includes high cost due to the disposable nature of the device, and dependence on the device company for raw data retrieval which can cause delays between data collection and data processing [81]. In addition, almost all the patch ECG monitors feature only a single lead ECG acquired from two closely-spaced electrodes. Compared with multi-lead ECGs, the one-lead ECG can only provide a limited value for diagnosis of specific cardiac disease, such as myocardial ischaemia [82].

Other than patch, wearable ECG monitor integrated in garment is also popular, which is usually via capacitive sensing through smart materials like e-textile. Such e-textile systems tends to be washable, flexible, stretchable, and thin. As an exemplar, an e-textile based stretchable electrodes connected with an electronic module that was made on a flexible print circuit were developed and integrated to a sportswear [83]. To overcome the shortcoming of having single lead ECG for most of the patch and garment based ECG monitors, Hsu et al devised a 12-lead noncontact ECG system that was attached to a vest and

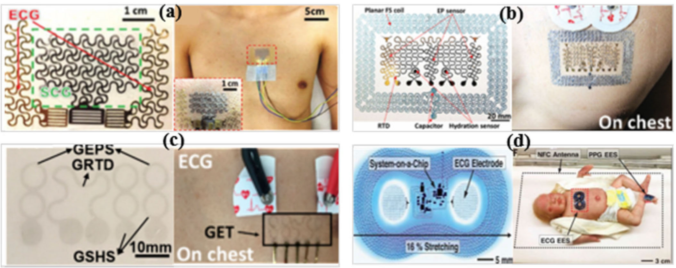

Fig. 6. Flexible ECG technologies: (a) an e-tattoo ECG [86], (b) a multiparametric epidermal sensor [87], (c) a graphene e-tattoo ECG [88], and (d) an epidermal sensing system with in-sensor analytics [89].

the locations of the electrodes can be adjusted [84]. For non-contact dry textile electrodes, the quality of the acquired ECG signal is a common issue. To address such a challenge, studies have been conducted to improve the surface characteristics of the electrodes, enabling a more effective contact area, *e.g.*, by implementing an electro-conductive elastic paste between skin and electrode [85].

Moreover, a wristwatch such as the Apple Watch has also been widely for cardiovascular monitoring, including HR measurement and AF detection [90]. With advances in novel material, fabrication and printing technology, flexible and stretchable ECG is now becoming the trend for future wearable and unobtrusive ECG monitoring (Fig. 6).

2) Continuous Blood Pressure Monitoring: BP is one of the most important vital signs that reflect cardiovascular and cerebrovascular functions. High BP, known as hypertension, is the main risk factor for cardiovascular morbidity and mortality, accounting for more than 10 million largely preventable deaths worldwide each year [91].

A study of 5700 patients with COVID-19 shows that hypertension is the most common comorbidity (3026 (56.6%) patients), followed by obesity (1737 (41.7%) patients), and diabetes (1808 (33.8%) patients) [92]. These studies indicate that the vulnerable population such as those with an underlying conditions suffer a higher risk of severe complications from COVID-19 [39], [93]. A recent study that included 44,672 confirmed cases further suggests the case fatality rate of those with pre-existing comorbid hypertension (6.0%) and CVD (10.5%) is significantly higher than those without any comorbid conditions (0.9%) [10].

Over the past hundred years, BP is usually measured by cuff-based sphygmomanometers by medical staff face-to-face. However, during this large-scale pandemic, repeated BP measurements significantly increase contact time, and places an extraordinary workload on health workers. As COVID-19 is highly contagious, the frequent interaction with patients also increases the possibility of infecting medical staff. Moreover, some COVID-19 infected patients experience a rapid deterioration in their clinical condition, presumably due to the "cytokine storm", which is the disastrous overreaction of the immune system and can cause sudden falls in BP [65]. Thus, continuous and unobtrusive methods for remote monitoring of BP in real-time may help to prevent sudden events and reduce the possibility of cross contamination. Novel wearable and unobtrusive technology that enables continuous BP monitoring remotely would enhance patient autonomy at home during the lockdown period of the pandemic while providing medical staff remotely with a more complete picture of their patient's BP profile. This would improve BP control and reduce the cases of comorbid hypertension with COVID-19.

Continuous BP monitoring can be implemented easily in ICUs through an arterial invasive line but challenging in the quarantine scenarios and in improvised hospitals where it is highly desirable for the remote measurements to be conducted in an unobtrusive and wireless manner. In recent decades, extensive research has been performed to transform the method of continuous BP monitoring without the use of a cuff. Here we focus on notable wearable and unobtrusive BP research done after 2016. Relevant research before 2016 may refer to earlier work [94], [95]. The pulse transit time (PTT) based method, using electrical and optical sensing techniques, is most widely studied. The typical PTT-based BP estimation model utilizes ECG as the proximal and PPG as the distal timing reference [96]–[98]. The advantage of this method is that the R-peak of the ECG signal is easy to detect, especially during resting conditions. Several studies use alternative cardiac signals for ECG, such as impedance plethysmography (IPG) [99], [100], phonocardiogram (PCG) [101], [102], or ballistocardiogram (BCG) [103], [104]. To improve the user comfort, a peripheral PTT-based multi-wavelength method has been proposed using two or multiple PPG sensors [105]–[107]. The method with multi-wavelength makes it possible to measure BP in a single site while with relatively explainable physiological model. For example, the work by Liu *et al* demonstrated that the multi-wavelength PTT on arterioles shows a good correlation with BP, and the algorithm developed from this outperformed the traditional arterial PTT-based method with better BP estimation accuracy [108].

Apart from the PTT-based BP estimation method, some other physiological features have been investigated to indicate BP changes, including PPG intensity ratio [109], Womersley number [110], radial electrical bioimpedance [111], modified normalized pulse volume [112], acceleration plethysmography (APG) [113], and diameter of a pulsating blood vessel [114]. Additionally, machine learning has also been applied to BP estimation to develop regression models between signal features and BP, and demonstrating promising estimation accuracy [115]–[120]. However, the interpretation of the data-driven model is nontrivial.

Cuffless continuous monitoring approaches can be implemented into wearable and unobtrusive devices, such as watch [121], glasses [122], [123], a wrist/armband [99], [124], [125], shirt [126], sleeping cushion [127], chair [128], smartphone [112], camera and flexible patch [114], [129], [130] as summarized in Fig. 8. All these platforms – with further refinements and developments – can be easily integrated with a miniaturized wireless unit for BP mHealth monitoring suitable for various application scenarios during the outbreak of COVID-19. The wireless unit could provide real-time access to medical staff, facilitating remote diagnosis and monitoring.

