Progress in self-powered medical devices for breathing recording

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ABSTRACT

Wearable and implantable medical technologies are increasingly being used for the diagnosis, treatment, and prevention of illnesses and other health concerns. One's respiration can be monitored using any number of different biosensors and tracking devices. Self-powered sensors, for example, have a reduced total cost, are easy to prepare, have a high degree of design-ability, and are available in a number of different forms when compared to other types of sensors. The mechanical energy stored in the respiratory system could be converted into electrical energy by using airflow to operate self-powered sensors. Self-recharging sensors and systems are now in development to make home health monitoring and diagnosis more practical. There has not been a lot of study devoted to the models of respiratory sickness or the output signals that connect with them. Thus, investigating the character of their bond is not only difficult but also crucial. This article examined the theory behind self-powered breathing sensors and systems, as well as their output characteristics, detection indices, and other cutting-edge developments. To help communicate knowledge to other academics working in this field and interested in this topic, we also explored the challenges and potential benefits of autonomous sensors.

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1. INTRODUCTION

One of the most essential vital signs is a person's respiration rate, which can reveal both general health trends and the prevalence of respiratory disorders. Traditional commercial and respiratory sensing devices are cumbersome to operate on a regular basis because to their size, expense, and complexity Figure 1. This study's theoretical and applied contributions center on a continuous, simple, and at ease method of evaluating respiratory limits. Touch monitoring techniques, the use of soft cloths, and other innovations have been studied by researchers to make breath monitoring more tolerable and practical [1]–[3]. Independent respiratory nerves have attracted the attention of biological sensing specialists [4]–[6]. As breathing is so crucial to human survival, sputum samples must be taken and examined for conditions like asthma, apnea, pneumonia, and tuberculosis [7]–[11]. The most up-to-date wearable and artificial sensors have played a pivotal role in the assessment of respiratory parameters such as breathing rate and energy, temperature, and specific inert gases in exhaust air [12]–[17]. Nerve activity and inactivity both contribute to increased respiratory awareness [1], [18], [19].

A devices that can directly convert biomechanical or thermal energy into electricity include triboelectric nanogenerators, piezoelectric nanogenerators (PENG), pyroelectric nanogenerators, hydroelectric nanogenerators, and hygroelectric nanogenerator devices [20]–[23]. The electrical impulses they release are intimately connected to the breathing system. TENG-driven airflow, for instance, can produce pulses whose dynamics are connected to the flow of air [24], [25]. Many developments in material science and micro/nanofabrication technologies have taken place [26]–[29] since the debut of self-contained polyvinylidene fluoride respiratory sensors in 1990 [27].

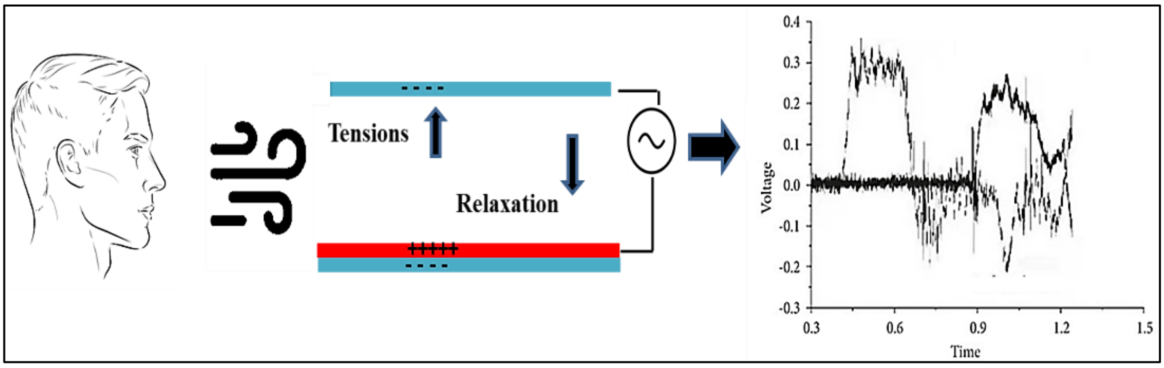

Figure 1. The airflow-based methodology used by most existing respiration tracking systems

