

AUTOMATIC BREATHING AND METABOLIC SIMULATOR:THE RESPIRING ROBOT

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ABSTRACT

Automatic breathing and metabolic simulator (ABMS) systems were first developed in the early 1940s and work continues today on a simulator of the human at work as a replacement for the human subject during respirator "man-testing." The systems' responsiveness to dynamically changing gas compositions and changes in simulated work rates have constituted the most complex design problems. The responsiveness requirement dictated the incorporation of a minicomputer. Our ABMS system is a "pendulum" ventilated lung with continuous gas-exchange metabolism simulation (no cyclic injection or withdrawal pumps and no combustion furnace) monitored by a complete breath-by-breath, on-line metabolism measurement system. Any desired protocol can be programmed by specifying, for each period of the protocol, the oxygen consumption ($\dot{V}_{O_2}$), carbon dioxide elimination ($\dot{V}_{CO_2}$), respiratory frequency (f_r), ventilation rate ($\dot{V}_E$), and the breathing waveform shape. All metabolic states from rest to supermaximal can be simulated: $\dot{V}_{O_2}$ from 0-6 l/min, $\dot{V}_{CO_2}$ from 0-7 l/min, and $\dot{V}_E$ from 0-130 l/min. The time constant for requested changes in metabolic state is nominally 1 minute. Corrections for changes in inspired gas composition are made immediately after every respiratory cycle. Results are monitored continuously. Our ABMS system meets all of the requirements as a candidate for complete "man-test" simulation for testing self-contained breathing apparatus using testing guidelines such as 30 CFR 11.

INTRODUCTION

Simulation of human respiration has proven over the years to be a greater challenge than many researchers' original expectations. This research effort has spanned nearly fifty years, since the early work using crankshaft-driven diaphragms with variable fulcrums to vary the stroke of the diaphragms. One large diaphragm produced the ventilation ($\dot{V}_E$), one smaller diaphragm injected CO_2 to simulate CO_2 elimination ($\dot{V}_{CO_2}$), and one smaller diaphragm withdrew gas to simulate oxygen consumption ($\dot{V}_{O_2}$). These early systems were very durable but produced poor simulations in many situations. For example,

$\dot{V}_{O_2}$ with the early systems was directly proportional to inspired oxygen concentration (FI_{O_2}), when a constant $\dot{V}_{O_2}$ was desired. Changes in simulated exercise protocol were all performed manually. Also, no monitoring of gas concentrations, pressure or temperature were integrated into the system. Improving the performance of automated breathing and metabolic simulator (ABMS) systems beyond these early systems has revealed a large number of significant technical problems. Several of these problems could not be solved until recent gas analyzer and computer technology became available.

Historically, the major problem in ABMS development has been incorporating ABMS-system responsiveness and computer intelligence. This responsiveness characteristics applies to monitoring subsystems, control subsystems, and the feedback from the ABMS brain (the computer). The human body's reaction to superimposed changes in exercise intensity and inspired gas concentrations is too dynamic to simulate without responsive monitoring, decision-making and control. For example, an adequate ABMS system, like the human body, must exhibit a $\dot{V}_{O_2}$ which is independent of FI_{O_2} . But, the ABMS system must do this without the benefit of numerous biochemical regulation mechanisms of the human, such as the blood's oxygen dissociation characteristics. Since practical considerations have forced ABMS designers to simulate $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ by withdrawal and injection of gases, a fast response control loop must exist from the monitoring of gas concentrations at the mouth, to verifying desired simulation conditions, and finally, to controlling adjustments of gas injection and withdrawal. Clearly, a responsive ABMS system must be defined as a system which will make the correct control adjustments within several breaths after a change in the environment of the ABMS system. Also, these control changes initiated by the ABMS system should be reflected as a correction observed at the mouth within several breaths. This implies, among other constraints, breath-by-breath monitoring of gas exchange.

Previously constructed ABMS systems have contributed significantly to the knowledge about ABMS system techniques. The early diaphragm systems described previously demonstrated the need for better monitoring and control, and also the necessity for injection of nitrogen during conditions of less than 100% oxygen and/or exchange ratios less than 1.0. ABMS systems which burned combustible gases to partly simulate metabolism revealed the hazards, significant maintenance requirements and near impracticality of such systems.

ABMS systems with separate inspired and expired ventilation flow pathways have shown undesirably long response times to changes in inhaled gas concentrations when the internal dead space of the ABMS system is several times larger than a human's lung volume. ABMS systems which use compliant elements for injection and withdrawal of gases have shown sensitivities to pressures developed at the mouth resulting in metabolism errors. The practicality of most former ABMS systems was minimal without automatic and dynamic protocol control. Typically, in the past, a single metabolic condition was time-consuming to set, verify, and maintain. Former systems lacked a set of measurements to completely profile the performances of a self-contained breathing apparatus (SCBA).

