

Computer animated graphics as a teaching tool for the Anesthesia Machine Simulator

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Computer Animated Graphics as a Teaching Tool for the Anesthesia Machine Simulator

by
J.J. Hekker

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October 1989

This report was submitted in partial fulfillment of the requirements for the degree of Master of Electrical Engineering at the Eindhoven University of Technology, The Netherlands.

The work was carried out from February 1988 until November 1988 under responsibility of Professor J.E.W. Beneken, Ph.D., Division of Medical Electrical Engineering, Eindhoven University of Technology, at the Department of Anesthesiology, College of Medicine, University of Florida, Gainesville, Florida, under supervision of M.L. Good, M.D., J.S. Gravenstein, M.D., and J.J. van der Aa, M.E.

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Summary

The existing Gainesville Anesthesia Simulator has been extended with computer based animated graphics, to help the clinician understand the nature of common yet infrequently observed undesired situations and the extremely rare critical occurrences. This development resulted in a first version of a computer based tutorial that will lead toward a self-contained educational package.

The educational package contains three parts: 1. a familiarity check, introducing the simulator user to the simulator's anesthesia machine and monitoring equipment, 2. a challenge phase, during which the user is confronted with either a machine malfunction or a patient problem, followed by 3. the feedback, an explanation in which computer animations guide the user through the same malfunction as encountered in the challenge phase, while pointing out effects on the monitored signals and display a possible method to correctly diagnose and correct the problem.

Presenting the combination of the Anesthesia Simulator and computer animations at several national and international meetings proved that the approach is a very useful tool to educate users of anesthesia equipment how to diagnose and correct problems with either anesthesia equipment or patient.

Samenvatting

Om anesthesisten duidelijk te kunnen maken wat er gebeurt in een beademings-apparaat, tijdens "gelukkig" zeer zelden voorkomende kritische situaties, is de bestaande versie van de Gainesville Anesthesia Simulator uitgebreid met een op een computer gebaseerde leraar. Deze ontwikkeling heeft geresulteerd in een studiepakket, dat zal evolueren naar een compleet zelf-onderhoudend studiepakket.

Het te realiseren pakket zal bestaan uit drie delen: 1. een kennismaking met de simulator; de simulator en de gebruikte apparatuur worden uitgelegd aan de gebruiker, eventueel door gebruik te maken van animatie technieken. 2. de testfase; hierin wordt de gebruiker blootgesteld aan een van de scenario's van de simulator. 3. de evaluatie; hierin wordt met behulp van animatie duidelijk gemaakt wat er nu eigenlijk fout ging in de simulator, wat het gevolg hiervan was op de gasstroom in de machine, en wat er aan gedaan kan worden om het probleem op te lossen.

Tijdens de verschillende demonstraties van de simulator in combinatie met de in de hoofdstuk 5 beschreven "feedback", bleek dat de ingeslagen weg de juiste was. De combinatie blijkt een goed hulpmiddel te zijn om gebruikers van anesthesie-apparatuur te helpen met het vaststellen en oplossen van de fouten die kunnen optreden, zowel in de anesthesie-apparatuur als de patient.

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Introduction.

This project was done as partial fulfillment of the requirements for the M.Sc. degree in Electrical Engineering at the Eindhoven University of Technology, division of Medical Electrical Engineering, Eindhoven, the Netherlands. The research was performed at the University of Florida, College of Medicine, Department of Anesthesiology, in Gainesville Florida, U.S.A. Funding for the research was provided by Ohmeda in Madison Wisconsin, manufacturer of anesthesia equipment.

In anesthesiology errors that result in patient injury are a relatively rare phenomena. However, efforts are made to make anesthesiology even safer as it is.

Some of the problems are machine related and can be solved easily, assuming the anesthesiologist is able to identify the problem, using the available monitoring equipment. The best way to learn is to do it; "fortunately" many malfunctions are so rare that it is quite unlikely that he will ever encounter such a malfunction during his training. The occurrence of many malfunctions is as low as 1 in 20,000 cases or less. Therefore, in many instants the malfunction is only seen in textbooks.

The Gainesville Anesthesia Simulator is one of the first attempts to teach anesthesiologists about machine malfunction in a clinical environment. It consists of an adapted anesthesia machine (Ohmeda Modulus II), in which certain malfunctions can be evoked. Computer controlable electronic and pneumatic solenoids and valves were added to introduce these malfunctions.

The simulation is real enough to let the anesthesiologist forget that he is dealing with a simulation. At this moment, research is done to provide the necessary data to test if the simulator really improves the skill of the users of the simulator. This is done by testing half of the anesthesia residents with the simulator while the other half follows the normal courses. Up till now, usage of the simulator required the presence of one of the members of the development team to show how to operate the simulator, explain the function of the monitoring equipment used on the simulator, and explain what is expected of the user.

The simulator should become a self educational device. But since a follow up on the introduced malfunction is always necessary, because the anesthesiologist might be able to correct the malfunction by instinct, without an understanding of the problem, the decision was made to use computer animated

graphics for a tutorial to introduce the user to the simulator, guide him through the scenario and provide feedback afterwards.

In this thesis the initial implementation of the tutorial is described.

Introduction of the feedback phase at several national and international meetings proved that the addition of animated graphics to explain what is going wrong, and why a certain action has results, is helpful. Most people did like the animated graphics because they finally were able to comprehend what is going on inside the anesthesia machine and the breathing circuit.

1 Introduction to Anesthesiology

Surgery evokes pain and undesirable hemodynamic changes, mediated by the sympathetic nervous system. Anesthesia blocks these responses. There are three types of anesthesia, local anesthesia, regional anesthesia (nerve block) and general anesthesia. We will limit ourselves to general anesthesia, in which the conditions we want to realize are: loss of consciousness, amnesia, analgesia* and muscular relaxation.

A general anesthetic typically employs a gas mixture containing oxygen, nitrous oxide and/or an anesthetic agent. These gases are mixed in the anesthesia machine. This machine delivers a constant gas flow (the fresh gas flow), to the breathing circuit. Some patients breath spontaneously; in others, however, muscle-relaxants paralyze the lung muscles, leaving the patient unable to breath by himself. These patients need to be ventilated artificially, either by a mechanical ventilator or manually by the anesthesiologist who squeezes a breathing bag.

*
Amnesia is loss of memory
analgesia is the loss of sensation of pain

1.1 Mechanical ventilation.

Gas is delivered to the patient through the breathing circuit. There are four types of breathing circuits: open, semi-open, semi-closed and closed¹.

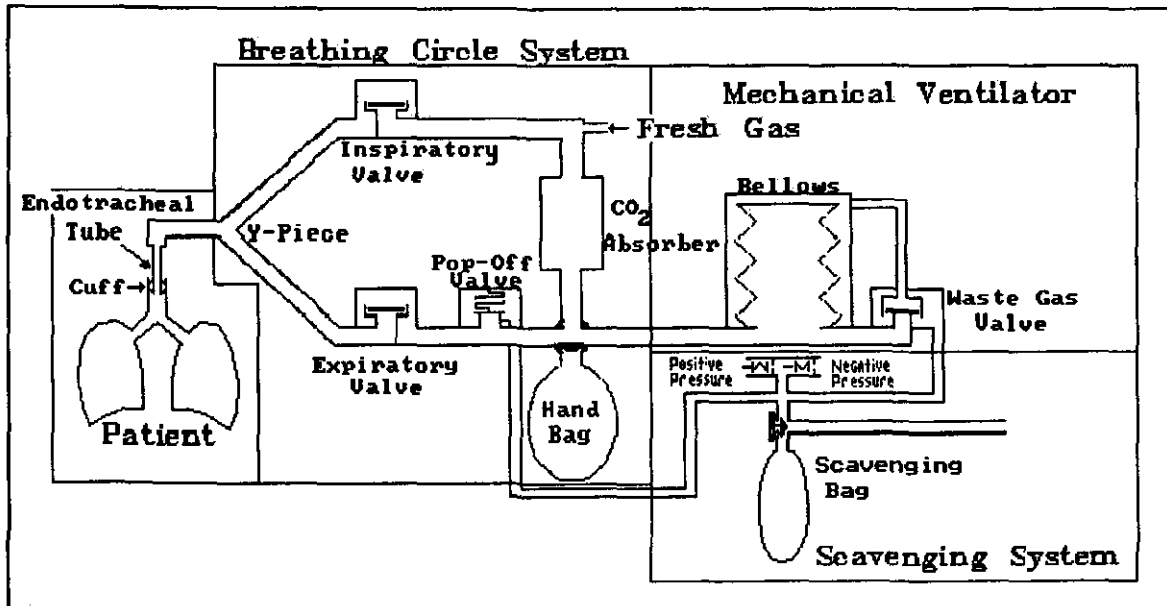


Fig. 1.1. Ventilating a patient through a breathing circuit.

In fig. 1.1 a schematic is presented to illustrate what is needed to ventilate a patient under general anesthesia while keeping him anesthetized. The various components are:

- Breathing Circle.
- Ventilator.
- Scavenging system.
- Anesthesia Machine (delivers the fresh gas flow).

In the next paragraphs, these components of the breathing system will be described in more detail.

1.2 The circle breathing system.

The breathing system used most often in the U.S.A. during general anesthesia is the circle breathing circuit. This system allows part of the expired gas to be re-used during inspiration. Since it is undesirable for a patient to inspire his expired CO₂, the CO₂ is removed from the circle system by a CO₂ absorber. Due to unidirectional inspiratory and expiratory valves the gas flow through the system is circular, which accounts for the name "circle system".

The circuit's inspiratory and expiratory limb meet in the Y-piece. This Y-piece connects to the endotracheal tube, which is inserted in the trachea of the patient. A cuff around the tip of the endotracheal tube can be inflated to assure a leak-free system.

1.3 The Ventilator.

Patients can breath spontaneously through the circle breathing system, but in most cases, especially when muscle relaxants are used, the patient's ventilation must be controlled. During inspiration, a positive pressure is used to force the gas mixture into the patient's lungs. This can be accomplished with the help of a mechanical device, a ventilator. Most anesthesia ventilators are pneumatically driven by the oxygen pressure. The mechanical ventilator has the advantage that, besides leaving the anesthesiologist's hands free, ventilation is very regular and constant.

The anesthesiologist must set several ventilator variables:

- Tidal Volume: The volume that is delivered by the ventilator during each inspiration.
- Rate: The number of breaths the ventilator delivers each minute.
- I : E ratio: The ratio between the duration of inspiration and expiration periods.

1.4 The Scavenging System.

The scavenging system collects the breathing circuit's excess gas to avoid pollution of the operating room. The scavenging system connects to the wall outlet for vacuum. The scavenging system has gravity-loaded relief valves to limit positive and negative pressure. The suction applied to the manifold can be controlled through a adjustable needle valve.

1.5 The Anesthesia Machine.

A typical general anesthetic consists of oxygen, nitrous oxide and a potent inhalation anesthetic. Nitrous oxide is not potent enough to achieve complete surgical anesthesia, therefore a volatile anesthetic agent is used in addition. This anesthetic agent is a liquid and needs to be vaporized. The entire gas mixture is prepared in the anesthesia machine.

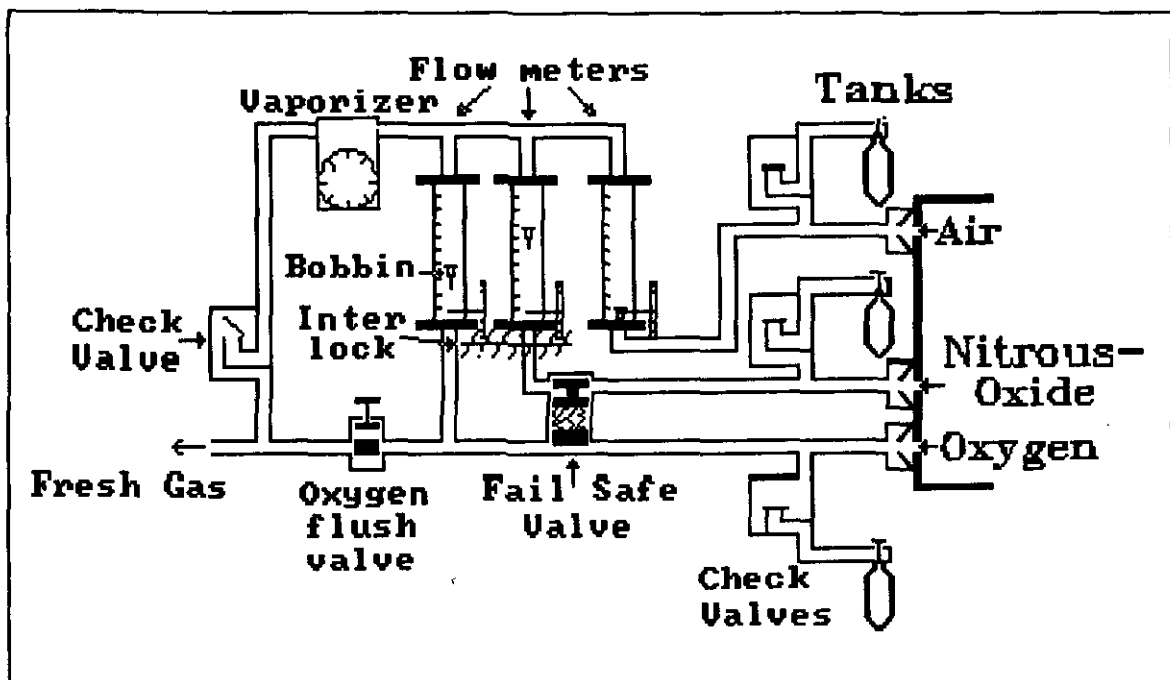


Fig. 1.2. Schematic of an anesthesia machine.