Wearable and portable nanogenerators powered by piezoelectric and triboelectric effects promote compact, lightweight, sensitive, and accurate autonomic respiratory and sensory systems [30]–[33]. Researchers have moved on to a more in-depth investigation of nanogenerators used in bioengineering, with an emphasis on TENG's potential future applications and preferences for biological sensors like respiratory monitoring [34]–[37]. It was the prospect of moisture and gas sensitivity that sparked the development of respiratory analysis, and present a current status report on this topic in their article [38].

In addition, a recent work on TENG-enabled autonomous respiratory monitoring was published by Su *et al.* [39], elucidating the specificity and functionality of the facility in both respiratory signal collection and cellular respiratory analysis. The nanogenerator-based respirator active biosensing is an important part of the development of these systems because of its many advantageous characteristics, such as its small size, low toxicity, light weight, simple composition, and wide range of uses. As smart remote monitoring sensors become increasingly popular, these auto-regulating respiratory systems may also be utilized to connect them. We have traced the development of self-regulating respirator monitoring systems, including topics such as device-type features, output performance, and respiratory sensor index. Mouth breathing is indicative of direct breathing conditions since it might stimulate the body's own regulatory nerves. Nanogenerators can be used to track gas levels in the lungs, and researchers have developed self-propelled heat sensors made of piezoelectric ceramic materials. Meanwhile, we outline issues and solutions related to self-monitoring of breathing patterns. There have been significant advancements, but there are still issues to be resolved. One of these is the difficulty in providing accurate diagnostic information based on the effects of the autonomic nerves. We may be able to learn more about the effects of the tools people use if we use artificial intelligence and other creative techniques to treating respiratory difficulties.

Self-powered sensors application in respiration tracking in 2011, Ankad *et al.* [40] first proposed using a self-powered sensor strip made of polyvinylidene fluoride or polyvinylidene difluoride for cantilever activation in a hearing aid. For a long time, the conscious stage of a respiratory monitoring system relied heavily on sensing applications that had both low functionality and big physical footprints. A few short years later, a technique for monitoring autonomic respiratory function was developed. There are three distinct purposes served by these devices: collection of respiratory signals, monitoring of respiratory temperature and humidity, and detection of exhaust gas cells [26], [40], [41]. Figure 2 classifies these ventilators by their intended usage, showing that the most prevalent types are implantable and portable.

