Respiratory Simulation

Wolfgang Heinrichs, MD, PhD, CEO of AQAI GmbH, Mainz, Germany

Introduction

Education for artificial respiration – traditionally this is done on a "see – do" basis. That means that practical demonstration of different ventilation modes are practiced in patients guided by the experienced ICU staff and on a try and error basis by the learners. As these patients require artificial ventilation for their lives this is not the approach that state of the art learning should be.

A second scenario: the hospital decides to buy a new set of respirators for the ICU. Introduction is done by the company and the staff gets a maybe one hour lesson how to use the new respirator. Within a specific ventilator system many different modes of operation may be available, and the model(s) most appropriate for use in a given situation may be subject, at least in part, to certain patient or use conditions. Realistically simulated patient loads can be invaluable in these situations, and care givers can make effective use of test lungs to allow the widest possible range of treatments to be investigated before application to the patient. For training and teaching applications, use of a realistically simulated patient is essential. Training the use of ventilators and the employment of various respiratory care techniques to medical professionals requires fidelity of the training scenarios, equipment and materials to the real-world, clinical setting. The next time experience is again in patients although the staff cannot be familiar with all the functions of the new machine after just one hour of demonstration.

Therefore hands-on experience is what is needed in quality respiratory care. And hands-on does not mean in patients: artificial lungs are needed for the learning and training period. Only after being familiar with all functions it should be allowed to make adjustments in patients.

Artificial lungs are available in different forms:

1. The most common form is a kind of elastic bellow (generally called "Test Lung") (Fig. 1). This type of lung is used to check the general functions of a ventilator or the tightness of the system. It has no properties that are similar to a real human lung in terms of mechanical behavior. And it is clear that it has no gas exchange properties.

2. Mechanically lungs like the "The Michigan Instruments Training and Test Lung™" (also known as the "Michigan Lung") – (See more at: http://www.michiganinstruments.com/training-test-lungs) (Fig. 2) work with bellows loaded by springs. Variable resistors can be added to the airway. These types of lungs allow sophisticated training on various ventilation modes. They are restricted by the principle of their construction: the compliance is a linear function (spring load), they cannot be recruited and they do not facilitate any gas exchange.

3. Electronically controlled lungs. The Ingmar ASL 5000™ (See more at http://www.ingmarmed.com/asl.htm) (Fig. 3). The ASL 5000 features a bellow driven by a linear motor. With software control it is possible to

realize nonlinear compliance, variable resistance and a recruitable FRC. It features breath by breath control of a dedicated "patient", nonlinear compliance and resistance effects, remote control capabilities and real-time data analysis. The ASL provides no gas exchange.

4. Animal experiments are frequently used to realize a physiologic or pathophysiologic behavior for advanced respiratory training. Canine and porcine models are still being used to teach the skills involved in mechanical ventilation, hemodynamic management and the physiology of lung-heart-interaction to this day. As realistic as these models may be, animal-based training is fragile and poorly reproducible.

5. Physiologic controlled lungs. This is the innovation that we have created during the past few years: TestChest and it will be described in detail in this chapter.

Introducing TestChest™ - a full physiologic artificial lung (Fig. 4)

TestChest – the innovation of lung simulation – provides a breakthrough in respiratory training. The simulation of human lung function is extremely realistic and thus makes animal experiments for teaching purposes unnecessary. AQAI Simulation Center Mainz, Germany (see Appendix A), and Organis, Landquart, Switzerland, have combined their experience in medical training, high-end technical design and mathematical modeling to create this lung simulator. TestChest is a complete solution for learning optimized respiratory therapy for acute and chronic lung diseases. Physiological and pathophysiological models support a lot of learning modules for training. TestChest is a tool easy to use for educating basic and advanced artificial respiration.

TestChest consists of a bellows system driven by a linear motor (Fig. 5). The volume of the bellows is about 8 L which means that TestChest can simulate a real human lung with a real FRC and a real vital capacity. By software the motor is controlled to realize nonlinear S-shape inspiratory compliance curve, hysteresis, recruitment and collapse of the lung. With its integrated oxygen, pressure and temperature sensors it calculates the oxygen uptake within the lungs on the basis of the well-known gas equations defined by the physiology and takes care of the shunt equations.