The components of an anesthesia machine are displayed in fig. 1.2. The machine consists of a high pressure circuit and a low pressure circuit. The machine used in the simulator is the Ohmeda Modulus II anesthesia machine. The common basic features of all anesthesia machines are depicted in this schematic which is therefore also applicable to other brands of anesthesia machines.

1.5.1 The High Pressure system.

The gases used in anesthesia are available through wall plugs, connected to the high pressure wall supply system, 50 to 55 psi. Whereas oxygen and air are available throughout the hospital, nitrous oxide is only available in the operating rooms. The anesthesia machine is connected directly to these wall plugs with color coded hoses*. The wall plug and hose connector have a gas specific diameter to prevent cross connection; this system is called the Diameter Indexed Safety System.

At the back of the anesthesia machine, there are tanks for oxygen, nitrous oxide and air. These tanks are backups in case a wall supply fails. The gas from these tanks is regulated to 40/45 psi inside the anesthesia machine; the oxygen tank (E-cylinder color green) contains circa 625 liter at atmospheric pressure, stored under a pressure (full) of 2000 psi. A nitrous oxide tank (E-cylinder color blue) contains circa 1590 liter at atmospheric pressure, stored under a pressure of 750 psi.

A number of safety devices is incorporated in the high pressure system (see also fig.1.2).

Both the reserve tanks and wall supply inlets have unidirectional check valves to prevent gas to flow into a part that normally has a high pressure, if its pressure is low for some reason. This prevents gas flow from a filled tank into an empty tank or into the wall supply system if the latter's pressure would decrease. A fail-safe valve between the supply lines for nitrous oxide and oxygen will close the nitrous oxide

* In the U.S.A. the hoses (and tanks) are color coded to indicate the use of the hose or tank. These color code is present on all connecting devices, wall outlet, wall connector, gas tanks and the back of the anesthesia machine. The color code for oxygen is green, nitrous-oxide is blue and air is yellow.

line if oxygen pressure drops below 30 psi. This prevents a hypoxic gas mixture (a gas mixture with less than 21 % oxygen) from being delivered to the patient. An oxygen flush valve allows the anesthesiologist to flush the breathing circuit with 100% oxygen if needed. The valve will supply a direct flow of 45-75 liters of oxygen per minute into the breathing circuit, bypassing the flowmeters.

1.5.2 The Low Pressure System.

From the high pressure system the gases flow to the low pressure circuit. Flow control valves are used to adjust the flow of gas from the low pressure circuit to the breathing circuit, the gas flow is measured by the flowmeters. By choosing a combination of oxygen flow and nitrous oxide flow, the anesthesiologist composes his gas mixture.

Part of the gas from the flow-meters flows through the vaporizer if the vaporizer is turned on. The concentration of anesthetic agent in the fresh gas flow is determined by the gas volume flowing through the vaporizer.

Several safety devices are included in the low pressure system (see also fig.1.2).

An interlock between the flow control valves for oxygen and nitrous oxide prevents the anesthesiologist from setting a hypoxic gas mixture. A check valve in the fresh gas line prevents gas from the breathing circuit from flowing into the low pressure system if the pressure in the breathing circuit is higher than the pressure in the low pressure circuit.

In fig.1.3 the Ohmeda Modulus II circuit is displayed. The system comes complete with unidirectional valves and CO₂ absorber. The inspiratory and expiratory hoses, the Y-piece and endotracheal tube are disposable and replaced for every patient.

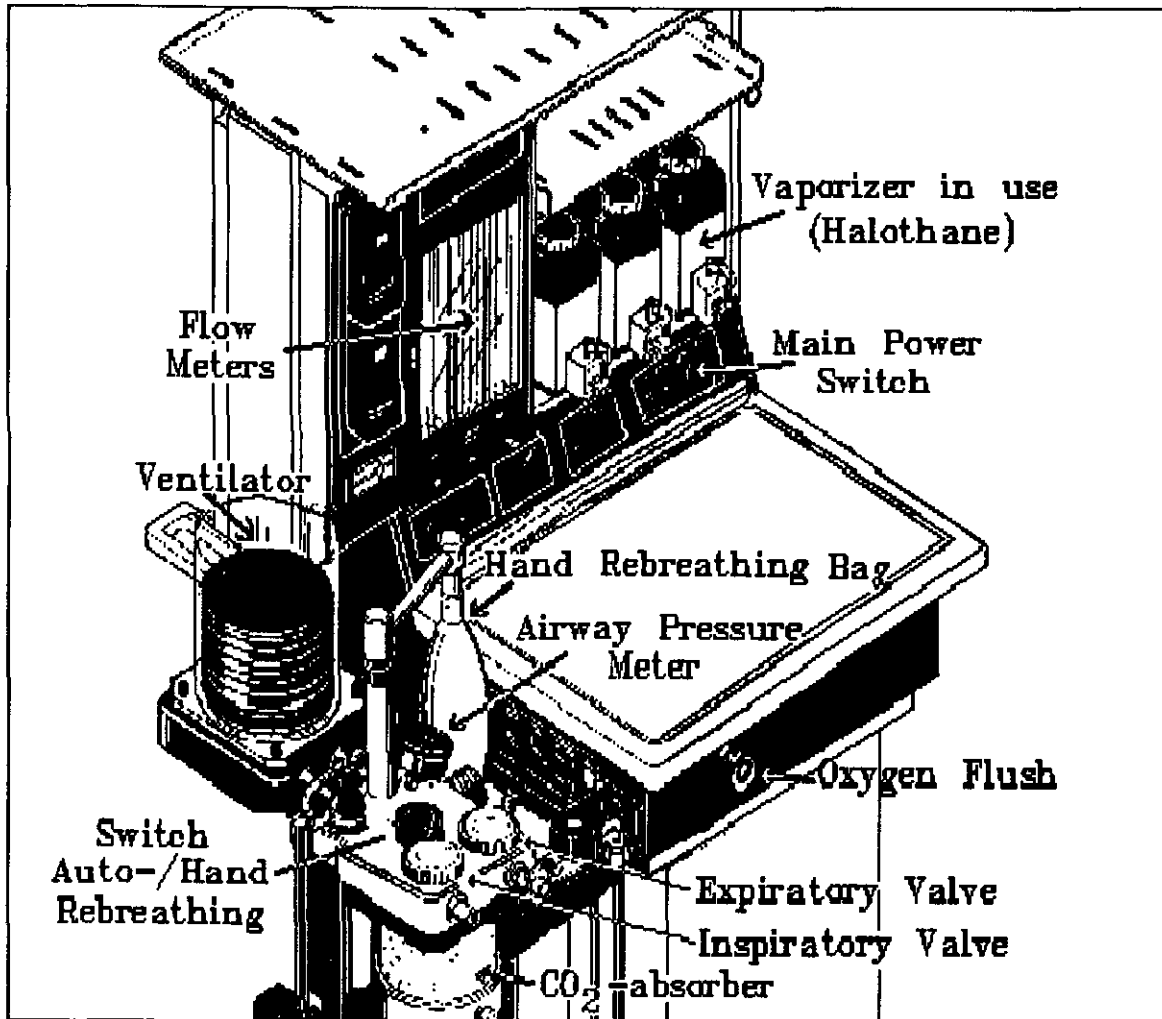


Fig.1.3. Ohmeda Modulus II Anesthesia Machine with part of the breathing circuit.

1.6 Monitoring the Patient.

Various monitoring devices are available to keep the anesthesiologist constantly updated about the condition of the patient. The signals from the patient (heart rate, blood pressure, CO_2 in the expired gas, oxygen saturation in blood) and machine settings (oxygen concentration, tidal volume, respiratory rate etc.) can be read from a variety of monitors many of which are available in a modern anesthesia machine. In the following paragraphs the most important monitors are described. These monitors are all part of the simulator. In fig.1.4 the position of several monitoring sensors in the breathing circuit is shown.

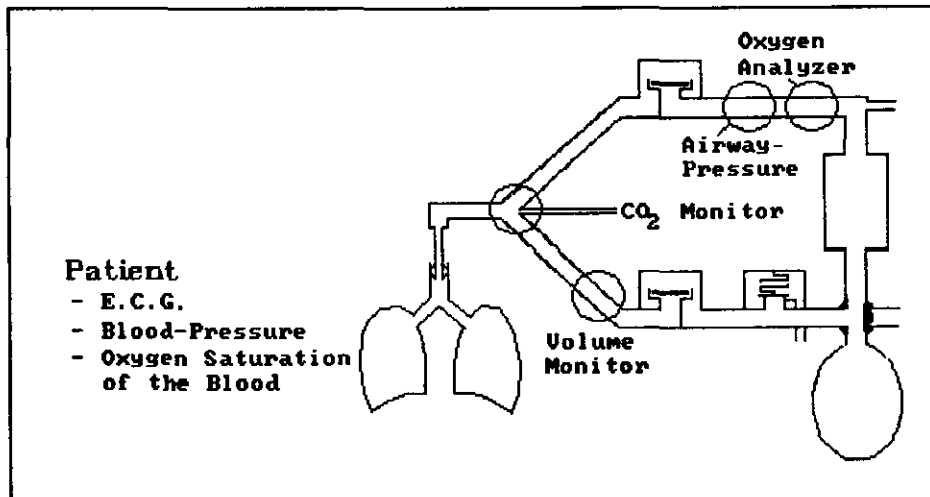


Fig.1.4. Position of the various sensors in the breathing circuit.

1.6.1 The capnograph (CO₂ monitor).

The CO₂ monitor measures the CO₂ in the breathing circuit at the Y-piece (see fig.1.4). A commonly employed method uses the infra-red absorption characteristics of CO₂. Concentration of the CO₂ in the inspired gas as well as the expired gas can be measured. In fig.1.5 the capnograph used in the simulator is displayed. There are two display screens. The bottom screen displays both (on the left) the minimum CO₂ concentration during a breathing cycle, and (on the right) the maximum CO₂ concentration during exhalation; the latter is referred to as the end-tidal CO₂ concentration.

