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**THE SECOND UNDERSEA MEDICAL SOCIETY WORKSHOP**

# *RESPIRATORY LIMITATIONS OF UNDERWATER BREATHING EQUIPMENT*

**HARVARD SCHOOL OF PUBLIC HEALTH**

**14–15 MARCH 1973**

**Workshop Chairman: DR. MARK E. BRADLEY**

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RESPIRATORY LIMITATIONS

OF UNDERWATER

BREATHING EQUIPMENT

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## THE SECOND UNDERSEA MEDICAL SOCIETY WORKSHOP

## RESPIRATORY LIMITATIONS OF UNDERWATER BREATHING EQUIPMENT

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# SESSION I

## Review of Recent Problems Posed by Underwater Breathing Equipment in Deep Diving

This session reviewed three recent deep diving operations during which divers experienced difficulty with their underwater breathing equipment.

A. SEALAB: Dr. Mark E. Bradley

During the SEALAB III experiment, thermally unsupported divers were working at 620 feet and breathing helium-oxygen with the MARK IX UBA. These divers complained bitterly that they were "unable to get enough gas" from their diving equipment. Their ability to perform work was severely limited by this situation, as well as by the deleterious effects of cold. More importantly, the inability of their UBA to meet ventilatory needs was such that one diver was unable to complete the rescue of a fellow diver. Subsequent laboratory study demonstrated that the MARK VIII (which has the same breathing circuit as the MARK IX) was unable to satisfy the respiratory requirements of men who were breathing dense gas and performing hard work.

B. MARK II DDS — 1010-FOOT OPEN SEA DIVE: Dr. Michael Storrie

In June 1972 1010-foot open sea dives were conducted with the MARK II DDS. The underwater breathing apparatus used during these dives was the Kirby-Morgan Band Mask. Helium-oxygen was the breathing medium. The divers were thermally supported. During excursions to 1010 feet from 850 feet, even minimal exercise resulted in moderate respiratory difficulty. Moderate work produced an intolerable degree of dyspnea; however, several divers were unwilling to be candid when asked to describe the difficulties they encountered with this diving equipment. Laboratory evaluation of the Kirby-Morgan Band Mask showed that the mechanical work of breathing dense gas with this apparatus was excessive.

C. DEEP DIVING USING NEON – RESPIRATORY CONSIDERATIONS: Dr. Robert W. Hamilton, Jr.

Ocean Systems, Inc. recently conducted a series of 640-foot open sea dives. Neon-oxygen breathing mixtures were used with the Kirby-Morgan Band Mask. During these dives, divers became hypercarbic while working, but failed to recognize this condition. The use of a hyperoxic breathing mixture ($P_iO_2$ ~ 1.6 ATA) may have been responsible for this situation. Laboratory tests showed that with $Ne\text{-}O_2$, this demand breathing apparatus failed to supply enough ventilation at 680 f.s.w. during moderate work.

## CONCLUSIONS

1. Serious respiratory difficulties have occurred during recent deep diving operations. These difficulties have been for the most part attributable to inadequate UBA function. As a result, the diver's ability to work has been limited and his safety has been jeopardized.

2. Respiratory limitations have been encountered with different types of underwater breathing equipment. Laboratory testing of this equipment has shown that it is unable to meet the ventilatory needs of working men who are breathing gases four times or more as dense as air.

3. Subjective reports of divers on UBA performance are often unreliable.

4. Use of hyperoxic breathing mixtures may mask $CO_2$ buildup and prevent a diver from recognizing that he is in difficulty.

## SESSION II

## Engineering of Underwater Breathing Apparatus

A. **BREATHING RESISTANCE STANDARDS:** Professor William Burgess

The standards for breathing resistance used by industry are based on limited experimental work by healthy young men. Experience has shown that the level of breathing resistance permitted by these standards is excessive in the usual industrial situation; therefore, these standards must still be considered tentative. The diving situation is very different from the industrial situation, and it's inappropriate to apply industrial standards for breathing resistance in respiratory protective devices to underwater breathing equipment.

