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Review

IoT-Based Wearable and Smart Health Device Solutions for Capnography: Analysis and Perspectives

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Abstract: The potential of the Internet of Health Things (IoHT), also identified in the literature as the Internet of Medical Things (IoMT), is enormous, since it can generate expressive impacts on healthcare devices, such as the capnograph. When applied to mechanical ventilation, it provides essential healthcare to the patient and helps save lives. This survey elaborates on a deep review of related literature about the most robust and effective innovative healthcare solutions using modern technologies, such as the Internet of Things (IoT), cloud computing, Blynk, Bluetooth Low Energy, Robotics, and embedded systems. It emphasizes that IoT-based wearable and smart devices that work as integrated systems can be a faster response to other pandemic crises, respiratory diseases, and other problems that may occur in the future. It may also extend the performance of e-Health platforms used as monitoring systems. Therefore, this paper considers the state of the art to substantiate research about sensors, highlighting the relevance of new studies, strategies, approaches, and novelties in the field.

Keywords: capnography; Internet of Things; wearables; artificial intelligence; monitoring; mechanical ventilation; healthcare

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1. Introduction

The aging of the global population and the increase in respiratory diseases have increased demand for monitoring support (capnography) for mechanical ventilation [1]. However, the pandemic caused by the new coronavirus (SARS-CoV-2 and its variants) has pressurized the whole world's health system. Therefore, the shortage of devices that compose intensive care stations, such as sensors and electronic components, is a key issue [2,3].

Studies point to solutions to integrate a global health system [4]. Moreover, this not only faces the scarcity of resources or medical equipment and supplies but is also needed to create effective strategies and protocols based on modern technologies that allow joining devices to a data matrix, networked together with practices from the Internet of Things, which operate faster, safer, and more effectively [5]. Innovative technologies have great potential, such as for obtaining, processing, cleaning, analyzing, and extracting data, capturing insights, and promoting actions [6].

In the severe context of the pandemic, with the lack of electronic devices, medical equipment, and personal protective equipment (PPE), the medicine, engineering, and scientific communities came together to find effective solutions to help healthcare systems and society cope with COVID-19 [7]. Concerns involved ethical, practical, and technologically beneficial protocols, including robotics, artificial intelligence (AI), microelectromechanical systems (MEMS), embedded systems (ESP32), 3D printing technology, and radio frequency identification (RFID), among others [8–16].

The capnograph appears in this scenario as an effective device to verify "if there is life in patients" in intensive care units. It is a non-invasive, reliable, safe, fast, practical, and easy-to-use technique, and this device can revolutionize mechanical ventilation support and help to save the lives of a much larger number of patients with respiratory diseases such as COVID-19 or other cases that require monitoring [17,18].

The application of modern general-purpose technologies by hobbyists grew significantly at the end of the past decade, even though some of them have demonstrated little audited technical feasibility. This advance enabled the use of these tools as "alternatives" for the deployment of emergency devices and systems including rapid prototyping (3D printing) technologies [19]. Robotic and telerobotic systems had also decreased the risk of coronavirus contagion for front-line health care workers, thus making it possible to fulfill processes safely, such as screening, investigation, monitoring, and therapy of patients remotely [20,21]. Tavakoli et al. [20] pointed out excellent techniques related to robotics applied to intelligent electronic devices and advanced autonomous systems, such as wearable robots that can be worn on the human body, with the function of inferring vital signs and displaying their verified levels through a "biofeedback" pattern that helps and increases their potential use [20].

Robotic, wearable, and autonomous medical systems can be effectively used to prevent the spread of COVID-19, and in addition, are able to assist patient screening processes. Therefore, smart technologies and digital solutions like telehealth and telepresence can enable more efficient and safer healthcare delivery by decreasing, for example, risk to life and contamination, among other benefits [20–23].

The scientific community has sought appropriate solutions to minimize the issues posed by the coronavirus, particularly "saving lives." The expectations around capnography monitoring systems can be amplified [24–29]. Modern technologies (wearable and smart) coupled with three-dimensional (3D) printing techniques, with the practices of additive manufacturing (layer-by-layer technique), provide the potential for excellent deployment [30].

Intensive care units (ICUs) that depend on monitoring support with mechanical ventilation are tending to improve significantly in a vast scenario that allies health and technology. This is the case of eHealth and the prodigious Internet of Healthcare Things (IoHT) or Internet of Medical Things (IoMT) [31–37].

The community has contributed a lot to the healthcare field by presenting prospective studies on the benefits of modern technologies that have enormous potential for implementation. Therefore, the Internet of Healthcare Things (IoHT) or the Internet of Medical Things (IoMT) can positively impact the future of capnography devices [38–42].

Innovations in healthcare, including the explicit applications of smart pills, home care, personal healthcare, autonomous robotics systems, and real-time health systems (RTHS) are examples that can integrate advanced systems with IoT techniques [43–47].

Smart devices that integrate wearable systems, such as the capnograph, can promote a prosperous future for mechanical ventilation monitoring support by conferring essential patient health care benefits [48–50], such as improved postoperative outcomes, increased overall efficiency, faster response times, high levels of accuracy, and safety [51–53].

In recent years, surveys on monitoring systems that add wearable and intelligent technologies have grown significantly. However, most of these works deal with generalized solutions, even applications in the health area. Nevertheless, it is not a straightforward task to detect and classify all the characteristics, criteria, and functions of smart and wearable solutions. Plenty of topics must be considered, such as innovative technologies, smart and wearable solutions, and capnography, as well as technical dilemmas like costs and security. Therefore, this leads to some of the generalized studies available today, where many works try to summarize everything or only focus on specific subjects. Given this heterogeneity of studies, they might not be able to establish, present, and summarize a broad view of these subjects.

In [54–57], the authors focused on the performance and feasibility of smart and wearable solutions, including real-time solutions, remote access, data security, robustness, reliability, accuracy, complexity, scalability, and continuous monitoring. In [58,59], the focus was more on the characteristics of wearable solutions, such as design, robustness, and accuracy, rather than on real-time functions and continuous monitoring. Nevertheless, the authors of [60,61] have focused their research on real-time applicability, autonomy, data security, robustness, reliability, and accuracy.

Even though these authors condense relevant points related to wearable and smart solutions, there are still some relevant topics to be addressed. While some analyze wearable and smart solutions and others deal with innovative and wearable technologies, none of them deals with capnography.

In this context, this survey addresses a general and detailed overview of capnography under three categories: (i) characteristics and functions of innovative technologies applied to health; (ii) performance and feasibility of wearable and smart solutions based on IoT for capnography, and (iii) open issues. Table 1 shows a comparative synthesis between the strengths of this survey and other previous studies.

Table 1. A comparison between surveys related to relevant questions of wearable and smart solutions.

Surveys / Relevant Points	Abdulmalek et al. [55]	Kashyap et al. [57]	Chang et al. [61]	Rodrigues, Postolache and Cercas [54]	Elhoseny et al. [56]	He and Lee [60]	Junaid et al. [58]	Stavropoulos et al. [59]	This Survey
Year	2022	2022	2020	2020	2021	2021	2022	2020	2023
Designer (Portable)							✓	✓	✓
Easy to use									✓
Safe and comfortable (patient)									✓
Real-time	✓	✓	✓	✓	✓	✓	✓		✓
Remote Access	✓				✓				✓
Autonomous						✓		✓	✓
Data Security	✓	✓			✓	✓		✓	✓
Continuous monitoring				✓	✓		✓		✓
Robustness	✓	✓	✓	✓		✓	✓	✓	✓
Reliability	✓	✓	✓	✓				✓	✓
Energy efficiency				✓					✓
Cost and economy				✓					✓
Accuracy	✓	✓	✓	✓		✓	✓	✓	✓
Complexity	✓	✓		✓	✓				✓
Scalability	✓	✓		✓	✓				✓

The main goal of this survey is to highlight IoT-based wearable and smart health device solutions for capnography, in detail, so that future researchers seeking new proposals and enhancements for the subject can easily find a roadmap to understand the current state of the art. From this main goal, the major contributions of this survey paper are stated as follows:

- By reviewing the literature and previous surveys on the topic, there is a related effort by researchers to test and validate health devices audited by innovative technologies, especially flexible ones. However, these studies have gaps regarding relevant points that this survey addresses, as indicated in Table 1 and discussed throughout the document;
- Background study regarding capnography and mechanical ventilation monitoring systems;
- Review of the main contributions pointed out by the research community on the topic;

- Analysis and discussion of the main features and functions of innovative technologies applied to healthcare;
- A comprehensive review of the performance and feasibility of smart and wearable solutions, emphasizing the importance and contributions of Internet of Things (IoT)-based solutions for capnography;
- A performance comparison table of several IoT-based wearable and smart health solutions, highlighting contributions, limitations, performance, and feasibility;
- Analysis and perspectives concerning relevant open issues and future perspectives within the area.