In summary, upon embarking on the concepts and design of the ABMS system described, past research clearly indicated a need for a radical change in design. Using the old design concepts, which were produced at considerable cost per system, undesirable shortcomings in the system were inevitable. Our system is radically different and solves all the classical ABMS system problems. It is responsive with respect to all necessary parameters; system dead space, measurement, intelligence, and control. The system does not burn combustible gases to simulate metabolism. Nitrogen injection is used to provide proper simulation under all conditions of O_2 concentration and desired exchange ratio. All variables which are currently required to establish a pass or fail decision after testing a SCBA are measured using true breath-by-breath monitoring techniques. All the injection and withdrawal techniques display no compliant characteristics. The design of the ABMS system is very similar to the human anatomy and dead-space compartments have volumes which are equal to a human. All dynamic protocols which are humanly possible are easily programmed/executed.

SYSTEM DESCRIPTION

This revolutionary concept in automated breathing and metabolic simulators has been constructed for a **totally** automated exercise protocol, such as the required "man-test" for respiratory protection device certification by the National Institute for Occupational Safety and Health. The **flexibility** and capability of this system can be appreciated when one understands the immense power of current mini-computers, the heart of the measurement and control functions. All of the simulator's intelligence, enabling it to perform as a human subject, the desired exercise protocol, and the recorded history of performance (resulting data) are stored on disk files in the computer. Almost

no constraints on behavior are built into the physical sub-assemblies of the simulator (such as crankshaft breathing drive which can produce only sinewave patterns). This simulator can actually record, summarize, and write reports on the results of a test as the test is conducted. This includes high speed processes such as the instantaneous control of the lung waveform and the breath-by-breath, on-line calculations.

Computer Controls

The computer directly and completely controls three sub-systems which are shown in Figure 1. The lung, which is a stepper-motor-driven piston design, is controlled to simulate any breathing waveform which is humanly possible. The second sub-system is a group of three valves which determine metabolism through adjustment of flow rates of N_2 and CO_2 into the lung and inhaled gas mixture of N_2 , CO_2 , and O_2 out of the lung. The third sub-system (Valve D) is an on-off isolation valve at the mouth of the simulator.

Breathing Simulation

The breathing is simulated by a large piston driven by a high-torque stepper motor. All breathing waveforms with ventilations ranging from 0 to 130 l/min STPD are programmable where the waveform can change nearly every breath. Sinewave, trapezoidal wave, triangle wave, and any other non-symmetrical waveforms are possible. Also, the inspired and expired times can be unequal. The piston design is gas-tight, if fitted properly, and has no undesirable complaint characteristics.

Metabolism Simulator

Carbon dioxide elimination ($\dot{V}_{CO_2}$) is simulated by CO_2 injection where $\dot{V}_{CO_2}$ is equal to the CO_2 injection rate minus the CO_2 lost through the exhaust flow. The oxygen consumption ($\dot{V}_{O_2}$) is simulated by O_2 withdrawal where $\dot{V}_{O_2}$ is equal to the O_2 lost through the exhaust flow. The N_2 injection is then used to balance the net flow rate into or from the lung which is not produced directly by piston movement. These flow rates are constant and enable simulation of all metabolic conditions ($\dot{V}_{CO_2}$, $\dot{V}_{O_2}$, and/or exchange ratio). The continuous-flow concept also performs a better inter-breath simulation of the progressive increase in expired CO_2 and progressive decrease in O_2 expired as with actual human subjects. Other ABMS systems display constant expired gas concentrations, which is a poor simulation and may affect results obtained when testing respirators.

This continuous flow concept is simple in concept; however, it requires a dynamic and intelligent monitor (the computer) to rapidly readjust the valve settings if inspired concentrations are changing. All ABMS systems are prone to errors if the system cannot respond to changes in inspired gas composition. A breath-by-breath analysis of mixed inspired gas composition is really required for any ABMS system because inspired gas composition can change dramatically in only seconds when testing respirators with pure O_2 supplies. The respiring robot system uses breath-by-breath analysis.

The final redundant check on the metabolism is an actual breath-by-breath analysis, which is independent of the actual control functions. The respiring robot system uses the information to "fine tune" the actual valve settings to achieve exact values of desired metabolism.

Measurements

All the measurements are effectively instantaneous and continuous; no slow speed multiplexing of electronics or mechanical valves limits the respiring robot system from continuous monitoring of all measured variables. All measurements are made with fast response sensors and most measurements are made at the mouth: O_2 and CO_2 concentration, flow rate (ventilation), pressure and temperature. These signals are processed digitally, primarily through numerous integration operations throughout inspiratory and expiratory cycles to calculate the desired parameters. Even though any conceivable parameter can be calculated, the following are currently calculated breath-by-breath and are also available as an average over any desired interval (typically one minute): oxygen consumption ($\dot{V}O_2$), carbon dioxide elimination ($\dot{V}CO_2$), expired ventilation ($\dot{V}_E$), inspired ventilation ($\dot{V}_I$), frequency of breathing (f), expired tidal volume (V_{ET}), inspired tidal volume (V_{IT}), inspired O_2 fraction (FI_{O_2}), inspired CO_2 fraction (FI_{CO_2}), expired O_2 fraction (FE_{O_2}), expired CO_2 fraction (FE_{CO_2}), peak inspired pressure (P_{PI}), peak expired pressure (P_{PE}), end tidal CO_2 (PET_{CO_2}), minimum inspired CO_2 (PMN_{CO_2}), minimum mouth temperature (TE_{MN}), maximum mouth temperature (TI_{MX}), expired time (t_E), and inspired time (t_I). All results are stored in standard units.