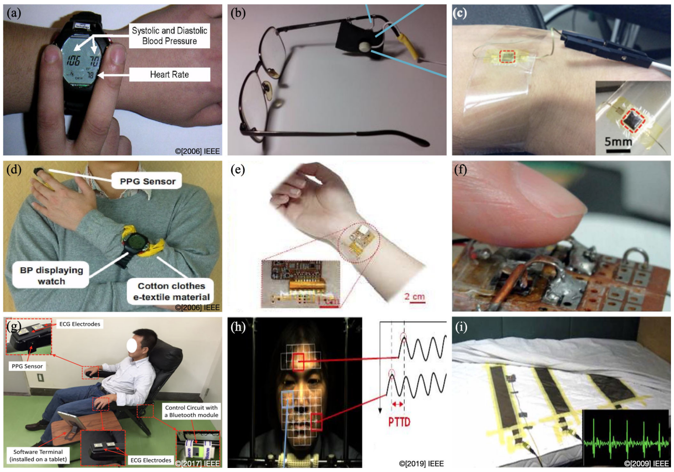

Fig. 7. Wearable/unobtrusive BP monitoring platforms with realization in daily objects: (a) BP watch [121], (b) BP eyeglasses [123], (c) flexible BP patch [129], (d) BP shirt [126], (e) wearable skin-like BP patch [131], (f) near-infrared phototransistor for BP [227], (g) BP chair [128], (h) BP camera [138], and (i) BP sleeping bed [127].

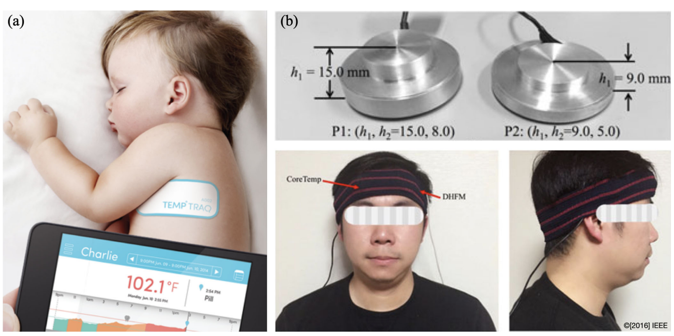

Fig. 8. Wearable temperature monitoring: (a) TempTraq temperature Bluetooth-enabled patch [145], (b) headband thermometry [143].

Twenty-four hour unobtrusive continuous BP monitoring can be equipped with flexible sensing, which may use a single skin-like patch [129], [130], or even a skin-like sensor that can also potentially address the issue of motion artefact [131]. Alternatively, a ring-typed device [132] provides a promising approach for long-term continuous monitoring due to its small size. However, all of these methods still need external power which is hard to miniaturize. Consequently, technologies that harvest energy from the human body or surrounding environment [133] should be further developed and integrated with BP monitoring devices. An alternative way is to use a wrist watch [134], [135] for daytime monitoring and a sleeping cushion [127] for overnight use (Fig. 7). Unobtrusive overnight BP monitoring on a sleeping cushion has been commercialized by Novocare [136]. In addition to continuous BP monitoring, this Novocare product can also measure SpO2 and ECG signals simultaneously, which would have a potential for monitoring COVID-19 patients continuously. The Samsung Galaxy Watch Active2 is another commercially available product for cuffless BP monitoring. Continuous BP monitoring with the wristwatch is enabled by the Samsung Health Monitor app that was recently approved by South Korea's Ministry of Food and Drug Safety [137].

Although techniques for continuous BP monitoring have demonstrated significant advances, there are still some obstacles that need to be overcome before their wide clinical application. One of the major challenges is that the measurement accuracy of many applications is still not good enough, especially during dynamic situations and when used for tracking responses to medications. Because of the dynamic nature of BP and its variability in different individuals, it is challenging to obtain accurate BP estimation for a long time without calibration. It is therefore highly desirable to find a simple and accurate way to calibrate BP individually and automatically. To address the issues of calibration and accuracy deviation, further research should be conducted to explore new estimation models that include more comprehensive physiological information or novel cuffless and unobtrusive principles to estimate BP directly with an auto-calibration procedure or without any calibration.

C. Wearable Devices for Clinical Symptom Monitoring

Studies have reported that the main clinical presentations of COVID-19 are fever (90% of cases or above), cough (around 75%) and dyspnea (up to 50%) [139]. These three symptoms are also the primary clinical features that are combined with the epidemiologic risk to screen suspected COVID-19 patients. Apart from the respiratory assessment stated above, it is also necessary to monitor temperature and cough for screening of suspected patients in a non-medical environment such as at home and in public places, and for monitoring confirmed cases for the progression of disease over time. Detection of these most common clinical manifestations of COVID-19 can be promisingly achieved via the state-of-the-art wearable devices. In this subsection, we will review current advances in wearable temperature monitoring and cough detection techniques and their potential applications to the early control of COVID-19 pandemic.

1) Temperature: Body temperature is one of the most important vital signs. By monitoring the body temperature of a person, we can identify in a precision manner whether they have a fever or not. It can indicate any signs of systemic infection or inflammation in the presence of a fever, as well as the effectiveness of treatments. During the COVID-19 outbreak, thermal scanning systems for mass screening of fever symptoms across wide populations, such as thermal infrared imaging and handheld noncontact infrared thermometers in public places such as airports. However, temperature measurements with these methods could be influenced by ambient temperature (*e.g.*, sunlight exposure) and other factors such as measured positions and head covers [140]. Besides, similar to traditional contact thermometers, they can only provide a snapshot of temperature change. A wearable temperature monitor with its ability to perform continuous monitoring, can potentially detect increases in body temperature earlier than standard monitoring [141]. This is of great significance to capture real-time temperature changes for suspected patients, asymptomatic patients, and those cared for at home.

Typically, wearable temperature sensors are designed by thermal-sensitive materials, with their resistance easily influenced by temperature on the basis of the mechanism of bioheat transfer. With advanced fabrication techniques, the designed sensors can either be attached to the skin or worn at a specific site on the body to monitor either the core body temperature or the skin temperature (Fig. 8). Han *et al.* designed a skin like flexible temperature sensor which used a resistance thermometer detector with the integration of near-field communication technique to achieve battery-free and wireless continuous monitoring of surface body temperature potentially anywhere on the body [142]. Huang *et al.* studied a dual-heat-flux method and developed a wearable thermometry which can measure the core body temperature by wearing a headband with built-in thermometer, with measurement error less than 0.1°C compared with the gold standard method [143]. Very recently, Atallah *et al.* reported results from a foam-based flexible thermometer that can be attached behind the ear to measure core body temperature in real-time, with an error of the developed sensor of -0.05 ± 0.14°C [144].

2) Cough Monitoring: Dry cough is one of the typical signs and symptoms of COVID-19. People infected with COVID-19 may spread the disease when they cough. As cough is a common symptom of other viral illnesses like cold and flu, people may not pay particular attention to this warning of their physical status. For COVID-19, continuous monitoring of cough is helpful for screening and clinical diagnosis of COVID-19 and increases the personal awareness for the illness.

Cough signals are typically acquired with an audio or mechanical sensor that can detect the coughing sound or the vibration caused by the cough, respectively. Such sensors include a microphone that can be wearable or placed near the user, or a piezoelectric transducer and high-sensitivity accelerometer that can be placed at the throat or the thoracic area [146]–[148]. With audio signal processing and recognition methods such as machine learning classification algorithms, the cough can be identified automatically [147]. In response to the COVID-19 crisis, Imran *et al.* developed an "AI4COVID-19" app based on hybrid deep learning and classical machine learning algorithms to detect COVID-19 coughing by using 2-second cough recordings that were acquired by mobile phone. It demonstrated an ability to distinguish the COVID-19 cough from non-COVID-19-related cough with over 90% accuracy [149]. With smartphone acquired audio signals, Monge-Álvarez *et al.* have used local Hu moments as a robust feature set with a k-nearest-neighbor classifier for automatic cough detection, and demonstrated the sensitivity and specificity of cough detection as high as 88% and 99% in various environments [150].