B. **AN ENGINEERING APPROACH TO THE EVALUATION OF UNDERWATER BREATHING APPARATUS:** LT Stephen Reimers

In simulation testing of underwater breathing equipment, variables such as tidal volume, breathing frequency, carbon dioxide production, and so on are controlled by a specialized collection of equipment. On the other hand, inhalation and exhalation pressures, external work of breathing, inhalation bag $CO_2$ levels, etc., are monitored.

Simulation testing is used to predict whether underwater breathing apparatus will be functionally adequate at depth. Recent evaluation of the MARK X UBA indicated that at 1,000 feet the external work of breathing would be excessive. The accuracy of this prediction was confirmed during physiological testing of this UBA. Because of these findings, the breathing circuit of the MARK X was modified. Subsequent simulator testing indicated a significant decrease in the breathing resistance of this UBA.

The present method of simulation testing of diver's breathing equipment at the Experimental Diving Unit (EDU) needs improvement. Flowmeters and differential pressure transducers that can be used underwater are needed. More detailed information is required on how divers breathe (i.e., tidal volumes and breathing rates) during physiological testing to ensure that the breathing machine accurately reproduces the diver's breathing pattern. Engineers need good standards for breathing resistance in underwater breathing equipment. The present standards which specify maximum allowable peak inhalation and exhalation pressures, have little meaning for most types of underwater breathing equipment. Moreover, these present standards need revision downward. Lastly, there is a need for a computer capability to facilitate analysis of the data which is currently being produced at the EDU.

C. **NUMERICAL ANALYSIS OF BREATHING EQUIPMENT:**
Dr. Donald Yankovich

Breathing equipment testing can be performed by computer simulation. With this method, each component of the breathing apparatus is first mathematically described. These individual components are then combined to describe the complete breathing equipment. Computer analysis of these mathematical notations is then done using control system theory. Predictions can then be made of the breathing equipment's operation.

As a further step, the characteristics of individual components can be systematically changed so that an optimally designed system is derived. This technique can thus analyze UBA performance and optimize its design; however, MIT requires information on the engineering characteristics of diving equipment and on the performance of the diver using this gear if they are to apply this method to the study of UBA.

## SUMMARY OF DISCUSSION

Major sources of impedance in underwater breathing apparatus occur as a result of poor check valve design, inadequate orifice size, and radical redirection of flow. There is often considerable variation in the breathing resistance of apparently identical pieces of underwater breathing equipment. Inadequate quality control by the manufacturer and a lack of good, solid specifications are at fault.

At present, most manufacturers of underwater breathing equipment simply put it together; they don't design it. The system for which underwater breathing equipment is made (i.e., man) is as yet insufficiently specified. Reasonable standards for breathing resistance in UBA's and information on how divers breathe while using UBA's are badly needed. A modeling approach to the optimal design of underwater breathing equipment has considerable potential.

## CONCLUSIONS AND RECOMMENDATIONS

1. Improve the design of check valves used in UBA. The ideal check valve should open easily, offer minimal impedance to gas flow and seat securely. See whether or not the Lennox valve (silastic, tricuspid valve) could be used in UBA.

2. Smooth bore, unkinkable tubing with a minimal interior diameter of 1 1/2 inches should be specified for use in underwater breathing equipment.

3. More compliant breathing bags for UBA use should be developed.

4. Standards which define the maximum level of breathing resistance in underwater breathing apparatus must be developed and promulgated to the diving community.

5. The procedures and equipment to be utilized in testing UBA need to be standardized, and this information disseminated to the diving community.

6. Physiological testing of divers who are using UBA must yield more specific information on the nature of the man's breathing pattern, his carbon dioxide production, etc., so that engineering evaluations of UBA performance can be improved.

7. Develop flowmeters and differential pressure transducers that can be used underwater.

8. The Experimental Diving Unit has considerable data on the performance of underwater breathing equipment, but has limited analysis capability. MIT has considerable analysis capability, but no information on the characteristics of underwater breathing equipment and diver function. As a first step, we recommend that a coordinated study between MIT and EDU be initiated to assist EDU in data analysis. Later, the computer simulation techniques of MIT should be used to assist in the evaluation of UBA performance and to optimize UBA design.