This breath-by-breath data is averaged and stored on disks for later reference and/or report writing and/or statistical analysis with other tests.

Temperature and Humidity

Temperature and humidity simulation with the respiring robot system is simplified by the similarity between the physical layout of the system and the

human anatomy. Two thermal reservoirs, the lung and the upper airway heat exchanger, are maintained at 37 degrees centigrade. Since the respiring robot system has a bidirectional airway flow in an identical manner as a human subject, the dynamics of expired and inspired air temperature changes will be closely simulated by maintaining only two thermal reservoirs at a constant temperature. The initial humidification is provided by pre-heating and pre-humidifying the injected air in the mixing chamber. Final humidification takes place in the lung. The water wets the entire mixing chamber and lung. Pump A in Figure 1 circulates the water to maintain a water film in the mixing chamber and lung. The respiring robot and human anatomy differ only in that the alveolar and branchi volume in the human are simulated as a single lumped volume above the piston.

Protocol

The protocol of a particular test is defined by a data file on the computer's disk. Any number of protocols can be written into any number of data files. New protocols can be written in minutes and old protocol data files are always retained for future selection. The 30CFR11 "Man-Tests" are a subset of the library of protocol data files. Protocols have no limits as to test time duration or the frequency at which requested metabolisms or breathing waveforms are changed. A practical maximum frequency of protocol change is 4 times/minute or every 15 seconds.

Maintenance

Daily maintenance involves very few items; checking the humidity water reservoir, dump the water accumulated in water traps and calibration of the gas analyzers. The lung piston should be greased bimonthly and the lung motor greased annually.

RESULTS

Performance during the last year of routine use has been very encouraging. A sophisticated system like the respiring robot requires many hours of testing under numerous conditions to verify its accuracy, proper operating procedures, and long-term reliability. The respiring robot operation has included constant metabolism tests, 30CFR11 "Man-Tests," and special transient exercise simulations at both room air and high oxygen environments. Tests have been performed with chemical and bottled SCBAs. Single SCBA test durations have been up to 120 minutes and actual testing of up to six hours in an eight-hour day.

Respiring robot metabolism and ventilation were measured using total collection of the expired gases in a 200 liter collection bag during a steady-state metabolism (Consolazio et al., 1963). Accuracy of the respiring robot depends primarily on the calibration of the gas analysis system and the maintenance of the response characteristics of the gas analyzers. Comparisons between the respiring robot and the collections for $\dot{V}_{O_2}$ s from rest to 3.0 l/min have been with 5%. The upper $\dot{V}_{O_2}$ range of the respiring robot extends to 6 l/min, but has not been validated. During an established steady-state work rate, variations in 30 second averages of $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are less than 10%, and overall averages differ less than 5% from the desired condition. Sudden changes in environmental conditions, such as when the SCBA is first connected to the respiring robot and the oxygen levels rise from 21 to 70% in a minute, produce temporary perturbations in $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are typically 20% over 90 seconds; however, the overall average over the same period deviates less than 5%. Perturbations of $\dot{V}_{O_2}$ are typically 100% which seem high; however, this is predominantly due to the washout of the lungs of the respiring robot in a manner identical to that of a human subject.

Transient metabolism control characteristics are dependent on the magnitude of the change requested. The time constant for changes in metabolism of 0.1 l/min is 10 to 20 seconds. The time constant for changes in metabolism of 1.0 l/min is one minute. These are the maximum rates of change; slower rates of change are implemented by computer software. These maximum rates of change for the respiring robot are only slightly faster than the human (Whipp and Wasserman, 1972). Typically transient characteristics are shown in Figure 2. Final programmed respiring robot transient characteristics are based on previously published and unpublished human subject testing by our laboratory (Bernard et al., 1977). Transient performance of an ABMS system ultimately has a very significant effect on the total average metabolism during an exercise protocol, because many protocol activities, such as most 30CFR11 "Man-Tests," are too short to achieve steady-state. This means that the subject or ABMS is a transient state the majority of the time. For example, laddermill activities during 30CFR11 "Man-Tests" achieve only 60% of the metabolic rate which would be achieved if the activity were continued.