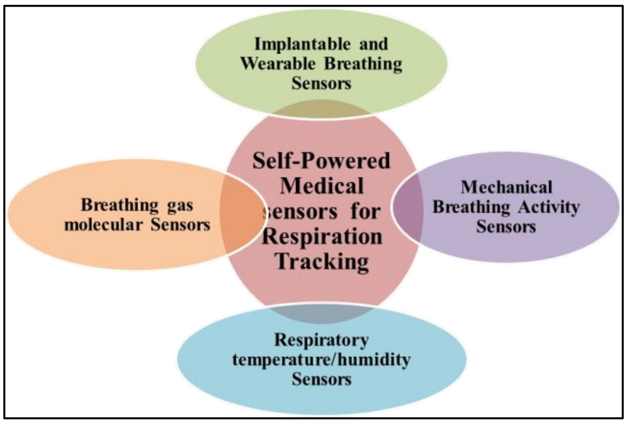

Figure 2. Self-powered sensors application in respiration tracking

2. RESPIRATORY TEMPERATURE/HUMIDITY MONITORING

Without the use of mechanical energy, human respiration generates heat and moisture [42]–[44]. Symptoms of elevated or decreased respiratory temperature or humidity are gathered by several self-regulating breathing devices. Xue and *et al.* [45] develop a breath-activated, highly sensitive pyroelectric sensing element for portable respirators made from polyvinylidene fluoride or polyvinylidene difluoride. The pyroelectric respirator sensor can also measure ambient temperature because it is linear in the positive temperature range and operates at room temperature. The most adaptable pyro-electric graphene nanogenerator was constructed by Roy *et al.* [46]. An achievable 4.3 V/kPa exists. Additionally, the heat generated by a person's constant breathing suggests that a pyroelectric respiratory sensor could be useful. This is because the pyroelectric output power is greater than 1.2 nW/m^2. Graphene oxide, reduced graphene oxide, and similar materials rely on the hydroelectric effect to power most self-activating respiratory sensors [47]. To track respiration, Zhao *et al.* [48] originally proposed an auto-charged moisture sensing element that uses single-graphene oxide to detect moisture signals in 2015. Hydroelectric effect [49], [50] is the name given to the mechanism by which graphene oxide generates electricity from water vapor. A single graphene oxide, capable of forming an oxygen-gradient if exposed to mechanical ventilation, can be prepared. When graphene oxide comes into touch with water, the resulting increase in H+ concentration stimulates the outer-cycle movement of strong, free electrons. Which have evolved a self-regulating respiratory system to generate respiratory power because they are particularly sensitive to fluctuations in humidity. A typical male subject in a research on the effects of dampening on emitted and induced voltages found that the voltage might reach 18 mV.

Graphene oxide can track a healthy patient's breathing rate and heart rate after a variety of exercises. Then, they demonstrated a stable dynamic transition in a graphene oxide nanoribbon network due to interactions between the individual nanoribbons [41]. The flexible effect membrane successfully achieved great breathability for writing and reading, with a low probability of failure over the long term. Using graphene oxide and lithium foil, they also created a ventilated detective battery [51]. In this battery, the graphene oxide layer works as a moisture collector and transporter, while the lithium foil triggers a redox reaction when exposed to water. This study shows great potential for application to next-generation respiratory biomedical sensor systems. On the basis of the hydroelectric action of graphene oxide, other researchers developed artificial respiratory sensors with a completely independent power supply [52]–[56]. With their aluminum breathing monitor-based humidity sensor, Bošković *et al.* [57] eliminated the need for an additional power source. The air humidity sensor is just as effective as an aluminum air battery thanks to the use of 1% silicone thin foam film as a composite capacitor. A porous and nanochanneled structure is advantageous for the dissemination of both ads and water molecules. This sensor can be used to track moisture levels in the skin and the pace at which a person breathes.

3. EXPIRATORY BREATHING GAS MOLECULAR DETECTION

Since effective ventilators have identified some of the gas emissions from the respiratory tract, this may be a means to strengthen the linkages between respiratory symptoms and illness identification and enhance the structure of respiratory observation schemes. The concentration of carbon dioxide can be used to neutralize odors in exhaust systems. Ankad *et al.* [40] proposed employing polyethylenimine-coated ethylene propylene membrane with a willow-coating as the sensing device in a 3D triboelectric ventilator to track respiration in real time. When it comes to exchanging substances like humidity, temperature, and gas molecules with the environment, this is one of the most important mechanisms in the body. Nitrogen oxides are associated with pulmonary inflammatory illnesses [58], acetone with diabetes [59], and ammonia with hepatitis [10], [60]–[63]. In addition, the presence of alcohol in the breath is a key factor in the diagnosis of drunk driving [64], [65]. By monitoring the voltage at the output, they can identify four distinct breathing patterns, from extremely powerful to extremely weak, and from long to brief. When comparing the solid and weak modes, the solid mode produces about three times as much power, whereas the short and long breathing cases both have a discharge pattern lasting 0.5 seconds at most with a maximum value variance of 0.5. Polyethylenimine is used as a CO_2 scanner in novel inventions to distinguish between exhalation and respiration based on changes in CO_2 concentration. The outputs of the triboelectric respiration sensor decreased by 11.73% after CO_2 were delivered at a speed of 6.5 m/s for an extended duration of time at a relative humidity of 37%. During this process, the relative humidity was kept constant at 37%.