# SESSION III

## Physiological Testing of UBA

**A. A LABORATORY METHOD FOR EVALUATION OF UNDERWATER BREATHING APPARATUS — WORK OF BREATHING IN THE USN MARK I DIVER'S MASK USING DENSE GAS:** Dr. Michael Storrie

Increased gas density, the impedance posed by underwater breathing equipment and immersion increase a diver's work of breathing. When mechanical work of breathing becomes excessive, ventilatory insufficiency occurs. Men were studied in a day, one atmosphere laboratory environment while exercising and breathing dense gas (80% SF6, 20% $O_2$) with the Kirby-Morgan Band Mask. Ventilatory work and power, and pulmonary compliance are measured in order to evaluate UBA performance.

Subjects were stressed close to their subjective limits of tolerance when they exercised at 1,000 kg-m/min and breathed SF6, $O_2$ with the Kirby-Morgan Mask. Average work of breathing was 11.4 kg-m/min during the 750 kg-m/min exercise level, and 16 kg-m/min for the 1,000 kg-m/min work load. These values exceed the 11 kg-m/min previously suggested as the maximum ventilatory power requirement acceptable for a UBA breathing dense gas. Operational use of the Kirby-Morgan Band Mask during a 1010-foot open sea dive demonstrated that indeed this UBA requires excessive respiratory work.

**B. PHYSIOLOGICAL TESTING OF AN AIR AND HELIUM HARD HAT SYSTEM AND A CLOSED—CIRCUIT UNDERWATER BREATHING APPARATUS:** Dr. Brandon Wright

The U.S. Navy Experimental Diving Unit has developed a method of physiologic testing of underwater breathing apparatus which provides quantitative physiological data on the immersed working diver at depth.

As part of this testing, the immersed diver pedals an underwater bicycle ergometer against various resistive loads. Continuous measurements of arterial blood pressure, electrocardiogram, inspired oxygen, inspired carbon dioxide, respiratory rates, and breathing apparatus pressures are made. Arterial blood for oxygen and carbon dioxide partial pressures, pH, serum pyruvate, and serum lactate, is drawn from a radial artery cannula. These measurements provide quantitative information which permits more precise evaluation of the functional capability of UBA.

EDU has recently conducted physiological testing of a prototype hard hat diving system and a self-contained, closed-circuit mixed gas underwater breathing apparatus (i.e., the MARK X). Using the helmet system in the $He-O_2$ recirculating mode, divers were able to perform heavy work at 300 feet, and their $PaCO_2$ remained below 50 mmHg. However, in the open-circuit air mode, arterial carbon dioxide tensions rose to unsafe levels with moderate work. During preliminary studies of the MARK X UBA at 1,000 feet, subjects were unable to perform moderate work and became hypercarbic. These studies indicate that at the depths and conditions studied, the primary limiting system is the underwater breathing apparatus.

## SUMMARY OF DISCUSSION

In the past, assessments of the acceptability of breathing resistance in UBA have been based on the subjective impressions of divers using the equipment. However, evaluations obtained by this method have little value. When queried, divers frequently tend to minimize the degree of difficulty that they experience in using diving equipment. Moreover, in time, divers tend to adapt to the limitations of their breathing apparatus.

Physiological testing of underwater breathing equipment provides objective information on the state of a diver's "well-being." The criteria which EDU and SUBDEVGROUP are using that define "well-being" are arbitrarily derived and the validity of these criteria needs to be confirmed.

The Submarine Development Group's limit of 11 kg-m/min for respiratory work is based on a clinical study which showed that patients with chronic pulmonary disease frequently develop "respiratory failure" if their ventilatory work exceeds this level. It isn't at all obvious that you can validly apply findings in patients with chronic lung pathology to the situation of the healthy working diver. In previous work, this group has noted a fall in pulmonary compliance when breathing resistance was excessive; therefore, they recommended that there be no fall in compliance when dense gas is breathed through underwater breathing equipment. In the discussion it was pointed out that this criterion may be spurious, as the fall in compliance which they observed was likely a reflection of the frequency dependence of compliance.