The rest of this paper is organized as follows. Section 2 introduces the capnography topic and Section 3 discusses the mechanical ventilation monitoring system. Section 4 presents the innovative solutions applied to healthcare and highlights wearable and smart IoT-based solutions, while Section 5 discusses the performance and feasibility of wearable and smart IoT-based solutions for capnography and brings analysis and perspectives on relevant open issues. Section 6 shares the lessons learned, and Section 7 concludes the paper.

2. Capnography

2.1. Backgroud

Capnography consists of a non-invasive technique used to monitor the level of carbon dioxide in exhaled breath ($EtCO_2$) and to measure the patient's respiratory status [62–65]. A characteristic of CO_2 is its absorption of infrared radiation in a very particular wavelength space [66]. A capnograph allied to a mechanical ventilation (MV) system can support the remaining respiratory muscles, allow the application of specific therapies, correct hypoxemia respiratory acidosis, and restore the patient's health [64].

Capnograph use has become regular in surgical and anesthesiologic procedures in operating rooms (O.R.). From 1988 and later, it has been used in intensive care units (ICUs) in monitoring respiratory depression and airway patency (APRS) [67]. It can also be used in cases of non-intubated patients because it is an effective mechanism for airway monitoring [67–69].

About a decade ago, capnography gained notable attention in the anesthesia and critical care literature [70]. As a result, it became integrated into the World Health Organization (WHO) and World Federation of Societies of Anesthesiologists (WFSA) international models, thus contributing to effective anesthesia practice as a "prescribed" safety monitoring method [71].

However, the COVID-19 pandemic intensified its use in emergency ventilation support as a "life-saving" measure in intensive care units (ICUs) [72,73], since this device could offer people with acute respiratory distress syndrome (ARDS) outbreaks a much more adequate and safer treatment than conventional monitoring treatments [74–78].

Improvements in monitoring techniques made it possible for medical science to identify five basic vital signs that healthcare providers need to monitor to check a patient's clinical status. These vital signs are heart rate, blood pressure, respiratory rate, blood oxygen saturation, and body temperature [79].

Ahrens [79] presents two more vital signs, capnography and systolic volume [80], in addition to the ones described by Elliot and Coventry [81], such as pain, state of consciousness, and urine output. For these authors, the combination of these signals provides an accurate analysis of the physiological functions of the patient.

Therefore, the function of a capnograph is to produce sources of infrared radiation through sensors that allow the calculation of CO_2 levels in a breath sample [82–85]. Consequently, this generates waveforms and numerical values for the exhaled breath that serve to identify adverse respiratory events, assisting healthcare professionals in making diagnostic decisions for the patient [86–88].

Bhende, M. S. et al. [86] described and summarized how expired CO_2 ($EtCO_2$) is the measurement of CO_2 at the end of expiration, i.e., the maximum concentration of expired

CO_2, while $PaCO_2$ is the partial pressure of CO_2 in arterial blood. Therefore, capnography is the graphical representation of expired CO_2 over time; the capnograph is the measuring instrument, and the capnogram is the waveform displayed by the capnograph, that is, a graph of the CO_2 concentration over time.

Bhende and LaCovey [87] define capnometry as the measurement of expired CO_2, providing CO_2 data in mmHg or CO_2. CO_2 is produced by cellular metabolism and transported through the bloodstream to the lungs, where it is eliminated in the respiratory process [88]. Therefore, the capnograph is an essential device in mechanical ventilation support that can detect CO_2 elimination levels through the lungs, tissues, and circulatory system and also check for lack of pulmonary perfusion [89,90], endotracheal tube malposition, esophageal intubation, hypoventilation, hyperventilation, and disconnections in the respiratory circuit, among other things [91,92].

2.2. Types of Capnographs

There are two types of capnographs according to the position of the sensor in the breathing circuit. The aspirating sensor is placed outside the circuit, and the non-aspirating sensor is placed in the circuit. The difference between them refers to the position of the sensor, as shown in Figures 1 and 2 [93].

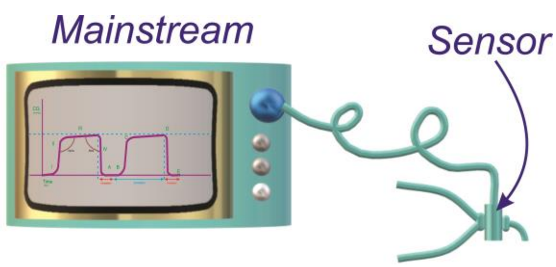

Figure 1. *Mainstream* capnograph illustration.

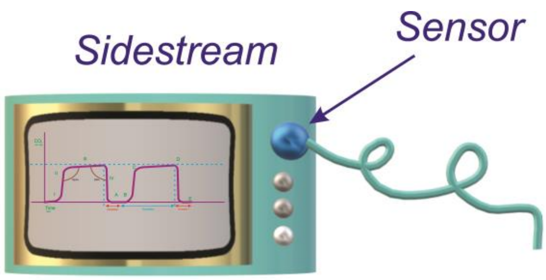

Figure 2. *Sidestream* capnograph illustration.

As the aspirating sensor is indicated for tracheal intubation, the collecting tube is close to the nasal cavity or even close to the intubation probe, while the distal one is at the distal end of the tracheal tube [93].

Bhavani-Shankar, K., et al. [94] explain that the main flow capnograph features a CO_2 sensor positioned between the endotracheal tube and the breathing circuit in the main unit. CO_2 is then inhaled through a sample tube connected to a T-piece adapter located in the endotracheal tube and breathing circuit.

Per these authors, the design of the main capnograph inserts new technologies with a lighter infrared sensor attached to the airway adapter. The sensor scatters infrared light through openings in the adapter to the photodetector normally located on the opposite side of the airway adapter [94].

Thus, the type of technology may impact the device, as the position of the sensor combines quality and versatility, as with the Microstream, an example of a sidestream that is related to conventional models and requires a smaller amount of sample, around 50 mL/min [95].

Thus, the light emitted to the photodetector measures $EtCO_2$, and this conventional technology suppresses sample demand through gas elimination. Measurement takes place directly in the airway, where the waves form most prominently, reflecting $EtCO_2$ in the patient's airway in real time [96–99].

For example, in sidestream capnographs, breath sampling is taken directly from the breathing circuit to the unit's internal sensor. These capnographs can be used on both intubated and non-intubated patients [99]. However, they require external filters to avoid problems with liquids and secretions in the lateral flow sampling system. Their disadvantages and limitations of use concern dealing with liquids and secretions, since a large number of breath samples limits the use of lower flow applications (neonates) [99].

Pons et al. [100] confirm that this technique involves some limitations, such as the realization of water vapor, which needs to be balanced to avoid errors in CO_2 readings. A rapid process of heating the current sensor above the temperature can solve the problem as it can unlock the airway adaptation spaces so that the sensor can tolerate high-humidity environments.

Another relevant solution in sensor innovations concerns the circuits used and their ability to limit power and not reach high temperatures, thus preventing burns to the patient's skin [101].

The first generations of conventional technologies presented major flaws and problems related to techniques and structures, such as weight, size, and design. Thus, pulling the endotracheal tube (ETT) could put the system at risk or break the equipment [99]. In order to overcome these flaws, the designs of capnography devices were improved to portable models with innovative sensors, which started to respond much more effectively to issues such as size and weight, thus allowing ease of handling, comfort, safety, and durability [102]. In these respects, respiration sensors may revolutionize the capnography monitoring approach and consequently, medical diagnostic procedures. Including non-invasive and individualized techniques, they can locate and identify errors and/or damage to the patient's health [102].

The diversity of airway adapters promotes numerous benefits, such as workarounds on sterilization and/or cross-contamination problems when used on a single patient. Moreover, experts consider this as the most feasible technique for neonatal patients because it adds less than 0.5 cc of dead space [103].

According to Cui, Yu et al. [104] the CO_2 sensor of lateral flow capnography is in the main monitor itself, away from the airway, with a compact pump that samples gas from the patient's airway through a 1.83 m capillary tube to the main unit. The sample tube is attached to a T-piece interposed in the endotracheal tube or else the anesthetic mask connector.

Duyu et al. [105] explain that the gas diverted from the patient typically includes anesthetic gases that must be routed to a gas scrubber or returned to the patient's respiratory system. Since the sample amount can be high (>400 mL·min^{-1}) or low (<400 mL·min^{-1}), the safe and optimal rate of capnography in children and adults considers the following value of 50–200 mL·min^{-1} [106–110].

