Mobile Monitoring in Anaesthesia using smartphones

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Abstract

An anaesthesiologist carefully monitors the patient’s vital signs for irregularities, ensuring the patients wellbeing. Most complications in anaesthesiology are caused by human error and evolve gradually over time (Cooper, Newbower, & Kitz, 1984). In this study we explore the possibilities of using a smartphone to monitor the patient in anaesthesia. A mobile monitor can reduce human error by keeping the anaesthesiologist informed outside the operating room, facilitating early detection and reducing biases during consults. Based on several pilot studies a prototype was developed and tested during a diagnostic reasoning experiment. In the experiment the anaesthesiologist was called by a nurse anaesthetist for a consult. Subjects had the task to diagnose six complications with the aid of the prototype mobile monitor. The resulting verbal protocols show what diagnostic reasoning process is supported by the mobile monitor and how it differs from the popular model of Gaba, Howard, and Small (1995). The observed reasoning resulted in several improvements in the design of the mobile monitor.

Doctor: Yes. More apparatus, please, nurse: the E.E.G., the B.P. monitor, and the A.V.V.

Nurse: Yes. Certainly, Doctor.

Doctor: And, uh, get the machine that goes 'ping'. And get the most expensive machine, in case the administrator comes.

Monty Python – The Meaning of Life (1983)

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1. Introduction

The field of anaesthesia strives towards a higher degree of patient safety. Maybe even more than other fields of medicine, since anaesthesia by itself is not therapeutic (Gaba, Maxwell, & DeAnda, 1987). In healthcare, patient safety is increased by continuously improving work processes and by training medical students according to the latest insights. At the same time hospitals need to cut costs, forcing them to be very efficient. For this reason, technical equipment is introduced in many hospitals. Examples are electronic patient databases, robots collecting prescriptions in the pharmacy and machines to automatically administer drugs to the patient. Such systems may save time (and thus money) and are less likely to make mistakes if properly set up.

To become even more efficient, several systems are developed to help clinicians with the collection of medically relevant information. Magnetic Resonance Imaging (MRI) and Positron Emission tomography (PET) scanners enable clinicians to gather information which was previously inaccessible. Patient monitors provide an overview of clinical relevant patient data which allows clinicians to integrate information quickly. The success of such systems depends on the information they provide, but also on the ease of interpreting this information and the ease of interacting with the system. Therefore it is important to take the capabilities of the users into account when designing such a system.

Designing machines accommodating to the limits of the human user is the concern of the field called *Human Factors Engineering.* The fundamental goal of human factors engineering is to reduce error, increase productivity and enhance safety and comfort while a human interacts with the system (Wickens & Hollands, 2000). Designing systems to reduce error in anaesthesia is very important. Misinterpretation of information or failure to interact with a system could lead to a series of adverse events potentially resulting in the patient's death.
Early efforts to improve safety in anaesthesia have dealt with improvements to the delivery system, the anaesthetic machine. These include engineered safety improvements, like unique gas-connectors which prevent misconnections, colour coding and interlocks to prevent the delivery of hypoxic gas mixtures (Petty, 1978). Many of current studies focus on the design of new patient monitors (van Amsterdam, 2010; Drews & Westenskow, 2006; Hooff & Cnossen, 2010; Kennedy, Merry, Warman, & Webster, 2009).

In this study we focus on designing a smartphone based mobile patient monitor for anaesthesiologists. More and more people are using smartphones. In the second quarter of 2011 42% of Dutch consumers were using a smartphone (Niezink, 2011). Using smartphones in healthcare settings is a relatively new phenomenon, but it's quickly growing due to the demand of innovation in healthcare (Kroes, 2011).

Structure of the thesis

In this thesis the design of a mobile patient monitor will be discussed. This thesis consists of four parts: the job of the anaesthesiologist, past research, design of new mobile anaesthesia monitor and finally a diagnostic experiment using the designed prototype will be discussed.

2. Background

The main goal of this thesis is to explore the potential of a patient monitoring application for smartphones. Before exploring this potential it is vital to have a basic notion of the complex working environment of the anaesthesiologist. In paragraph 2.1 a description of the anaesthesiologist's job is given along with a short overview of its difficulties. The mobile monitoring application will be based on patient data provided by monitoring equipment already available in the operating room. An overview of the current monitoring equipment is given in chapter 2.2

2.1. The job of the anaesthesiologist

An anaesthesiologist is a medical specialist who is involved in the whole surgical process. The anaesthesiologist is responsible for the patient's well-being from the time of administering general anaesthesia before the operation until the recovery afterwards. Short-term decision making and teamwork are very important in this line of work.