Fig. 6 shows as an example a pressure volume loop registrated with a Hamilton S1 ventilator. This loop shows a lower and upper inflection point as well as a marked hysteresis between in- and expiration – it

cannot be distinguished from a comparable human situation.

The oxygenation of the artificial patient can be shown by an artificial finger that simulates oxygen saturation curves. Pulse amplitude can vary according to different states of intravascular filling. Heart-lung interactions are modeled in this way, supporting the latest generations of ventilators in advanced or automatic respiratory modes (Fig. 7).

TestChest can be equipped with a mass flow controller for CO_2 production. Together with an adjustable dead space, realistic capnograms will be generated and can be shown on any CO_2 monitor.

The physiologic calculations inside TestChest also realize the concept of muscular activity for spontaneous breathing. This results in two modes of spontaneous activity: the P0.1 concept for triggering a ventilator and the possibility to load a certain breath on TestChest which will be executed at a given respiratory rate. As the spontaneous breath is composed on a data set of muscular activity, it can easily be modified in amplitude. With this it is possible to simulate muscular strength as well as muscular failure – an important tool for teaching weaning concepts.

The muscular model is the basis for another model: The intrapleural pressure can be calculated. This signal is given as a data stream which is then used in an electro-pneumatic pressure generator that can be connected directly to advanced ventilators, supporting this concept as a replacement for an esophageal balloon. Using this option all concepts of transpulmonary pressure during ventilation is supported as well as advanced trigger options or advanced pressure support functions.

As TestChest can determine the exact time point when the muscular activity begins to inspire, it is possible to simulate NAVA (Neurally Adjusted Ventilatory Assist) as a mode of ventilation based on neural respiratory input from the respiratory center. In this case the electrical activity of the diaphragm is simulated with a little interface box and the appropriate signal is generated for the ventilators that are equipped with this mode of triggers.

This high-end lung simulator is the ultimate tool for basic and advanced training for anesthesiologists, intensive care physicians and nurses. For the safety of patients in respiratory failure this training is just as important for the safety of patients experiencing respiratory failure as flight simulator training is to pilots: it offers training in an environment where no harm will result to trainees or passengers (patients). TestChest eliminates the need for animal experiments and provides a breakthrough in training.

- TestChest realistically replicates pulmonary mechanics, gas exchange and hemodynamic responses.
- TestChest simulates respiration from normal spontaneous breathing to mechanically ventilated severely diseased lungs.
- TestChest is programmable and can be remotely operated to simulate in an unprecedented way the evolution of diseases as well as the recovery process.

Software

TestChest is designed to have no controls except the power switch. It can therefore be placed anywhere and there is no need for any interaction with the model itself. All communication is done via standard network connections using TCP/IP. After start-up, Basic Control software (running on any Windows-PC) automatically establishes communication with TestChest (Fig. 8).

A set of standard parameters is loaded by default, representing a fully healthy and passive lung. Indicators continuously inform the user about the actual communication status.
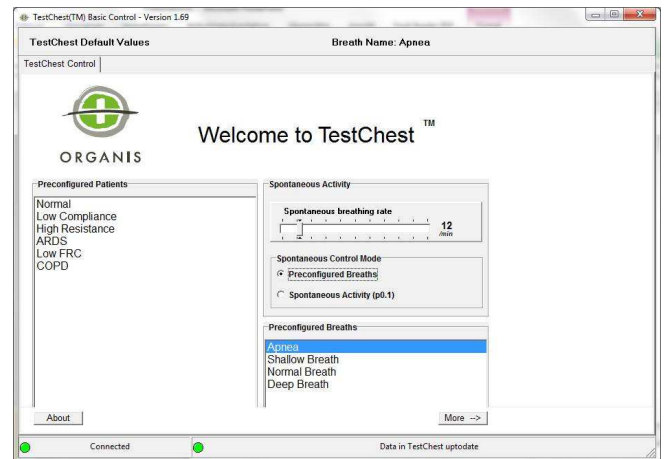
Basic Control features:

- Selection of preconfigured patients.
- Selection of preconfigured spontaneous breaths.
- Start of a calibration procedure. These functions allow the immediate use of all advanced TestChest properties.
- For those who want to influence the parameters directly, Basic Control can access all values that are used in the TestChest physiological model to setup the artificial lung.