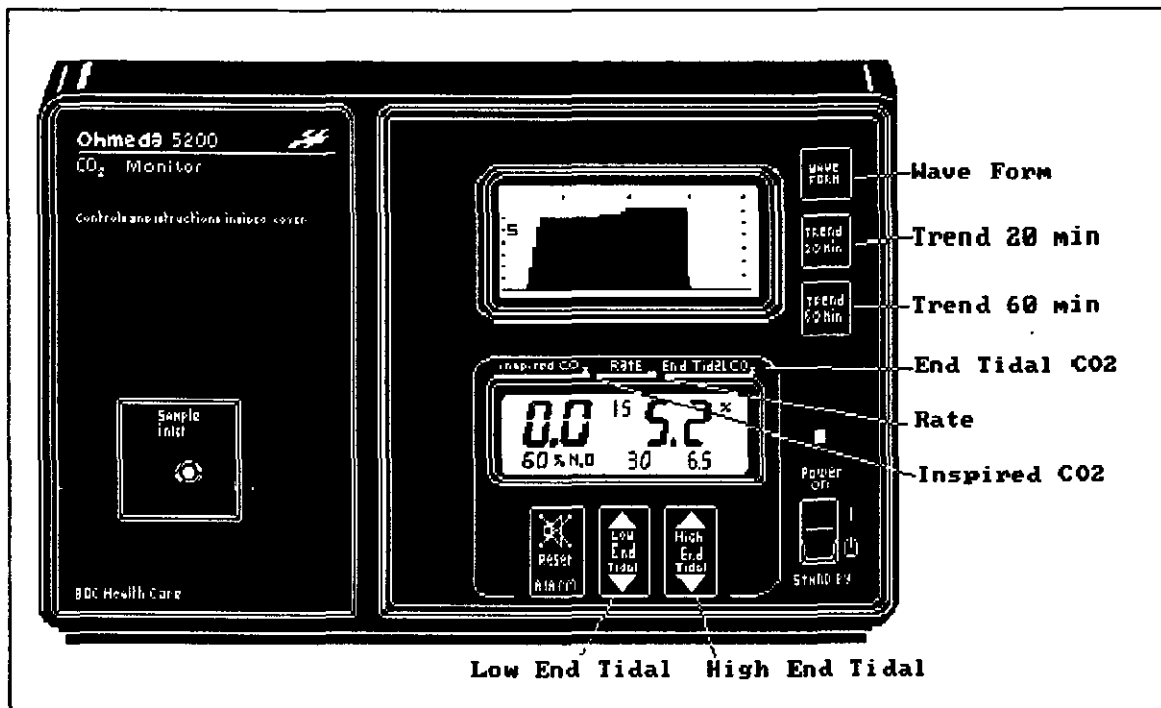


Fig.1.5. Capnogram model 5200, displaying a normal capnogram.

The top display shows the CO₂ concentration against time, the capnogram. In a normal capnogram (such as the one displayed) the CO₂ level goes up sharply in the beginning of expiration and is (almost) constant during the expiration. During inspiration the CO₂ level drops to zero.

1.6.2 The pulse oximeter.

The pulse oximeter measures the percentage of hemoglobin that is saturated with oxygen, and thus the oxygen saturation of the blood. The hemoglobin saturation measurement is based on the differences in infra-red absorption of hemoglobin and oxihemoglobin as a function of the light's wavelength. The probe for this non-invasive monitor is placed on one of the fingers of the patient. This instrument also has two display screens. One displays the oxygen saturation (for a normal, healthy person about 98 - 100%), and the heart rate. The other display shows the plethysmogram. This display helps the anesthesiologist to determine whether the pulse oximeter is receiving a strong enough pulse, and thus whether the displayed saturation values are trustworthy or not.

1.6.3 The physiologic monitor.

On this monitor the lead II electrocardiogram is displayed. Invasive blood pressure can also be displayed. The E.C.G. signal is measured by surface electrodes. Most often the blood pressure is measured with a blood pressure cuff and an automatic inflation device. In the simulator, however, the blood pressure is continuously measured through an intra-arterial pressure sensor. Measured variables are: systolic, diastolic and mean pressure. Both blood pressure and heart rate are displayed on the oscilloscope.

1.6.4 The oxygen analyzer.

The oxygen concentration in the inspired gas is measured by an oxygen analyzer in the inspiratory limb (see fig.1.4). In the simulator, the oxygen analyzer is incorporated into the ventilator. The oxygen analyzer sensor is placed at the CO₂ canister.

1.6.5 The volume monitor.

The exhaled tidal volume is measured by a spirometer, positioned in the expiratory limb of the breathing circuit, see fig.1.4. Rotations of a turbine are detected by two optical sensors that make it possible to discriminate between flow in the forward and reverse direction. The measured variables, tidal volume and respiratory rate, are displayed on the ventilator. The minute ventilation is calculated from these two variables.

1.6.6 The airway pressure monitor.

Excessive airway pressure can damage the lungs. The pressure in the breathing circuit is measured by a manometer; its position in the breathing circuit is displayed in fig.1.4. The airway pressure sensor is located in the inspiratory limb of the breathing circuit.

1.7 Anesthesia Mishaps.

Patient injury from anesthesia is rare. It is estimated that the incidence of anesthesia related death is less than 1 in 1000². Table I contains the results of an survey of common errors in anesthesia³. Both human errors (69 %) and machine failure (31 %) are shown.

Table I Frequent Critical Incidents.

| Category | Percent of total |
|--|------------------|
| Disconnections in Breathing Circuits | 8.5 |
| Incorrect Gas Flows | 5.9 |
| Inappropriate Airway Maintenance | 5.6 |
| Interchanges of Drug Syringes | 5.3 |
| Missing Equipment | 4.8 |
| Overdoses of Intravenous Drugs | 4.2 |
| Problems with Sources of Oxygen or Nitrous-Oxide | 3.9 |
| Disconnections of IV Apparatus | 2.9 |
| Wrong Connections in Breathing Circuits | 2.6 |
| Overdoses of Inhalation Anesthetics | 2.3 |
| Interchanges of Drug Ampules | 2.3 |
| Premature Extubations (judgement errors only) | 2.3 |
| Inadequate Fluid Replacement | 2.2 |
| Problems with ECG Monitors | 2.0 |
| Problems with Blood Pressure Monitors | 2.0 |
| Problems with Other Monitoring Devices | 2.0 |

Many critical events in anesthesia are felt to be preventable. Despite frequent checks of the machinery, one should always confront the possibility that something can go wrong with the system during a case. Most malfunctions are not lethal if detected soon enough. For example, disconnects in the breathing circuit, or a malfunctioning valve (see chapter 2) rarely cause injury if they are rapidly detected and corrected.

Anesthesiologists are primarily trained to take care of the patient, and there is less attention towards the anesthesia equipment. An educational package that teaches students (as well as experienced anesthesiologists) what can go wrong with an anesthesia machine, how to identify the problem using the

displayed signals, and how to solve the problem, could improve this situation.

An anesthesiologist must learn to differentiate between the problems he can correct, and the ones he cannot. In the first case he has to send for another anesthesia machine. In the second case he might be able to rapidly solve the problem, whereas waiting for another machine would cost valuable time.

The problem is how to teach an anesthesiology student all there is to know about anesthesia machines, including how to deal with machine malfunction. More specifically, the problem is that machine malfunctions occur so infrequently, and if they occur, they cause so much tension, that learning how to deal with them through the normal practice of anesthesia is virtually impossible. We proposed to solve this problem through the use of a simulator, an anesthesia machine that can generate these malfunctions, so that dealing with them can be learned in training sessions. In other high risk areas (aviation, nuclear power plants), simulators have been used for many years. This proposal has led to the development of an Anesthesia Machine Simulator, described in the next chapter.

2 Gainesville Anesthesia Simulator

The Gainesville Anesthesia Simulator attempts to reproduce the working environment of the anesthesiologist as realistically as possible while creating a number of undesired situations. The simulator consists of a modified anesthesia machine, connected to an artificial patient. A mechanical lung, connected to the breathing circuit with an endotracheal tube inserted into the plastic trachea of a mannequin head, simulates a mechanically ventilated patient under general anesthesia.

In the anesthesia machine a number of computer controllable actuators and computer readable sensors have been incorporated to create a challenge to the clinician responsible for the simulated patient. Information from several monitors is available to the clinician, as it is during routine anesthesia practice. In the simulator some of the signals are computer generated and therefore controllable. These include E.C.G., intra-arterial blood pressure and oxygen saturation. The CO₂ concentration, airway pressure and flows are actually measured in the breathing circuit.

In the current version of the simulator 15 different scenarios have been implemented. Nine scenarios are commonly, yet infrequently, observed machine malfunctions, while the other six represent patient related problems. A typical scenario starts with a mechanically ventilated, "stable" patient under general anesthesia. Gas flow settings and ventilation have been set to keep the patient stable. Then within a few minutes, a mishap, just like one encountered in clinical anesthesia, is created by the computer controlling the simulator.

The clinician is allowed to react spontaneously to the events. Sensors incorporated in the simulator allow the computer to monitor all actions taken. When the clinician takes the action that corrects the problem, the simulation stops, while the simulation will be aborted after four minutes otherwise. If a human brain does not get oxygen for 4 minutes, irreversible brain damage occurs. For this reason a time limit of four minutes is introduced.

In the following paragraphs the implementation of the different scenarios in the simulator is explained in more detail. What the effect of these events is on the various signals and what action is considered correct, is discussed in chapter 6.

2.1 Machine malfunctions.

The machine malfunctions that can be generated are:

1. Incompetent inspiratory valve. This malfunction is created by a solenoid placed under the inspiratory valve. If actuated, a pin will lift the valve up and prevent it from properly re-seating in the closed position. The user has to push the pin down in order to correct this problem. A sensor records this action.
2. Incompetent Expiratory valve. This is similar to (1), except the expiratory valve is disabled.
3. Exhausted CO₂ absorber. The CO₂ absorber is situated in the canister. The exhaustion of the absorber is simulated by a valve that allows some of the gas to bypass the absorber.
4. Canister Leak. The canister contains absorbing material. Like in (3), a valve, concealed in the CO₂ canister opens to the atmosphere, thus creating a leak in the breathing circuit.
5. Ventilator disconnect. The hose that connects the ventilator to the breathing circuit is pushed off pneumatically, creating a disconnect.
6. Vaporizer Leak. A leak in the halothane vaporizer (halothane is used in the anesthesia simulator) is introduced by a valve that allows all gas in the low pressure circuit to flow out of the system.
7. Loss of oxygen supply pressure. This malfunction is implemented by closing the oxygen wall supply line with a valve. A side effect is that the nitrous oxide supply will be closed by the fail-safe valve in the anesthesia machine. When actuated, the anesthesia simulator will sound a low oxygen pressure alarm.
8. Hypoxic Gas Mixture. This is simulated by activating a three way valve which closes the oxygen supply and opens a nitrous oxide connection. Both nitrous oxide and oxygen wall outlets will then supply nitrous oxide to the anesthesia machine.
9. Scavenging System Obstructed. Two valves are activated. These valves close the high pressure relief valve of the scavenging system and obstruct the vacuum hose, effectively obstructing the scavenging system.

2.2 Patient related problems.

Some of the simulated problems are patient related. In the simulator set-up, the patient is simulated by a mechanical lung. The compliance of the lung can be altered by two springs on each side of the lung. The oxygen consumption of the simulated patient is zero. To simulate CO₂ production, a gas flow of approximately 200 ml of CO₂ per minute is introduced into the lungs.

The following scenarios have been implemented:

1. Hypo-ventilation (a too low setting for tidal volume or ventilation rate; the per minute ventilated oxygen volume is then inadequate for the patient). This problem is generated by decreasing the tidal volume setting on the ventilator.
2. Deep anesthesia (the anesthetic agent concentration in the gas mixture is too high for this patient). The clinical signs created by the simulator include a decrease in heart rate and a lowering of the blood pressure of the simulated patient.
3. Light anesthesia (the concentration of the anesthetic agent in the gas mixture is now too low; the patient will start to wake up). This is simulated by increasing heart rate and blood pressure and by decreasing the compliance of the lungs (lungs become more stiff). This is done pneumatically by pistons that move the compliance springs next to the mechanical lung. Consequently airway pressure will increase. A side-effect is that the sheets covering the lung move, creating the impression that the patient is moving.
4. Cuff Leak. The cuff that surrounds the endotracheal tube is normally inflated with air, so that no anesthesia system air can escape. Now a valve deflates the cuff. The result is that part of the tidal volume will not be delivered to the lung (if the lungs have a low compliance, often none of the tidal volume will be delivered to the patient).
5. V-Q Mismatch. Pulmonary ventilation and perfusion are not well matched in the patient, creating relative hypoxemia. In the simulator, the scenario is realized by slowly decreasing the oxygen saturation displayed on the pulse oximeter.

6. Endobronchial intubation. This problem simulates that the endotracheal tube has slipped down into one of the mainstem bronchi. This is realized by closing off one of the bronchi of the mechanical lung with a valve. One of the bellows of the mechanical lung will no longer move, which is also visible on the pressure monitors on the front of the lung.

2.3 The Simulator as a Teaching Device.

Many simulated events are potentially lethal and can therefore only be taught without a human patient. The anesthesiologist trained with the simulator will be able to recognize the signs that are characteristic for each malfunction. For him, a glance at the monitors will, in an emergency, often be enough to diagnose the problem, where otherwise valuable time might have been lost in the identification of the problem if the characteristics of the problem were never seen before.

The simulator has travelled all over Europe and the U.S.A. and some of the designers travelled with it. The designers explained the system's many features while demonstrating the system. Also they had to explain why certain steps are followed, and why certain effects can be observed on the monitors during the different malfunctions.