A patient under general anaesthesia is given pain blockers, hypnotics and muscle relaxants. In this thesis general anaesthesia will be referred to as anaesthesia.

Pain blockers ensure that the patient does not feel anything during the operation and hypnotics keep the patient unconscious. Due to the muscle relaxants the patient is not able to breathe autonomously. Therefore the anaesthesiologist manually ventilates the patient by placing an endotracheal tube in the patient's trachea during the administration of the general anaesthesia. This endotracheal tube will be connected to a ventilation machine which controls the breathing of the patient. Once this is all done, the patient is prepared for surgery.

Anaesthesiologists often rely on routine, but vigilance is warranted. A human being is intrinsically complex. An effectively infinite number of patient states is possible, making it impossible to anticipate all possible patient states and situations (Pott, Johnson, & Cnossen, 2005). However monitoring patient states and reacting to complications is extremely important. De Waal & Buhre (2010) discern four major categories of systems of the human body that are monitored during anaesthesia, which will be discussed next.

Cardiovascular system

Some fundamental aspects of the cardiovascular system are monitored for every patient under anaesthesia, regardless of the kind of anaesthesia, type of surgery or state of the patient. The main components of the cardiovascular system are the heart and the blood vessels. This system is roughly divided in two loops. One of the loops, called the pulmonary circulation system, transports oxygen-depleted blood from the heart to the lungs where the blood gets oxygenated. The oxygenated blood then returns to the heart. The other loop is the systemic circulation system which transports the oxygenated blood to the rest of the body and oxygen-depleted blood back to the heart. In addition to oxygen nutrients are transported to the cells. Carbon dioxide (CO_2) and other waste are carried in the opposite direction by the oxygen-depleted blood.

Respiratory system

The respiratory system is tightly coupled to the cardiovascular system. It introduces air to the interior of the lungs where gas exchange takes place. Oxygen is exchanged for CO_2 and other waste, which are then exhaled. During the operation the patient is ventilated by a machine which lets a mix of oxygen, air and anaesthetics flow into the lungs. The machine pressurizes the lungs to create an inflow and depressurizes to create an outflow of “used” air. During the operation the anaesthesiologist controls the pressure, the composition of the mix of gasses and the respiratory rate.

Anaesthesia depth and awareness

While under general anaesthesia 0,1-0,2% of all patients report some kind of intraoperative awareness (de Waal & Buhre, 2010). Most patients experiencing a form of intraoperative awareness do not experience any form of discomfort such as pain or stress, but they recall certain events or things being said during the procedure. To minimize the number of patients that do experience discomfort it is important to maintain an adequate depth of anaesthesia without overloading the patient with drugs. A significant part of monitoring this is still being done by looking at the patient’s pupil diameter, the position of the pupils and respiration. In addition to prevent the patient feeling discomfort, an adequate depth of anaesthesia ensures that the patient is immobilized, which allows the surgeon to work with greater accuracy.

Other monitoring

Depending on the patient’s medical history and the type of surgery additional forms of monitoring like neuromuscular monitoring may be used. During most operations temperature is measured, because body temperature is influenced by the use of anaesthetics. A low body temperature (hypothermia) could lead to numerous adverse outcomes (Sessler, 2008). Also urine production is often measured; lower urine production can indicate for example blood loss or heart failure.

2.2. Available monitoring equipment in anaesthesia

At the University Medical Centre of Groningen (UMCG), where this research was done, the anaesthesiologists have two devices at their disposal for perioperative monitoring. The Dräger Primus, the ventilator machine, is combined with a Phillips MP-70 patient monitor as shown in Figure

Figure 1 Dräger Primus ventilator with Philips MP70 patient monitor

1. Together they display the variables set by the anaesthesiologist such as ventilation pressure and gas mixture and the patient's variables which will be discussed in the next paragraph. With the ventilator machine the anaesthesiologist is able to change the gas mixture and pressures simply by pressing a few buttons.