Lateral flow capnographs therefore have the basic benefit of monitoring non-intubated patients and those receiving concomitant oxygen administration using nasal cannulas [111]. Microstreams, on the other hand, can provide safe monitoring in the sedation process [112], as they meet the standards required by the American Society of Anesthesiologists (ASA) and Joint Commission International (JCI) [113]. The innovative laser technology called molecular correlation spectroscopy (MCS) has revolutionized lateral flow capnographs because it does not use a sensor in the airway and can be used in intubated and non-intubated patients of all ages [114].

3. Monitoring System for Mechanical Ventilation

3.1. Emergency Ventilators

Pulmonary respiration establishes gas exchange in human tissues. It maintains and generates various vital metabolic functions when affected by pathologies or inductions, as in the case of respiratory diseases, sleep apnea diseases, anesthesia, or congenital abnormalities [115].

These respiratory dysfunctions can be either temporarily, totally, or partially replaced by a mechanical ventilation system using two distinct methods [115,116]:

- Invasive: in cases where the device is triggered to the patient via an endotracheal tube or tracheostomy
- Non-invasive: in cases where the device is connected to the patient via masks

Healthcare professionals can designate monitoring support (capnography) by mechanical ventilation to patients subject to the following conditions: cardiorespiratory arrest; hypoventilation and apnea; elevation in $PaCO_2$ with respiratory acidosis; respiratory failure due to intrinsic lung disease; hypoxemia; and mechanical failure of the respiratory apparatus [117,118].

To understand how mechanical ventilation monitoring support works, it uses the following scheme: it checks the method as an appropriate way to ventilate the patient to ensure the right amount of oxygen moves to vital organs and maintain arterial oxygen saturation. It can also ensure efficient CO_2 removal in addition to high $PaCO_2$ levels, provided there are no contraindications, or minimization of oxygen toxicity at the lowest possible FiO_2 levels. Due to this fact, it can avoid crossing the limits of alveolar pressures of 25–30 cm H_2O, which usually correspond to plateau pressures of 30–35 cm H_2O [119]. As a result, it can impair gas exchange due to alveolar hyperdistention and consequent compression of the adjacent capillary and can cause lung injury induced by direct ventilation [119].

Otherwise, medical ventilation systems can cause stress and shear forces that usually lead to lung injury. Stress is defined as the internal distribution of forces contrary to the force exerted by a unit area, while the shear is the deformation of the stressed structure. Clinically, tension can be assessed by transthoracic pressure [120].

In intensive care units (ICU) and emergency rooms, the use of mechanical ventilation systems as a therapeutic measure can save lives [121,122]. Thus, Melo et al. [123] state that mechanical ventilation (MV) consists of a method to support the treatment of patients with acute or chronic acute respiratory failure [124].

Since MV totally or partially replaces spontaneous ventilation, it can provide adequate gas exchange and reduce the work of the respiratory muscles and, consequently, metabolic function.

Experiments with MV have allowed new scientific discoveries and improvements in capnography's quality of monitoring. This is achieved by using several sensors connected between the cannula and tracheal cannula (OCT) [125] and a circuit that measures the CO_2 value at the end of expiration, known as end-tidal ($EtCO_2$) [126]. Therefore, the impact of the disruption of global supply chains related to medical supplies caused by the pandemic of COVID-19 has prompted the scientific community to gather their efforts and use creativity in search of quick, safe, and effective solutions [127].

The new generations of IoT-based health devices could be leveraged as knowledge discovery and dissemination techniques in the context of the COVID-19 pandemic and can still be applied in future pandemic crises, as they have excellent implementation properties [128].

In this respect, the global health crisis has contributed to sharpening the use of modern technologies in healthcare that were previously in general use, mainly using solutions and techniques based on Internet of Things (IoT) standards, since they confer high-level automation potential [129].

In the most severe period of the COVID-19 pandemic, the scientific community developed applications, equipment, medical supplies, and emergency systems to mitigate the lack of such equipment and devices [130]. Thus, new designs of emergency ventilators, such as “manual bags or resuscitation devices”, could be used in locations that did not have access to mechanical ventilators. However, this type of hand-held device could only be used for a short period (a few hours) [131].

The application of automated designs allowed the development of new projects with manual bagging (BVM) to expand their usage time and implement other parameters, such as open-loop control and the use of closed-loop sensors through assisted ventilation with patient feedback [131–133].

In the interim, healthcare applications and systems have undergone a systematic and operational revolution, including their techniques and functions. These changes have promoted advances in capnography systems and mechanical ventilation through safe, rapid, continuous, dynamic monitoring and ease of handling [134].

Ronen et al. [135] proposed an intelligent algorithm called the “Integrated Pulmonary Index—IPITM” to support an intelligent monitoring system. They presented a device implemented with low-cost materials integrated with open-source software and platforms.

Rahaman, Ashikur et al. [136] implemented a monitoring system based on the Internet of Things to easily allow communication between numerous devices. This device can provide functions for different sensor techniques, platform types (e.g., open-source), and other applications. Therefore, the health crisis has converged on the progress and re-establishment of new research areas in healthcare. In addition, it was favorable for strengthening the Internet of Things (IoT) through its functions that can accelerate innovation processes and implementations with hardware and software associated with other technologies [137].

3.2. Use of Capnography in Mechanical Ventilation Support

Capnography is a technique for monitoring the concentration or partial pressure of carbon dioxide (CO_2) during mechanical pulmonary ventilation (MV) and can be used to help with the real-time metabolic status of the patient. This method assesses the patient’s respiratory status and analyzes and tracks their respiratory rate (or respiratory rhythm—“RR”) factors during direct measurement of the expired carbon dioxide (CO_2) portion and indirect measurement of arterial partial pressures of CO_2 [137].

When circulation is regular, CO_2 production remains constant and $EtCO_2$ changes frequently with ventilation and then reaches $PaCO_2$. In contrast, during shock or cardiac arrest, $EtCO_2$ levels represent pulmonary blood flow and cardiac output, not minute ventilation [138].

Aminiahidashti, Hamed et al. [139] confirmed that if ventilation (v) and perfusion (q) are conveniently aggregated, $EtCO_2$ can be equal to $PaCO_2$. It is usually 2–5 mm Hg lower than $PaCO_2$. $EtCO_2$ characterizes the $PaCO_2$ of all ventilated alveoli, and $PaCO_2$ characterizes the $PaCO_2$ of all perfused alveoli. Despite this, the correlation v/q is close to 0.8, because there is usually some dead space (airways and alveoli).

Therefore, when the alveoli are not dispersed, the CO_2 concentration is zero, while, in the alveoli, the CO_2 concentration is regular. Moreover, liquid $EtCO_2$ usually decreases the $PaCO_2$ in case there is a v/q imbalance, as occurs with shock, CPR, pulmonary embolism, and others. In this case, moderate ventilation amplifies the $PaCO_2$ and increases the $EtCO_2$–$PaCO_2$ difference, as in asthma, atelectasis, pneumonia, and emphysema, where the missing $EtCO_2$ is found in esophageal intubation [140].

The waveform should generally be a rectangle with rounded corners, while irregular shapes may indicate different situations, and the relationship of the amount, rate, and shape of $EtCO_2$ should be consistent or indicate improvement. Even if the $EtCO_2$ waveform analysis is considered simple, the healthcare provider needs to understand the formation of the waves and the numbers produced. When capnography shows exhalation, the waveform should measure and show the peak amount of CO_2 at the end of exhalation [141].

Correct reading of a capnogram allows health professionals to evaluate the patient’s clinical picture. They can follow some guidelines and verify that, although variation in ventilation $EtCO_2$ occurs with age, the readings considered normal, regarding quantity, shape, and trends, do not change, neither for men nor for women (of all age groups), and the usual value of $EtCO_2$ is 35–45 mm Hg [141–145].

Since the respiratory rate of a regular adult produces 12 to 20 breaths per minute with an exhaled CO_2 amount of 35–45 mm Hg, an exhaled capnography waveform is a clear graphical measure of the amount of CO_2 that person exhales. That is, the usual waveform of the incoming capnography translates into a rounded rectangle; when a person exhales CO_2 the graph goes up, and during the opposite it goes down [146].

Duckworth [141] explains that when a healthcare professional reads the capnography observing these phases (as shown in Figure 3), his analysis has more consistency. When observing Phase 1, for example, which represents inspiration, the baseline will usually be zero because the patient inhales, and CO_2 is not eliminated.