The teaching potential of the simulator would increase tremendously if any user could just walk into a classroom, sit down at the simulator and start a case. Explanations about the simulator and how to use it, as well as helpful information about how to proceed in difficult situations, would need to be part of the simulator software. After a short introduction, the simulator would start a critical event that the student has to manage. After the scenario, an instruction and explanation of what to do and what to look for in which signals is given; if necessary the subject gets a retry.

What is needed is a tutor, that can work for 24 hours if necessary. Since a computer is already in use for the operation of the simulator system, another computer could be used to show the user, in a simplified manner, what actually happened inside the system, preferably in a graphics animation. This is the main subject of this thesis: an educational device for the anesthesia simulator.

Thanks to the experience gained while travelling with the simulator, a concept for the tutorial had already taken form. It had to consist of three parts:

- Part 1: An introduction to the system. Since there is a difference in monitors and anesthesia machines from the various manufacturers, one cannot expect the anesthesiologist to know all components and brands of monitors, although most anesthesia machines and monitoring equipment functions are basically the same. An introduction regarding the major components used in the simulator is needed if asked for.
- Part 2: A challenge. In this part the user is asked to solve a malfunction in the system. Meanwhile the computer will monitor all actions of the user so that feedback is possible.
- Part 3: Feedback. The user is told what the malfunction was, and shown what the effect of this malfunction was, preferably in a graphics animation on a computer screen. A possible approach to finding the solution to the problem can also be given.

This was, in a nutshell, the proposal for the educational package. In chapter 5 the implementation of these parts in the final program will be explained in detail.

After the decision was made to implement the educational package on a personal computer, the choice of a programming language became important. Quickly, programming language like BASIC, PASCAL and C* were discarded, mainly because they lack graphics (animation) capabilities. Almost all graphics packages (like Halo, Harvard Graphics etc.) were also discarded because no PC hardware interfaces were available for them. With these languages one can do animation, but communication capabilities are not part of these packages.

The relatively new programming language Smalltalk (Copyright Digitalk Inc.) looked promising. It combined graphics (as shown in the demo) with the interface to hardware. The decision was to use this language. In the next chapters, a more detailed description of Smalltalk and animation in general will be given.

* C ++, a new object oriented language, based on the programming language C was not available at the time this project was started and was therefore not included as a possible option.

3 Animation as teaching device

A picture says more than a thousand words. And animation attracts more attention than a still picture.

When testing the simulator it became obvious that the inside of the anesthesia machine is a mystery to many. Often drawings had to be made to explain how things work.

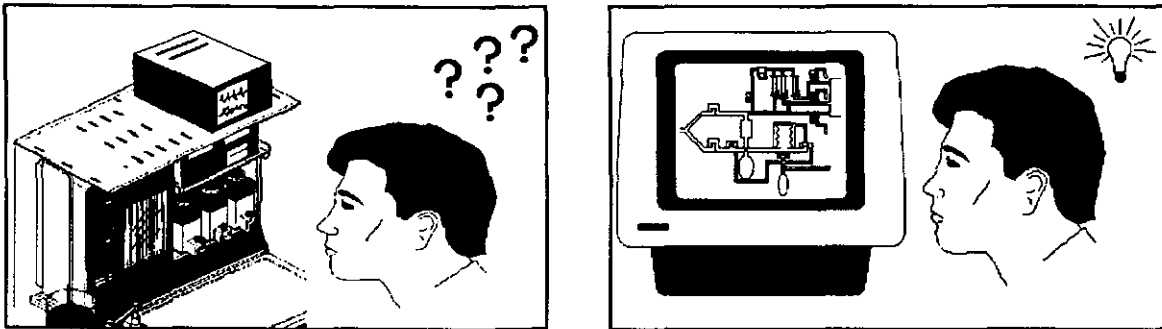


Fig.3.1. Understanding of the anesthesia machine through animated graphics.

Since a computer screen is used for the animated graphics, the same screen can also be used for the explanation. How this might work is visualized in fig. 3.1. The subject is challenged by one of the scenarios from the simulator. While probably able to solve the problem, he still might not understand all the aspects of the system. Using animated graphics, the same malfunction can be repeated, step by step. In the animation it is then explained what happens in the system during the malfunction and why a certain action will have a specific effect.

Animation has been known for a long time, especially in cartoons. In these animated movies, drawings are projected successively at a rate of around 25 pictures a second: at such a display frequency the impression of fluent motion is created. In a computer there are basically three different methods to do animation (for movie animation only the two first methods are available):

1st Method:

The main character of the movie is placed in front of a static background picture. Subsequently this character is replaced by another drawing, depicting the same character one frame later. A smooth and realistically moving effect

will appear when projecting the separate drawings in succession, if subsequent drawings differ only slightly.

In computer games the same method is used. The background is drawn into a display memory and a main character is displayed in front of it. In order to get a moving character, the separate parts of the character are stored in memory and displayed if needed. This works well if the moving objects are relatively small (at most 1/20 part of the screen).

There are some reasons for choosing not too big moving objects. The background of where the object is to be projected has to be stored in memory, because it needs to be restored subsequently. The location of the moving object has to be calculated, then the background has to be stored in memory, next the figure has to be projected on this place and finally the saved background has to be restored to its original location.

2nd Method:

Show the animation as a movie. Store all the screens in memory or on (hard-)disk and just change the contents of the display. Memory management in a computer is fast enough to make this possible. This is the preferred method if the animated part of the display is relatively large (like 1/2 of the screen). Since the entire screen is updated, the old screen can be discarded. The problem here lies in retrieving the screens from storage. The fastest way would be to store all screens in memory. However, the data representing a color screen is in the order of 100 kByte. Therefore the amount of memory needed is enormous.

If it would be possible to read the data from hard disk and write it straight to display memory, retrieval of the screens would be fast enough. But since DOS, the disk operating system, will not let you address the display memory directly, it is not clear as yet of how to do this.

3rd Method:

Instead of keeping all the different animation pictures stored, calculate every new picture. In theory this might be possible, but practice proved that it is simply not fast enough. Calculating points on a screen of size 640 x 350 pixels takes too much time.

Since the animation to be used in the Simulator would fill the entire screen (the gas molecules moving through the system go everywhere), method 2 was chosen.

With the current access times of hard disks and the limitations of Smalltalk and DOS, it is not possible to read pictures from disk fast enough for animation. It was decided to load all animation frames into memory, accepting the need for lots of memory.

In the next chapter Smalltalk animation is explained in more detail.

4 Smalltalk, a programming language

Once it was decided that the main emphasis in the programming language was on animated graphics, Smalltalk, a new but very promising object oriented language, was chosen. Smalltalk combines graphical applications (as shown in the animation in the program demo) with I/O programming features.

We started with Smalltalk\V 2.00, which included black and white graphics, but a color upgrade was available. Smalltalk\V 2.00 uses virtual memory to suggest an almost unlimited amount of memory. This virtual memory uses disk space as a memory extension. The Smalltalk environment, called the image, contains all defined objects and is stored in this virtual memory.

In August 1988 Smalltalk\V 286 arrived. This version of Smalltalk was written specifically for use with a 286 or 386 microprocessor; extended memory over 640 kByte up to a maximum of 16 MByte is addressable, but virtual memory is no longer supported.

4.1 The structure of Smalltalk

Smalltalk is an object oriented language. Objects⁴ are programming blocks that combine procedures and data and perform computations. The use of objects contrasts with the use of separate procedures and data in conventional programming languages.

Object-oriented programming entails sending messages from one object to another. Message sending is a form of procedure call, but instead of naming a procedure to perform an operation on an object, one sends the object a message. A selector in the message specifies the kind of operation. Objects respond to messages using their own procedures, called methods, for performing operations.

An important principle in programming, data abstraction, is supported by sending messages. The principle is that calling programs should not make assumptions about the implementation and internal representation of the data types used. Its purpose is to make it possible to change the underlying implementation without changing the calling program. A data type is implemented by choosing a representation for values and writing a procedure for each operation. A language supports data abstraction when it has a mechanism for bundling together all of the procedures

for a data type. In object-oriented programming, the class represents the data type whose values are its instance variables, and the operations are the methods the class responds to.

Compared with conventional languages, classes correspond to types. For example, if `number` is a type (class) then "1" is an instance of class `number`. Sending the message "+ 2" to "1" will give "3" as answer. Here "+" is the selector, and "1" is the object the message is sent to. The operation is to add "2" to "1" which is possible since both are instances of class `number`.

Sending the message "+ a" to "1" will give an error; "a" is an instance of class `character` and class `number` has no selectors allowing you to add an instance for number and an instance of `character`. Objects know which class they belong to.

4.2 Animation in Smalltalk.

Animation in Smalltalk is done by instances of class `Animation`. An instance of class `Animation` is an array of individual frames of the animated figure. After being defined, the new object (animation) can be told to go to a place on the screen with messages like "go:'numberOfSteps' or goto:'placeOnScreen'". After every step (the size of the step can be defined by message speed:'numberOfPixels' to object) the next frame of the array will be displayed; an animated figure thus appears to move on the screen. These messages, sent to the object, cause the procedures for this object not only to display the figure on its place of the screen, but also to store the underlying background in memory so it can be restored after the figure is moved.

In Smalltalk the animation is done as described in chapter 3 (method 1). In one demo animation provided with Smalltalk\V 2.00, four dogs, each in a different shade of grey, bounce around in a box. Here sometimes the background had to be saved (two dogs projected over each other when only one of the dogs moved). Immediately the speed of the moving object decreased. In the revised version, Smalltalk\V 286, the dogs in color became unacceptably slow. From this it became clear that the choice of animation technique 2 was the right choice.

4.2.1 Computer Animated Graphics Simulation.

The animation in the implemented tutorial is done by completely restoring the animated part of the screen as described in method 2, chapter 3. Early efforts, that used Smalltalk\V 2.00 for animation, showed this to be possible. However, due to the Smalltalk code necessary to perform animation, only two screens fit in the available 640 kByte memory at one time.

The complete set of screens was read into virtual memory, but with only two screens in real memory, the next two screens had to be loaded from disk. This unloading, searching and loading took several seconds, and was therefore unusable. A different approach used a combination of techniques 1 and 2: update only the screen parts that change. This way, all of the small elements could be stored in memory at the same time. The resulting animation was too slow, and the animation became jerky.

The release of Smalltalk\V 286 solved the memory problems. This version allows the user to address extended memory up to a maximum of 16 MByte. Thus all necessary screens could be loaded into memory (if enough physical memory is available).

The screens used in the different scenarios are stored on disk. Reading them from disk takes 50 seconds due to two factors:

- The Smalltalk language does not have a message to save the instance containing a picture (an instance of class **ColorForm** contains the bit map of the picture), to disk, so one had to be written. Smalltalk allows reading or writing to disk under program control, but only one byte at the time. Thus 40 kByte (one third of the screen) transfers to/from disk take a long time.

- Storing 10 screens for 15 scenarios of one third of the screen would consume approximately 6 Mbytes. To reduce this space requirement, a condensing program was written. Instead of 40 kBytes the average size was reduced to 16 kBytes. A disadvantage of condensing is that the original picture has to be restored by expanding the file.

These two factors require a trade-off: full picture data on disk takes too much time reading, while expanding the condensed file takes too much computing time. Trying out both methods showed that reading data from disk took more time compared to

reading and expanding a condensed file, and therefore the compactor method was selected.

Since the animation screen is mostly white, the easiest method to condense the available screens is to check the picture bit map for hexadecimal value 255 (all 1's in the screen memory) and to count them as long as they are successive. When reading the file, the numbers following the value of 255 indicate the number of 255's to be printed to the screen.

Additional information on this method of condensing files is provided in the code for class **DisplayObject**, subclasses **ColorForm** and **Form**, instances `readAndRestoreFrom:'aFileName'` and `writeShortTo:'aFileName'`.

The full screen animation implemented in the current version of the animated graphics uses eight full screens. It is displayed constantly to illustrate the basic functioning of the anesthesia machine.