We have created a more sophisticated software tool which adds look and feel to the use of TestChest: The Advanced Software. The Advanced Software adds an extended physiological model to the respiratory models of TestChest, controlling circulation, metabolism, volumes, pharmacology and more (Fig. 9). These models make it possible to get a view of the whole patient and to treat him with drugs, physiotherapy, positioning, etc.
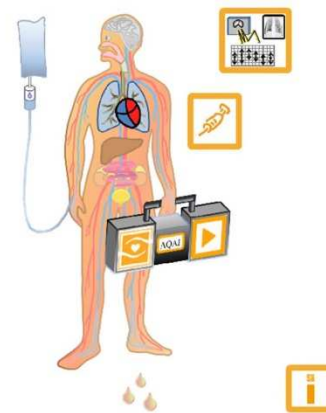
One of the most important features of the Advanced Software is the development of cases over time. A scenario player is included which can influence all parameters of the TestChest as well as the virtual patient by various states. States can be switched automatically. This results in a case where the lung initially is in a mild stage of lung failure, after a while the invasiveness of ventilation has to be increased, a recruitment may be necessary and if done so, the situation may improve finally.

In instructor facilitated modes of learning, the scenario states can be selected manually; this facilitates that the instructor can teach at the various states before moving on to the next chapter.

The hardware requirements include a server PC (Windows based Laptop) which runs the various physiological and pharmacological models. Together with a wireless access point it is possible to run the Advanced Software from any computer that is integrated into this network, e.g. on Tablet PCs, Smart PCs, Smart Phones or iPad (Fig. 11).
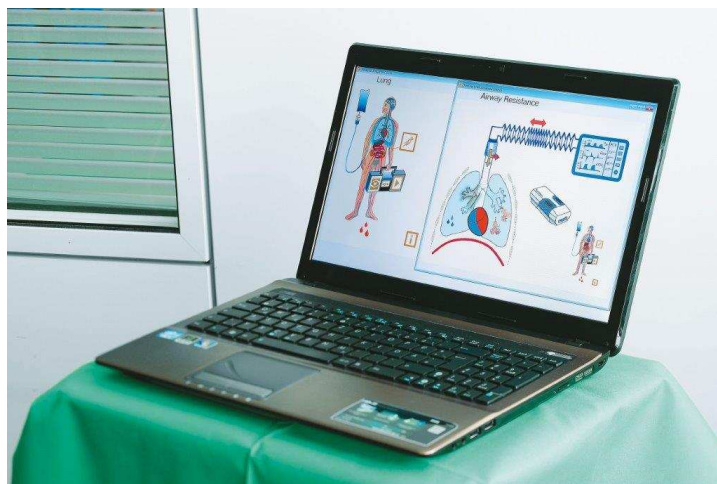
TestChest Advanced is both a preconfigured tool and a highly flexible open system: the models behind it can be accessed by experienced users and modified to create individual reactions.

Learning contents

AQAI has developed several learning modules especially designed for TestChest. All learning modules have a standardized structure:

- AQAI TestChest Advanced Control Software.
- Preprogrammed scenarios for the various tasks. The user can work through the lectures step by step or can start at a certain level. In all cases, the TestChest is preprogrammed automatically with the correct reactions. Curves can be derived from the ventilator or from the software which will present real-time graphs of flow, volume, pressure, gas exchange parameters and more.
- PowerPoint presentations that explain the concepts of artificial ventilation. These presentations can be used to introduce a certain topic
- List of references.
- A reference book: Neil R. MacIntyre and Richard D. Branson (2009) Mechanical Ventilation – Second Edition.

Learning modules support various topics (Fig. 10):

- Basic and Advanced Respiratory Therapy
- ALI / ARDS
- Weaning
- COPD

They are strictly organized to support certain learning goals. Appendix B lists some of these learning objectives. They can be used in a self-learning manner. They can also be used in instructor facilitated learning.

Appendix C shows as an example a brief

description of the cases that are covered by the learning module "Basics and Advanced Artificial Ventilation".

Appendix D shows as an example the chapter "Trigger" of the learning module "Basics and Advanced Artificial Ventilation".