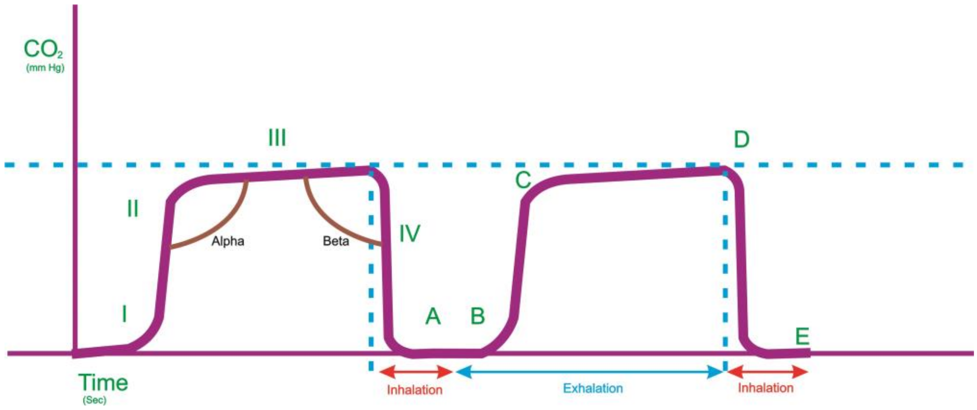

Figure 3. Illustration of a normal capnography waveform.

In Phase 2, which is the beginning of expiration, the CO_2 moves into the alveoli through the dead space examined from the airways, generating a rapid increase in the graph. This phase checks the CO_2 emitted from the alveoli and mixed with the gas that was in the dead space, and the graph increases as the denser CO_2 gases from the lower part of the lungs rise and pass through the sensor [141].

Finally, in Phase 3, when the sensor captures the CO_2-rich gas that was in the alveoli, because it is a constant value the graph settles into a plateau. Thus, the limit of the breathing moment, the peak measurement at the end of this phase, is equivalent to the $EtCO_2$ reading. After the end of Phase 3, the patient inhales again and transports clean air through the sensor, influencing the graph, which, returns to zero, and Phase 1 restarts [141].

As the capnograph presents unique characteristics, it can examine hypoventilation, endotracheal intubation, and inadequacy in the ventilator circuit that causes patient deaths and sequelae and can detect the location of the tracheal cannula or cannula (TCO) [147]. After intubation, it makes the appropriate MV adjustments, corrects the main changes in the fortuitous acid, and integrates a non-invasive procedure, which is simple to operate and of easy access in some places [148].

The potential of capnography as an additional technique for monitoring ventilatory function is a reality. It can be observed when dealing with patients with acute respiratory distress syndrome (ARDS). ARDS are outbreaks caused by COVID-19 or anesthesia procedures in adult, pediatric, and neonatal patients who are subject to moderate or deep sedation. In these cases, one can see how capnography is a fast, effective, and safe technique [149–151].

For example, during the most severe moment of the COVID-19 pandemic, there was a need for social isolation, sanitary measures, and safety protocols to save lives. However, these demands were not enough to decrease the number of deaths and sick people. This was due to lack of knowledge about the coronavirus, such as its form of contagion and time of contamination [152]. In addition, there was an increase in the number of deaths and sick patients from coronavirus worldwide. Uniting science and technology is essential in confronting a broad crisis in the health care system aggravated by the lack of medical equipment and devices [153].

After dialogues, discussions, and studies of emergency protocols, healthcare providers in hospitals and intensive care units were forced to make quick, life-saving decisions. Moreover, one of these decisions was about ventilator sharing practices combined with the capnograph, which proved to be an essential and effective monitoring device to support mechanical ventilation [154,155].

Capnography can promote numerous benefits, such as ease of use, patient comfort, continuous monitoring, safety, and practicality in the administration of medications and therapies, and can also improve the weaning process, unlike what occurs with a conventional monitoring system [156]. It can then be used to let the respiratory muscles rest and allow the application of specific therapies to correct hypoxemia and respiratory acidosis. In addition, it recognizes defects in tube positioning, malfunction of the lung ventilator, circulation damage, and breathing difficulties [157].

In summary, capnography can effectively provide the health network system or health professionals with a fast and safe practice. It can help in the decision-making of physicians and health care professionals and make possible the analysis and identification of images of conditions that can threaten life and leave sequelae in the patient [158].

4. Innovative Solutions Applied to Health Care

As respiratory diseases have increased in complexity due to the increasing aging of the global population in recent years and the severe health crisis caused by the COVID-19 pandemic (SARS-CoV-2 and its variants), the demand for devices based on digital techniques (IoHT), such as the capnograph, indispensable for integrating monitoring and ventilation support, has increased [158,159].

Singla [160] stated in a recent study that digital medical devices could represent a revolution in healthcare services as they integrate innovative and robust technologies. This means excellent performance and deployment potential through functions and mechanisms to collect, process, clean, analyze and extract data and capture insights [161].

From this perspective, the academy has contributed to addressing remote patient monitoring (RPM) methodology in various studies on "digital health systems and applications." In addition, it has explained the functions these devices can provide to healthcare providers and physicians, such as effectively and remotely sending and receiving patient health status data for analysis, consultation, and correct prescription [160,161].

Saha, Roy, and Chakraborty [162] proposed a device that can effectively address the issue of demand for health care devices with the goal of monitoring patients and environments or identifying disease-spreading elements and causes, such as COVID-19.

This prototype has demonstrated robustness and effectiveness when compared to other similar prototypes. Since it comprises a network architecture with wireless and wearable sensors based on IoT techniques, it also applies wearable and cloud technologies to manage and monitor real-time patient data through a cell phone application [163].

Abdul-Jabbar and Abed [164] implemented an Internet-of-Things-based real-time monitoring system for pacemaker patients. Their work is based on the techniques presented by [163], and although it was designed for more general patient health use, it has great potential for the implementation of capnography devices [163].

Anan, Safayat Reza, et al. [165] proposed an IoT-based remote monitoring system for asthma patients called the "Asthma Tracker and the Asthma Tracker Website". It allows physicians to remotely monitor patients and recommends the appropriate treatment. This device uses the Android platform, a website, and numerous sensors with ESP8266 microcontroller applications tuned with the Arduino Integrated Development Environment (IDE). Its robust architecture consists of a MAX30100 pulse oximeter and heart rate sensor, a GY-906 MLX90614 non-contact precision thermometer, a DHT11 humidity and temperature sensor, a MQ-135 gas sensor, and an AD8232 ECG sensor [156]. The authors further developed the back-end utilizing Django—an open-source web architecture based on

Python—and the front-end through a website application, hypertext markup language (HTML), cascading style sheets (CSS), JavaScript, and jQuery. This device overall showed acceptable results, mainly due to its ease of use and robustness of the sensors [165].

Wang, Yang, and Mao [166], on the other hand, suggested the "ResBeat" device to track patients' breathing level in real time, without contact, and for a longer time. This innovative solution applied the tools of the usual 5 GHz Wi-Fi through bimodal data channel state information (CSI). This was accomplished through a technique called "subcarriers to modulation", which has the function of sending data with orthogonal frequency division multiplexing (OFDM/OFDMA).

Singh, El-badawy, and Malarvili [167] implemented a portable capnography device with a CO_2 infrared sensor, an Arduino Mega2560, a 2.8" display, and a 16GB memory card. This system included a dynamic framework to measure respiratory rate and estimate the CO_2 concentration in the respiratory system. According to these authors, the device was implemented with specific algorithms for reading CO_2 in the process of inspiration, expiration, and respiratory rate. Moreover, it presented satisfactory results. Therefore, it can be very useful to support monitoring in hospital and home environments [167].

Javaid et al. [168] evaluated that technique and creativity are abundant in the current scenario. Therefore, the scientific community has been creating wearable and smart solutions based on the IoT, which integrates its characteristics related to production process, such as changes in time, material (spare), techniques, and designs (portable), with applications in modern technologies and open-source hardware and/or software.

The Auto Tag solution was deployed by [169] in later work with new (real-time) functions. To minimize errors in values, measurements, and false interferences caused by channel hopping in RFID systems, the authors applied tuning techniques for a simple calibration process following the precepts of the Federal Communications Commission (FCC).

Yang, Wang, and Mao [170] proposed a very impactful solution (also) named "Auto Tag" through RFID tag technology, available on the market, with a high potential for implementation. To measure respiratory rate and identify respiratory problems and abnormalities, the system was based on an unsupervised uniform variational autoencoder.