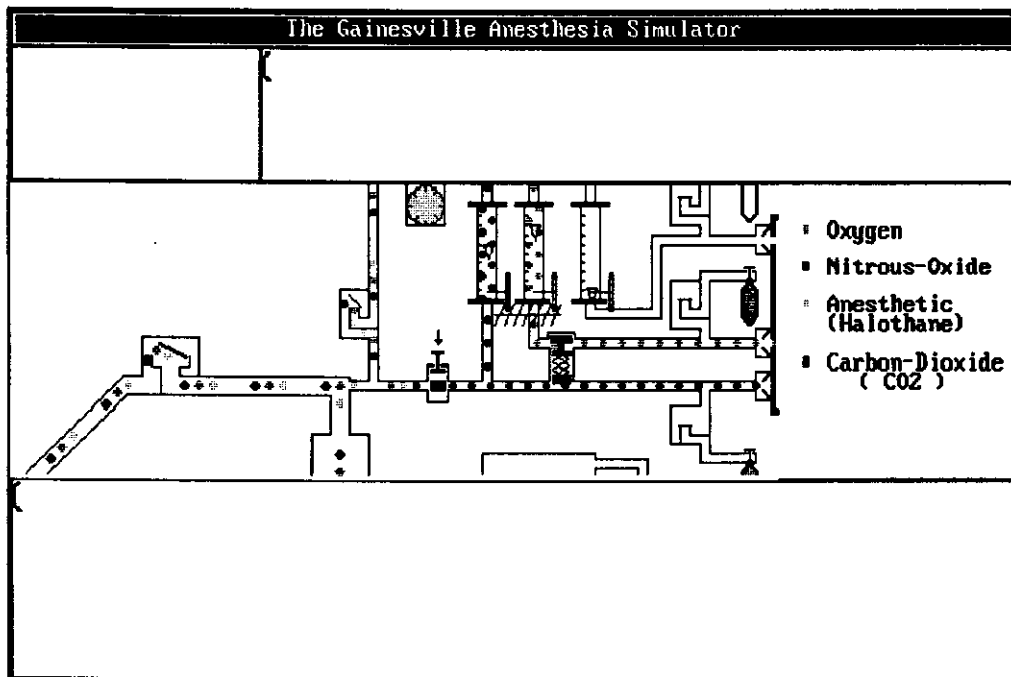


Fig.4.1. Animation in the Feedback phase.

As became apparent at several meetings where the system was shown, the feedback phase with animation was the most important part of the system. It shows not only animated graphics, but

also text, that explains what is going wrong and how to solve the problem. This meant that the whole screen would have to be used for both animation and text. The set-up shown in fig.4.1 was chosen. In the center one third of the screen, the animation takes place. We zoom in on this part from a still picture of the whole system after start up. The surrounding boxes are for the text and/or additional graphics (left top box), giving the feedback. Because only one third of the screen had to be updated, 10 frames for animation could be stored in the available 2.0 MBytes of memory.

5 Computer Aided Tutorial. (for use at G.A.S.)

While demonstrating G.A.S. at meetings, the simulator got a lot of attention, but there was always the need for a development team member to be present, not only to tell the people how to operate the machine but also to show them what went wrong and how to find the malfunction.

A computer aided tutorial should be capable of guiding someone through the system. The tutorial should teach the user how to start the simulator and how to operate it. After the simulation of an incident, it should show what went wrong in the system, why it went wrong and what could have been done to solve this problem.

Toward this goal, G.A.S. was divided into three parts:

- Introduction.
- Challenge.
- Feedback.

In the following paragraphs these phases are explained in more detail.

5.1 Introduction

The Gainesville Anesthesia Simulator is basically a standard anesthesia machine; it is real equipment with intact functions, but with a simulated patient. This simulated patient is considered to be a normal healthy young woman, with no known problems, already anesthetized.

Not all the trainees will be familiar with all the equipment and monitors that are used on the machine. Therefore an introduction to the Simulator is needed. The basics of the machine can be explained (for example through animated graphics) through a simplified schematic, combining anesthesia machine, breathing circuit, ventilator and scavenging system (see fig.5.1). The relation between schematic and machine can be pointed out, where the different parts are situated, how they work, how to take them apart, etc. We can indicate where monitoring equipment is located and show in graphics what the

"normal" signals look like. If necessary, a summary of possible abnormal signals can be given.

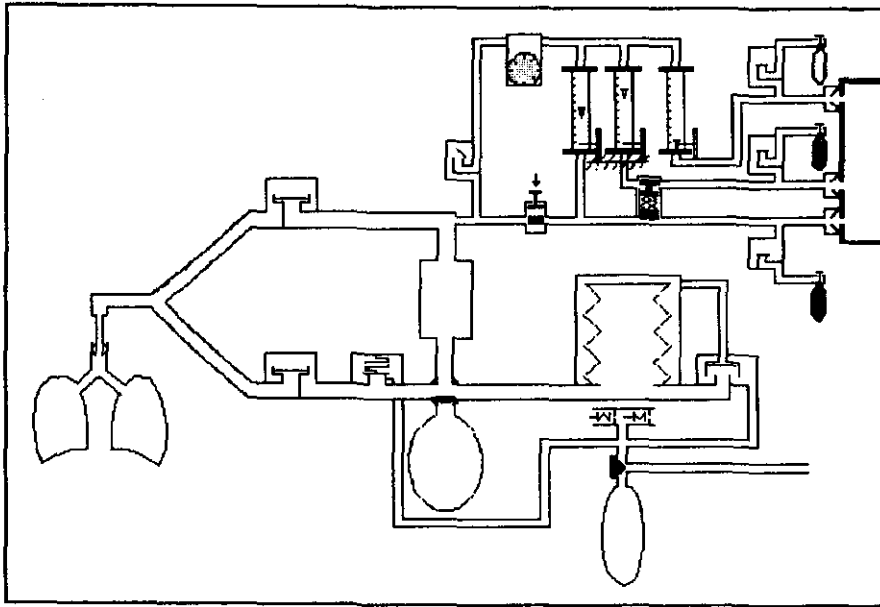


Fig.5.1. The total schematic of the anesthesia machine including breathing circuit, ventilator and patient.

Since an introduction may not be needed for everyone, the user can define his familiarity with the equipment. For example:

- Never worked with an anesthesia machine/do not know the equipment used here: Complete introduction.
- Performed anesthesia but some of the apparatus is unfamiliar: Choose apparatus unfamiliar with.
- Used the simulator before/need no additional information.

The last option is most likely to be chosen, since people tend to skip manuals. The user is subsequently asked to change some of the settings on the anesthesia machine. The computer can check the user's responses through the various sensors built into the simulator, and act accordingly.

The introduction currently implemented works as follows: A screen "Familiarity Check" is opened, where certain categories of equipment can be chosen. Information is given through scanned images of the anesthesia machine and images of the equipment used on the anesthesia machine. An example of such a screen is shown

in fig.5.2, where the location of the capnograph on the machine is chosen.

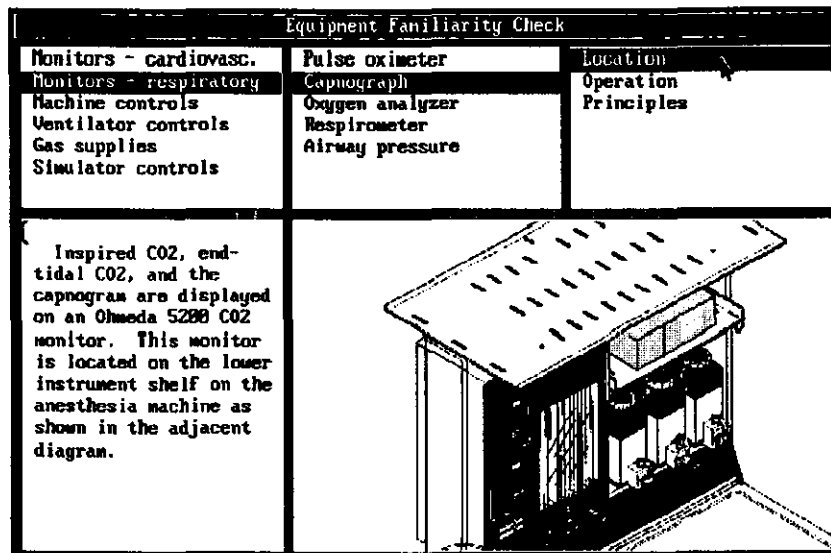


Fig.5.2. Tutorial screen information about capnograph, location of capnograph on machine and the manufacturer.

Using this screen, the user can choose the equipment with which he is unfamiliar. Subsequently a choice of subjects is offered (see table I). Finally a choice can be made between either Location, Operation or Principles.

- Location: the location or position of the chosen subject on the anesthesia machine is highlighted in bright red.
- Operation: a new screen (fig.5.3) will appear with a scanned image of the chosen subject with additional information. From here, either go back to the main screen, ask for additional information or exit to challenge.
- Principles: tells you how the selected subject works. Choosing the capnograph, for example, will inform you that the CO₂ percentage is measured by taking a gas sample in the Y-Piece and analyzed by using the optical absorption characteristics of CO₂.

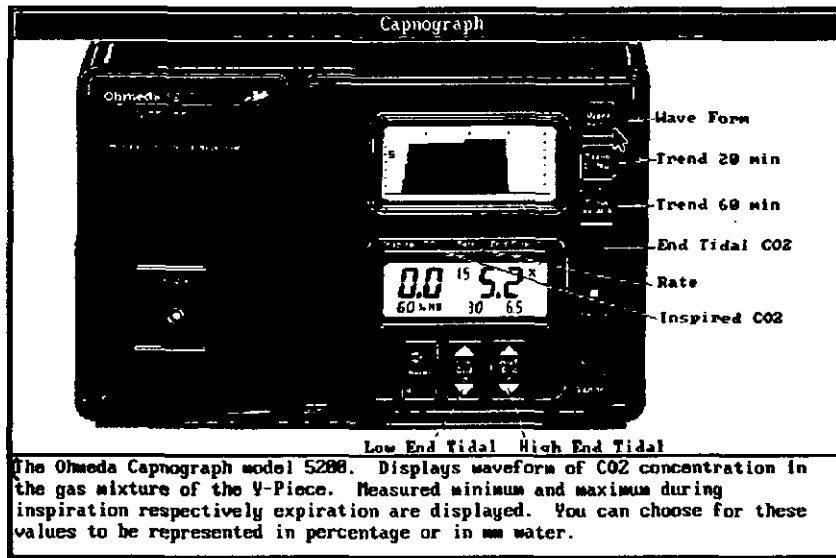


Fig.5.3. Choice "Operation" of capnograph in familiarity check leads to explanation of the operation of the capnograph through pictures.

Table II General classes and subclasses of equipment in Equipment Familiarity Check.

| | |
|---------------------------|--|
| Monitors - cardiovascular | Physiologic monitor Blood Pressure Pulse Oximeter |
| Monitors - respiratory | Pulse Oximeter Capnograph Oxygen Analyzer Respirometer Airway Pressure |
| Machine controls | Flow meters CO ₂ absorber Unidirectional Valves Switch Auto/Hand vent. Vaporizer Scavenging System |
| Ventilator controls | Ventilator Volume Flow meter Oxygen Sensor |
| Gas supplies | Wall outlet Flow meters Vaporizer Fresh gas outlet Breathing circuit Scavenging System |
| Simulator controls | Touch Screen Patient model Endobronchial tube |

5.2 The challenge phase.

The challenge phase is the phase where the user gets the chance to practice one of the 15 simulator scenarios. He will get a total of four minutes to diagnose the fault with the help of the monitors and to solve the problem. During this time the machine functions as during clinical practice, alarms go off and monitors give abnormal signals.

During the challenge phase, the computer screen is blank except for the word loading when the pictures are loaded from disk, and ready to indicate that the loading is finished. Reading 10 pictures from disk takes about 50 seconds. With a fastest response of a user of about 90 seconds, there is no waiting time for the user of the simulator when proceeding to the feedback phase.

The computer will record the actions of the user during the challenge phase for use in the feedback phase. The idea is that people follow a scenario in trying to find a malfunction, rather than random guesses.

5.3 The feedback

In the feedback phase, animation is used to explain the scenario played in the challenge phase. To show the gas flow inside the system, colored balls, representing 'molecules' of the different gases used in anesthesia, move inside the schematic diagram (fig. 5.2). The color of these balls is adjusted to the standard gas color code in the U.S.A. (see table III page 39). Black instead of grey is used in the animation for CO₂ balls, and red to indicate halothane (the halothane label is normally red). Some of the faults in the simulator are easy to recognize but hard to solve. Even when told what went wrong, it is often still not understood why a certain action is required.

A good example of such a problem is the scenario where nitrous oxide, instead of the expected oxygen, comes out of the oxygen pipeline, creating a hypoxic gas mixture. The action required seems quite simple, switch from oxygen wall supply to oxygen tank supply. What most people do not realize is that, with the oxygen wall supply line still pressurized (with nitrous oxide instead of oxygen), the check-valve between the wall supply and the oxygen tank will remain closed. Thus no oxygen will flow

from the oxygen tank. Only after disconnecting the wall plug, the oxygen tank supply will open the check valve and supply the oxygen.