Full Scale Simulation with full respiratory functions

TestChest can easily be connected with an intubation head (Fig. 12). This combination adds more realistic features to the respiratory simulation. Especially all modes of non-invasive ventilation can be simulated with this head. The various learning modules support this by special chapters on NIV. Although NIV is gaining more and more attention, it is important to know limits of NIV and to decide for an intubation airway in time, if the situation detoriates. The Advanced Software with its capability of developing cases can realize such scenarios where NIV initially works well but over time when the lung function gets worse a decision for a conventional airway approach has to be done.

One of the big limitations of mannequin simulators is that even though people call them high fidelity, they are low fidelity when it comes to breathing. The internal lungs of these simulators are limited very much to basic mechanical functions. The reason for this is mostly the limited space inside the mannequins. On the other hand simulation mannequins of today are constructed in a way that they can be fully mobile, e.g. for kind of emergency training.

If the focus of training is on respiration and lung function, mobility does not play a big role. So it can be worthwhile to combine the mannequin simulators with a high-end respiratory simulator to get the whole picture (Fig 13).

AQAI has developed an interface to certain full-scale mannequin simulators. The advanced features of TestChest can thus replace the more basic respiratory functions inside the mannequin. Using the 3G-family of Laerdal all functions of both simulators can be controlled from one single platform.

This combination allows full-scale simulating experiences for any kind of respiratory training courses that cannot be realized with any other simulator. Any kind of respiratory support is possible in intensive care as well as in anesthesia and emergency medicine. All common functions of the full scale mannequin remain active, e.g. heart and breathing sounds, pulses, airway features and resuscitation.

As the Advanced Software adds hemodynamics and pharmacology, the functionality of the mannequin is even enhanced. The interface is constructed in such a way that the user may control the simulation from the original software of the mannequin as well as from the full graphical representation of AQAI's Advanced Software. This results in maximum flexibility (Fig. 14).

Conclusion

Respiratory simulation can be achieved on various levels of reality. Traditionally these artificial lungs offer pure mechanical properties. Even the more sophisticated lungs do not provide a physiology and a gas exchange. Therefore it was a chance and a dream to develop an artificial lung that overcomes all these known limitations. TestChest is the answer to this. It is so perfect that even highly sophisticated ventilators do not recognize that they are working on an artificial lung. Thus TestChest supports all these new modes of ventilation where some intelligence is built into the ventilators. One example of this is the "IntelliVent™" mode of the Hamilton machines but also concepts of transpulmonary pressure or NAVA triggering in machines from other vendors.

Appendix A

AQAI GmbH Simulation Center Mainz

AQAI – The name is an abbreviation: "Angewandte Qualitätssicherung in Anästhesie und Intensivmedizin" – Quality applied to anesthesia and intensive care medicine

AQAI started as an initiative to improve quality in anesthesia and intensive care medicine. For more than 15 years we have hosted an information system on complications and critical incidents. Today it is one of the largest databases on these kinds of the world. In the simulation center Mainz this initiative gains advantages from putting theory into practice. We realized this idea not only for anesthesia but also for the entire field of medicine in an interdisciplinary manner. We do training for various professions with all types of patient and virtual reality simulators. Today AQAI has the experience of more than 15 years of training and education in full-scale-patient-simulation. We do more than 500 training days per year with a team of 12 employees coming from anesthesia, intensive and emergency care medicine, mathematics and physics. We are one of the largest private simulation centers in Europe.

To enhance the comprehensive training spectrum and to make it more realistic AQAI developed a package of add on products for simulation. One of the most important tools is the AVS – AQAI Video System, the ultimate tool for simulation recording and debriefing.

Furthermore AQAI developed interfaces for PiCCO™-monitoring, TIVA-TCI-infusion-pumps, EEG-monitoring and servo-controlled vaporizers (SIS - Simulation-Interface-Software) to make patient simulation as realistic as possible.