Silva et al. [171] pointed out an experimental wearable device suitable for general-purpose patients. The architecture included embedded technology and IoT-based e-Health platform techniques to provide the functions of monitoring, processing, and creating the database. It can be applied to artificial neural networks to check vital signs, detect diseases and adverse situations, and send alert messages with patient information in real time. The basis of this prototype applied the Arduino UNO R3 technologies, an embedded platform, and included several sensors such as an AMS 5915 blood pressure sensor, AD8232 electrocardiogram sensor, MAX30100 respiration sensor, and IR MLX90614 body temperature sensor. According to the authors, this model presented sensors with excellent performance and performance [171].

Although previous studies have focused on one of these techniques (IoT or IoHT), none of them has been able to combine wearable, smart, and IoT technologies with capnography. Table 2 highlights the main contributions available in the related literature on the state of the art, which can be used to check the current status of the survey, while showing whether the solution applies to IoT, in general, or to IoHT.

When summarizing the contributions of the reviewed articles, it can be observed that only four reviews do not address the Internet of Things topic. The others dealt with this technology through new concepts and applications. Thus, the number of works that discuss IoT-based monitoring systems in this study helps to support the importance of this study and answer the questions raised by this survey. However, these lack a deep analysis of pertinent issues, such as application to capnography, performance, and criticism. Therefore, to overcome this gap, this study describes, in the following subsection, approaches to and perspectives on IoT-based smart and wearable health device solutions for capnography.

IoT-Based Wearable Smart Health Device Solutions for Capnography

Ahmed et al. [172] considered that an Internet of Things (IoT)-based healthcare system is already an attribute of developed countries. In addition, with these techniques, they proposed an automated, intelligent, and digital architecture to provide physicians with remote patient health status monitoring support. The authors aimed to make the system affordable and practical.

Dusarlapudi et al. [173] suggested a system that uses the techniques of IoT, telemedicine, and unsupervised machine learning called the One-Class SVM method to collect data and report about patients' health conditions. This prototype applied the support vector machine—SMV algorithm method to check patient data and produce deviation representation graphs through the Python programming language. This system integrated the accelerometer ADXL335 to the Arduino microcontroller, using the software PLXDAQ to compare the data of a healthy individual with a sick one to develop a diagnostic method that can assist the health professional in his decisions [173]. It also uses a contactless device with the usage of Bluetooth-tuned MEMS accelerometer technology and a Triaxial Accelerometer with the ADXL335 sensor. The open-loop architecture enables the use of numerous analog and digital signals to detect and correct errors [173].

The AIRE prototype proposed by Jara, Zamora, and Skarmeta [174] uses the protocol called YOAPY to integrate sensors in an efficient, safe, and scalable way, including signal elimination, data calibration, and real-time monitoring. This architecture can contribute effectively to the perception and identification of problems in healthcare services, constituting an essential tool for planning, formulating actions, and avoiding errors in the system [175].

Table 2. Summary of the most relevant contributions available in the literature.

Reference and Year	Title	IoT in General	IoHT	Contributions
[162], (2022)	Cloud-Assisted IoT System for Epidemic Disease Detection and Spread Monitoring	✓		The researchers discussed wearable technology, network architecture, wireless and wearable sensors, and the Internet of Things, and developed a prototype that uses a mobile application; the authors highlighted that this model, when compared to other technologies, demonstrated real-time monitoring, robustness, and effectiveness.
[164], (2020)	Real Time Pacemaker Patient Monitoring System Based on Internet of Things	✓		The approach of these authors provides a discussion of the Internet of Things related to the remote monitoring system. They proposed a new electrocardiogram (ECG) monitoring method for use in pacemaker patients. This model applies IoT techniques, operates in real time with remote access, and has the ability to send and present data that is displayed on a particular website (www.thinger.io) through the Wi-Fi protocol.
[165], (2021)	Research and development of an IoT-based remote asthma patient monitoring system	✓		The researchers addressed and discussed the disease asthma, remote patient monitoring (RPM), and technological applications such as the MAX30100 pulse oximeter and heart rate sensor, precision non-contact thermometer GY-906 MLX90614, humidity and temperature sensor DHT11, MQ-135 gas sensor, AD8232 ECG sensor, Android studio, Java, and programming languages. In their research they implemented a monitoring system that allows physicians to monitor asthmatic patients from a remote area. The authors even developed the back-end using Django—open-source web architecture based on Python, and the front-end through a website application, hypertext mark-up language (HTML), cascading style sheets (CSS), Javascript, and jQuery.

Table 2. *Cont.*

Reference and Year	Title	IoT in General	IoHT	Contributions
[166], (2020)	Resilient Respiration Rate Monitoring with Real-time Bimodal CSI Data	-	-	The authors' discussion covers monitoring, wireless fidelity sensors, data preprocessing, biomedical monitoring, fading channels, and orthogonal frequency division multiplexing—OFDM. They presented a monitoring system called ResBeat, based on 5 GHz Wi-Fi techniques to exploit bimodal channel state (CSI) information, including amplitude and phase difference, for real-time, long-term, contactless respiratory rate monitoring. Although the authors did not use IoT, the device demonstrated effectiveness and efficiency, as it was extensively tested in three different environments, compared to two alternative methods, and was considered to have superior performance and feasibility.
[167], (2021)	Design and validation of a handheld capnography device for cardiopulmonary assessment based on the Arduino platform	-	-	The research addresses the pertinent issues of capnography, discusses the technologies of infrared CO_2 sensors, and discusses Arduino-specific algorithms for reading CO_2 in breathing. They developed a portable monitoring system for use in hospital and home environments.
[168], (2021)	Sensors for daily life: a review	-	-	The researchers contributed a detailed review of types of modern sensors that are used in everyday life, discussing associated nomenclature and measurements for sensors, in addition to the numerous applications of the technology of these devices. Their study considers a relationship with the health area that attends to a variety of cases, including the elderly, athletes, and patients at risk.
[169], (2019)	Unsupervised Detection of Apnea Using Commodity RFID Tags With a Recurrent Variational Autoencoder	✓		The authors' approach considers a discussion about the impact of the Internet of Things applied to health, particularly in the vital signs monitoring system, to assist patients with respiratory diseases. They implemented the AutoTag system, applying an unsupervised recurrent variational-autoencoder-based method for estimating respiratory rate and detecting abnormal respiration with commercially available RFID tags.
[170], (2018)	Recurrent Variational Autoencoder for Unsupervised Apnea Detection with RFID Tags	-	-	The researchers addressed the application of the Internet of Things in healthcare and discussed RFID technologies, frequency-hopping with real-time calibration for RFID systems. They also analyzed the importance of monitoring continuous breathing in cases of apnea. To answer these questions, they suggested a new method of respiratory rate monitoring system called "Auto Tag" with the function of a recurrent variational autoencoder for detection of apnea and respiration.
[171], (2019)	Prototype of On-Board Platform for Measuring Vital Signs Using IoT	✓		The research discusses embedded technology e-Health platform techniques based on the IoT, artificial neural networks, Arduino UNO R3, embedded platforms, and the application of various sensors, such as the AMS 5915 blood pressure sensor, AD8232 electrocardiogram sensor, breathing apparatus MAX30100, and IR body temperature sensor MLX90614. They developed an experimental wearable device indicated for general-purpose use.

Table 2. *Cont.*

Reference and Year	Title	IoT in General	IoHT	Contributions
[176], (2018)	An Intelligent Real Time IoT Based System (IRTBS) for Monitoring ICU Patient	✓		The authors addressed relevant issues of the Internet of Things, (IoT) such as high technicalization, robustness, and accuracy, in addition to studying sensors and intercommunicating devices. The researchers proposed an IoT-based monitoring system with remote access, fast communication between the health team, proactive and fast treatment, error reduction and time savings.

Prajapati, Parikh, and Patel [176] suggested an IoT-based wearable device called the "Intelligent Real-Time IoT Based System (IRTBS)." This system can provide real-time monitoring, identify emergencies, quickly and securely send patient data, and check communication delays. Therefore, it can help medical staff save time and reduce errors in decision-making.

Dharani, J. M. et al. [163] developed the "health monitoring system-UPHM" through smart sensors and wearables based on the Internet of Things (IoT) standard and integrated cloud computing. Their prototype includes flexible, scalable, and general-purpose techniques through smart wearable sensor technology, a LM 35 temperature sensor, a AD8232 ECG sensor, and a vibration detector, in addition to Arduino and Raspberry Pi 3 platforms.

This UPHM device offers healthcare services remote, continuous, and effective monitoring as it is constituted by IoT and cloud technologies. In addition, it relies on a so-called "on-demand" control to enable the healthcare provider, when authorized, to check the system information and make the best decisions [163].