D. Unobtrusive Sensing for Physiological and Symptomatic Monitoring of COVID-19

While wearable devices can provide a continuous recording of the health status of a user by attaching a sensor or device to the body, technology enabled by unobtrusive sensing could provide a contactless form to capture the health information of one or even more users for in-home monitoring or public places. The advantages of unobtrusive sensing includes: 1) capability for monitoring during the night when a wearable may cause intrusiveness for sleep; 2) pervasive monitoring at home without the awareness of the user to address the low adherence of certain wearables; and 3) it is a noncontact way to measure vital signs in public places (*e.g.,* airport) that prevents the risk of infection and monitors mobile passengers unobtrusively while minimizing additional hold-ups that create crowds.

There are two main means to achieve unobtrusive sensing for health monitoring: 1) by integrating sensors into the objects of everyday life (*e.g.*, bed, toilet seat, and weight scale) [95]. Such sensors usually work by capacitive sensing using smart materials like e-textiles or by measuring the mechanical displacement of the body (*e.g.,* ballistocardiogram, BCG); and 2) by using ambient sensors such as cameras to detect the vital signs of a user in a contactless way. For the former, the article by Zheng *et al.* provides a comprehensive review of the technology and application [95], thus will not be listed here.

For noncontact monitoring, it generally comprises camera-based, radar-based, or laser-based methods. The infrared thermal camera is one of the most well-known unobtrusive technologies being used in the COVID-19 pandemic, to recognize any persons with fever at the hospital entrance or public places like airports [151]. From a technical perspective, it allows indirect detection of the information that is pertinent to and can be calibrated to human body temperature. For example, Lin *et al.* developed a contactless thermal camera based temperature monitoring system, which can monitor forehead temperature continuously by applying deep learning based face detection and object tracking algorithms [152]. Nevertheless, similar to the use of a handheld infrared thermometer, it needs to overcome challenges such as interference from environmental factors. Video-based sensing is among the most popular solutions for noncontact vital signs monitoring. By using an RGB or infrared camera and extracting the cardiorespiratory related signal via video-motion analysis, the cardiac rhythm and breathing patterns could be detected. Imaging PPG (iPPG) is a representative technology relying on the video-based sensing. The iPPG can indicate the local changes of dermal blood volume, and can be used to estimate physiological parameters including HR, SpO2, RR and BP [138], [153]. Wang *et al.* recently reported an infrared remote PPG with modified RGB camera, which can extract HR variability with good performance [76]. Another recent work by Yan and the colleagues demonstrated a camera-based facial PPG that can detect AF from multiple patients using a deep convolutional neural network algorithm [154]. Vainer proposed an approach which integrated infrared thermography with chemical physics to provide a high-resolution noncontact evaluation of RR and breathing waveforms [155]. Wang *et al.* have attempted to implement a depth camera system with deep learning algorithm for recognizing breathing patterns for screening COVID-19 [156].

In addition to its potential in ubiquitous monitoring at home and in improvised hospitals for people are at isolation or quarantine, the noncontact health sensing technology is very promising in simultaneous real-time vital sign monitoring on multiple

TABLE I
WEARABLE TECHNOLOGY FOR MONITORING PATIENTS WITH COVID-19

Clinical Evaluation of COVID-19	Measurements	Sensing Technology	Implementation	Maturity	Clinical Adoption Scale	Exemplary Products	Early Warning for COVID-19
Respiratory Assessment	RR	Respiratory airflow sensing thermistor, humidity/CO_2 sensor	Chest/abdominal strap [41], vest, facial mask [46], flexible patch [45]	High	Low	RespiraSense, Spire, Zephyr, AirGo	≥20 bpm
		Chest wall movement detection via strain/triboelectric/accelerometer					
		Derivation from cardiac signals such as ECG/PPG					
	Lung/Heart Sound	Piezoelectric acoustic sensing	Patch [60]	Medium	Low	Smartphone	Crackles
	SpO2	Optical sensing	Wrist-worn band/watch, earbud, ring, patch, flexible skin-like e-tattoo [36]	High	Low	Oxitone 1000M [26], Viatom Checkme O2, Nonin WristOx2, Wavelet Health Wristband, Huawei Honor Band 5 [157]	≤ 94%
Cardiovascular Evaluation	ECG/HR	Electrical/capacitive sensing	Patch, vest, watch, flexible skin-like e-tattoo [89]	High	Medium	MCOT, Zio^{XT}, SEEQ, CAM™, VitalPatch, Apple Watch [158]	Arrhythmia, HR > 100 beats per min
	Cuffless BP	Multi-modal sensing including electric, optical, mechanical	Watch [121], wristband [124], glasses [123], ring, flexible patch [129]	Medium	Low	SOMNOtouch™ NIBP, ViSi Mobil® System, Galaxy Watch Active2 [137]	≥ 140/90mmHg
Clinical Symptom Monitoring	Body Temperature	Thermal sensing	Patch [145], headband [144]	High	Medium	TempTraq®, Fanmi Thermometer patch	≥38°C
	Cough	Mechanical or piezoelectric sensing	Patch [148], smartphone microphone [147]	Medium	Low	ResApp Health with a smartphone microphone	Dry cough

subjects where there is limited clinical resources. Further it could be applied in the large-scale screening of potentially contagious patients in public places such as airports, which is of great significance to mitigate the spread of COVID-19.

E. Multi-Parameter Physiological Monitoring Using Wearable and Unobtrusive Sensors for COVID-19

By integrating wearable sensors for various purposes as discussed above including SpO2, RR, ECG, HR, BP, and other health information (Table I), a BSN could be set up to realize continuous monitoring and analysis of multi-physiological parameters. Fig. 9 presents an example of 24 hour monitoring of multiple physiological parameters by integrating the wearable devices and unobtrusive monitoring into a BSN. Connected with a hospital information system via mHealth systems, wireless BSNs allow medical staff to monitor the status of patients remotely, which helps to shift medical healthcare from hospitals to individuals and reduce the exposure to the virus, providing a promising way to release the burden on the healthcare system and decrease risk of infection during the pandemic.

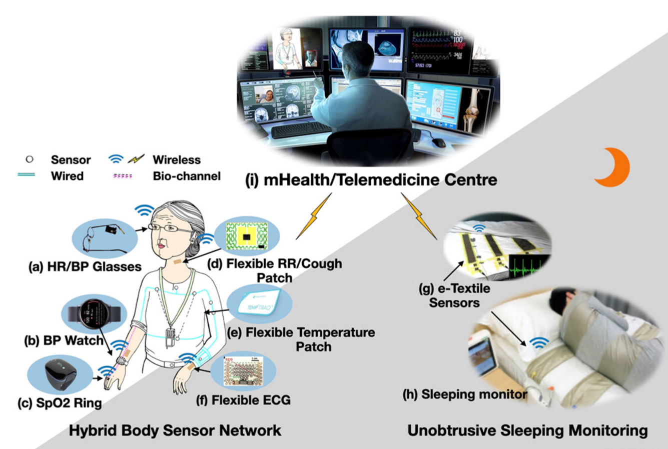

Fig. 9. A proposed unobtrusive 24 hour multiple physiological parameters remote monitoring system consisting of a BSN connecting with wearable and flexible devices: (a) a HR/BP glasses [123], (b) BP watch [137], (c) SpO2 ring [159], (d) flexible RR/cough patch [45], (e) flexible temperature patch [145], and (f) flexible ECG sensor [86]; an overnight monitoring system: (g) sleeping cushion [127]/(h) sleeping bed [136]; and (i) mHealth/Telemedicine Centre [160].