A high blood-alcohol concentration in the exhaust is indicative of drunk driving. Wen *et al.* [66] created a self-regulating alcohol respirator based on a blow-driven triboelectric nanogenerator. With the help of a triboelectric respiration sensor, researchers were able to pinpoint CO_2 sensitivity in human respiratory monitoring and promote the development of autonomous respiratory neurotransmitters. Sensors in this system measure concentrations from 10 to 200 ppm, and the response/recovery time is 11-20 seconds. Alcohol-filled breathing has been shown to improve human respiration by Xue *et al.* [67]. This e-skin combines the elasticity of elastin with the resiliency of the triboelectric effect and the gas-sensitivity of sandwich nanostructures. This self-driving system may identify an intoxicated adult driver when hit. Piezo-gas-sensing arrays constructed from polyvinylidene fluoride were used to create respiratory sensors, which were also established by their team. Thus, five distinct sensory elements have been found that react to distinct gas signals [68].

That's why this gadget has been validated for its ability to detect exhaust system ethanol saturation. Each of these steps helped foster a more methodical approach to self-control, which in turn led to markedly enhanced efficiency. The presence of ammonia in higher concentrations in the exhaust gas is a telltale sign of a specific illness. In 2019, Wang *et al.* [69] created nanocomposite films with enhanced respiratory strength and resistance to NH_3 at trace concentrations. Next, they conceptualized a theoretical model for human respiratory analysis and the role of the NH_3 sensor, which led to the development of a triboelectric self-powered respiratory sensor [70]. The triboelectric respiration sensor relies on the NH_3 sensor, which is not without its own significance. The triboelectric respiration sensor can recognize the rhythm of breathing and the energy released during normal chest expansion and contraction if it is attached to the chest via an external gas collection device. As NH_3 levels rise, the output function of triboelectric respiration sensors increases dramatically. This technology allows for the detection and measurement of NH_3 biomarker traces in outside electricity and also distinguishes between the traditional, deep, exhaling, and rapid airflow patterns of the zip hatha breathing style. The air we breathe is filled with nitrogen dioxide, a gas that is just as dangerous as the others. Using TENG, Su *et al.* [71] created a portable membrane sensor inspired by the alveolus that can monitor human breathing and detect NO_2.

Membrane sensor emissions modeled after the alveolus can reveal variations in time and breathing effort. Incorporating breath monitoring and NO_2 detection into a single function, this feature gives a novel approach to sensing harmful gases. By expanding and contracting, gas injected from the inside or outside could generate an electrical gap between the latex membrane and the sensitive film. Using a tungsten trioxide composite sheet, the Alveolus-inspired membrane sensor demonstrated impressive sensitivity, detecting NO_2 concentrations as low as 80 ppm and as high as 340.24%. The NO_2 sensor choice is greater in the Alveolus-inspired membrane sensor than in the case of other gases.

4. SENSING OF MECHANICAL BREATHING ACTIVITY

During inspiration and exhalation, our respiratory system inverts the direction of several mechanical markers, including the compression of the sternum and the flow of air [72], [73]. However, many autonomous respiratory systems use pressure impulses to mechanically detect changes in an object's physical condition [74]–[78]. Recent years have seen an increase in the use of size and output aspects in a variety of sensory perceptions to more properly depict self-regulating respiratory system systems for the gathering of respiratory tract data. Because of this change in signaling, the devices that detect whether they are powered by the body's motion or by air flow must be moved to a new site. The power for the nerves implanted in the torso, heart, and throat comes primarily from the recipient's movement. Given their mobility, they often produce more force than other forms of air-driven air flow. In contrast, the gas-collecting respiratory systems in the nose and mouth reflect the effects of high temperatures, humidity, and the identification of molecules. In order to gather energy, detect mechanical signals, and monitor the mouth, breathing sensors are commonly implanted. Most commonly, breathing sensors are implanted to record the mechanical output of breathing. One study just released a bilayer triboelectric sensor for sensing pressure based on direct conversions of communication stress, with resolutions of 0.34 Pa and 0.16 Pa related to variations in the amount of air pressure, respectively [79]. Movement, breathing, and heart rate can cause a fluctuation in pressure, which may be detected by a momentary interaction between one of the rubber films and the fluorinated ethylene propylene membrane. When combined with an air bag and linked to the research facility, the system can detect autonomous breathing monitoring in real time. Human respiratory monitoring based on pressure-sensing microsphere TENG was developed by Liu *et al.* [80].