Appendix B

Typical learning objectives in artificial ventilation

The user will be able to…

- understand the concepts of artificial ventilation, such as flow control, pressure control, volume control, flow trigger, pressure trigger.
- understand compliance and resistance.
- setup various ventilators to achieve stable ventilation conditions.
- interpret curve traces and values derived from the ventilator.
- understand the concept of nonlinear compliance curves, lower and upper inflection points.
- understand the concept of time constants.
- define the correct PEEP.
- understand the difference between extrinsic and intrinsic PEEP.
- understand the concepts of pressure support and mixed mandatory / spontaneous ventilation modes, such as BIPAP or APRV.
- support various kinds of spontaneous activities.
- optimize ventilator settings according to various rules: low tidal volume ventilation, avoid barotrauma, avoid atelectrauma, recognize limits of ventilation.
- administer protective lung ventilation and understand the concepts of ventilator induced lung injury.
- understand the concept of closing volume, recruitment, open lung and lung collapse and its effects on gas exchange as well as on heart lung interactions.
- optimize ventilator settings according to permissive hypercapnia and shall also understand any limitations of this concept.
- understand the concept of high expiratory resistance.
- optimize ventilator settings according to permissive hypercapnia and shall also understand any limitations of this concept.
- optimize the ventilator settings in view of supporting spontaneous breathing and avoiding muscular fatigue
- understand the concepts of weaning and muscular fatigue.
- optimize the ventilator settings in view of supporting spontaneous breathing.
- understand the concept of muscular training, resting periods.
- learn how to treat patients in difficult weaning situations and will experience his / her knowledge in various cases

Appendix C

Patient #	Basics and Advanced Artificial Ventilation
	The Basic Software includes a number of test patients with certain properties. There are 3 almost normal patients: • **Normal Patient** • **Low Compliance Patient** • **High Resistance Patient** These 3 patients are useful for the start of working with TestChest and help understanding the concept of this lung simulator. There are no special functions in these patients and they are not used together with the Advanced Software. The Basic Software also includes 3 patients with certain pathologies: • **ALI / ARDS Patient** • **Low FRC Patient** • **COPD Patient** They can be used as training examples with the TestChest. In combination with the AQAI Advanced Software, these patients show additional features and develop more reality by adding scripts and the possibility to do certain treatments. They can also be used during the various exercises demonstrated in the advanced artificial ventilation part. The learning modules "ALI/ARDS", "COPD" and "Weaning" will add more clinical examples with more detailed reactions to various therapies.
1	**Normal Patient** This is a patient with healthy adult lung properties. Gas exchange is fairly normal.
2	**Low Compliance Patient** The low compliance patient shows a markedly reduced compliance but otherwise shows no major pathologies. This patient can also represent a child 2-3 years of age.
3	**High Resistance Patient** The high resistance patient is a patient with an acutely increased resistance. This patient shows a longer expiration and needs higher forces during inspiration.
4	**ALI / ARDS Patient** Patient after thorax trauma. When seen first he still breathes spontaneously. The total compliance is reduced to 30 ml/cmH$_2$O and will be decreasing within the next scenario states. At a certain point he will show desaturation and ventilation is indicated. This can be achieved by noninvasive ventilation at first. During the progress of the disease, the patient has to be intubated.

Patient #	Basics and Advanced Artificial Ventilation
4 (cont'd)	Recruitment maneuver shall be performed and this therapy finally results in adequate gas exchange.
5	**Low FRC Patient** This is a patient with a marked restriction in lung capacity. He also shows a stiff thorax. Resulting from this the patient demonstrates a marked upper inflection point. Moreover heart lung interactions are present and result in marked drop of blood pressure if higher pressures are applied. To a certain extend this phenomenon can be treated with some volume load. Oxygenation is reduced because of increased shunt fraction. If the patient breathes spontaneously he has a shallow rapid breathing. He will not show much ability for recruitment.
6	**COPD Patient** Patient with a burn out chronic lung disease. CO_2 is markedly elevated, oxygenation reduced. He has an increased resistance and a long expiration because his muscles are weak at the end of expiration. He can be treated with bronchodilators resulting in a reduction of resistance. He can be supported with noninvasive ventilation to reduce the CO_2 and to improve oxygenation. This patient cannot be trained in muscular strength – see learning module "COPD" for these effects.

LEARNING MODULE   *Basics of Artificial Respiration*

TOPIC: Trigger

LEARNING OBJECTIVE:

- *You will be able to learn about the concept of triggering a ventilator.*
- *You will learn the difference between pressure control of trigger and flow control of trigger.*
- *You will understand why flow control of trigger decreases the amount of breathing work in most patients.*
- *You will understand how self-triggering of respirators occur and how to avoid it.*

SUITABLE FOR LEARNING STYLES:

Self-Learning

Instructor facilitated learning

BACKGROUND:

Trigger means that the inspiratory support of the ventilator is synchronized with the muscular activity of the patient and the wish to inhale.