Table III Color coding for gas used in anesthesia.

| Gas | Color code |
|----------------|------------|
| Air | yellow |
| Oxygen | green |
| Nitrous-oxide | blue |
| Carbon-dioxide | grey |
| Helium | red |

Using animation instead of words makes all of this easier to understand, as shown in fig.5.4 and fig.5.5.

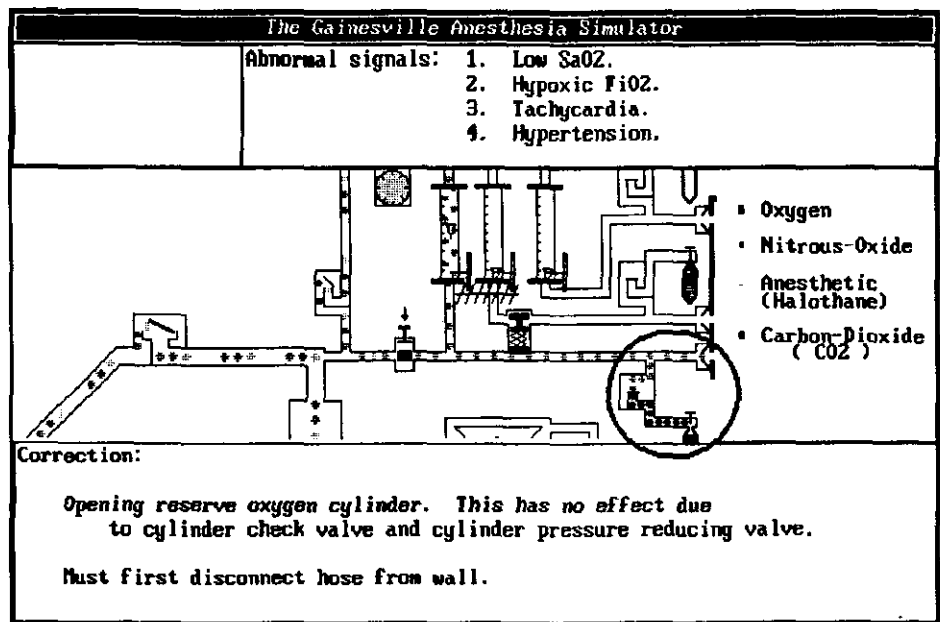


Fig.5.4. Wall supply pressure prevents oxygen from tank to flow into circuit.

Here it is clear that the nitrous oxide pressure in the wall supply system keeps the valve closed, so that opening the oxygen

tank has no effect (fig.5.4). Only after disconnecting the wall plug, the oxygen will flow out off the tank (fig.5.5).

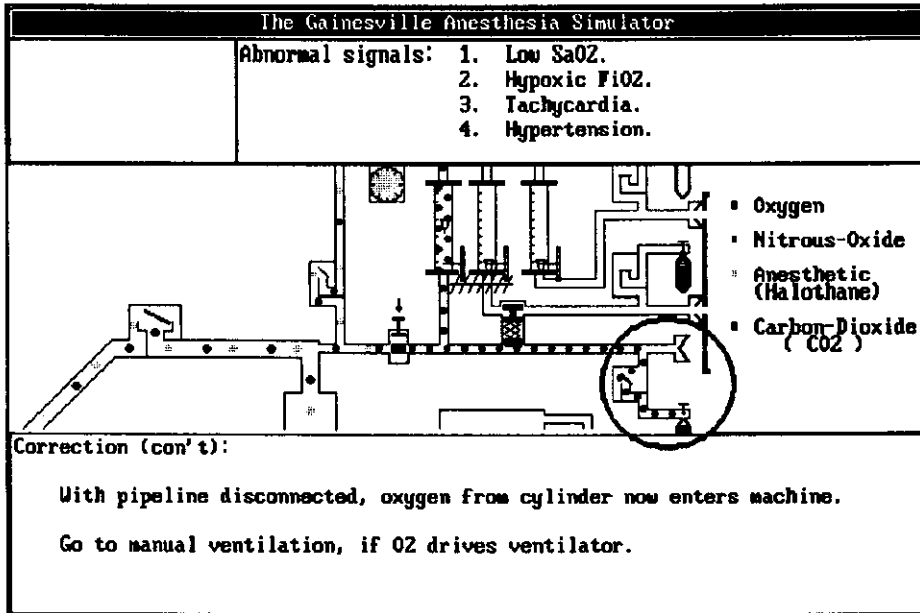


Fig.5.5. Oxygen from tank will flow if wall plug is disconnected.

To indicate there is still nitrous oxide coming out of the wall supply line, a blue ball is printed in the opening of the wall.

6 Malfunctions in the Simulator.

In the following 15 paragraphs the malfunctions occurring in the anesthesia machine simulator are explained in more detail, including a possible method for making a diagnosis. To our knowledge, never before has an attempt been made to specify what to do if certain 'alarming signals' (or just 'signals') can be observed on the monitors. In this chapter, general applicable methods are given to identify the problem at hand. We realize that the given scenarios are not perfect yet and are open for suggestions. More studies, that take into account the frequency at which malfunctions occur, might give a better defined outline. In paragraph 6.2., the animations dealing with the different malfunctions are described in more detail.

6.1 Malfunctions implemented in the Anesthesia Simulator.

The malfunctions are combined in groups. In the first four paragraphs, the main problem is an elevated expired and/or inspired CO₂ level. The next three scenarios have a leak, either in the breathing circuit or in the low pressure circuit. Then two scenarios deal with patient problems due to an incorrect setting on the anesthesia machine, followed by four scenarios where the oxygen supply to the patient fails for some reason, so hemoglobin oxygen saturation decreases. Finally, three scenarios deal with specific machine problems.

6.1.1 Hypo-ventilation.

The patient is hypo-ventilated when he does not get enough oxygen and the produced CO₂ is not adequately removed. The effects can be observed on the CO₂ monitor (fig.1.5). The waveform of the CO₂ concentration in the gas is not changed, but the maximum CO₂ percentage in the expired gas increases. There are three possible causes for increased expired CO₂:

- inadequate CO₂ removal from the breathing circuit
- CO₂ rebreathing
- increased CO₂ production

Since the capnogram does not show inspired CO₂, the cause is increased CO₂ production. There is no sign of malignant hyperthermia (exceptionally high fever) or hyper-metabolic state. A possible cause is that the patient is being hypo-ventilated, possibly because of low tidal volume and/or low respiratory rate. Try increasing either one or both of these variables.

This scenario is simulated by changing the tidal volume setting of the ventilator. The tidal volume becomes approximately half of its original value. The idea is for the anesthesiologist not to unconditionally trust the equipment but to check the measured values with the chosen settings. In the simulator the problem is solved by increasing tidal volume and/or respiratory rate.

6.1.2 Inspiratory valve malfunction.

The malfunction in this simulation is an incompetent inspiratory valve. If the valve is (partially) stuck open (fig.6.1), part of the expired gas is allowed to flow back into the inspiratory limb during expiration.

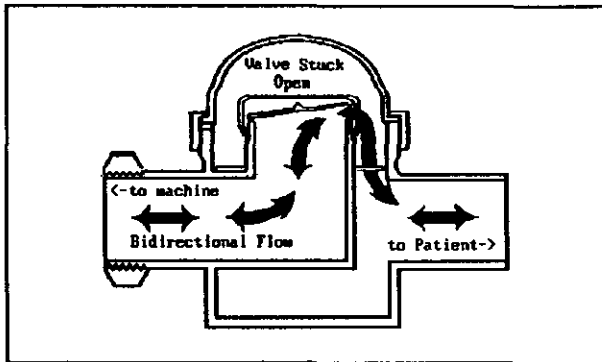


Fig.6.1 Malfunction; inspiratory valve is stuck open.



Fig.6.2 Waveform on the Capnograph.

Due to the back-flow in the inspiratory limb, the following alarming signals will appear on the various monitors.

1. Capnogram demonstrates sloped Phase IV*.
(note that the measured inspired CO_2 will still be zero, because inspired CO_2 is calculated as the minimum value of CO_2 concentration)
2. Measured tidal volume in expiratory limb decreased.

The alarming signal on the capnograph indicates CO_2 rebreathing. There are four possible causes of rebreathing:

- inspiratory valve malfunction
- expiratory valve malfunction
- exhausted CO_2 absorber
- a leak in one of the limbs

The tidal volume, measured in the expiratory limb, is decreased; this suggests a leak. A check of the peak airway

* The capnogram displayed on the Capnograph fig.2.4 is considered "normal". We distinguish four phases: Phase I is the level of Inspiratory CO_2 concentration, Phase II the upstroke, Phase III the level of the Expiratory CO_2 concentration and Phase IV the downstroke.

pressure monitor assures us that there is no leak; the airway pressure has not changed. This can be double checked by a positive pressure check of the breathing circuit:

Remove patient from breathing circuit and increase pressure in the breathing circuit by obstructing the Y-Piece. The pressure in the system should increase.

The capnograph on the simulator displays a capnogram that is so characteristic for CO₂ rebreathing due to an incompetent inspiratory valve, that it is possible to reach a conclusion based on this alarming signal alone (fig.6.2).

The response of the anesthesiologist should be to open the inspiratory valve dome, and replace or reseal the valve leaflet. In the simulator the valve is forced completely open by a solenoid valve, allowing about 50% of the gas to flow back in the inspiratory hose. The required action is to press down the pin; the sensor will send the response to the computer.

6.1.3 Expiratory valve malfunction.

This is comparable to the previous simulation, but here the expiratory valve is stuck open (see fig.6.3), allowing part of the expired gas to be rebreathed during inspiration.

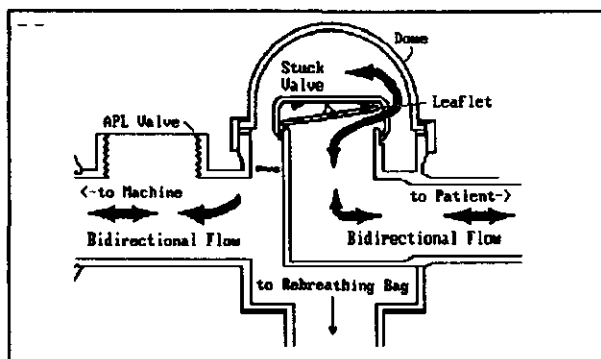


Fig.6.3. Malfunction: Expiratory Valve stuck open.

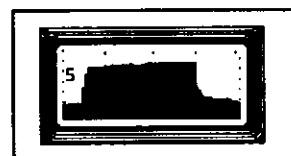


Fig.6.4. Waveform on the Capnograph.

Because of the partial rebreathing of the expired gas through the expiratory limb during inspiration, the alarming signals that will appear on the monitors (if present) are:

1. Capnogram - inspired CO_2 present.
2. Spirometer in the expiratory limb shows bi-directional flow.

Again we have inspired CO_2 (fig.6.4). Of the four possible causes, two are immediately discarded; there is no sign of a leak and the capnogram does not show the characteristic waveform for an inspiratory valve malfunction. The remaining two possibilities, exhausted CO_2 absorber and incompetent expiratory valve, cannot be told apart based on the waveform alone. The reverse flow alarm on the volume monitor will make this distinction possible; an expiratory valve malfunction is the only possibility. In the simulator, the spirometer is connected to the ventilator, which does not give negative flow. Therefore a second method is given to come to this conclusion.

To differentiate between the two malfunctions, increase the fresh gas flow. The expired gas will then be completely removed from the system by the scavenging system, effectively removing the CO_2 absorber from the system. With an exhausted CO_2 absorber, the inspired CO_2 will go back to zero.

If increasing the fresh gas flow does not change the inspired CO_2 , we have an incompetent expiratory valve. The expected action is to open the expiratory dome valve and replace or re-seat the valve leaflet. In the simulator, the malfunction is created by means of a solenoid valve which forces the valve open; this pin has to be pushed down.

6.1.4 Exhausted CO₂ absorber.

During anesthesia the CO₂ absorber gets exhausted. Normally the color of the absorbent will slowly change from yellow to purple (the indication that it is exhausted). Tunneling can cause the absorber material to be exhausted without any visual signs. The following alarming signals appear on the monitors:

1. Capnogram shows elevated end-tidal CO₂.
2. Capnogram shows inspired CO₂.

Again we have CO₂ rebreathing (fig.6.4); the same four possibilities as before have to be checked. For the same reasons mentioned in 6.1.3 the choice is between exhausted CO₂ absorber and incompetent expiratory valve.

Transforming the system into an open system (increase the fresh gas flow), will bring the inspired CO₂ back to zero. The conclusion is an exhausted CO₂ absorber.