The integrated system can be employed for prescreening thus stratifying people in wider populations based on their level of risk for COVID-19, for monitoring infected patients with mild severity at home or an isolated place, for tracking disease development of patients admitted to an improvised hospital, and for overseeing health status after discharge.

To deploy wearable and unobtrusive systems into clinical practice, challenges such as security, unobtrusiveness, personalization, energy efficiency, robustness, miniaturization, intelligence, network, digitalization, and standardization (SUPER MINDS) need to be addressed. The design concept of "SUPER MINDS" for development of wearable technology has been further elaborated by Zheng *et al.* [95].

In the next section, we will introduce the wearable-based mHealth and telemedicine technologies that empowers the ubiquitous health monitoring to prime and support of the healthcare systems and improve the wellbeing of the population being affected by COVID-19.

III. Mobile Health and Telemedicine Technology for Tracking, Monitoring, Diagnosing, and Treating COVID-19

Telehealth technology including mHealth and telemedicine is not new but has emerged as a critical tool in the fight against COVID-19 [161]. The fast spread of COVID-19 has caused an overwhelmingly high burden to health care systems, even for well-resourced countries like the United States [12]. To meet this crisis, we need an immediate digital revolution of the analogue health care system, by transforming the health care delivery and scaling up the healthcare systems by the power of electronic or digital health technologies [162]. mHealth and telemedicine, combined with the preceding wearable devices and unobtrusive sensing and augmented by technologies such as Internet of Things, big-data analytics, AI and blockchain [163], can alleviate the challenge with a paradigm shift in health care. With virtual care such as video consultation [164] and further through remote monitoring of the health status of patients, delivery of interventions and treatment to patients at home, the care can be shifted from hospital to improvised hospital, community and home. Furthermore, these digital health technologies can minimize unnecessary exposure and cross-infection. With a surge of COVID-19 case at the time of writing, the United States has transitioned rapidly to telemedicine by relaxing prior telemedicine rules [162]. There are also specific guidelines recommending telehealth and remote checks whenever feasible to reduce direct contact as well as to limit the time and personnel resource in clinic rooms [73].

In this section, we will discuss recent mHealth and telemedicine technologies that have potential to tackle COVID-19 with discussion of telemedicine in remote patient care along with management strategies for affected patients. Emphasis will be on mHealth tracing and assessing suspected and infected patients with COVID-19, and telehealth technologies such as tele-imaging, tele-ICU, tele-rehabilitation, and telerobotics for remote health services and care delivery. At the end of this section, we will present an exemplary application of the wearables with mHealth for the management of patient with acute myocardial infarction (AMI).

A. Mobile Health Monitoring of COVID-19

mHealth is a public health platform supported by mobiles devices, such as mobile phones, health monitoring devices like wearable, flexible and unobtrusive devices, personal digital assistants *e.g.*, a tablet computers, and other wireless devices [165]. A remote mHealth system generally includes three main components: 1) a wearable or portable device collecting the data on the health status of a user; 2) a network and communications interface transferring the collected data to a remote monitoring station such as a mobile phone, or medical server; and 3) a remote cloud analytics platform integrating the continuously acquired big data, exploiting useful information, identifying important parameters and patterns critical for the patient's health, and facilitating the most optimal practices including diagnosis and treatment.

The rapid development of digital technologies and surge in mobile connectivity have laid a solid foundation for mHealth technologies. With smartphone-linked wearable sensors, point-of-care diagnostic devices, mobile medical-grade imaging, built with real-time data streaming and supported by smart clinical decision support tool, mHealth can ideally track, diagnose, and manage various physiological progress and disease conditions [166]. Beyond video visits or virtual consultants, mHealth can be used to trace the contacts of infected people, and provide support and care both for patients with suspected or confirmed COVID-19 and for those requiring other routine clinical services.

1) Contact Tracing Technology: Effective contact tracing and case isolation are known to be one of the key strategies to control the COVID-19 outbreak [167]. Without an effective vaccine or treatment available for COVID-19, contact tracing, quarantine and social distancing will continue to be the main measures to contain the pandemic [12]. Compared with the SARS outbreak of 20 years ago, the current emergency of COVID-19 is occurring in a much more digitized and connected world. Mobile technology for the purpose of surveillance or isolation, *e.g.*, to trace the source of the infection in an area, or to track the contacts of infected people, is instrumental to help fight against the COVID-19 pandemic [168].

A contact-tracing app that builds a library of close contacts and immediately alerts contacts of positive cases can achieve epidemic control if used by enough people [169]. The large-scale collection of mobile data from millions of users raises concerns over privacy and confidentiality [168]. To address these issues, Yasaka *et al.* developed a peer-to-peer contact tracing app that uses an anonymized graph of interpersonal interactions to conduct the contact tracing. While tracing the contact, it preserves the privacy of the user, and can be potentially applied to the COVID-19 pandemic [170]. Very recently, Apple and Google have been collaborating to develop a Bluetooth Low Energy based contact tracing platform, which aims to overcome the issue of interoperability. By exchanging anonymous identifier beacons among close contacts without collecting personally identifiable information or location data, the platform is able to notify those phone users who have been in contact with a newly diagnosed user [171]. This technology will hopefully have a wide application once it becomes available.

2) Remote Physiological Monitoring: mHealth can also provide remote health checks and monitoring, partially transferring the care from hospital to home. Hospital-at-home care can be an important option for patients with newly diagnosed COVID-19 but with mild symptoms, for patients with non-COVID-19-related diseases, and for patients who have had an early discharge from hospitals. In addition, it can provide monitoring of persons under investigation in home quarantine.

Mobile sensors or monitors such as smartwatches, pulse oximeters, or thermometers, are essential for remote health monitoring. Mobile ECG is among the most commonly used health monitors during the pandemic to remotely track the patients' arrhythmia problems. The Mayo Clinical has published a guideline for circumventing QTc-prolongation for COVID-19 patients treated with "off-label" repurposed drugs such as hydroxychloroquine and lopinavir/ritonavir that can potentially cause unwanted QT-interval prolongation and a risk of drug-induced sudden cardiac death [172]. In this guideline, the KardiaMobile 6L device by AliveCor, Inc, a handheld ECG monitor that received an emergency clearance from the FDA for QTc monitoring, has been suggested to measure the QTc of COVID-19 patients as a vital indicator to help guide the rapid and safe usage of these drugs. Such mobile technology is also recommended by the Indian Heart Rhythm Society for a similar purpose of monitoring drug interactions on QTc [173]. Another application of wearable technology with mHealth was reported in the University of Oxford, where the technology has been used to monitor COVID-19 patients in the isolation ward [109].