The most important part of this TENG is a thin triboelectric layer formed of thermal expanding microspheres and polydimethylsiloxane; pressure changes cause varied points of interaction, leading to changing charges on the triboelectric surface. This 33 mm^2 pressure gauge, attached to the chest or the head, may produce consistent output values while being sensitive to changes in breathing posture. The recorded signal showed a notable distinction between shallow and deep breathing at 30 and 9 breaths per minute, respectively. The microsphere-based sensor may also be used to pick up on hand gestures, which can provide useful information for making noninvasive medical diagnoses.

For the most part, electrical objects must be placed in close proximity to people for respiration signal monitoring devices to work [81]–[83]. Conversely, Chen *et al.* [84] identified a void in the study of unaffected respiratory nerves and designed a microstructure sensor with a self-powered gauge sensor that recognized data gathering without direct skin contact. The basic mechanism of action is the electrostatic events that occur between the highly charged of multi-layered components. Consistent with the substantial disparities between the various processes of a healthy subject, an self-powered microstructure sensor can monitor sensitive breathing and heart rate in a non-invasive mode while functioning under body weight. The improvement in consumers' sense of well-being brought about by the development of offline auto charged microstructure sensors has prompted a revaluation of monitoring systems for the quality of sleep. Additionally, scientists have developed a breathing device that can be used without any additional parts by only touching the skin. A majority of these rely solely on the sensor clustered in close proximity to the throat, chest, and abdomen. In those specific areas, the skin is in close contact to the breathing nerve, allowing for direct extraction of breathing signals. Because the force of body motions is larger than the force of air currents, mechanical breathing activity technology is typically easier to learn than natural nasal and oral breathing. Air flow generated by respiration can also power energy-efficient respiratory neurons. A TENG respirator-driven air sensor was introduced which utilizes a thin coating of nanostructured polytetrafluoroethylene flexible that, when exposed to air flow, acrylic nozzle becomes transparent [25]. TENG responds in kind to varying respiratory conditions, and an increase in charge transferred by respiration correlates strongly with total gas transformed.

5. IMPLANTABLE AND WEARABLE BREATHING SENSING ELEMENTS

Since of concerns over testing's impact on subjects' well-being and ethical norms, only a small number of research on the collection of respiratory signals have been conducted in vivo. Animal experiments have proven that it is possible to conduct a small number of investigations in this area. Natural breathing is made possible for the first time when the heart, lungs, and diaphragm work together as an integrated biological system to harvest energy from rest and relaxation [85]. After being implanted into the Sprague abdominal cavity, Dawley of adult mice, energy can be harvested from the normal diaphragm movement that occurs during the breathing cycle, and the nanogenerator prostheses can emit electrical signals associated with the respiratory and ventilation component [15]. These days, electronic surveillance equipment that can be taken anywhere can be used in a wide variety of configurations and modes of operation [86], [87].