Simulator performance compared to that of a human subject is shown in Figures 3 and 4. Plotted data are of 0.5 minute averages for a 30CFR11 30-minute "Man-Test" No. 2. Both $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ for the human show more variability than those of the ABMS which is expected due to the variability in human subject breathing. These comparisons show good agreement with the

exception of a slight phase shift between the human and the respiring robot. This phase shift can be removed; however, its effect is very small in terms of overall SCBA performance testing. Data in Figures 3 and 4 were collected under room air conditions. Tests using the respiring robot with SCBAs show similar results as shown in Figures 5 and 6 for a 30CFR11 10-minute "Man-Test" No. 2. Major differences in results between room air and SCBA conditions occur when donning and removing the SCBA. The sudden changes in oxygen concentration cause perturbations of the metabolism (primarily $\dot{V}_{O_2}$) for both the human subject and the respiring robot. This can be observed in Figure 5 at the beginning of the test using the simulator. Human data shown in Figures 5 and 6 were measured at room air conditions for practical considerations. Respiring robot results in Figures 5 and 6 were measured using a chemical oxygen SCBA. The differences in transitions between the human and the simulator are caused primarily by human variability between tests and slightly inappropriate protocol requests to the simulator with regard to a specific subject's response.

Repeatability has been a major performance goal. Two methods have been used to evaluate repeatability; comparisons with human test durations using SCBAs, and comparisons between total gas exchange throughout a test protocol. A one-hour protocol was used where the work rate cycled from rest to 1.0 l/min oxygen consumption. The mean SCBA duration of more than 20 tests using human subjects was 68 minutes. Based on the same failure criteria, the mean duration of 27 tests using the respiring robot was 83.6 minutes with a standard deviation of 12.2 minutes. For these 27 tests, the measured total mean volume of CO_2 delivered to the respirator was 45.8 liters with a standard deviation of 2.1 liters. Total mean volume of O_2 consumed was 52.0 liters, with a standard deviation of 4.8 liters.

Instantaneous recordings of expired gases show similar waveforms when comparing human subjects and the simulator. At 1.0 l/min, $\dot{V}_{O_2}$ and conditions of normal breathing and hyperventilation, Figure 7 shows the instantaneous CO_2 during an expiration for the simulator and the human subject.

Nearly daily operation for two years has produced a maintenance record including a total of two days of down time. This service record includes all sub-systems, such as computer, lung, control, and measurement.

DISCUSSION

The respiring robot is an ABMS system which overcomes all the traditional limitations which former ABMS systems have had with respect to the ultimate

goal of accurate simulation of dynamic exercise protocols like 30 CFR 11 certification "Man-Tests." No limitations have been observed in one year of operation involving SCBAs which would preclude the respiring robot from becoming a total replacement for evaluating human subjects' metabolism and breathing effects on SCBAs. Of course, the biomechanical aspects of SCBAs will always require human subjects for a thorough evaluation.

Routine maintenance is minimal. Calibration of the gas analyzers, checking levels of the water reservoirs, and checking CO₂ and N₂ gas supplies are the extent of preoperational procedures. No mandatory overhaul or replacement is required of any component. Periodic inspections have revealed no noticeable wear on moving parts after hundreds of hours of operation.

Operational precautions which have been observed are minimal. Checks for leaks caused by defective tubing and fittings must be done periodically. Even seemingly minor leakage at certain locations within the system can cause significant errors. To identify these problems immediately, the respiring robot has an automatic means to do a total system leak check using a mouth isolation valve. In practice only several tests have been disrupted due to leaks. A more potentially serious problem comes from prolonged conditions of inspired gas at high temperature and humidity. Condensation of water vapor must be prevented when possible, or trapped where condensation does occur. Bottled oxygen SCBAs can produce inspired gases which have high water vapor saturations at temperatures of as high as 50 degrees centigrade. Proper locations of heating and water traps will control the problem; however, frequent checking of water traps and heaters is judicious during high humidity environments.

The heart of the respiring robot is the computer software, which is beyond the scope of this paper. The size and complexity of the software required can be appreciated when considering that one computer performs all protocol control, metabolism control, breathing control, and measurement functions simultaneously. These functions include everything from the simple operator-computer interaction to the most complex mass balance calculations. The software dependence enables the system performance, simplicity of mechanical design, and flexibility.

The total software dependence of the respiring robot allows a complete change in the operational objective by simply changing the current running program in the respiring robot computer. This is a powerful feature when

future requirements change and new knowledge mandates changes in the respiring robot's operating characteristics. This also enables certain "bench tests" to be performed on the respiring robot without changing the mechanical configuration.

