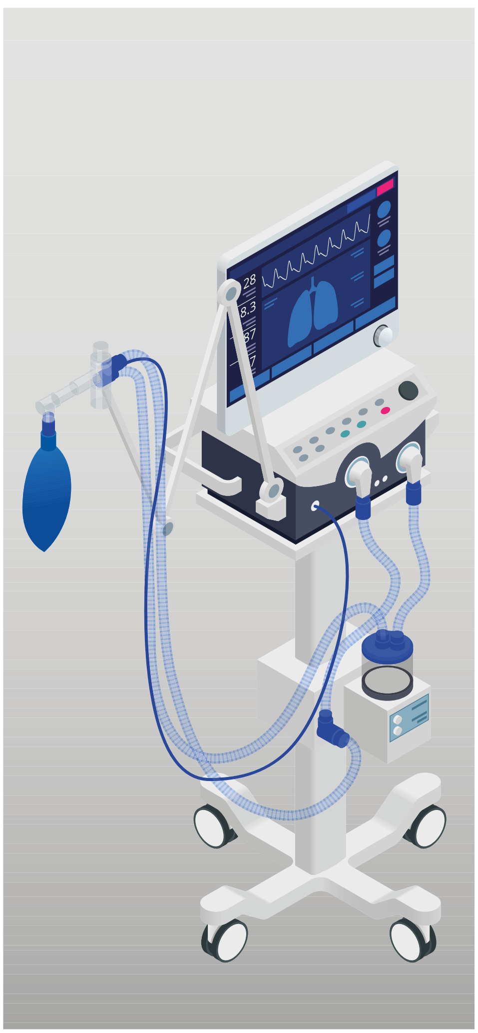
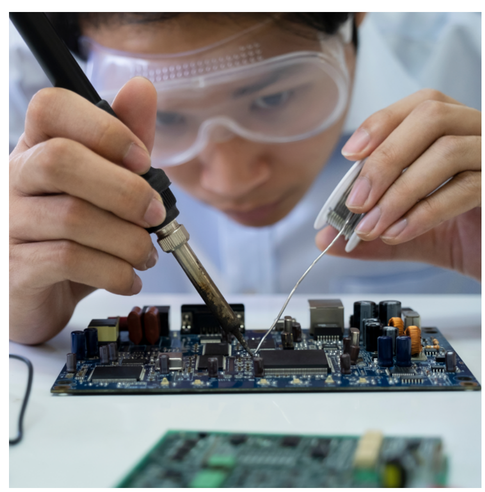
PRIORITIZING PATIENT SAFETY: A DEEP DIVE INTO THE SENSOR TECHNOLOGIES IN VENTILATORS

The use and benefit of various Sensors for designers and patients in invasive and non-invasive ventilators.





Prioritizing Patient Safety: A Deep Dive into the Sensor Technologies in Ventilators

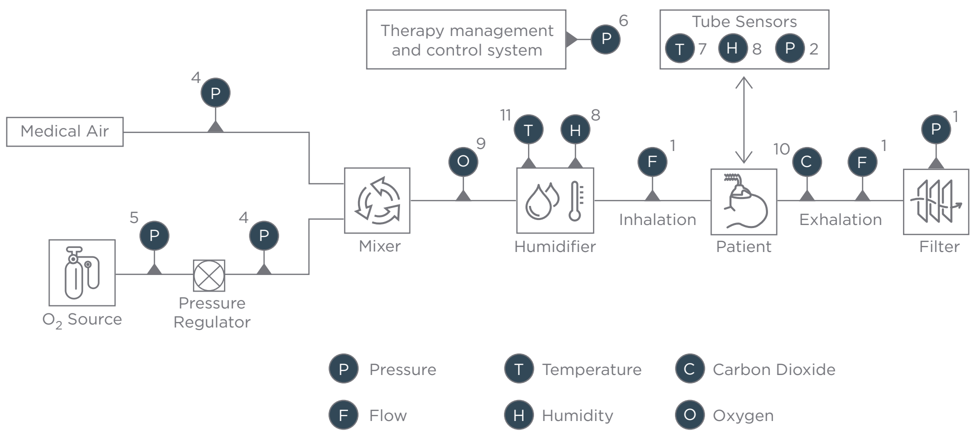
INTRODUCTION

Using sensors in ventilators has revolutionized how patients are treated and cared for in medical settings. Modern sensors can provide real-time monitoring and precise control, improving the ventilator's performance and enhancing the overall patient experience. This whitepaper will provide an overview of the common sensor technologies in medical ventilators and their importance and impact for manufacturers and patients. We will also cover best practice considerations for determining the quality of a sensor, choosing a suitable sensor for your specific design and reflect on using the latest technologies.