Pressure control trigger detects a drop in the pressure system of the ventilator during expiration (caused by the patient inspiration)

Flow control trigger detects a flow into the lungs at the beginning of the inspiration

The **NAVA trigger** detects muscular activity from the diaphragm indicating that the diaphragm is contracting and thus starts an inspiration.

The ideal trigger would determine the beginning of the inspiration in the central nervous system. This today cannot be realized.

All ventilators measure variables like pressure or flow and are able to start a new inspiration if a preset value (the trigger threshold) is reached. While the older time triggers are no longer present in modern machines, the most frequently used triggers are pressure (the inspiration starts if a certain pressure drop in the system occurs) or flow (the inspiration starts, if a certain inspiratory flow into the patient is detected). Flow triggering has been shown to decrease the work the patient

must perform to trigger inspiration (Sassoon et al 1989). The following graph shows the typical flow, volume and pressure curves that are used with these triggers.

Fig. 1 Graphical representation of Flow- and Pressure-Trigger:
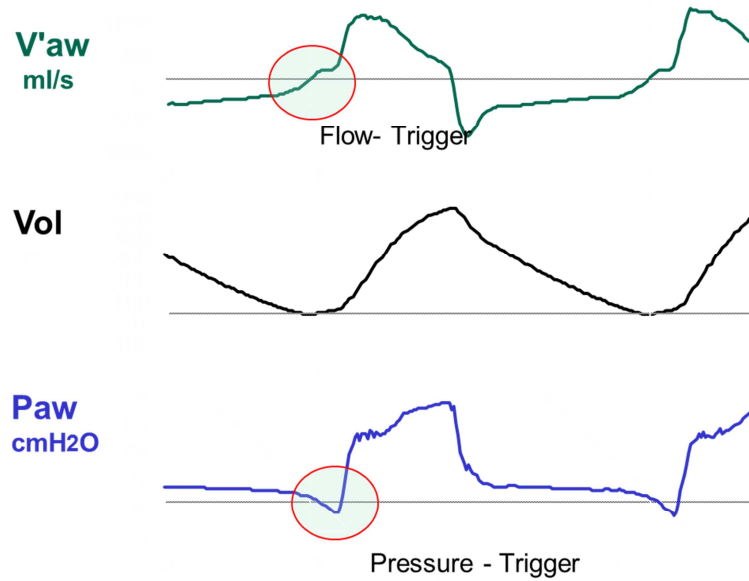
MATERIALS:

- TestChest
- Ventilator
- Advanced Software running on PC / Tablet PC

ACTIVITY:

Use the AQAI Advanced Software.

Click on the radio, select Learning Module "Resp. Basics" and select the scenario file "Trigger". Click on "Load Scenario" to activate the learning module and the topic.

Your screen should look like the picture above.

Select the single exercises step by step. Each exercise will set the TestChest into different trigger activities, expressed by different P0.1 values.

Connect the ventilator to the TestChest and practice different modes of ventilation (e.g. volume control, pressure control). In each mode try different trigger settings (e.g. pressure trigger, flow trigger with varying sensitivities) and observe if the ventilator triggers or if self-triggering occurs.

Observe pressure and flow patterns if you switch from exercise to exercise. In each of the settings try to optimize the ventilator settings.

Work at least one hour on the various conditions until the concepts of the trigger sensitivity and the trigger mode are fully understood.

ASSESSMENTS:

The trainer: select certain exercises from the scenario player blinded for the trainee. Ask the trainee to select appropriate settings on the ventilator. Make adjustments of the single parameters e.g. the P0.1 and observe how the trainee reacts with the respirator settings.

Ask the trainee to point out the difference between pressure and flow trigger and how to avoid self-triggering.

References:

Neil R. MacIntyre, Richard D. Branson (2009) Mechanical Ventilation. Second Edition Chapter 1; pages 13-21

Sassoon CSH, Giron AE, Ely EA et al (1989): Inspiratory work of breathing on flow-by and demand-flow continuous positive airway pressure. Crit Care Med 17:1108-1114