The performance, ease, and efficiency of autonomous respiratory systems tend to decrease significantly with rising living standards and educational levels [88]–[90]. Making artificial, wearable nerves to help with social problems [86], [91]–[94]. The aforementioned self-regulating breathing apparatus can take the form of a handheld electronic gadget, a face or stomach mask, or a combination of these. However, there are many benefits to using implanted sensors, such as increased precision and the capacity to track targeted biological signals over time [87], [95]. But when implantable monitoring devices advance, their power consumption decreases [87], [96]. Combining energy harvesting with the collection of respiratory symptoms is a common feature of energy-efficient respirator systems. Raj *et al.* [97] demonstrated the feasibility of using triboelectric sensors as a real-time input for monitoring the human body. Triboelectric layers, electrodes, and spacers compose it, and a bendable multilayer shell encases the entire assembly. An implantable triboelectric active sensor in the pericardial sac can keep tabs on more than just your heart rate and blood pressure. The output of the implantable triboelectric active sensor peaked at 4.8 V during breathing, increased to 6.3 V, and then dropped to the true condition of ventilation. For the purpose of autonomously monitoring a person's health, Chen *et al.* [98] developed a multimodal triboelectric nanogenerator.

It can produce an open-circuit voltage of 14 V and a short-circuit current of 5 A when run on the heartbeat of a Yorkshire pig. In addition, the output peaks of an implantable triboelectric nanogenerator mirror those of a normal breathing cycle. Additionally, the concept of an implantable triboelectric nanogenerator that can harness the force of mechanical respiration was introduced [87]. Then, it can measure the forced mouse's vital volume by inserting itself under its left chest. Riboelectric nanogenerator implants show promise for future AI-enhanced hospitals. Wearable sensors are more adaptable and simpler to duplicate than artificial energy sensors [50], [88], [99]–[101]. The respirator mask [102] and the chest/abdominal belts [103], [104] are just two examples of various wearable devices that can be used in conjunction with the respirator sensor. In order to create an efficient face mask, Liu *et al.* [105] use electrospun polyetherimide nonwoven as electret materials. Cost-effectively removing sub-micron particle matter and harvesting energy from air flow using polyetherimide's potential retention properties in high humidity can be achieved with a smart face mask. The mask can function as a self-sufficient biological sensor, picking up on changes in breath volume when a person breathes in and out. The average human takes about 21 breaths each minute. An liquid crystal display (LCD) screen with this method can be used to evaluate a filter's performance. Graphene fibers are used to monitor respiration by harvesting energy from the environment through a process of moisture-electric energy transition [106].

When connected to a mask, this device's maximum output voltage is 292 mV, making it capable of detecting variations in human breathing patterns. It was introduced by Shahhaidar *et al.* [107] that advanced diatom frustrations of cellulose nanofibril-based TENG respiratory monitoring could generate an average of 85.5 mW/cm^3 with an effective interaction capacity of 4.9 cm^2. Thanks to the DF-CNF TENG, they were able to create a smart mask that recycles waste energy. Energy related with breathing is generated by the movement of a film made of fluorinated ethylene propylene between the two layers of improved cellulose nanofibre found in diatom frustules. Single TENG mode uses less power than the TENG-based dual-sensing breathing sensor. This sensor, which measures skin temperature and has a high output despite its small size, will find application in future wearable health monitoring systems. Smart facial masks and flexible materials, e skin, and chest/abdominal bands are also the subject of ongoing investigation [108]. Current self-powered breathing monitoring systems were outlined and compared in Table 1 for their benefits and drawbacks.

Table 1. The benefits and limitations of modern self-powered respiratory tracking systems

Signals	Advantages	Disadvantages
Molecular	Multitarget indicator recognition Extremely high precision Inexpensive	Sensitive to another's immediate environment
Temperature/humidity	Minimalist design Portable	Laggard rate of response Sensitive to another's immediate environment
Mechanical	Superior sensitivity Easy construction Abundant output voltage Reasonable price	Easily affected by the surrounding environment

6. CONCLUSION

In recent years, there has been a rise in the use of biomedical monitoring programs, especially those that track respiratory health. In order to investigate their perspectives, we will be comparing the pros and cons of modern air conditioning systems to other methods of signal collection. Air flow-driven respiratory tract production is closely correlated with flow-related variables such as duty cycle, intensity, and density of cross ventilation throughout breathing. The respiratory system's pyroelectric and hydroelectric effects are highly sensitive to the temperature and humidity of the exhaust gas, yet they are easily adjusted by external stimuli. Additional information on the chemical composition, useful for disease diagnosis, can be gleaned from the respiratory sensor for cell detection. Further, the creation of effective artificial electronics has been sparked by an intelligent healthcare system that draws on the internet of things' many features.