Arterial cannulation is central to the EDU method of physiological testing. Arterial cannulation of the immersed diver involves a slight but not altogether insignificant risk. It should be possible to develop a method to measure respiratory gases in immersed divers and to establish a correlation with blood gas concentrations. This would hopefully eliminate the need for arterial cannulation.

EDU has arbitrarily chosen an arterial $PCO_2$ of 50 mmHg as the "cutoff point" which indicates whether an underwater breathing apparatus is functionally adequate or inadequate. Dr. Saltzman's work, discussed in Session V, suggests that the appropriateness of this value needs further consideration. EDU needs better quantitative information on the energy expenditures of the working diver. Ergometric tests which closely simulate a working diver must be devised, and a method developed to measure a diver's oxygen consumption.

Until we're more certain which physiological parameters best define the adequacy or inadequacy of UBA function, measurement of respiratory mechanics should be performed in conjunction with assessments of ventilation and gas exchange during physiological testing. The Experimental Diving Unit is best suited to conduct these integrated studies. Eventually a standardized physiological test protocol should be devised to evaluate UBA performance.

## CONCLUSIONS AND RECOMMENDATIONS

1. Subjective evaluation of UBA performance is unreliable. Objective physiological criteria must be used to establish UBA functional adequacy.

2. Determine the effects of UBA performance on pulmonary mechanics and ventilation and gas exchange with an integrated study.

3. Develop a standardized protocol for physiological testing of UBA.

4. Develop techniques to measure the respiratory gases and oxygen consumption of the immersed diver.

5. Devise ergometry which more closely simulates a working dive.

## SESSION IV

## Effects on Respiratory Mechanics of UBA

A. **ESTIMATE OF MAXIMUM EXPIRATORY FLOW BASED ON THE EPP CONCEPT AND WEIBEL'S LUNG MODEL**: Dr. Johannes Kylstra

Equal pressure point theory is used to define the dynamic behavior of airways during expiration. Hydrodynamic equations are then applied to the anatomy of Weibel to calculate the cumulative pressure drops in the airways during maximum expiration. Using this model, predictions are made of maximum expiratory flow rates as gas density is increased. The predicted flow rates correlate closely with the experimentally observed values of Wood and Bryan. Connective-accelerative and entry effects at the EPP appear to account for most of the cumulative pressure drop down Weibel's version of the tracheobronchial tree.

B. **THE MEASUREMENT OF PULMONARY FUNCTION AT HIGH DENSITIES – CONSIDERATION OF AIRWAY COMPRESSION**: Dr. Russell Peterson

This presentation reviewed the many studies of pulmonary function conducted during the University of Pennsylvania's 1,200-foot dive. As gas density increased, there was the expected progressive diminution in maximum voluntary ventilation, peak inspiratory and expiratory flow rates, etc. However, at relative gas densities of six and greater, maximum expiratory flows did not decrease as much as expected. This phenomenon may be a function of the presence of higher levels of external resistance at the deeper depths. Imposing some external impedance may limit dynamic compression of airways, thus modifying the Starling resistor behavior of the lungs. It's important to note in this study that subjects who were breathing gas mixtures with densities of 27 grams/liter could still achieve ventilations compatible with moderate work.

### C. EFFECTS OF EXTERNAL RESISTANCE ON MAXIMUM EXPIRATORY FLOW AT INCREASED GAS DENSITY: Dr. James Vorosmarti

The basic fact established by this study is that a certain amount of external resistance can be tolerated at depth without any decrement in maximum effort-independent flow. Of more practical importance is the fact that while a certain amount of resistance can be tolerated before maximum flow is impaired, it does not mean that such resistance can be allowed in underwater breathing apparatus. Information related to maximum flow applies only in the situation where a diver must do severe exercise for short periods of time and can tolerate the added respiratory work required to produce maximum flow. Minimal equipment resistance helps ensure that expiratory flow is limited only by the lungs. Moreover, as respiratory work is directly related to external resistance during inspiration and expiration, this requires that external resistance is minimal.