In an actual case the anesthesiologist will be expected to replace the absorbent, but in the simulator there is no need to change the absorber. Lowering the canister, as if to replace the absorber, and pushing it back up will be enough to solve the problem.

6.1.5 Cuff Leak.

The cuff around the tip of the endotracheal tube is inflated with air to make lungs and breathing circuit a closed system. The problem simulated is a leaking cuff, causing the cuff on the endotracheal tube to slowly loose pressure. The end result is that part of the tidal volume will not be delivered to the patient. The following alarming signals will appear on the monitors:

1. Peak airway pressure reduced or absent.
2. Expired tidal volume low or absent.

A combination of these two signals is characteristic for a leak in the system. There are three possibilities: a leak in the breathing circuit, a leak in the connection between ventilator and breathing circuit or a leak in the low pressure circuit of the anesthesia machine.

To isolate a cuff leak, the following procedure is recommended:

1. Switch to manual ventilation. This does not improve matters (note that switching to an ambu-bag* will not have an effect either).
2. Perform a positive pressure leak check of the circuit (disconnect patient and generate pressure in breathing circuit). No leak is found in the breathing circuit.
3. Listen at trachea for leak during inspiration with positive pressure breath. This locates the leaky cuff of the endotracheal tube.

The above eliminations lead to the cause of the problem: a leak at the endotracheal tube. After the conclusion is reached, the anesthesiologist can re-inflate the cuff; pack the pharynx or replace the endotracheal tube. With the simulator, re-inflating the cuff is sufficient.

6.1.6 Canister Leak.

A leak in the canister allows part of the gas to flow out of the system. Due to this malfunction the following alarming signals will appear on the monitors:

1. Peak airway pressure reduced.
2. Expired tidal volume low or absent.

As indicated in 6.1.5., these signals are characteristic for a leak. The same scheme as before is used to isolate the leak:

1. Switch to manual ventilation. This does not improve matters.
2. Do a positive pressure leak check of the circuit (disconnect patient and generate pressure in breathing circuit). Discover leak of circuit.

If there is a leak in the breathing circuit, the next step is to find the location of the leak. The breathing circuit is made up of separate elements. Thus check the most likely spots: the connections (these include Y-Piece, inspiratory and expiratory hoses) and around the canister seals. Following this

* An ambu-bag is used to ventilate a patient by hand without an anesthesia machine and a breathing circuit. The bag can be used with room-air or oxygen from a tank.

elimination process the conclusion can be reached that we have a leak around the canister gasket*.

Suggested action is to re-seat the CO₂ canister, or to take the canister off, clean away absorber granules and re-attach. In the simulator, lowering the CO₂ canister and pushing it back up is enough to solve the problem.

6.1.7 Ventilator Disconnect (Leak).

During a case the ventilator hose may get disconnected or a leak may develop. The consequences of a disconnect are quite drastic: no gas whatsoever will be delivered to the patient. In case of a leak, the following alarming signals will appear on the monitors:

1. Peak airway pressure reduced.
2. Expired tidal volume low or absent.

Again, as in paragraphs 6.1.5 and 6.1.6, these signals suggest a leak in the circuit. The same approach is recommended:

1. Switch to manual ventilation. This corrects the problem.

Therefore the leak must be between ventilator and breathing circuit. A leak can be found through the same procedure as described in paragraph 6.1.6: check the most likely spots, the connections between ventilator and breathing circuit. Checking the ventilator connection leads to the discovery of the disconnect of the ventilator hose from the ventilator. Re-attaching the ventilator hose to the ventilator will solve the problem.

* The canister gasket is the ring around the top of the canisters to make them airtight.

6.1.8 Deep Anesthesia

In this simulation, the selected anesthetic concentration is too high for this particular patient. The alarming signals that accompany this particular problem are:

1. Bradycardia (relatively slow heart beat).
2. Hypotension (abnormally low blood pressure).

Since we find all other signals (oxygen saturation of the blood, capnogram, tidal volume, peak-airway pressure) "normal", consider deep anesthesia. The proper action is to reduce anesthesia by decreasing the concentration of anesthetic agent.

6.1.9 Light Anesthesia.

Here, in contrast to the previous problem, the selected concentration of anesthetic agent is too low. The patient starts to wake up and might even move. The alarming signals accompanying this problem are:

1. Tachycardia (relatively rapid heart action).
2. Hypertension (abnormally high blood pressure).
3. "Normal" to increased airway pressure.

Again with the other available signals (pulse oximeter reading, capnogram, tidal volume) unchanged, consider light anesthesia. The proper action is to increase the concentration of the anesthetic agent.

In the simulator not only the signals for heart rate and blood pressure are changed in this scenario, but the compliance of the lungs is also decreased. This is accomplished by moving the springs on the side of the mechanical lung. This results not only in increased airway pressure, but also has the side-effect that the sheets covering our "patient" move, creating the impression of a moving patient.

6.1.10 Hypoxic gas-mixture.

This scenario is the most appreciated in the simulator. This rare but dramatic problem can develop during a case. What happens is that somewhere in the hospital the main oxygen wall supply line is filled with a gas other than oxygen.

In the simulator, nitrous oxide comes out of the oxygen wall supply, causing a fresh gas flow consisting of pure nitrous oxide. All the oxygen in the breathing circuit will be replaced by nitrous oxide. The patient no longer gets oxygen and becomes hypoxic. The following alarming signals can be observed on the various monitors:

1. Oxygen analyzer shows low FiO_2^* .
2. Pulse oximeter shows hypoxemia.
3. Tachycardia may be present during early hypoxemia. Turns into bradycardia with advanced hypoxemia.
4. Hypertension may be present during early hypoxemia. Turns into hypotension with advanced hypoxemia.

According to the oxygen analyzer, the inspired oxygen is low. There seems to be a loss in oxygen supply to the patient. Since the result of this is hypoxemia, we start the elimination technique for hypoxemia; first turn off the nitrous oxide. After this, trace the "oxygen path".

1. Check fresh gas flow hose for kinks or obstructions.
2. Check fresh gas flows for adequate oxygen flow rate.
3. Check for leak in low pressure system (disconnect fresh gas flow tubing and occlude outlet with finger). Watch for bobbins to drop with occlusion. If they do, there is no leak.
4. Check fresh gas flow for oxygen by holding the oxygen analyzer in front of the fresh gas outlet.

The first three checks are adequate, since we seem to have a gas flow to the breathing circuit with no oxygen. Consider contaminated wall oxygen supply (this will be confirmed by 4.). For this reason switch to the oxygen tank supply instead of the wall supply.

Opening the oxygen tank will have no effect by itself. The pressure of the wall supply is 50-55 psi, whereas the pressure from the oxygen tank is converted to 40-45 psi. The check valve

* FiO_2 is the fraction of inspired Oxygen.

in between the two lines will keep the oxygen of the tank from flowing into the system while the wall supply line is pressurized (see fig.5.3 and 5.4). Disconnecting the wall supply line from the wall outlet will free the oxygen tank supply check valve.

Switching from mechanical ventilation to hand ventilation is suggested (if the ventilator is driven by oxygen) to save oxygen.

One of the deficiencies of the current simulator is that the mechanical lung does not consume oxygen, while the CO₂ production is simulated by a constant gas flow of 200 ml/minute of CO₂ into the lung. Therefore it takes a relatively long time for the gas mixture in the breathing circuit to loose all the oxygen. In a real patient, oxygen in the breathing circuit will disappear fast if the fresh gas flow does not contain any oxygen (as simulated).

In the simulator the fresh gas flow will be 100% nitrous oxide in order to "speed up" the scenario. In reality what "most often" occurs, is that somewhere in the hospital the lines for oxygen and nitrous oxide are crossed over. The effect will be that during the case, where often a 60% (nitrous) - 40% (oxygen) mixture is used, the cross over of oxygen and nitrous oxide will not have a significant effect. At the end of the case, where nitrous oxide is turned off, allowing the patient to loose the inhaled nitrous oxide by ventilating with 100% oxygen, what is delivered is 100% nitrous oxide. Since everything went normal during the case, the anesthesiologist is challenged even more.

6.1.11 Vaporizer Leak or disconnect.

The anesthesia machine simulator is equipped with three vaporizers. However, only the vaporizer for halothane is used. To prevent leaks, the vaporizers have built in safety features. If the vaporizer dial shows off, the vaporizer is completely removed from the system. The only possible malfunctions occur when:

- the vaporizer is not connected properly
- the filling cap is not tightened properly
- there is a leak in the vaporizer

During this scenario the signals on the monitors are similar to the ones mentioned in the previous paragraph.

1. Oxygen analyzer shows low FiO_2 .
2. Pulse oximeter shows hypoxemia.
3. Tachycardia during early hypoxemia. Turns into bradycardia with advanced hypoxemia.
4. Hypertension during early hypoxemia. Turns into hypotension with advanced hypoxemia.

Again we seem to have a loss of oxygen supply. The same actions as in paragraph 6.1.10. are suggested:

1. Check fresh gas flow hose - it is not kinked or occluded.
2. Check fresh gas flow settings for adequate oxygen flow rate.
3. Check for leak in low pressure system: disconnect fresh gas flow tubing and occlude outlet with finger. Watch for bobbins to drop with occlusion.

The bobbins will not drop; there is a leak in the low pressure system.

A leak in the low pressure system can have several possible causes. Check for the most likely spot, the vaporizer.

1. Check vaporizer cap; tighten if loose.
2. Turn off vaporizer to remove from circuit.

If this does not correct the problem the malfunction is a leak in the anesthesia machine, too difficult to solve. Here the anesthesiologist has to switch to an ambu-bag and send for another anesthesia machine. In the simulator the malfunction is a leak in the vaporizer, turning off the vaporizer will remove it from the system and the proper response is ensured by the oxygen analyzer, which shows increasing values.

6.1.12 Endobronchial intubation.

Endobronchial intubation can have two causes: during the case the endotracheal tube can slide down into one of the trachea, or it can be inserted into one of the trachea during intubation. In either case the result is that only one of the lungs is ventilated. This causes the following alarming signals to appear on the monitors:

- 1: Pulse oximeter shows low values.

The oxygen saturation of the blood is not high enough; for some reason the patient does not get the ventilated oxygen into his blood. The following approach is recommended:

1. Check Oxygen analyzer; it shows adequate FiO_2 .
2. Check ventilation. Breath sounds are present and expired CO_2 is normal.
3. Check for shunt*, either by listening to breath sounds or by checking the movement of the lungs. Discover breath sounds are $R > L$.

In the simulator there is as yet no possibility to check breath sounds. Since only one of the lungs is ventilated, a look at the pressure gauges on the test lung will show that only one of the lungs is moving, a clear indication of endotracheal intubation.

The anesthesiologist will have to pull back the endotracheal tube until breaths sound Right = Left. In the simulator pulling the tube will correct the problem.

6.1.13 V - Q mismatch.

The patient's lungs have a low compliance and therefore he does not respond to normal fresh gas flow settings. The tidal volume delivered to the patient is not enough to get the blood saturated. The malfunction shows on the monitor:

1. Pulse oximeter shows low values.

* Shunt: only one of the lungs is ventilated.

Like in endobronchial intubation, the gas delivered to the patient does not provide enough oxygen to the blood. The following approach is recommended:

1. Check Oxygen analyzer; it shows adequate FiO_2 .
2. Check ventilation. Breath sounds are present and expired CO_2 is normal.
3. Check for shunt (see 6.1.12); breath sounds are equal bilaterally.

Since we seem to be ventilating the patient with the proper gas mixture, and the expired CO_2 is normal, the only possibility left is that we have a V/Q mismatch. The problem can be solved for this patient by either adding PEEP to improve V/Q ratio or to increase FiO_2 .

6.1.14 Oxygen Loss in wall supply.

Since the central gas supply delivers all gases, there is a complex system of pipes throughout the hospital. Accidents happen: a leak can occur, somebody closes a vital valve, etc. It is feasible for the pressure of the oxygen supply to drop below 30 psi. This low pressure activates the fail safe valve in the high pressure system of the anesthesia machine, and closes the oxygen and nitrous oxide line. No fresh gas will be delivered to the breathing circuit.

Also the ventilator is rendered un-operational since it relies on oxygen as the driving gas. Thus no gas will be delivered to the patient. The following will happen:

1. Fresh gas-flow decreases to zero.
2. Ventilator sounds alarm.

The approach is straightforward: start with checking the gas pressure gauges. There is no pressure in the central oxygen pipeline. Conclusion is that the oxygen pipe line pressure is lost, causing the fail safe valve to close the nitrous oxide pipe line.