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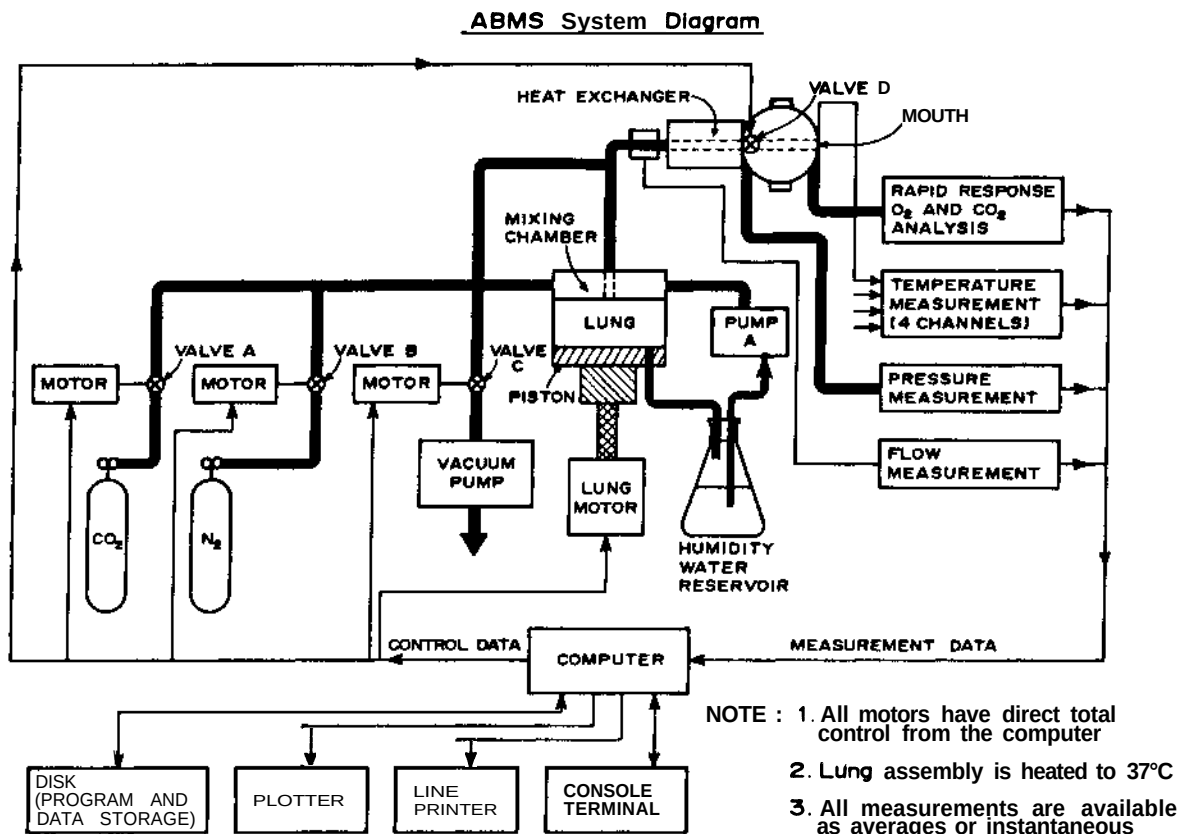


Figure 1. Diagrammatic representation of all the ABMS system components.