### D. TRAINING THE VENTILATORY MUSCLES: Dr. David Leith

Five-week programs of ventilatory muscle exercise can increase voluntary static maximum and minimum airway pressures by 50 to 60 percent (static training), and can increase ventilatory muscle endurance so that 95 percent of the control 15 second Maximum Voluntary Ventilation (MVV) could be maintained for 15 minutes compared with 80 percent before endurance training. In diving, breathing equipment increases ventilatory load, and ventilatory muscle fatigue may impede human performance. Thus, respiratory muscle training may be helpful to the diver.

E. **EFFECT OF CHEST WALL CONFIGURATION ON THE MECHANICAL WORK OF BREATHING:** Dr. Michael Goldman

The mechanical work of breathing can be estimated by measuring the appropriate area on the respiratory volume-pressure diagram. The conventional approach, using the Campbell diagram, does not include distortional work which is associated with deformation of the chest wall from its relaxed configuration. During increased ventilations, up to 25 to 30 percent of the total mechanical work of breathing can be distortional work.

In order to assess the elastic cost of distortion during breathing, one must measure the separate volume displacement of the rib cage and abdomen. Konno and Mead showed that changes in the anterioposterior and lateral diameters of the rib cage and abdomen can be linearly related to the volume changes of each compartment. Changes in the A-P dimensions of the rib cage and abdomen are sensed with magnetometers and summed to give an output which is related to the volume displacements of each compartment. Both transthoracic and transgastric pressure are measured. The latter pressure is needed to assess the work done by the abdominal muscles and the work done by the diaphragm against abdominal muscle activity.

Comparing this technique with the Campbell method, one finds that at low ventilations, the two techniques give comparable results. However, as ventilation increases above 40 liters per minute or so, the new method reveals systematically greater work than does the Campbell technique. These results are interpreted to indicate that as ventilation increases, distortion from the relaxation configuration appears and this distortion is associated with an increasingly greater elastic work.

An additional advantage of the new method is that one can partition the work done by each component of the chest wall (namely: rib cage, diaphragm, and abdomen), and describe the actions and interactions of each compartment. Immersion, pressure breathing, breathing through underwater breathing apparatus, and respiring dense gas represent mechanical constraints applied to the diver's chest wall. These constraints, acting in combination, may deform the geometry of the chest wall from its optimal configuration. This deformation may place the diver's respiratory muscles at a mechanical disadvantage with the result that ventilation and gas exchange are adversely affected. With this method, one can describe in quantitative terms the mechanical results of breathing in the presence of increased ventilatory loads, and can define the limits of ventilatory loading which a diver may safely tolerate.

## SUMMARY OF DISCUSSION

At present we know a fair amount about the mechanisms which limit flow in airways when dense gases are breathed. Moreover, it appears that we can accurately predict what airway flow rates will be for gases of different densities. Considerably less is known about the effects of immersion, of pressure breathing, and of breathing against added external resistance on the mechanical properties of the respiratory system. Absolutely no quantitative information exists concerning the mechanical results of the interaction of these conditions. Conditions of immersion, dense gas breathing, and so on, represent mechanical constraints applied directly to the diver's respiratory pump (i.e., chest wall). The interaction of these constraints has mechanical results which ultimately impair the diver's ventilation and gas exchange.

## CONCLUSIONS AND RECOMMENDATIONS

1. Develop the use of magnetometers as a means of measuring the pulmonary ventilation and breathing pattern of divers.

2. Initiate a systematic study of the effects on chest wall mechanics of immersion, pressure breathing, breathing through external resistances, and breathing dense gas which will include the separate actions of these stresses and their combined interactions. The information from such a study will help to define the limits of ventilatory loading which a diver can tolerate and provide a rational basis for the development of underwater breathing equipment and the optimal utilization of this equipment.

3. Investigate the usefulness of ventilatory muscle training for divers.

## SESSION V

# Effects of Underwater Breathing Equipment on Ventilation and Gas Exchange

### A. IMMERSION AND NEGATIVE PRESSURE EFFECTS ON LUNG FUNCTION AND INERT GAS EXCHANGE: Dr. Claes Lundgren

During head-out immersion of subjects sitting erect, cardiac output increases by more than 30 percent and perfusion of muscle tissue (anterior tibial) increases by more than 100 percent. This increased transport capacity of the circulation for gases in immersion markedly increases the rate of nitrogen elimination during oxygen breathing. Moreover, preoxygenation during immersion seems to have considerably greater protective value against the bends than conventional preoxygenation. These observations suggest that the hydrostatic pressure effects that underwater breathing apparatus may exert on a diver may influence his inert gas exchange and risk of decompression sickness.