Naranjo-Hernández, David et al. [177] showed a capnography prototype called "smart vest" based on the MQTT protocol with open-source code. This system proved to be effective, non-intrusive, and robust. It was developed though wearable and smart technologies and e-Health application tools based on the Internet of Medical Things (IoMT) standard. This system was created to monitor the breathing of patients with chronic obstructive pulmonary disease (COPD). Therefore, this framework was characterized as a portable, comfortable, and secure device with interoperability and scalability, which can exhibit accurate capacitance and high detection sensitivity, as it uses the principles of capacitor induction (LC). This system can also impart high sensitivity and precision capability to efficiently detect patients' vital signs [177].

Van Loon K. et al. [178] proposed the "frequency modulated continuous wave (FMCW)" radar system to check patients' breathing through remote monitoring. This digital capnograph model presented unique and specific characteristics with great potential for the implementation of new techniques that can improve signal-processing algorithms, such as early identification of respiratory diseases and improvement of mechanical ventilation support.

Bae, Kwon, and Kim [179] presented the ubiquitous portable Vital (u-Vital) device composed of a system called the vital block (VB), with the function of collecting a patient's electrocardiogram (ECG), blood oxygen saturation (SpO2), non-invasive blood pressure (NiBP), and body temperature (BT) in real time. This framework applied the wearable concept, offered a real-time sensing algorithm, and was based on the IoMT. Consisting of a patient monitoring device (PMD) and a vital signs server (VSS), it can store and manage the patient's clinical data through wireless protocols such as Wi-Fi and Bluetooth [179].

Chowdhury, M. F. et al. [180] developed a solution using a new generation of MEMS IR emitters and detectors embedded in SMDs. Priya et al. [181] clarified that all types of health data could be subordinated to a diversity of queries to deduce overly useful intelligence and to mechanicalize and condition various manual tasks.

George, Moon, and Lee [182] described an intelligent, wearable health system via an eight-channel wireless device, using Bluetooth Low-Energy (BLE) technology. It consists of a signal that can be transferred to a personal computer (PC) capable of processing and classifying using MATLAB mathematical software.

The academy has pointed out new perspectives on health and monitoring systems. For instance, in the study case proposed by Ronen et al. [135], the "intelligent respiratory monitoring: clinical development and validation of the IPITM (Integrated Lung Index) algorithm", they presented an innovative device implemented with low-cost materials integrated with open-source software and platforms.

Another impactful capnograph device was suggested by Chowdhury, M. F. et al. [180] who applied MEMS IR technologies and an SMD-embedded technique based on the IoT. It also uses non-dispersive infrared (NDIR) technology, considered one of the most sensitive techniques to measure carbon dioxide (CO_2) in the human breathing process. Although this model does not use wearable techniques, its creators argued that it has excellent potential for adjusting to these technologies. In addition, they pointed out that the system can offer real-time and remote monitoring, as they apply a new generation of infrared (IR) emitters and detectors. Moreover, they use the techniques of complementary metal–oxide–semiconductor (CMOS) memory with patterns in deep reaction ion engraving (DRIE) [168].

Zaveri, Karan A., et al. [183] developed a modern and bold healthcare system to monitor the vital signs of patients in a home quarantine situation. This device aggregated an IoT-based heart rate measuring (BPM) system with a pulse sensor and NodeMCU technology and featured native Wi-Fi integration features with increased processing power and memory. Hence, this model can have a great impact in a crisis scenario, similar to what happened with the COVID-19 pandemic, which, at its most severe moment, with the lack of emergency devices, required changes in the production chain and new protocols. Therefore, this system can be very useful because it integrates high-performance sensors with the function of receiving and sending readings, within the established period, through the Blynk application [183]. It can also provide real-time, continuous monitoring and enable the physician to make appropriate decisions according to the patient's clinical condition. That is, the health professional can be warned in case of severity and request an ambulance to send to a convenient location [183].

The wearable model suggested by Priya et al. [181] was targeted at patients who need continuous respiratory rate monitoring, such as the elderly, Alzheimer's patients, and paralysis patients. This combines numerous excellent IoT-based functions. For example, the doctor accesses the patient's data and has the possibility to make better decisions as appropriate [181]. In addition, this system includes data processing that is sent via a low-power 433 MHz transmitter to the local server and cloud. This can be accessed by a smartphone app at any time since they are stored in the cloud [181]. This architecture has high-level sensors that can read any parts of the body of people with disabilities and allows them to send a message through the Global System for Mobile (GSM); even those who live alone can send a Short Message Service (SMS) message [181].

New generations of health devices can be leveraged for knowledge discovery and dissemination techniques, and many new applications can be developed. For example, Ketu and Mishra [184] confirmed this hypothesis by explaining that solutions with similar characteristics to those addressed in this paper can positively impact the application of the e-Health system. The techniques of these technologies have excellent potential for expansion if combined with wearable technologies, IoHT, and smart sensors. To fulfill all the criteria of this study, Table 3 then provides a summary of these solutions, highlighting contributions, limitations, performance, and feasibility.

Table 3. Summary of wearable and smart IoT-based devices for capnography.

Authors with Reference	Title	Contributions	Limitations	Performance	Feasibility
Dharani et al. (2018) [163]	IoT Based Advanced Universal Patient Health (UPH) Observation System Using Raspberry Pi 3B	The researchers talked about wearable and smart technologies based on the Internet of Things (IoT) standard and integrated cloud solutions. The contribution of the authors adds to the issues related to innovative technologies (Arduino and RaspBerry Pi 3 platforms), modern and flexible sensors, scalable techniques, and the development of the prototype health monitoring system UPHM.	Needs to focus on security and data privacy	Robust, portable, flexible, remote access, real-time, continuous monitoring.	Low-cost, economical, effective, and efficient
Ahmed, Zia Uddin et al. (2018) [172]	Internet of Things Based Patient Health Monitoring System Using Wearable Biomedical Device	The researchers proposed an automated, intelligent, digital IoT-based architecture to provide doctors with remote patient health status monitoring support. The relevance of this study consists of an affordable and practical system.	Sensor instability and patient data security	Portable Real-time, continuous remote monitoring	Low energy consumption and cost, economical, effective, and efficient
Dusarlapudi et al. (2021) [173]	COVID-19 patient breath monitoring and assessment with MEMS accelerometer-based DAQ—a Machine Learning Approach	The authors' discussion covers the concepts and methods of wearable and smart technologies, the accelerometer device, wireless modules, radio frequency identification (RFID) tools, Arduino, and approaches to the IoT and telemedicine resources.	Updating the system change in the epidemiological profile	Robust Real-time Remote access Continuous monitoring	Efficient and effective solution.
Jara, Zamora-Izquierdo and Skarmeta (2013) [174]	Interconnection Framework for mHealth and Remote Monitoring Based on the Internet of Things	The researchers discussed the complex issues related to the personalized health framework with patient data, which can be dynamic and incomplete. Therefore, there are difficulties with mining, analysis, and bias. They contributed an interconnection framework approach to mobile health (mHealth) based on the Internet of Things. They applied the concepts and methods of innovative technologies to develop a continuous monitoring system for vital signs, with remote access, wearable, and with an efficient, safe and scalable sensor.	Needs to focus on security and data privacy	Robust, Flexible Portable, Continuous monitoring, remote access, and real-time.	Low energy consumption and cost, economical, effective, and efficient

Table 3. *Cont.*

Authors with Reference	Title	Contributions	Limitations	Performance	Feasibility
Prajapati, Parikh and Patel (2018) [176]	Smart Vest for Respiratory Rate Monitoring of COPD Patients Based on Non-Contact Capacitive Sensing	The researchers investigated concepts and applications of capacitive sensing technologies and an e-Health platform based on the Internet of Medical Things (IoMT) to be used in the development of a respiratory rate monitoring system for patients with pulmonary disease (COPD) during the period between respiratory rehabilitation and home exercises with the following functions: non-contact, portable, intelligent, wearable, low-cost and comfortable.	Lack of qualified professionals	Robust Continuous monitoring Real-time, proactive and quick treatment.	Low-cost, economical, effective, and efficient
NARANJO-HERNÁNDEZ et al. (2018) [177]	Smart Vest for Respiratory Rate Monitoring of COPD Patients Based on Non-Contact Capacitive Sensing	The researchers investigated concepts and applications of capacitive sensing technologies and an e-Health platform based on the Internet of Medical Things (IoMT) to be used in the development of a respiratory rate monitoring system for patients with Pulmonary Disease (COPD) during the period between respiratory rehabilitation and home exercises with the following functions: non-contact, portable, intelligent, wearable, low cost and comfortable.	Lacks security, interoperability and scalability	Robust Real-time, portable, non-contact, comfortable monitoring.	Low-cost, effective and efficient
Loon et al. (2016) [178]	Wireless non-invasive continuous respiratory monitoring with FMCW radar: a clinical validation study	The authors studied the application of "frequency-modulated continuous wave radar" technology to verify its safety in measuring respiratory rate and to present wearable, non-contact, non-invasive monitoring solutions for use by postoperative patients. They developed a reference monitor (pneumotachograph at the time of ventilation and capnography during spontaneous breathing).	Algorithm unavailability and radar inaccuracy FMCW	Robust Portable, non-contact, remote access, real-time, continuous monitoring	Low-cost, economical, effective, and efficient