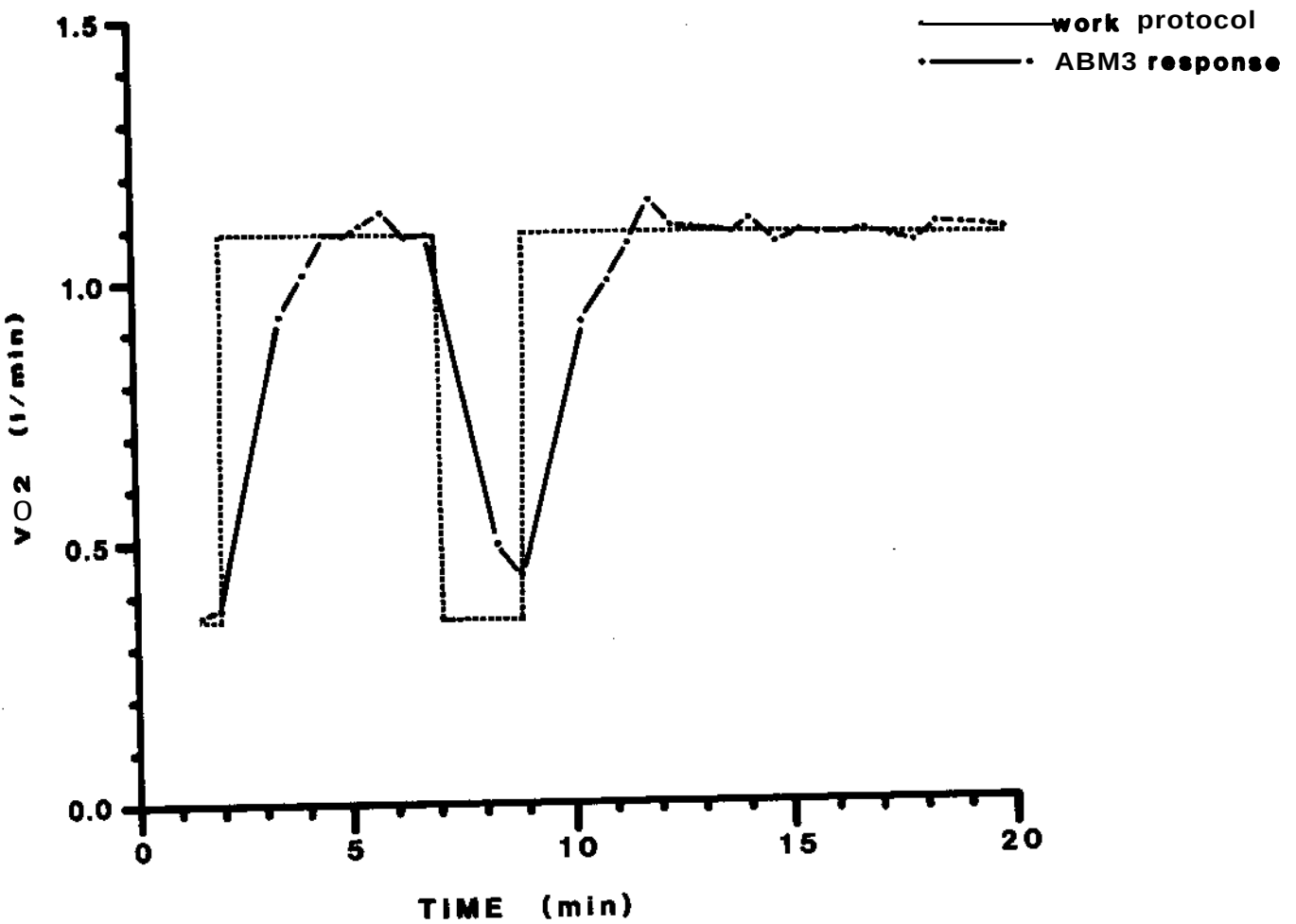


Figure 2. Response characteristics of the ABMS are compared to the actual requested work protocol.

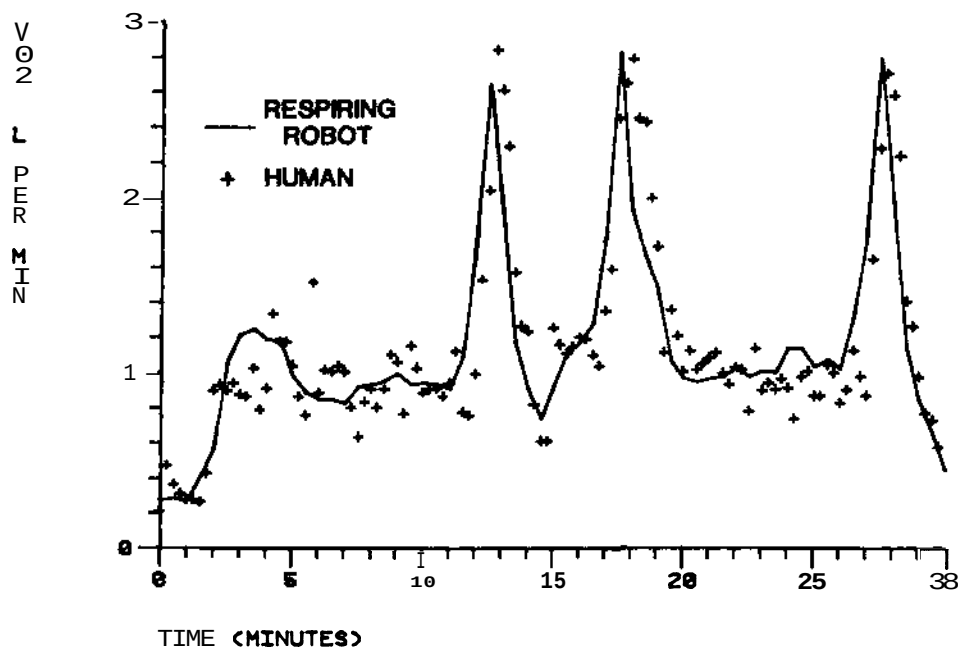


Figure 3. Oxygen consumption ($\dot{V}_{O_2}$) is compared between the human subject and the ABMS system for a 30-minute 30 CFR 11 man-test #2.