The anesthesiologist will open his oxygen cylinder. To prevent oxygen from flowing back in the wall supply, through a possibly malfunctioning check valve, it is wise to disconnect the wall plug from the wall outlet. Switch to manual ventilation to preserve oxygen in the oxygen tank, if the ventilator is driven by oxygen.

6.1.15 Scavenging System obstructed.

For some mysterious reason, the scavenging system got obstructed by a double failure. The pressure check valves in the system got obstructed (which can happen without any visible signs) and the vacuum hose got kinked or occluded (for example by rolling a piece of equipment over it). The following alarming signals will appear on the monitors*:

1. Elevated peak inspiratory pressure. Shows PEEP**, that was not selected.
2. Arterial pressure depressed.

Disconnecting the patient from the breathing circuit causes a decline in pressure in the breathing circuit. For this reason it is obvious that the scavenging system is obstructed, so that excess gas cannot leave the system.

Solve the problem by disconnecting the scavenging system or by eliminating the obstruction.

6.2 Malfunctions in Animated Graphics.

Two types of animation are implemented. The first type consists of 10 screens projected over each other (only the text in the boxes around the animation changes). These were made with Smalltalk V\2.00. The second type is more complicated, and starts out with an intact breathing circuit; then a fault is introduced, which changes the animation, and the viewer is taken through the scenario step by step. In the latter scenarios, pictures showing normal flows are loaded first. While going through the script, small parts of the pictures are updated.

The program is written such that the viewer can only see the animations. During the animation where malfunctions are shown, pressing the right mouse button once will stop the animation, after which pressing the left mouse button repeatedly

* Compared to other malfunctions, this one is controversial. On the simulator, the ventilator with standing bellows allows the pressure in the system to build up only to a certain point, after which the bellows functions as an over-pressure valve.

** A Peep-Valve is a valve used to maintain Positive End Expiratory Pressure in the patient.

will let you go through the pictures one at the time. Pressing the right mouse button once again will bring you back to the animation. Pressing the left mouse once during animation will bring you to the next phase of the scenario or display the next text.

In order to show the gas flow as smoothly as possible, the movement of the small balls (size 5 x 4) is 5 pixels every frame in the anesthesia machine part where a maximum of two colors is mixed. In the breathing circuit and all the other places where three or more colors are mixed the balls are size 7 x 5 or 5 x 5, and move 7 pixels every frame. Consequently the cycle of drawings in the anesthesia machine is three frames while the cycle in the rest of the system is five.

Originally these numbers (cycle of 5 and cycle of 3) were chosen to make a cycle of fifteen frames. An I : E ratio of 1 : 2 (5 inspiration, 5 expiration and 5 respiratory pause) could be easily realized. Memory shortage prevented this. To animate as good as possible with the present pictures, a cycle of ten is used if the major part of the screen contains the breathing circuit and ventilator and a cycle of nine if most of the anesthesia machine is shown, with satisfying results.

6.2.1 Hypo-ventilation.

This scenario does not change anything in the breathing circuit. For this reason only the normal flow in the breathing circuit and ventilator is shown. The normal flow pictures are stored in the directory "normal.flw", the program used to run the scenario is stored in file "prefnorm.flw", the text cycled stops if the string 'stop' is read.

6.2.2 Inspiratory valve malfunction.

This scenario is shown with the inspiratory valve constantly open. In the top left corner the capnogram (fig.6.2, file "capnogra.ml") will be displayed to show the characteristic waveform. Pressing the left mouse button will flip through the text until 'stop' is read. To emphasize the CO₂ flowing back into the inspiratory limb, the bi-directional flow in the

inspiratory limb is picturized not only by colored balls going back and forth but also by arrows, showing the two directions of the flow during inspiration and expiration. The pictures are stored in directory "stuckins", the scenario to run is stored in file "prefstuc.ins".

6.2.3 Expiratory valve malfunction.

Here the scenario is shown with the expiratory valve constantly open. In the left top corner the capnogram (fig.6.4, file "capnogra.m2") with elevated inspired CO₂ is shown. Again a bi-directional flow, this time in the expiratory limb, is picturized using colored balls going back and forth and by arrows pointing in the direction of the flow. The pictures are stored in directory "stuckexp", the scenario in file "prefstuc.exp".

6.2.4 Exhausted CO₂ absorber.

In this scenario the exhausted CO₂ absorber is illustrated by allowing black balls to flow around in the system, whereas normally they disappear in the CO₂ absorber. In the top left corner the same waveform as in 6.2.3. is displayed (normally the capnogram changes slowly to elevated CO₂ in case of exhausted CO₂ absorber since it is a gradual process; in the simulator the simulation causes the signals to be approximately the same). The pictures are stored in directory "CO2exh", the scenario in file "prefnorm.flw".

6.2.5 Cuff Leak.

The leak of the cuff is illustrated by showing gas coming out of the bronchia and disappear into the surrounding air. The pictures are stored in directory "cuffleak", the scenario in file "prefnorm.flw".

6.2.6 Canister Leak.

The leaking canister is illustrated as in the cuff leak by showing gas coming through a hole in the CO₂ absorber and disappear into the surrounding air. The pictures are stored in directory "cannleak", the scenario in file "prefleak.abs".

6.2.7 Ventilator Leak or Disconnect.

The animation is started with the normal flow pictures, but with no text shown. Pressing the left mouse button will cause the ventilator hose between the ventilator and the breathing circuit to become disconnected. A picture of the ventilator with collapsed bellows and no gas ("bwbellow") is displayed. The animation continues by gas flowing constantly into the CO₂ absorber ("lek1" through "lek5"), and out of the system through the disconnect. The patient is no longer ventilated.

In the next step a switch to hand ventilation is suggested. In the animation, forms ("hand1" through "hand10") are written to the original pictures allowing hand ventilation to be animated. This animation is shown through a window (only the left part of the screen is animated, in order to be able to keep a picture of the ventilator still being disconnected). After re-attaching the ventilator hose back on the ventilator, the system is working perfectly again, which is shown as the final stage. The pictures necessary for the show are stored in directory "ventdisc", the scenario in file "prefvent.dis".

6.2.8 Deep Anesthesia.

As in hypo-ventilation, the anesthesia machine is working perfectly, only the settings are incorrect. Therefore the same animation figures are used as in paragraph 6.2.1.

6.2.9 Light Anesthesia.

See deep anesthesia, paragraph 6.2.8.

6.2.10 Hypoxic gas mixture.

The animation for this malfunction is so complicated that the complete scenario could only be developed in Smalltalk V 286. The following animation was developed (see also paragraph 5.3.). In the animation we want to show nitrous oxide coming out of the oxygen line. To prevent the loading of a complete new set of pictures, the screens of this scenario are colored differently from the screens used in other scenarios.

Light green is the color in the oxygen tank up to the check valve, and dark green the color in the rest of the circuit. For nitrous oxide the tank is colored dark blue, where the rest is light blue. In Smalltalk V 286 this is disguised by defining these light and dark combinations as one color. Changing a color (for example green to blue, to show nitrous oxide coming out of the oxygen wall supply line) does not affect the part that has to stay the original color (the oxygen tank, which was originally dark green). Changing color is much faster than replacing a part of the picture.

The animation starts out normal, with no text. In the next step, green is turned into blue, as nitrous oxide is coming out of the oxygen wall supply line.

In the next phase the user is supposed to turn off nitrous oxide. This is animated by exchanging part of screen 10, which is not used in the normal animation, with the original pictures. The next step for the user is to open the oxygen tank (file "oxylock"). Gas flows to the check valve, and is stopped by the nitrous oxide pressure from the wall supply line (see fig.5.3). This is indicated by green and blue balls on either side of the check valve. After disconnecting the wall plug from the wall ("valvelos"), oxygen will flow out of the tank into the system ("oxygen1" through "oxygen3").

In the animation the nitrous oxide in the circuit is replaced by the oxygen. Since there is no nitrous oxide in the system anymore, blue is turned into white. The ventilator is turned off by copying part of form 3, where the bellows is down, to forms 1 and 9, where the bellows is up.

The code for changing a color to a different color during a program is done by evaluating:

```
Dos new setPaletteRegister:'presentColorNumber'  
      to:(CurrentPalette at:'newColorNumber + 1')
```

The complexity of the scenario made the animation text (file "prefcont.oxy") about 5 pages long, which takes several

seconds to compile. The pictures for animation are stored in directory "hypoxic".

6.2.11 Vaporizer Leak.

The animation starts out with the normal flow pictures, but with no text. At the start of the fault, the vaporizer leak occurs. All the gas out of the anesthesia machine will flow into the room, and no fresh gas will be delivered to the patient. Meanwhile the patient will be ventilated continuously with his expired gas with a decreasing oxygen percentage. This effect is created by putting five forms ("lek1" through "lek5") over the original pictures to create new pictures. By turning off the vaporizer (color red is made white) the problem is solved and gas flows into the breathing circuit again. No anesthetic agent will be present however. The pictures for the animation are stored in directory "vapodisc", the scenario for animation in file "prefvapo.dis".

6.2.12 Endobronchial Intubation.

As in the first animations, this animation consists of one set of pictures. Shown is the normal system with the endotracheal tube slid down in the right trachea. Therefore only one of the lungs is ventilated and moving. The pictures are stored in directory "endointu", the scenario played in file "prefnorm.flw".

6.2.13 V - Q Mismatch.

See deep anesthesia, paragraph 6.2.8.

6.2.14 Loss of oxygen wall pressure.

Again the system starts out normal, with no text. Next the oxygen pressure drops to zero, and the tenth picture, with no oxygen in the pipe line and the fail-safe valve obstructing the path of the nitrous oxide, is displayed. The ventilator is stuck in the top position. Opening the oxygen tank ("oxygen1" through "oxygen5") will pressurize the system, and a normal fresh gas flow is the result.

The same technique as with the hypoxic gas mixture is used, but now opening the tank has a direct effect. The next step is to disconnect the wall plug from the wall outlet. Also the ventilator is turned off; this is done by copying this part from picture 3, where the ventilator is down, to picture 1 and 9, where the ventilator is up. The pictures used for the animation are stored in directory "oxyloss", the scenario played in file "prefoxy.los".

6.2.15 Scavenging System Obstructed.

This scenario is not as clearly represented as the other 14. The malfunction asks for two faults in the system. The over-pressure valve must be blocked and the vacuum hose must be obstructed. The animation shows a slow expansion of the scavenging bag during five expirations ("scavbloc.1a" through "scavbloc.5e"). After this the bag will not expand any more. In the system this is true because of the natural over-pressure valve formed by the bellows that prevents the pressure from getting too high. The pictures for the animation are stored in directory "scavbloc" while the scenario played is stored in file "prefscav.blk".

Conclusions and recommendations:

We have shown that it is possible to perform animated graphics on a PC, to create both a tutorial, in combination with the simulator, and a stand alone system, usable for teaching the principles of the anesthesia machine and how to deal with possible problems.

Creating animated graphics takes more time than one would think. Graphics look good, but take a long time designing and drawing. Changes can only be suggested after a preliminary version is implemented. All the imperfect details do not show in the still pictures, but come forward during the animation. Removing all these flaws was very labor intensive.

The animated graphics proved to be a helpful addition to the anesthesia simulator. Most users voiced the opinion that it really helps them understanding what is going wrong, and that a graphical presentation is more likely to be remembered than a textbook. Therefore I conclude that this animated graphics, presenting a simplified diagram of an anesthesia machines, is a step forward in the evolution of the anesthesia simulator.

The current animation still is not real time. I think it is possible with the present status of technology to implement a real time version in Smalltalk. There is the need for a faster computer and a faster hard drive. At the moment the animation runs on an 8 MHz AT machine. On faster machines the animation is too fast; there it has to be slowed down. An alternative is to add new screens to make the animation more fluent. Then it might also be possible to do real time animation, in synchronization with the breathing cycle. The tutorial is a first implementation and many improvements can be added. However the framework has been developed.

The loading of the screens is as fast as currently possible in Smalltalk. In order to do this faster, a primitive function has to be added to load from disk directly into memory. One suggestion is based on the observation that in all the animations there is at least space for one more screen; if this screen were to be filled with all the parts that are needed to make the scenario animations, the time needed to load the forms for the animation from disk while animating would not be needed. Furthermore, the different scenarios written in the text files starting with "pref" can be made shorter by creating new instances, for example an instance of class Array to run 9 or 10 screens until the left button is pressed. Finally, the animations that consist of one set of pictures can be transformed into scenarios.

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