Mobile technology has an ease of use, with the user being able to monitor their continuous events without input from professional staff. But challenges may also exist including the quality of the health information collected by the wearable or mobile monitor, the appropriate and timely interpretation of an abnormal events, and common concerns over privacy and confidentiality. To address these challenges, relevant technologies, for instance, techniques for motion artefact reduction during the sensing stage and signal quality assessment of the collected data, data encryption during the transmission as well as policy on the use of health data are essential. For example, a study by Khamis *et al.* developed specific motion artefact suppressing algorithms targeted for use in remote telehealth ECG recordings due to the fact that such unsupervised measurements are much more susceptible to being corrupted with noise or through poor measurement technique [174]. Moreover, for the emergent COVID-19 pandemic, the diagnosis of health condition deterioration should not totally rely on any remote cloud analytics platform as it might yield unfavorable outcomes due to possible false positive and false negative rate. Such automated diagnosis technique based on the physiological parameters acquired via telemedicine systems cannot completely replace well-trained clinicians. Nevertheless, it can serve as a decision support tool allowing the caregivers to deliver timely interventions to patients in certain situations, especially when minutes in time may make a big difference.

B. Telemedicine for Managing Patients With COVID-19

Telemedicine is the use of telecommunications to diagnose and treat diseases [175]. At the present time, telemedicine can be delivered by phone and secure telecommunication platforms [73]. For patients with mild illness and the vulnerable population with comorbidities, telemedicine can provide them the required care while minimizing exposure. While for patients with diagnosed SARS-Cov-2 infection, telemedicine can help manage patients at a distance, monitor remotely critically ill patients in the ICU, and monitor those discharged from the hospital during their recovery. Accordingly, in this section, we will mainly discuss three specific applications of telemedicine on managing patients with COVID-19, namely tele-imaging, tele-ICU, and tele-rehabilitation. Other telemedicine technologies that can facilitate the diagnosis and management of patients such as telepathology and telerobotics will also be covered.

1) Tele-Imaging: The organs and deep tissues of patients infected with SARS-CoV-2 can be badly damaged. Medical imaging plays a substantial role in monitoring and diagnosing diseases. Lung infections diagnosed with CT represents one of the common clinical indications for COVID-19. Tele-imaging transmits patient medical images, such as X-rays, CTs and MRIs, from one location to another, with the aim to diagnose diseases remotely. For example, tele-imaging can send the image of COVID-19 patients in isolation to the radiologist who can effectively make a diagnosis while working remotely.

There are various specialized tele-imaging techniques including tele-ultrasound, tele-X-ray, and tele-CT (Table II). With image processing, AI-enabled algorithms, and clinical metadata computing features, tele-imaging techniques could be deployed for remote diagnosis, progression prediction, and decision-making. Of note, the AI-assisted image processing methods for diagnosis of COVID-19 are comprehensively discussed in another review [182]. People with COVID-19 symptoms can attend a (mobile) imaging center and get a CT image to check for possible lung infection. Diagnosis can then be achieved remotely through an in-network picture archive and communication system (PACS) film reading, or from a cloud service. Thus, an available mobile or portable medical imaging facility, *e.g.*, mobile ultrasound/X-ray/CT/MRI (Fig. 10), are crucial to the decision-making paths in about clinical and diagnostic management of COVID-19, particularly for tracking the development of a patient's conditions and evaluating whether they have reached the standard for recovery. Such mobile imaging technologies can be used in mobile emergency units or improvised hospitals. As an example, a CT mobile platform that is self-contained with automated scanning workflow has been reported for remote diagnosis of patients in temporary mobile cabin hospitals and at the Fangcang Shelter Hospital [112], [182].

To minimize contact, streamline patient throughput, reduce radiation exposure, and improve imaging quality, one of the principal aspects for tele-imaging is automatic patient positioning and anatomical localization. To date, many CT imaging devices have deployed computer vision techniques to track patients, and measure their position, shape, height and width contours using 3D optical or infrared cameras, and to automatically align the anatomical location of the patients with the isocenter of

TABLE II
PORTABLE IMAGING SYSTEMS WITH REMOTE ACCESS AND CONTROL

Medical imaging techniques	Functions	Weight/size	Communication Networks (Transmission Rate)	Advantages	Maturity	Exemplary Products	COVID-19 Application Scenarios
Tele-ultrasound	Imaging scan for different body parts including lung	System: 4-8kg; scanner: 0.2-0.5kg/mobile size (handheld)	Mobile phone or tablet, 4G/5G (150Mbps ~10Gbps), or LAN (10Mbps-1Gbps)	Real-time, fast diagnosis	High	Butterfly/Lumify (Philips)/Vscan (GE) portable ultrasound system [176, 180, 181]	Home, community care, improvised hospital, hospital
Tele-X-ray	Lung imaging, body imaging	400-750kg/4-6.5m^3	Short distance wireless communication - UWB (480Mbps up to 1.6 Gbps)	Fast, low dose, high imaging quality	High	Optima XR220amx, GE portable X-ray machine [177]	Mobile emergency units, community care, improvised hospital (including ICU and CCU), hospital
Tele-CT	3D imaging of the lung and other body parts	~1600kg/13-20m^3	Wireless communication - 5G (10Gbps), or LAN (10Mbps-1Gbps)	Automatic positioning, rapid and accurate scanning, lower does	Medium	BodyTom, Samsung portable CT scanner [178]	Mobile emergency units, community care, improvised hospital, hospital
Tele-bedside MRI	3D imaging of brain, neck, knee	640-930kg/1-5m^3	Controlled with a wireless tablet, view images on a mobile phone, 5G (10Gbps).	Without shielded room, fast diagnosis	Medium	Hyperfine, portable MRI [179]	Mobile emergency unit, community care, improvised hospital, hospital

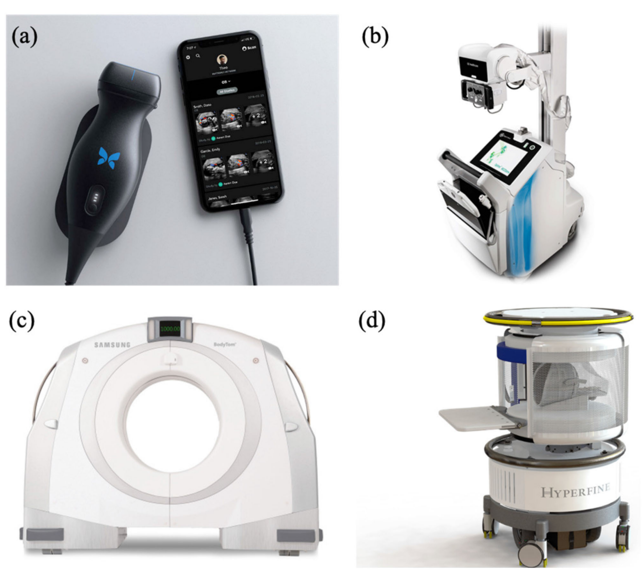

Fig. 10. Portable medical imaging devices (a) portable ultrasound system (Butterfly) [113], [176], (b) Optima XR220amx portal X ray (GE) [177], (c) BodyTom CT scanner (Samsung) [115], [178], and (d) portable MRI (Hyperfine) [166], [179].

the bore. The AI-enabled U-HAPPY (United imaging Human Automatic Planbox for PulmonarY) scanning CT designed by Wang *et al.* presents one example of such automatic and accurate CT scanning technologies [183]. In that study, the performance of automatic localization and radiation doses were evaluated in three scenarios, *i.e.*, fully automatic, semi-automatic, and manual scanning, and it demonstrated that the fully automatic scenario significantly outperformed the others (Fig. 11). It was reported that this kind of technology has been used in Wuhan during the COVID-19 outbreak, has prevented cross infections among medical staff and infected patients, and provided doctors a robust foundation to work on. A further example of the application of tele-imaging in Wuhan during the outbreak is that, the infected patients in Wuhan were provided with remote CT scans, which were then transmitted to the physicians at the West China Hospital in Sichuan Province with the aid of 5G communication. While decreasing the chance of infection, the tele-imaging can also free up the medical resources in the epicenter, thus the local resources can be prioritized to those with utmost need [169].