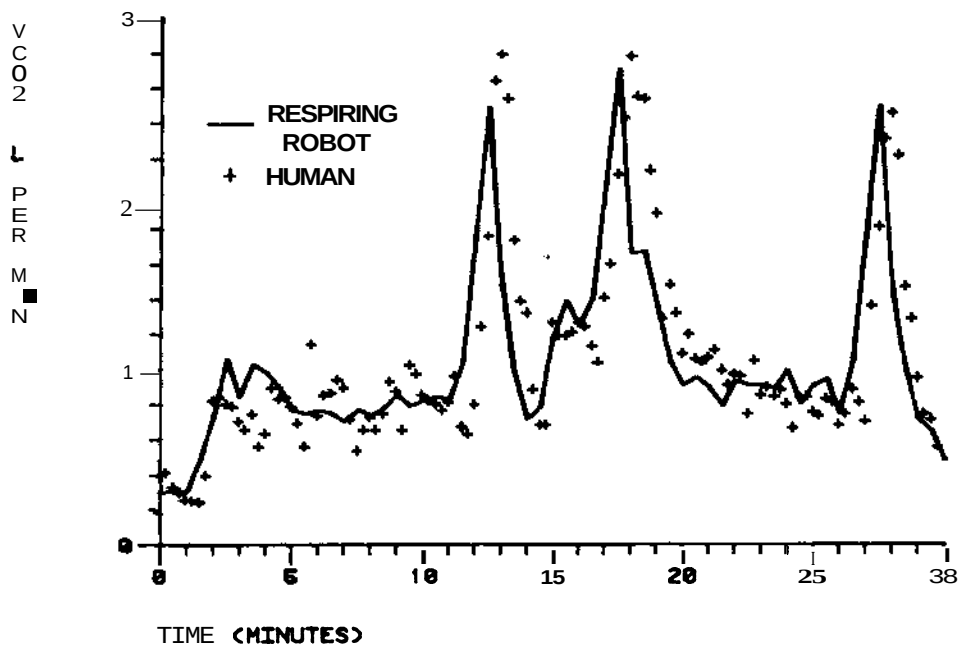


Figure 4. Carbon dioxide elimination ($\dot{V}_{CO_2}$) is compared between the human subject and the ABMS system for a 30-minute 30 CFR 11 man-test #2.

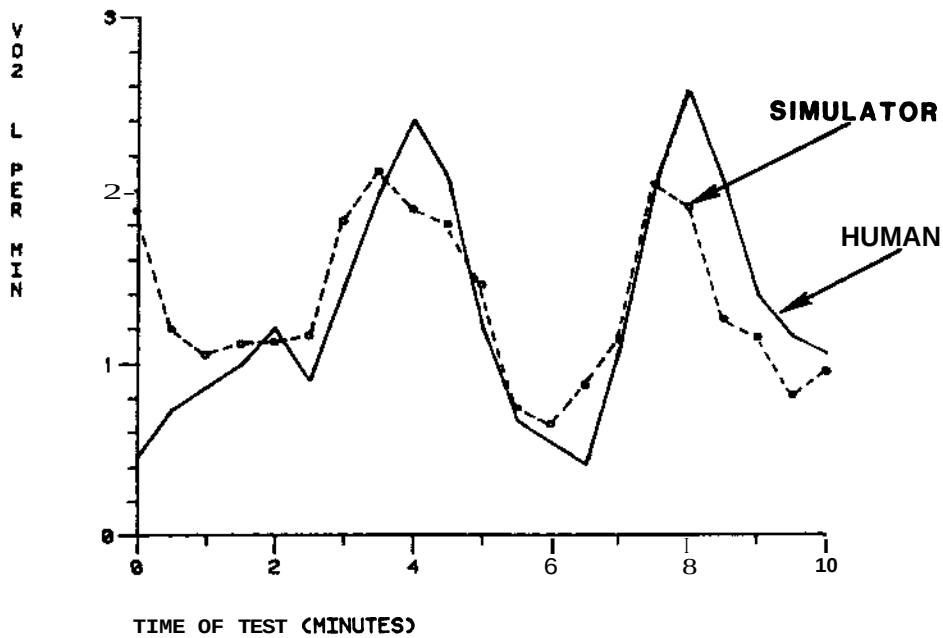


Figure 5. Oxygen consumption ($\dot{V}O_2$) is compared between the human subject and the ABMS system for a 10-minute 30 CFR 11 man-test #2.