2.2.1. Variables represented on patient monitors

The Philips MP-70 IntelliVue patient monitor is customizable by the user. Colour, alarms, variables and positions of the variables can all be set. Customizing the layout is a complex procedure requiring various steps. Mostly the anaesthesiologists use roughly the same layout and the same colours for the monitor. In this paragraph the variables in the 'standard' layout configuration will be explained along with some examples of interpretations by the anaesthesiologist.

Heart rate (HR)

Heart rate is the number of contractions (heart beats) per unit of time. This is typically expressed as beats per minute. As explained in section 2.1 the function of the heart is to pump oxygenated blood through the body and the oxygen-depleted blood back to the lungs for gas exchange.
During surgery a changing heart rate can indicate pain or it can be influenced by anaesthesia. In the operating room heart rate is typically measured with electrodes on the torso, but it can also be measured with a pulse oxymeter or invasively using central venous pressure.

Oxygen Saturation (SpO_2)

Oxygen (O_2) saturation is a measure of oxyhaemoglobin (haemoglobin chemically bound to an O_2 molecule). This is typically measured with a pulse oxymeter, this device calculates an estimation of the oxygen saturation using a measure of light absorption of the pulsing arterial blood alone (oxygenated blood is bright red, oxygen depleted blood is dark red or blue). Usually this device is clipped to the patient's finger or earlobe and the measurement is expressed as a percentage. This variable is called the saturation of peripheral oxygen (SpO_2).

A low saturation indicates a lack of oxygen going to the organs; if this continues for too long, this can lead to damage to the organs.

Blood pressure (BP)

In this study blood pressure refers to arterial blood pressure. High blood pressure (hypertension) among other things can indicate pain and low blood pressure (hypotension) can indicate shock. Both indicate a physical imbalance. Systolic (maximum pressure after contraction of the heart) and diastolic (minimum pressure when atria are relaxed) blood pressure are measured in millimetre of mercury (mmHg). Often the mean blood pressure is calculated. Blood pressure is measured peripheral using a (Riva-Rocci) cuff or invasively using an intra-arterial cannula. The arterial measurement is more exact and continuous, but causes the patient more discomfort and therefore not always used.

Tidal volume (TV)

The tidal volume is the maximum volume (ml) of air pumped into the lungs by the ventilator machine. The ventilator machine can be set in two ways, volume-controlled (pressure varies) or pressure-controlled (tidal volume varies). Both settings are used and differ from patient to patient and from the preference of the anaesthesiologist. Lower volumes may indicate ventilating problems

Positive end-expiratory pressure (PEEP) and Peak airway pressure (PAWP)

Positive end-expiratory pressure *(*PEEP) is set on the ventilator machine and is the minimum lung pressure and lies above atmospheric pressure. This pressure is maintained by the ventilator machine to prevent the lungs from collapsing during exhalation. The Peak airway pressure (PAWP) is the maximum pressure of air pumped into the lungs and can be set on the ventilator machine or vary when the tidal volume is set. Both of these pressures are measured in millimetre of water (mmH_2O)

End tidal CO_2 ($etCO_2$)

The end tidal CO_2 is measured in kilopascal (kPa) and represents the CO_2 concentration in the expired air. The body consumes oxygen and produces CO_2 as a waste product. A low CO_2 can indicate a problem in the circulation or the oxygen supply, but a high CO_2 could also indicate problems.

2.2.2. Curves represented on patient monitors

Most commonly four different curves are shown on the patient monitor. The curves give a graphical display of the course of the represented variables and will be explained in the order they are placed on the monitor

Electrocardiogram (ECG)

An electrocardiogram (ECG) is an interpretation of the electrical activity of the heart muscle over time. This curve provides information about the functioning of the heart. An anaesthesiologist is able to detect heart failure from the shape of the curve. Because an ECG is based on electrical activity measured from the skin, it is easily distorted by external signals. For example, electric surgical equipment could distort the ECG. Fluctuations in heart rate presented on the monitor can also be caused by such external signals, because heart rate is often derived from the ECG.

Figure 2 ECG curve with Heart Rate

Plethysmogram

The plethysmogram is a curve which is a visual presentation of the volume of blood through an arterial blood vessel. This is measured by the pulse oxymeter which also measures saturation. The peaks indicate the maximum amount of blood in the vessel. Lower peaks could thus indicate a problem with a decreased blood flow to the arterial blood vessels.