On the pandemic situation, these theoretical and practical studies have been contributing to the rapid and wide applications of tele-imaging technology to COVID-19 patients located in isolated, underdeveloped and resource-deficient areas.

2) Tele-ICU: Rapid deterioration can occur in patients with COVID-19, in particular the elderly with pre-existing cardiopulmonary conditions. The surge of ICU admissions as a result of the deterioration can pose great challenges to the current critical care setting, in terms of the demand on medical resources and the safety of medical staff [184]. In response to COVID-19, most of current hospitals or medical centers remain an architectural layout of an "open bay area" ICU with all the intensive care beds and onsite care in one open space. Such architectural layouts can significantly increase the chance of staff infection, in particular when the ICU is overloaded with a surge of critically ill patients admitted from the pandemic. To minimize cross infections and reduce the staff workload, it is highly desirable to reduce the presence of bedside staff through remote care delivery, for example by remotely providing clinical decision

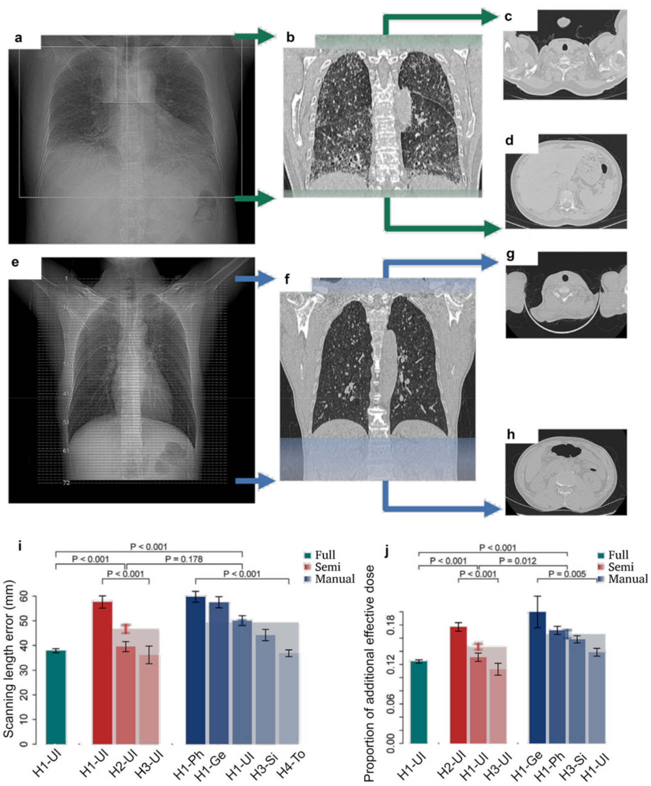

Fig. 11. Intelligent CT performance testing, (a)–(d) full automatic results, (e)–(h) manual results, and (i)–(j) comparison of the scanning length error and radiation dose among the full, semi and manual scenarios [183].

supports and controlling parameters for ventilators and infusion pumps outside of the ICU.

A tele-ICU, with a centralized remote patient monitoring center and several satellite intensive care sites, enables off-site clinicians to supervise patient conditions and interact with bedside staff to consult on diagnosis and treatment options through *e.g.*, audiovisual communication and patient data sharing. Use of tele-ICU was reported to have positive clinical outcomes including lower mortality rate and shorter length of stay as well as reduced staff workload associated with faster response to alarms and off-site care plan review compared with a traditional ICU [185], [186]. Tele-ICU facilitates the collaboration between bedside and off-site staff. Because of the change of critical care process, tele-ICU further leads to improved adherence to best practices. The tele-ICU runs on an integrated ICU platform that enables the exchange of health information electronically in real-time among the central and satellite units. Practical ICU platforms include the eICU (Philips) [187], Virtual ICU (GE Healthcare [188]), Tele-ICU (advanced ICU care) [189], and eMobile platform (Health First hospitals) [190]. Patient data from monitors, ventilators, infusion pumps, EMR and other sources are collected and stored in the platform. With extensive data from various sources, the predictive data analysis is critical to assess risk thus allow timely intervention. At HIMSS 2020, CLEW, a technology company for intelligent healthcare, demonstrated its AI-powered tele-ICU solution to support treating COVID-19 patients with respiratory deterioration prediction models, which was later implemented in two Israeli hospitals [191]. Regarding remote control or automation of ICU equipment, Gholami *et al*. proposed to employ AI techniques to monitor the surrounding medical equipment connected to patients, for example in tracking of the airflow measurements, identifying types of ventilator asynchrony, and adaptive control of ventilators [192]. The system also includes a hemodynamic model that analyzes BP and blood flow data to control fluid inputs of infusion pumps. To develop generalizable AI algorithms for tele-ICU, the application of large, heterogeneous, and comprehensive datasets is essential, of which the standardized data collection and procession is of comparable importance [193].

The value of tele-ICU depends on the model to be leveraged within the current clinical settings, practices, and medical/personnel resources [194]. For example, applying 'high-intensity' models would be beneficial to the situations (*e.g.*, COVID-19) requiring a proactive approach for acute patient care with overloaded critical care capacity. In such models, tele-ICU can also extend beyond the ICU, to a tele-critical care solution that includes also the emergency department, general wards, pre-ICUs, and step-down units, to manage patients with high risk with timely intervention, thus preventing ICU overloading in a pandemic like COVID-19 [195]. There is a strong need for well-designed tele-ICU systems to deal with the global health emergencies like COVID-19. Recently, UW Medicine shared their recommendations of tele-ICU to support rapid preparation for the COVID-19 crisis by integrating a teleconferencing tool, documentation templates, dashboard metrics, and EMR data [196]. Hong *et al*. called for increased investment in facilitating tele-ICU infrastructures, as the current capacity of tele-ICU does not meet the established demand of patients in the United States during the pandemic [197]. To achieve reliable and real-time connectivity, care standardization, patient comfort, staff safety and clinical decision support, innovative technologies, such as Internet of Medical Thing, 5G, AI and various autonomous monitoring and regulation techniques, are expected to strengthen the benefits of tele-ICU and help future scaling up.