While the combination of immersion and oxygen breathing enhances inert gas elimination, it also causes rapidly developing pulmonary atelectasis. This atelectasis appears to be the result of an increase in airway closure and trapping of gas in the lungs. Thus, underwater breathing equipment which imposes additional negative pressure breathing on the immersed diver may cause deleterious pulmonary effects.

### B. EFFECTS OF ALTERED ENVIRONMENT AT SIMULATED DEPTHS ON GAS EXCHANGE: Dr. Herbert Saltzman

During recent experimental dives at Duke University, it's been shown that resting arterial $PaCO_2$ appears to rise as ambient hydrostatic pressure is increased. The slope of rise of $PaCO_2$ is approximately in the order of 0.5 mmHg per atmosphere of ambient pressure increase. This rise in $PaCO_2$ does not seem to be related to increased gas density or to increased inspired oxygen concentration.

A subsequent experiment has demonstrated marked lengthening of the time to break-point of men breathholding in a $HeO_2$ environment at 200 feet. Moreover, dogs exposed to high pressures of helium-oxygen show a change in the electrochemical potential difference for bicarbonate between plasma and CSF which would indicate an increase in the concentration of CSF bicarbonate.

The consistency of these findings suggests that with increased ambient pressure, a central CSF alkalosis may be developing. The mechanism responsible for this phenomenon is unclear. However, one possibility is that changes in hydrostatic pressure may alter the permeability of blood-brain membranes for bicarbonate.

## SUMMARY OF DISCUSSION

Excessive negative pressure breathing can produce deleterious pulmonary and cardiovascular effects. We need to determine, therefore, what level of pure NPB can be safely tolerated, and how much negative pressure breathing can be allowed when combined with external impedance-dense gas breathing. Underwater breathing equipment must then be designed which limits the total amount of negative pressure breathing to which the diver is subjected.

Much of the discussion of this session centered on Dr. Saltzman's presentation. A major implication of this work is that we may not yet know what exactly constitutes a "normal" $PaCO_2$ for a diver at 1,000 feet breathing $HeO_2$. This knowledge is of critical importance to the interpretation of UBA physiological testing where changes in $PaCO_2$ are used as an index of UBA performance.

In summary, Dr. Saltzman pointed out that "gas exchange does not appear to be the limiting factor in conditions that we have looked at in the laboratory to this time. Respiratory mechanics do, however, seem to be limiting in deep diving and in the real frontier."

## CONCLUSIONS AND RECOMMENDATIONS

1. Determine what amount of negative pressure breathing can be safely permitted in underwater breathing apparatus and set standards.

2. Duke University should continue to study the relationship between changes in hydrostatic pressure and arterial $PaCO_2$, including study of the mechanisms involved in this phenomenon. This information is needed to define what constitutes homeostatic normalcy in deep diving.

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| | |
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| Dr. David Leith | Harvard |
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| Dr. Michael Storrie | SUBDEVGRUONE |
| Dr. James Vorosmarti | RNPL, United Kingdom |
| Dr. Brandon Wright | EDU |
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NOTE: Dr. David Elliott, SURG CDR, RN, President of the Undersea Medical Society, was in attendance for the first-day session.

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**13. ABSTRACT**


This report presents the proceedings of the Second Undersea Medical Society Workshop on "Respiratory Limitations of Underwater Breathing Equipment," held at Harvard University School of Public Health on 14-15 March 1973.

Individual presentations along with conclusions and recommendations for future research in the following areas are presented:

- Recent Problems Posed by Underwater Breathing Equipment in Deep Diving
- Engineering of Underwater Breathing Apparatus
- Physiological Testing of UBA
- Effects on Respiratory Mechanics of UBA
- Effects of Underwater Breathing Equipment on Ventilation and Gas Exchange


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| Physiological Testing | | | | | | |
| Respiratory Mechanics | | | | | | |
| Ventilation and Gas Exchange | | | | | | |