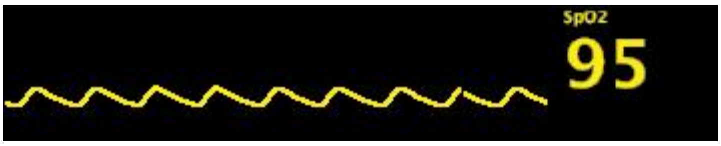


Figure 3 Plethysmogram curve with SpO_2 value

Capnogram

The capnogram is a visual presentation of the amount of CO_2 in the respirated air and is measured by the ventilator machine. The capnogram reflects the elimination of CO_2 and indirectly the production of CO_2 by the organs. During inhalation the CO_2 concentration is approximately 0% as the ventilator machine pump a CO_2 free mixture into the lungs. During exhalation the CO_2 normally increases to a maximum just before a new inhalation. The peak of the curve depicts the $etCO_2$ value explained earlier. The capnogram is a good indicator for adverse respiratory events.

Figure 4 Capnogram with end tidal CO_2 value

Ventilation pressure curve

What is represented by the ventilation curves depends on the type of ventilation set on the ventilator machine. There are two common types of ventilation that were mentioned in section 2.2.1.: volume-controlled ventilation and pressure-controlled ventilation. With volume-controlled ventilation the total volume of air is set by the anaesthesiologist and the machine calculates the needed pressure. More often the patient is ventilated pressure controlled, where the anaesthesiologist sets the pressure to reach a certain volume. In this case the anaesthesiologist has direct control over the ventilation pressure. The PEEP and PAWP values depict the maximum and minimum of the ventilation pressure curve.

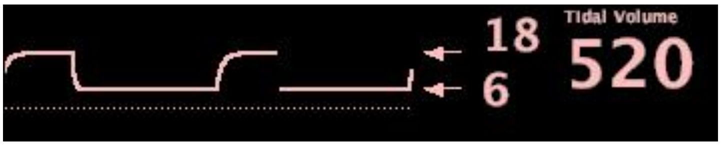


Figure 5 Ventilation pressure curve with PAWP, PEEP and tidal volume

Trends

In addition to these four curves, the patient monitor has a function to show trends. These trends are line graphs which show how certain variables changed over time. The anaesthesiologist can select a variable through a menu structure to show its trend. For example the trend of the heart rate can be viewed over the last 30 minutes.

3. Earlier research

A lot of research has been done in the field of improving patient safety in anaesthesia. In this chapter an overview is given of this research. The overview is roughly divided into three parts in which safety in anaesthesia, the cognitive processes of the anaesthesiologist and the technical aids that have been developed over the years will be discussed. These paragraphs will give a historic overview of research being done so far and serves as a basis for the development of the mobile monitor.

3.1. Safety in Anaesthesia

Since ether narcosis was successfully demonstrated by William Morton on October 16th at the Boston Massachusetts General Hospital in 1846 (Lyons & Petrucelli, 1987) and since the first publication of John Snow concerning the safety of ether narcosis (Ellis, 1994), the field of anaesthesia has come a long way. In this paragraph an impression of this improved safety is given and we will discuss the research on human error in anaesthesia.

3.1.1. Risks of anaesthesia: mortality and complications

In 1954 Beecher and Todd published their extensive study on anaesthesia and surgery related deaths over the period of 1948-1952. In the light of today's number of deaths the results were very high. One in every 2680 patients died because of the used form of anaesthesia and one patient in every 1560 died of an anaesthesia related cause. The study by Beecher and Todd (1954) marked the beginning of contemporary efforts to study, quantify and improve the risks associated with anaesthesia (Botney, 2008). In the years that followed the study of Beecher and Todd, the mortality rate dropped. Smalhout (1972) reported a rate of 1 in 3250 for anaesthesia related deaths in the Netherlands and 10 years later Cooper (1984) reported approximately 6400 anaesthesia-related deaths in the United States. This translates into an anaesthesia-related death rate of one in 3125. Of these deaths half was classified as preventable. Today the risk of dying from anaesthesia-related causes has dropped even further, Arbous et al. (2001) estimate the incidence of anaesthesia related deaths 1 in 7143 and recent studies of Lienhart et al. (2006) indicate a mortality rate of 1 in 250.000 for healthy patients and a rate of 1 in 10.000 – 15.000 for less healthy patients. Amalberti, Auroy, Berwick, & Barach (2005) and Li, Warner, Lang, Huang, & Sun (2009) even indicate a risk of 1 per million for healthy patients.