Table 3. *Cont.*

Authors with Reference	Title	Contributions	Limitations	Performance	Feasibility
Bae, Kwon, and Kim (2020) [179]	Vital Block and Vital Sign Server for ECG and Vital Sign Monitoring in a Portable u-Vital System	The researchers discussed wearable and smart technologies, addressing the potential of the Internet of Things techniques applied to healthcare. They proposed the ubiquitous Vital (u-Vital) handheld device composed of a system called the vital nlock (VB) with the function of collecting a patient's electrocardiogram (ECG), blood oxygen saturation (SpO2), non-invasive blood pressure (NiBP), and body temperature (BT) in real time.	Needs to focus on security and privacy of patient data	Robust Portable, real-time processing, data generation and storage.	Effective and efficient solution
Chowdhury et al. (2019) [180]	MEMS Infrared Emitter and Detector for Capnography Applications	The approach discussed by the authors shows the importance of a portable, low-cost, more widely used capnography monitoring system, accessible to developing countries, that uses the technologies of a new generation of surface mounted devices (SMD) and micro-electro-mechanical systems (MEMS).	Sensor update	Robust Real-time, portable, non-contact, comfortable monitoring	Low power consumption and cost, effective and efficient.
Priya, G. et al. (2020) [181]	IoT Use Cases and Applications	The researchers analyzed concepts and applications of the Internet of Things related to health, health systems, Arduino microcontrollers and machine learning to apply and develop an intelligent prototype. They also disputed numerous case studies on the smart health system. Finally, they presented a wearable and intelligent monitoring system, based on the IoT, which has a great impact on the lives of patients with paralysis and Alzheimer's.	Sensors with limited capacity	Portable, lightweight, continuous monitoring, real-time, remote access.	Effective and efficient solution
George, Moon and Lee (2021) [182]	Extraction and Analysis of Respiratory Motion Using a Comprehensive Wearable Health Monitoring System	The researchers discussed a novel technique for monitoring respiratory functions, such as respiratory rate and tidal volume, with the goal of showing an innovative multisensor approach with application of a new wearable sensor technology with the connection of acoustics and biopotentials and implementation of a lightweight and extensive wearable vital-sign monitoring system.	Need for further research, analysis, and methods.	Robust High level, multisensor, real-time processing.	Effective and efficient solution

Table 3. *Cont.*

Authors with Reference	Title	Contributions	Limitations	Performance	Feasibility
Zaveri et al. (2021) [183]	IoT based real time low cost home quarantine patient aid system using Blynk app	The researchers discussed IoT, NodeMCU, air quality, oxygen separation level (SpO2), LCD display, heart rate, body temperature sensing, cloud computing, and the Blynk app and proposed a "Home Quarantine Monitoring System" to monitor COVID-19 patients through an application based on IoT-cloud and Blynk. This system uses sensors that collect essential data and sends them to a central server that stores them to be applied whenever there is a need.	Sensor upgrade	Robust Portable, real-time and continuous monitoring High performance (processing, memory and sensors)	Viable model in a crisis scenario, economical, reliable and highly functional

5. Analysis, Discussion, and Open Issues

The previous sections discussed relevant issues about capnography, mechanical ventilation monitoring systems, and innovative solutions addressed in the literature, with an emphasis on wearable and intelligent devices (capnographs) based on the internet of things.

In this section, the main solutions discussed above will be analyzed and compared. The following precepts were considered in order to filter the contributions referred to as "high performance" with great potential for implementation: the use of robust and portable devices, patient safety and comfort, autonomous and easy-to-use devices, improved usability of care, and sustainable and continuous monitoring.

Vijayalakshmi and Deepa [185] also analyzed hardware and software that can be applied in healthcare. This technology is proving to be very useful and impactful in complex monitoring structures, as is the case with IoT, which is a creative and functional technology that opens horizons in the medical field.

Specifically, in the context of respiratory diseases that require continuous monitoring, the IoT is an excellent technology, as it grants efficiency in storing and processing data while allowing physicians and healthcare providers to monitor patients remotely [185].

Wearable and smart technologies have also played a relevant role in monitoring systems, demonstrating extraordinary potential for implementation in healthcare devices combined with IoT techniques. Al-Halhouli, A. T., et al. [186] discussed the possibilities and contributions of wearable sensors that can be applied to individualized health in the case of a monitoring system for patients with infectious diseases, such as COVID-19.

According to Ahmed et al. [172], monitoring systems that operate with IoT-based wearable and smart technologies can significantly decrease mortality rates. They offer an automated system that works over the internet and brings together the following benefits: ease, safety, efficiency, and speed of care.

Dusarlapudi et al. [173] designed a smart wearable prototype that applies "embedded camera" technology and works as follows: the wearable module takes an accelerometer reading and then transmits it by a wireless 433 MHz radio frequency module to another Arduino board that has the function of sending data through the serial port. Then, it uses the Parallax Data Acquisition Tool (PLX-DAQ) to generate an Excel file containing data readings and interpretation graphs in real time. This device works by using the IoT and telemedicine resources to send patients' health status reports to the system-enabled physician. The relevance of its architecture includes real-time, continuous, and remote access monitoring benefits used for COVID-19 patients and/or other severe cases that require respiratory rate (RR) monitoring [173].

Even though the devices addressed in this paper are excellent and capable of handling several issues, changes in the epidemiological profiles of populations in the last two decades have changed the actual framework, and studies converge on new solutions. For instance, the global health crisis caused by the recent pandemic of COVID-19 has disrupted production chain processes for medical devices used in the monitoring systems, such as the capnograph and ventilators. This situation has led to a major shortage of these devices worldwide [187,188]. Li, Wei et al. [189] explained that COVID-19 exposed the weaknesses of the conventional healthcare system, and that healthcare providers alone would not be able to cope with this scenario.

In contrast, this situation could have been made more flexible by employing some creative and innovative solutions that had already been pointed out by the scientific community even before the pandemic. Those solutions had excellent implementation potential, as in the case of [174], which proposed the AIRE prototype and innovative protocol YOAPY to integrate sensors in an efficient, secure, and scalable way. It sought to solve problems such as signal elimination, data calibration, and real-time monitoring.

According to Jara, Zamora-Izquierdo, and Skarmeta [174], wearable and smart technologies based on IoT techniques can be biomedical solutions and still allow a balance of social, economic, and environmental costs. This analysis recently confirms that among today's essential technologies, smart and connected wearable technologies have great potential to help in the medical field.

Wearable devices based on the Internet of Things (IoT) have already developed greatly in recent years. They can facilitate the gathering of health-targeted data to an effective extent never seen before. Although there are still many challenges to be overcome, these studies can provide government and healthcare professionals with important analysis and information on the latest trends and prospects for using these technologies in "smart health" [189].

The solutions presented in [163,176,187,190] can be considered innovative and easy to implement, serving as models for new devices (capnographs, for instance). The prototype "Intelligent Real-Time IoT Based System (IRTBS)" and the Advanced Universal Patient Health Observation System (UPH) have enormous potential to develop, organize and execute other monitoring systems in a continuous, intelligent, sophisticated and effective way.

Bae, Kwon, and Kim [179] built an advanced easy-to-use portable "ubiquitous Vital" (u-Vital) system. This scheme is composed of a vital block (VB), a patient monitoring device (PMD), and a vital signs server (VSS), which operates with continuous monitoring functions based on IoT techniques. It allows data storage for further analysis and manages the measurement of vital signs. In addition, the collected vital signs are sent via Wi-Fi and Bluetooth to a VSS. The prototype then offers a real-time detection algorithm for the R-point that refers to one of the waves that translates the ventricular activity and that corresponds to the depolarization of heart muscles with long-term ECG analysis [179].

The prototypes suggested by [20,177,179] can offer an intelligent robust architecture, low-environmental-impact, self-sufficient solution with a wide potential of use, and maintain the quality of the patient's health. When checking patients' vital signs, it transmits them at the same time to a server and performs a real-time analysis through wireless systems Wi-Fi Bluetooth protocols and efficient algorithms improving its use in ICU environments.