COMMON SENSORS USED IN MEDICAL VENTILATORS

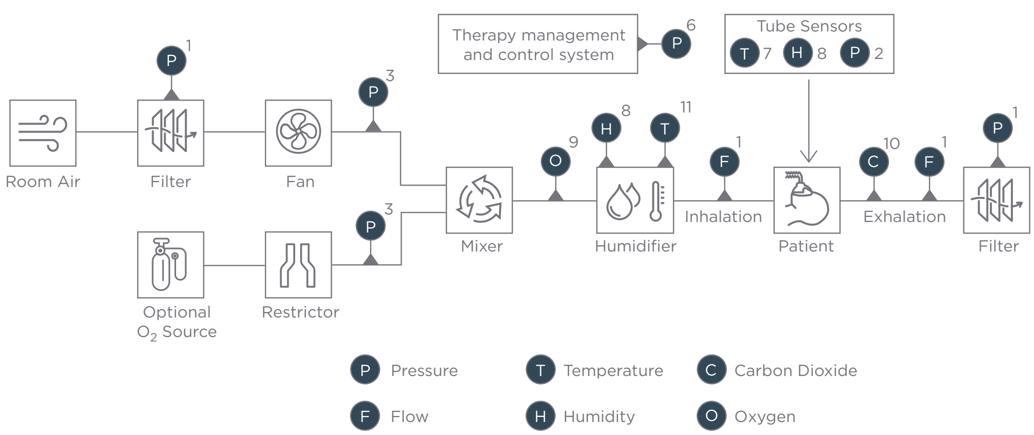
The following diagrams highlight the various sensors typically used in medical ventilators, including pressure, flow, temperature, humidity, carbon dioxide and oxygen sensors, as well as their placement and function within the device. These sensors work together to provide life-saving support and comfort to patients.

INVASIVE VENTILATOR



1. Diff. Pressure 0 to 5 cmH_2O or Flow +300 slpm
2. Gage Pressure 30 to 45 cmH_2O
4. Gage Pressure 35 to 90 PSI
5. Gage Pressure 3500 PSI
6. Barometric Air Pressure
7. Temperature 60 to 120 F
8. Humidity 0 to 100% RH
9. O_2 Sensors
10. CO_2 Level 30,000 to 40,000 ppm
11. Temperature 120 to 220 F

NON-INVASIVE VENTILATOR



1. Diff. Pressure 0 to 5 cmH_2O or Flow +300 slpm
2. Gage Pressure 30 to 45 cmH_2O
3. Gage Pressure 60 to 100 cmH_2O
5. Gage Pressure 3500 PSI
6. Barometric Air Pressure
7. Temperature 60 to 120 F
8. Humidity 0 to 100% RH
9. O_2 Sensors
10. CO_2 Level 30,000 to 40,000 ppm
11. Temperature 120 to 220 F

VENTILATOR TECHNOLOGIES

PRESSURE AND FLOW

Pressure and flow sensors serve critical functions within ventilators. These sensors are generally used with oxygen sensors to ensure patients receive the correct ventilation and oxygenation. Most ventilation therapies are pressure-controlled or volume controlled. In ventilation, positive pressure is used to drive the air/oxygen mix to the patient. Flow sensing measures the volume of air/oxygen mix delivered.

The selection of the correct sensors for the ventilator depends on the type of ventilation being provided:

- Non-invasive ventilation uses a mask or nasal cannula to deliver therapy to the patient. The therapy is provided through positive pressure from a fan.
- Invasive ventilation typically uses an endotracheal or tracheostomy tube to deliver therapy. A combination of hospital air lines and bottled sources provides pressure. Invasive ventilation is used when the patient's condition is critical.

Invasive Ventilators

The standard pressure measurement range for invasive ventilation varies from 3500 psi to 5cmH_2O. Long-term stability, accuracy, and response time are crucial parameters in pressure sensing. Medical practitioners frequently require devices with long lifecycles, typically up to 15 years. This lifecycle highlights the need for sensors that can maintain reliability over an extended period.