It's encouraging to see how quickly research on energy-based respiratory monitoring is progressing. Nasal congestion, mouth breathing, and chest motions are all components of remarkable self-regulating breathing systems. The expelled gas contains information on airflow, humidity, temperature, and molecules, while chest motions reveal largely mechanical information in the form of pressure changes. Most respirators these days are integrated into some kind of mask, belt, or other similar piece of clothing. To maximize customer satisfaction, it's best to minimize the consumption of resources. Researchers are now able to create breathing sensors that are both energy efficient and comfortable for users thanks to the use of flexible materials. Free of its reliance on an external power source, a gadget with autonomous sensors can reduce its power consumption. However, cutting-edge micro/nanofabrication techniques may provide a more involved path toward fabricating a compact and integrated system. Thanks to a pliable breathing mechanism made of microscopic pledges, personal wearable equipment is now possible.

Physical and biochemical indications of respiratory activity, such as respiratory rhythm, respiratory capacity, acetone, respiratory moisture, and so on, may reveal the state of health or illness in the human body. The devices' reliability is in question if other gadgets can detect many of the aforementioned signs simultaneously and in real time. Creating an encapsulating strategy for systems, like covering a device in thin layers of expandable polymers, could increase its reliability. Respiratory monitoring devices, in general, should be confined to a single position during this time, as doing so will maximize the likelihood of receiving a clear signal. Future progress depends on the robustness and anti-jamming characteristics of the respiratory system. For long-term learning and real-time performance, one of the biggest challenges is keeping the energy system's sensory properties consistent throughout daily life.

Even with recent advancements in self-operating sensors and gadgets, there is still a power supply constraint. Despite the fact that energy can be harvested from the environment via potentially dangerous technologies including piezoelectric, triboelectric, and pyroelectric devices, the overall energy efficiency of the respiratory monitoring system is insufficient to match the power consumption of the system. Improving the efficiency of the energy collecting system so that it can provide real-time propulsion will be a significant challenge. Terminals like PCs and mobile phones should then receive the sensor data for the self-regulating respiratory system, process the data, and provide an analysis of the users' respiratory health. The wearability of the device depends on its ability to send and receive data wirelessly. Wireless transmission of received signals increases the power consumption of the equipment. Power consumption, on average, can be measured in millimeters rather than watts, and is greater than that of several devices that capture less portable electricity.

Researchers have created sensors based on nanomaterials to detect respiratory diseases. Unfortunately, accurate medical diagnosis is still rather far. Giving customers and doctors access to test results and expert opinions is another priority for the respiratory monitoring program. Even worse, state-of-the-art artificial respiratory nerves still fail to adequately aid in the identification of respiratory diseases. The primary difficulty is that reliable diagnosis of respiratory problems is complicated by the fact that each user's breathing variations will cause signal discrepancies. Artificial intelligence (AI) has been widely employed in disease diagnosis, therefore it might be used to handle symptom management as well. However, current medical diagnostics and healthcare require multitasking, self-regulating respiratory systems.

Collecting data on gas exchange, respiration rate, and other respiratory system organic characteristics is common practice when making a diagnosis of respiratory disease. A key artificial intelligence site with high accuracy for respiratory disease, a smart city's wireless sensor system has recently benefited greatly from the rapid growth and popularity of 5G. With any luck, we'll soon be able to take use of digital communication via the ease of wireless sensors in self-driving vehicles.

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