On the other hand, the model developed by Chowdhury, M. F., et al. [180] uses the SMD embedded technique and MEMS IR technology, applied to capnography with a new generation of infrared (IR) emitters and detectors and complementary metal–oxide–semiconductor (CMOS) memory, standard in deep reaction ion etching (DRIE), and was found to be very effective to provide real-time and remote monitoring.

The prototypes created by [169,170], called "AutoTag and RFID tag systems", operate with an active platform of commercial RFID readers and tags. Therefore, they can lessen the action of unstable environments and still function as a ubiquitous, continuous, and remote monitoring system with broad device integration. These technologies are considered low-cost and they use commercially available materials and integrate the benefits of credibility, security, and privacy [135,169,170,191]. As such, automated electronic devices with IoT-based wearable and smart technologies offer the healthcare service a digital monitoring system in real time and remotely. They can also identify emergencies, produce information in a fast, time-saving manner, and check over communication delays [176,177,192].

Yang, Wang, and Mao [169,170] proposed the "AutoTag" solution based on an unsupervised uniform variational autoencoder. This measures the respiratory rate to identify eventual respiratory problems and abnormalities by using RFID tag technology. Initially, the goal was to develop a system (AutoTag) to only monitor breathing and apnea [170]. However, the implementation presented in [169] suggests that the AutoTag system would also answer problems related to other respiratory diseases. AutoTag uses IoT concepts along with some sensors for respiratory rate monitoring and parameter calibration.

The ResBeat [166], a flexible respiratory monitoring system, was implemented using bimodal channel state information (CSI) data. This device considers logging the 'amplitude' of bimodal CSI in real time to improve the robustness of respiratory level measurement at different sites. ResBeat's basic differences from IoT-based wearable systems refer to the implemented techniques that achieve other purposes. The ResBeat model applies 5 GHz Wi-Fi, bimodal channel state information (CSI) data, and "subcarriers to modulation" with orthogonal frequency division multiplexing (OFDM/OFDMA) [166]. Therefore, this device can provide "flexibility", while it is considered a "resilient system". This is because it integrates adaptive capability, data pre-processing, and signal distinction in respiratory monitoring. The prototype demonstrated high performance with mutually complementary data. Its performance was found to be satisfactory in all three test scenarios, demonstrated by respiration rate evaluation, which achieved high-accuracy results [166].

Zaveri Karan A. et al. [183] proposed the "Home Quarantine Monitoring System" to monitor COVID-19 patients through an IoT-cloud- and Blynk-based application. This method supports secure and fast real-time remote monitoring and wide applicability when compared to other devices available on the market. Moreover, it presents numerous benefits, such as versatility, speed, security, and cost savings. The cloud technology of this prototype can be adjusted to enable a fast and proactive connection with the healthcare team, as it uses sensors that collect essential data and send it to a central server that stores it to be applied whenever it is needed [183].

Priya et al. [181] developed a wearable health technology device based on smart IoT techniques. It uses machine learning tools to assist people with paralysis in their routine activities. It has functions to check, analyze, examine, locate and store medical data and present statistical samples. An innovative function of this device is a "medicine dispenser", a pill holder attached to a bell with an alarm program to let the patient know when it is time to take the medicine. It also has a pulse sensor that allows heart rate detection to display the patient's condition through the LCD panel, showing whether a patient is agitated, for example [181]. This section has delved into some of the functions and applications of different healthcare devices, in particular wearable smart devices applied to the capnograph. It is understood that this state-of-the-art knowledge base can contribute to the emergence of new solutions and advances in the healthcare research field.

Healthcare providers' understanding of how to handle capnograph devices is vital in treating respiratory illnesses such as COVID-19. Smart devices that detect data quickly and securely and provide continuous monitoring may produce a real impact on saving patients' lives, not only by providing better patient care but also by enabling better administration of healthcare services.

The solutions discussed above answer some of the questions raised in this work. Such models demonstrated extraordinary performance, including production flexibility; portable and easy-to-use designs; safe, fast, and effective real-time medical analysis; remote access; and time and resource savings. However, there are still some relevant open issues that need to be discussed.

Open Issues

According to the analysis carried out in this study, the following open issues are identified:

- Application of modern and flexible sensors in capnography. Modern and flexible sensors can considerably reduce the cost of the capnograph in terms of development and production because they are abundantly found in the market and considered robust devices by the literature.
- Application of the IoT Blynk platform in capnography. The IoT Blynk platform provides the ability to integrate and develop devices with remote and real-time management. It can offer to healthcare professionals a continuous and fast monitoring system, since it has a robust, dynamic, effective, and efficient architecture.
- 3D prototyping technologies to develop capnographs. The use of 3D technology has been an excellent alternative in device development, primarily "emergency" devices. These devices were widely used in the most serious period of the COVID-19 pandemic due to their low cost and fast production process. The use of 3D technology can involve lightweight and comfortable materials, offering remarkable functions and features, such as safety, ease of use, adjustability, and flexibility.
- Development of a flexible and intelligent monitoring system. This can promote evolution in mechanical ventilation support and revolutionize healthcare systems worldwide, making service stations in intensive care units much more dynamic and safer. Furthermore, it may impact e-Health applications and help in other contexts of pandemic crises in the future.

6. Lessons Learned

The capnograph is a basic device in anesthesiologic practices and in respiratory diseases monitoring systems. In addition to improving and optimizing the mechanical ventilation service, it is equipment that helps save lives. Even though recent literature has investigated monitoring systems (emergency ventilators) due to the crisis caused by COVID-19, capnography still needs to play a major role and be supported in academic studies.

The growing advance of the Internet of Things has led to the emergence of new models of health systems that support cutting-edge technologies such as smart and flexible devices. These can add excellent functions and prodigious features, including autonomy and robustness, and can still be fast, light, secure, scalable, adaptable, portable, and easy to use. In this study, open-source solutions were approached with the following aspects: the usage of economical materials, easy use and maintenance, and a simple and fast production process.

7. Conclusions

The context of the global health crisis caused by the COVID-19 pandemic was somehow faced, with creativity, good cheer, and resilience. This has helped the scientific community to analyze, reflect, and address the best measures and investment techniques in protocols based on innovative technologies that could avoid a situation of "chaos" in the global health system during pandemic periods.

The capnography devices studied in this paper proved to be viable and can largely contribute to mechanical ventilation monitoring systems, both in critical and regular periods. Therefore, it is expected that this study can strengthen the dialogue between its peers and contribute to future perspectives on the topic.

Based on this literature review, it was possible to perceive the need to develop smart and wearable solutions based on IoT for capnography, which can offer real-time monitoring, verify emergency situations, reduce communication delay, save time, enable medical teams to make decisions more correctly, reduce possible errors, and save lives.

The essential factors that hinder the deployment of this type of system are performance and technical and economic viability, which need to be aligned together. An option to adjust these factors would be supported by studies and research applying wearable and flexible sensors available on the market with innovative technologies, including Bluetooth, Wi-Fi, 6LoWPAN, RFID, ZigBee/IEEE802, and 433 MHZ receiver–transmitters. Furthermore, embedded known systems, such as Arduino, RaspBerry Pi, NodeMCU, PIC, and ARM9 can be adjusted to 3D prototyping methods considered flexible, safe, and easy to use, using light and comfortable materials, with structured architectures and platforms, and structured and connected to the Internet of Things (IoT) applied to health (IoHT, IoMT).

The accuracy and performance of the capnograph can considerably improve mechanical ventilation. Its size, lightness, ease of handling, and flexibility are notable functions that effectively support the continuous monitoring system and help healthcare providers to develop a quality service. Therefore, smart devices that can quickly and securely detect data and yet provide continuous monitoring can positively impact healthcare solutions by providing better patient care and enabling better administration in healthcare services.

To improve the applicability of health monitoring systems covering the strengths highlighted throughout this study, there are numerous important parameters that can be increased. For example, to establish functions that can operate with security protocols, Internet of Things standards applied to healthcare emerge as excellent resources, since they can integrate devices that start working with continuous monitoring and remote access in real-time. Other techniques have shown an impact on monitoring systems, such as modern, flexible sensors and 3D prototyping technologies that, in addition to being low-cost tools, have a faster production process, and use lightweight, adjustable, sophisticated, and comfortable materials. Accordingly, this review answers pertinent questions and points out other aspects related to the performance and viability of several healthcare solutions, since the focus of this work is to present an analysis and check which perspectives place wearable and intelligent solutions based on IoT in capnography.

In conclusion, this deep study of the state of the art demonstrated that there are promising guidelines for studies to follow in further investigations regarding IoT-based wearable and smart health device solutions for capnography.

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