EXPERTS CORNER: CONSIDERATION FOR PRESSURE/FLOW SENSOR

Accuracy	Typically varies between 0.5% FS (Full Scale) – 1.5% FS
Resolution	Requirements vary from .05% to 0.1% FS
Long-term Stability	Sensors should maintain 1% FS total error band initially and less than 1%FS shift for 10 years
Diagnostics	Simplified error read-out capabilities

Non-Invasive Ventilators

Non-invasive therapy is often preferred, supporting reduced complications, improved recovery times, and lower costs (Nava & Hill, 2009). Non-invasive ventilation is also becoming more common in-home care settings. For non-invasive ventilation, flow is typically measured in a bypass configuration. The benefit of this approach is low flow impedance in the airpath.

Another advantage is that the bypass reduces the contaminants exposed to the sensor. Flow sensing technologies include thermal mass flow and delta pressure.

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TEMPERATURE

Temperature sensors are used to monitor the temperature of the air being introduced to the patient and, in some instances, to monitor the exhalation temperature. For some designs, a temperature sensor is also used to monitor the room air temperature to understand better if the incoming air will need to be heated or cooled as part of the process.

The temperature of ventilated air being introduced to the patient must closely match that of body temperature. Matching the body temperature will minimize the work that the patient's body would do to equilibrate the incoming air temperature and can help improve overall patient comfort.

EXPERTS CORNER: CONSIDERATION FOR TEMPERATURE SENSORS

Response Time	Responses to changes in temperature are typically determined by the size of the sensing element (shorter is better)
Accuracy	Modern sensors aim for accuracy within 0.1°C
Stability	Stability ensures accurate readings over the life of the system
Reliability	Ability to operate in different environmental conditions (e.g. high moisture resistant) while remaining accurate over time

HUMIDITY

Humidity sensors serve the critical function of reporting humidity levels in the patient airway circuit, which helps the ventilator system tailor humidity levels for optimal patient comfort and outcomes. Key characteristics to help evaluate quality and performance include accuracy of relative humidity, response time to humidity changes, recovery time from saturation, and temperature accuracy. The latest trends in humidity sensor technology include barometric pressure measurement and often allow humidity levels to be set by the system based on room conditions or by the care provider for patient needs.

EXPERTS CORNER: CONSIDERATION FOR HUMIDITY SENSORS

Accuracy	Aim for a typical accuracy of ±2% relative humidity (RH)
Response time	Aim for less than 5 seconds t63% with 1m.s-1 air flow
Recovery Time	Recovery from condensation should be less than 30 seconds t100%

CO_2 DETECTION

Measuring the concentration of carbon dioxide (CO_2) in a patient's exhaled air provides essential information regarding the patient's condition. In exhaled breath, healthy humans have a CO_2 concentration of about 3.8% by volume. Deviation from this number can indicate several health problems surrounding the lungs. Respiratory infections, asthma, COPD, pneumonia, and sleep apnea often result in low exhaled CO_2 concentrations. Adding a CO_2 sensor to a ventilator will provide medical professionals with a vital measurement to track the effectiveness of treatments and therapies administered to the patient.

There are several technologies and products designed to measure CO_2 concentration. Electrochemical sensors, metal oxide semiconductors (MOX), and non-dispersive infrared (NDIR) sensors are the most common.

Unfortunately, Electrochemical and MOX sensors have drawbacks. Electrochemical devices use wet chemicals and have a relatively short life span, averaging a couple of years at best. In addition, MOX sensors can be sensitive to several gasses, which may impact test results.

NDIR sensors have many advantages. They can be "tuned" to detect only CO_2 and aren't affected by other gasses. They measure optical properties without consuming or altering the sample gas concentration and are stable over a wide temperature range, with excellent long-term performance.

The "heart" of an NDIR device is an optical sensor called a thermopile, along with a special optical filter designed to detect the wavelengths of infrared (IR) energy absorbed by CO_2 molecules. An IR source shines light through the sample, and the thermopile/filter can measure how much IR energy has been absorbed. The more energy absorbed, the higher the CO_2 concentration.