3) Tele-Rehabilitation: For patients with COVID-19, timely pulmonary rehabilitation (PR) can enhance respiratory function and improve quality of life. PR is essential in particular for elderly patients with underlying conditions and for patients after discharge but with symptoms of breathing difficulty [198]. For inpatients with COVID-19, PR is necessary to relieve symptoms like dyspnea, anxiety and depression. Rehabilitation interventions should be conducted as a routine therapeutic care with four main aspects to be covered, *i.e.*, position management, physical exercise, respiratory management and psychological intervention [198], [199]. Pulmonary tele-rehabilitation (Tele-PR) could help combat COVID-19 by shifting the care following an early discharge from hospital to home.

Supervised tele-PR is one aspect of telehealth intervention that involves the delivery of PR care through a telecommunication platform that connects the patients with a central healthcare professional team. Remote assessment and monitoring of a patient's health conditions is the key for supervised tele-rehabilitation system. A tele-rehabilitation strategy should vary depending on a patient's cognitive and functional status. For instance, different respiratory physiotherapy plans are recommended to patients with spontaneous breathing, with invasive mechanical ventilation for those in an acute phases [200]. Tele-rehabilitation should also be performed following the 4s principle, *i.e.*, simple, safe, satisfy, save, in particular to prevent the spread of virus through droplets [201]. For outpatients and isolated cases, self-managed PR can be facilitated via e-consultation with their health conditions monitored by wearable devices like a pulse oximeter. It is noteworthy that the educational videos and instruction manuals in an e-consultation platform should be elaborately prepared and the real-time supervision is recommended to support patient conduct of tele-PR in an effective and safe way [202]. To promote physical exercise as an example, patients with mild to moderate symptoms can, for example, use posture and movement monitoring technologies, such as depth-cameras or wearable systems [203]–[205]. With remote feedback on the monitored information from the patients, training effectiveness can be ensured with improved motivation, which can potentially relieve stress and anxiety.

4) Other Telemedicine Technologies: The abovementioned telemedicine technologies, *i.e.*, tele-imaging, tele-ICU, and tele-rehabilitation offer great potential for coping with patients with COVID-19. Other telemedicine technologies such as teleconsultation, telepathology, telesurgery, and telerobotics can also streamline the remote health care practice. Here we will highlight telepathology.

Regarding telepathology, there are benefits in accelerating diagnosis thus early intervention of COVID1-9. For example, COVID-19 testing can be made available to the public by setting up testing booths at accessible places. Such booths will provide a safe and easy way to test subjects with minimum risk [206]. The subject can get the testing result immediately when the result becomes available to an app or platform which the subject can access via their smartphone. Further, the test results can be linked to platforms such as contact tracing and teletriage systems that can help prevent the spread of virus and manage the infected patients.

C. Telerobotics

Apart from various telemedicine technologies, telerobotics can also make major contributions in response to the pandemic by delivery of services and care remotely. Telerobotics refers to remote control of semi-autonomous robots, which conceptually lies between teleoperations and autonomous robots [216]. Given its capability to extend human sensing and manipulation capability, telerobotics has enormous potential for assisting physician and healthcare workers during the pandemic. The assistance can free up human resources to prioritize workload, and decrease contact with patients with COVID-19. Telerobotics can be potentially deployed for combating COVID-19 in four aspects [217]: *i)* disease prevention, *e.g.*, autonomous disinfection [215], *ii)* diagnosis and screening, such as automated temperature measurement in public area or hospital [218], and automated or robot-assisted nasopharyngeal and oropharyngeal swabbing for the test of COVID-19 [219], *iii)* patient care delivery, as an example, a social robot can provide social interaction and adherence to treatment regimen, and *iv)* disease management, with an exemplary application in the aforementioned tele-ICU for interventions *e.g.*, changing position for patients and teleoperating machines such as ventilators. Despite all of these advantages of telerobotics, great attention should also be paid to relevant hazardous risks of telerobotics, for example, issues of control stability and rigid moving parts with potential to unintentionally injure patients, particularly in the case of unstable networks and asynchronous time delays.

D. An Exemplary Application of the Wearables With mHealth for the Management of Patient with Acute Myocardial Infarction

The aforementioned wearable devices and unobtrusive sensing joined with the telehealth technologies can play a central role in disease management for various application scenarios including early screening, remote diagnosis and post-hospital rehabilitation (Table III). Here we take the management of patients with AMI as an example to describe the specific strategy.

AMI is a potentially life-threatening urgent condition. For patients with AMI, effective reperfusion therapy should be given immediately to prevent sudden death. Predominantly dealing with infectious respiratory disease for the current crisis, most medical centers do not have dedicated cardiac care units (CCUs). For both patients and healthcare workers, a safe medical environment and proper protection should be ensured to reduce the risk of contracting the virus. For this reason, the conduct of patient triage is a huge challenge when one needs to consider both the emergency cardiac condition of the patient and the reduction of infection risk for the medical staff. Recently, the Peking Union Medical College Hospital (PUMCH) made recommendations for the management of AMI inside medical centers on the basis of their clinical experience in treating patients with COVID-19 [220]. To further improve the efficiency and effectiveness of managing AMI with balancing the care needs of cardiovascular emergency while considering the risk of exposure, Ji *et al.* proposed a closed-loop monitoring strategy for AMI from home to hospital and post-hospital using wearable devices and mHealth technology (Fig. 12) [5]. This strategy was formulated in accordance with the recommendations from PUMCH and the guidance for cardiac electrophysiology jointly published by the Heart Rhythm Society, the American College of Cardiology and the American Heart Association [73]. This strategy is advantageous in resource conservation by remote delivery of care and management of affected patients via telehealth. A study by Treskes *et al.* has investigated the effect of such mHealth technology on managing patients with AMI, and demonstrated feasibility and overall patient acceptance of such smart technology [221]. Fig. 12 presents a flow chart for the application of wearable devices and mHealth or telehealth for virtual triage, tele-diagnosis and tele-treatment, as well as the tele-rehabilitation of patients affected with the COVID-19, which is further elaborated below.

The proposed closed-loop strategy starts with a broad population, in which the wearable devices are available to monitor their real-time health status, in particular those indicative of the clinical features and symptoms of COVID-19, *e.g.*, SpO2, RR, lung

TABLE III
MHEALTH AND TELEMEDICINE TECHNOLOGIES WITH COVID-19 POTENTIAL APPLICATION SCENARIOS

Technologies		Functions	Communication Mode	Target Population	Maturity	Representative Products	COVID-19 Application Scenarios
mHealth		Remote physiological monitoring	Short distance wireless communication: Bluetooth (2Mbps), NFC (424kbps), BSN/BAN (10Mbps), LAN (1Gbps), and ubiquitous wireless communication: 4G/5G (150Mbps~10Gbps)	General population and caregivers	Medium/ high	Apple Watch [158], Huawei Honor Band 5 [157], Galaxy Watch Active2 [137]	Home, community care, improvised hospital, hospital and others
		Remote consultation		Population at-risk	High	Huawei remote consultation [207]	
		Contact tracing technology		Infected patients/contact people	Medium	COVIDSafe [208], TraceTogether [209]	
Telemedicine	Tele-Consultation	Remote professional consultation	Ubiquitous wireless communication: 4G/5G (150Mbps~10Gbps), internet	Suspected/infected patients	High	sataCommHealth Tele-Consultation [210]	
	Tele-Diagnosis	Remote multidisciplinary diagnosis		Suspected population/patients	High	Y.Jan Health Systems [211]	
	Tele-Pathology	Remote molecular testing and immunoassay		Suspected population/patients	Low	TeleConsult Europe [212]	
	Tele-Imaging	Remote/mobile CT imaging		Suspected/infected cases	High	BodyTom® [213]	Improvised hospital, mobile emergency unit, hospital
	Tele-ICU	Remote care delivery		Patients with severe/critical symptoms	Medium	Advanced ICU Care [189]	Hospital
	Tele-Rehabilitation	Remote assessment, monitoring and follow-up after discharge		Patients after discharge	Medium	TheraNow [214]	Home, community care and others
Tele-Robotics		Care service, intervention and treatment		Patients and healthcare workers	Low	Disinfection robot [215]	Improvised hospital, hospital, home and others