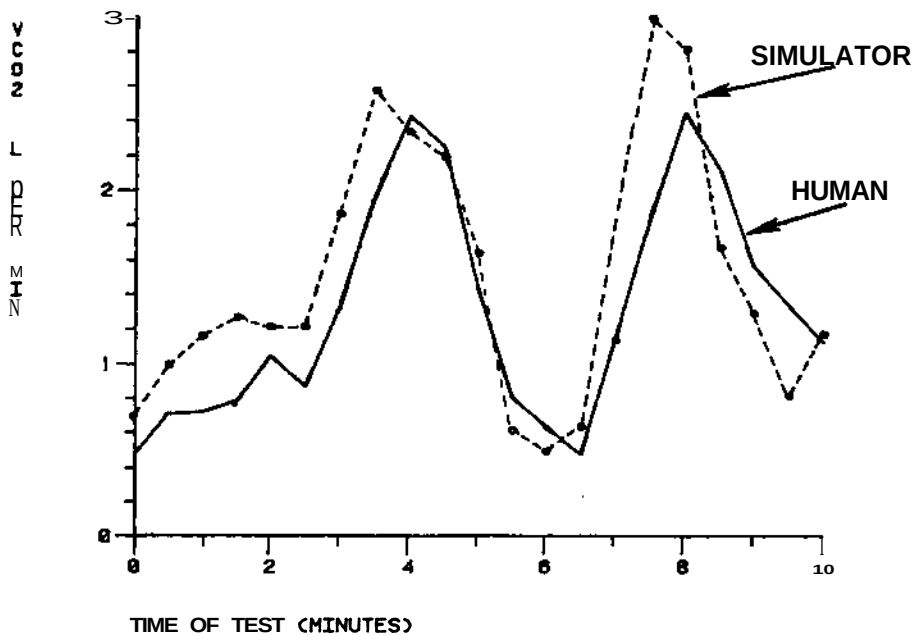


Figure 6. Carbon dioxide elimination ($\dot{V}CO_2$) is compared between the human subject and the ABMS system for a 10-minute 30 CFR 11 man-test #2.

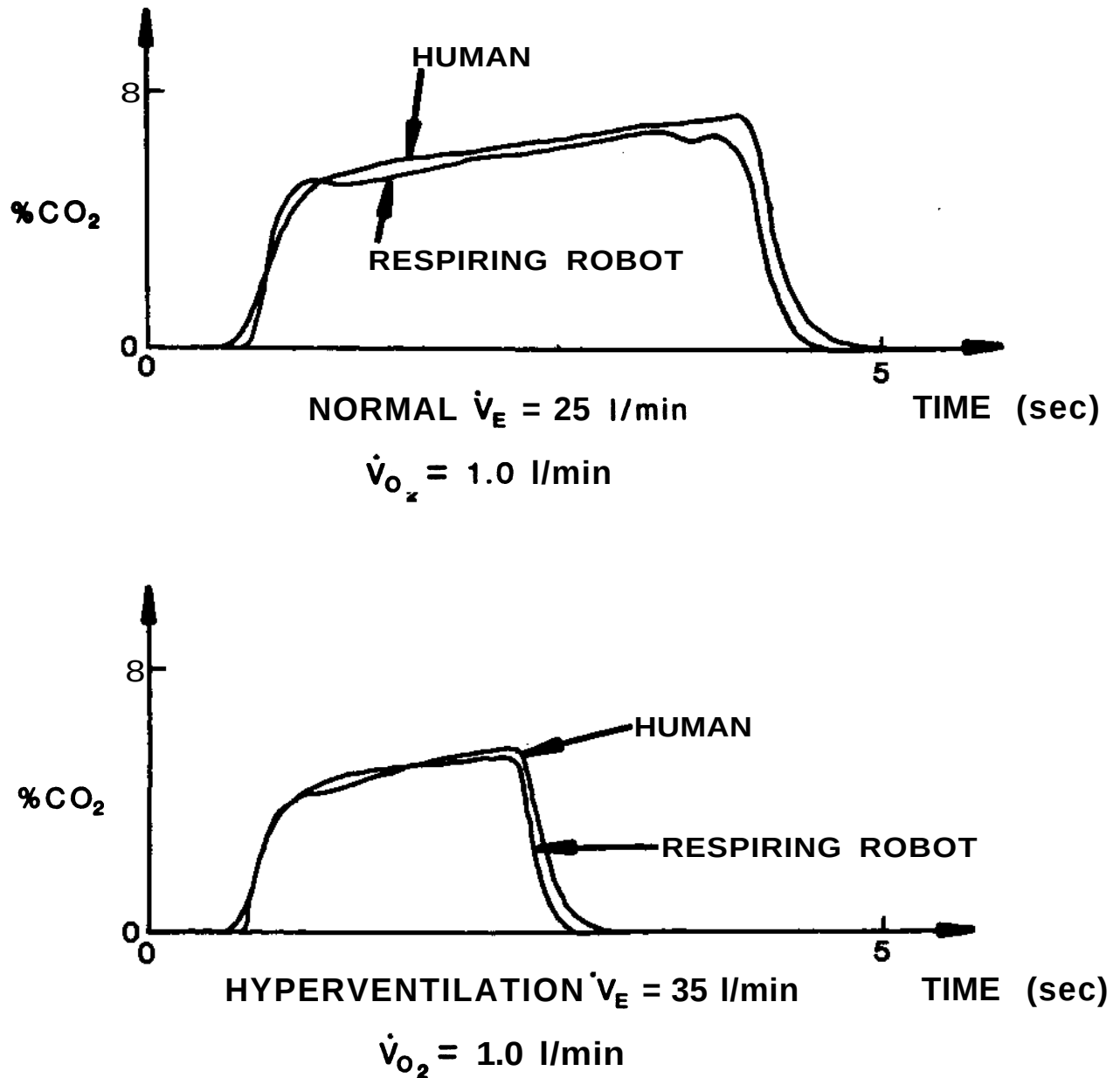


Figure 7. Instantaneous carbon dioxide concentration during an expiration is compared between the human and the ABMS system. Results are shown for both normal and hyperventilation conditions.