EXPERTS CORNER: CONSIDERATION FOR CO_2 DETECTION

Package	Preferred that the sensor use a small hermetically sealed package
Filter	Ensure CO_2 filter winder is included with a minimum 4.26µm bandpass
RTD	Ensure reference RTD is included with 1kΩ at 0^{o}C
Sensitivity	Higher sensitivity is better to accurately measure changes in CO_2 concentrations

OXYGEN

Supplying the correct amount of oxygen to a patient is critical to a patient's health. Insufficient oxygen can result in respiratory failure—while too much oxygen can lead to oxygen toxicity. Therefore, medical ventilators must measure flow and oxygen concentration to determine the amount of oxygen delivered to a patient. While CO_2 measurements are diagnostic—providing information on the patient's condition—O_2 measurements are used to control the therapy to the patient.

- Hypoxia and hypoxemia occur when insufficient oxygen is supplied to body tissue and blood. These conditions have symptoms like headaches, confusion, difficulty breathing, and rapid heart rate. Hypoxia and hypoxemia have the potential to be life-threatening.
- Oxygen toxicity occurs when too much oxygen is supplied to a patient leading to hyperoxia. This condition can result in effects on the central nervous and pulmonary systems. In severe cases, hyperoxia can lead to cell damage and even death.

There are several different sensor technologies for measuring O_2 concentration. The most common are electrochemical, metal oxide semiconductor, paramagnetic, and spectrometer. Unfortunately, many of these solutions have drawbacks. For example, electrochemical sensors have a limited product life and need replacement regularly, while paramagnetic sensors may drift. As an alternative, sensors that utilize thermal conductivity are recommended as they provide excellent long-term stability and product life and can be calibrated for humidity and air density changes using additional sensors.

EXPERTS CORNER: CONSIDERATION FOR OXYGEN SENSORS

Technology	Ensure it utilizes solid-state (SS) technology for long-term reliability
Response Time	Aim for a response time of <0.5s
Signal Output	Preferably provides digital output
Multifunction	Allows for temperature, humidity and barometric pressure data

THE LATEST TRENDS

The advancement in sensor technologies has significantly improved the design and functionality of medical ventilators. The latest sensors are smaller, more accurate, have a digital output, better stability and reliability and multifunctional capabilities. The following list outlines several significant improvements in sensor technologies and how they enhance medical ventilators' design and patient care.

Smaller Size

Smaller sensors can make medical ventilators more compact and portable, which is particularly useful for in-home use as it makes the device less intrusive and easier to transport. They can also reduce the cost and complexity of the device, making it more accessible to a broader range of patients. Smaller sensors can also help with weight and power consumption in portable ventilators, making them more feasible to carry around.

Greater Accuracy

Sensors with greater accuracy can improve the precision and effectiveness of medical ventilators, particularly for patients with complex respiratory conditions. Larger accuracy ranges provide more detailed measurements of the patient's breathing, ensuring they receive the optimal level of support. Greater sensor accuracy can also provide practitioners with valuable patient insights, ultimately helping to prevent complications and improve patient outcomes.

Digital Output

Digital output capabilities have enabled easy integration with other digital devices, such as computers and telemedicine systems, allowing for remote monitoring and adjustments to the ventilator settings. These capabilities can be beneficial for both in-hospital and home use, as it allows for more efficient and effective treatment and improved communication and coordination between healthcare providers. In addition, compared to analog, digital output reduces the chance of noise and distortion of signals, has improved quality and reduces the risk of errors.

Greater Stability and Reliability

Improvements in stability and reliability have played a crucial role in the design of medical ventilators. Using newer technologies can help bolster the device's long-term accuracy and consistent functioning, particularly in critical care situations, and minimize maintenance and downtime. This results in a more efficient, cost-effective, and patient-centric healthcare experience.

Multifunction Stability

Sensors with multifunction capabilities can provide multiple readings and data points in one device, improving the precision and effectiveness of medical ventilators, particularly for patients with complex respiratory conditions. Multifunction capabilities can also reduce the number of sensors required for the device and make it more compact and cost-effective, particularly for portable and in-home ventilators.

ABOUT TE CONNECTIVITY

TE is a global technology leader, providing sensors and connectivity essential in today's increasingly connected world. We are one of the largest sensor companies in the world. Our sensors are vital to the next generation of data-driven technology. TE's portfolio of intelligent, efficient, and high-performing sensor solutions are used for customers across a wide range of industries including HVACR, automotive, industrial and commercial transportation and aerospace and defense, to medical solutions and consumer applications.

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Reference:

Nava, S., & Hill, N. (2009). Non-invasive ventilation in acute respiratory failure. The Lancet, 374(9685), 250–259. https://doi.org/10.1016/s0140-6736(09)60496-7