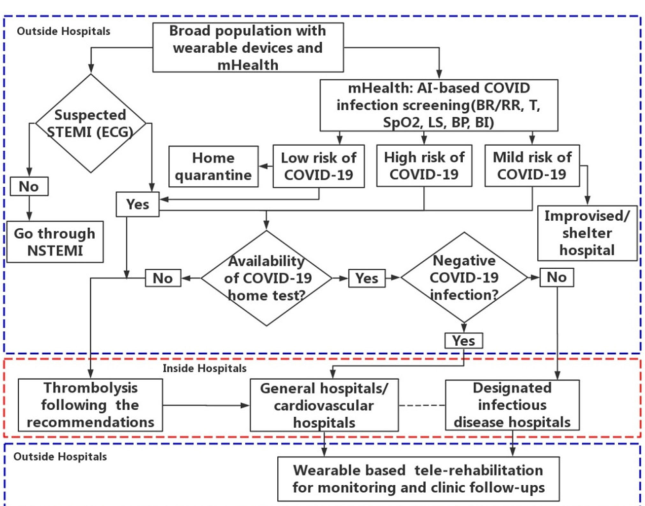

Fig. 12. The applications of wearable devices and mHealth in closed-loop management of AMI patients during the COVID-19 pandemic [5].

sounds, ECG/HR and BP. ST-segment – a further measurement parameter based on the ECG – can be extracted to diagnose the damaged cardiac function that consists of ST-segment Elevated Myocardial Infarction (STEMI) and Non-STEMI (NSTEMI). These vital signs data can be analyzed in real-time by on-node processing with AI algorithms for pre-screening, and in parallel transmitted to hospitals via mHealth systems for diagnosis and risk stratification. AI-empowered wearables and mHealth can provide decision support for the caregiver and allow the real-time triage of people outside hospitals into three categories: low, mild, and high risk of developing COVID-19 using those relevant physiological parameters examined in the above sections, while patients with underlying cardiovascular conditions, such as suspected STEMI for example, can be identified.

For patients with AMI who were admitted to the hospital, the multidisciplinary joint medical consultations from the cardiology department, infectious diseases department, emergency departments and other departments are needed for precise diagnosis and an optimal treatment regimen. But for medical staff, it is necessary to reduce the contacts with patients identified with STEMI and suspected infection, thus reducing the transmission of SARS-CoV-2 and preventing cross- infection. To achieve this, tele-diagnosis via an mHealth or telehealth solution can provide a safe platform for clinical decision making based on the digital medical data collected from on-site testing and the real-time continuous vital signs from the wearable devices. Such a platforms also allow tele-rehabilitation for monitoring and clinical follow-up after the patient is discharged from the hospital. Beyond the telemedicine strategy for managing patients with AMI, there are also various guidelines and recommendations involving telemedicine solutions made for patients with other cardiovascular conditions including heart failure andcongenital heart disease [222]–[226].

In summary, mHealth and telemedicine empowered by wearable devices or unobtrusive sensing will potentially relieve the burden on the current health care system by shifting health services and care from hospital to home, and by transforming the current health system through delivering service and care at a distance while circumventing cross-contamination. With concerns such as regulations in the use of the technology and privacy properly addressed, such technology can help increase the clinical productivity and improve clinical outcome, which may be adopted even after the immediate crisis has resolved.

IV. Conclusion and Future Directions

In this paper, an overview of wearable devices, unobtrusive sensing and telehealth with their potential applications in the fight against COVID-19 is presented. With successful implementation and deployment of these emerging technologies during the evolving pandemic, the burden on healthcare systems can be reduced by shifting service and care from hospital to improvised hospital and home; the clinical outcome can be improved through timely intervention by identifying any deterioration and exacerbation at an early time; the diagnosis and treatment can be rapid with screening of suspected and asymptomatic/presymptomatic cases; and the contacts between medical staff and patients can be minimized by remote monitoring and care. They are therefore very promising for combating pandemics such as COVID-19.

There have been significant advances in developing these systems for transforming the health care systems in the past decades. Some of the technologies have already been applied in emergency crises like COVID-19. Further, the physicians and healthcare staff are increasingly adapting to using these technologies, recognizing their potential for scaling up current healthcare provision. However, most of these technologies still have limited use in this pandemic, due to issues such as motion artefact, power consumption, and real-time processing of data; the "SUPER MINDS" design of wearable sensors and systems remains a big challenge [95]. In addition, many of the technologies have limited evidence on the outcome of their implementation. Furthermore, the cost-effectiveness of wearable sensor-based monitoring at scale and its use in early-stage screening still needs robust independent evaluation.

Though wearable devices and telehealth offers tremendous potential in helping to improve the management of infectious diseases like COVID-19, overcoming aforementioned challenges to enable more widespread adoption remains a fundamental concern. In the following, we suggest some promising directions on the development and deployment of wearable devices, unobtrusive sensing and telehealth for future research and application:

i) To develop more sophisticated multi-parameter flexible and stretchable sensing based wearable devices and mHealth platforms with robust functionality but at an affordable cost, allowing application in a wider range of both clinical and public contexts;

ii) To develop automated AI-based decision support systems that integrate and view multiple real-time, near real-time datasets and electronic health records simultaneously to assist providers with timely and efficient detection of anomalies and exacerbations;

iii) To design patient-oriented telehealth technologies and services, and undertake proper evaluation to ensure effectiveness and safety and to ensure delivery by a workforce with the necessary knowledge and skills;

iv) To investigate the impact of telemedicine on metrics such as patient outcomes, and the evaluation of patient and provider satisfaction, to improve the experience of both parties;

v) To develop image-guided tele-robotics or mobile robotics with remote access by essential caregivers eliminating the need to enter ICUs or traveling to front lines for patient care, drug administration, ventilator control and other care services

vi) To integrate seamlessly wearable-based mHealth technologies with telerobotics for a closed-loop management of COVID patients spanning monitoring, prevention, diagnosis, treatment to rehabilitation, which would provide effective and efficient care while reducing the infection risks to healthcare workers;

vii) To identify and address the ethical issues, privacy risks and security threats that may result from the deployment of wearable devices, unobtrusive sensing and telehealth, with combined endeavors of science, technology, legislation, and policy, so as to realize the full potential of these technologies.

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