While mortality rate provides an estimate of the risk of dying during anaesthesia, the large variety of injuries and complications that can result from anaesthesia should also be considered. Nyst & van der Schaaf (2005) suggest also a 'near miss' reporting system instead of only reporting adverse events. However this system has not yet been adopted throughout the field.

Not all deaths and injuries can be avoided, but many can. Unexpected and unwanted events are commonly referred to as complications (Rowbotham & Smith, 2007). In 1978, Cooper, Newbower and Long found that hypoxia and airway loss were the most common complications resulting in death and major disability. Today the most frequent complications during anaesthesia are arrhythmia, hypotension, adverse drug effects and inadequate ventilation (Rowbotham & Smith, 2007). The equipment that is at the disposal of the anaesthesiologist has become more reliable over the years, more drug research lead to safer drugs and some complications are still inevitable simply because the patient is too sick. The most common cause of complications is still human error.

3.1.2. Human error

As mentioned earlier, human error was found to be a significant contributor for many documented complications. To study complications and anaesthetic mishaps Cooper, Newbower and Long, (1978) and Cooper, (1984) used a form of critical incident analysis. Most described incidents were caused by human error (82%). Other studies found human error rates varying from 56 up to 80% (DeAnda, Gaba, & Lee, 1990; Fletcher, McGeorge, Flin, Glavin, & Maran, 2002; Short et al., 1996). However the statement that around 80% of anaesthetic incidents involve human error is potentially misleading. This value by itself suggests that anaesthesiologists have a major human error problem, but similar values are found in most other domains as well (Reason, 2005).

Human error has been generically defined as: *instances of man-machine or man-task misfits* - (Rasmussen, 1982). There is however more than one definition and for the field of anaesthesiology we will define human error as*: a failure to perform an action as intended* (S. J. Wheeler & Wheeler, 2005).

Human errors can be subdivided into slips, mistakes and lapses (Reason, 1990). Slips are actions (or lack of action) by the anaesthesiologist which did not occur as planned (Gaba, 1989). For example: missing a vein when taking a blood sample.

The distinction between a slip and a lapse can be very hard for researchers to identify objectively, this is probably why Gaba (1989) omitted lapses. Lapses involve memory failure and may be only be apparent to the person who experiences them (Reason, 1990). An example is to forget to administer antibiotic prophylaxis prior to tourniquet inflation (S. J. Wheeler & Wheeler, 2005). Slips and lapses occur when actions do not go according to plan, mistakes happen when the plan itself is faulty. A mistake is defined by Gaba (1989) as a decision resulting in an action or lack of action by the anaesthesiologist which is causally linked to a possible or actual adverse outcome. For example: treating a patient on the basis of a wrong diagnosis. Mistakes can be subdivided into two categories: rule-based and knowledge-based mistakes (Reason, 2005). Rule-based mistakes occur with familiar or trained–for problems. A large part of the anaesthesiologist's job is applying rules: *if x then do y.* It is a form of pattern matching and this can go wrong in two ways. A good rule can be applied in the wrong situation and a bad rule can be applied. Knowledge-based mistakes occur when an anaesthesiologist encounters a previous unseen situation. Under these conditions, practitioners are forced to use slow, effortful, online reasoning (Reason, 2005). This can lead to premature fixation on a hypothesis and reliance on an incomplete mental model. An additional factor is the highly resource limited capacity for conscious thought; humans can only attend to and manipulate one or two discrete items at one time.

3.2. Cognitive processes of the anaesthesiologist

Because human error is involved in a large portion of complications that arise, it is important to discuss the cognitive processes of the anaesthesiologist. Anaesthesiologists need to be very flexible with their attention, switching from one source of information to the other, trying to ensure good decision making to maintain the patient's health. In the following paragraphs an overview is given of the role of attention and diagnostic reasoning.

3.2.1. Attention – vigilance

Information processing is a key element to the anaesthesiologist's job, therefore it is important to understand the limitations of human attention. Attention is a vulnerable resource. If it decreases or is defective for example due to fatigue, people are often less capable to perform their tasks as well as they would normally do (St. Pierre, Hofinger, & Buerschaper, 2008). There are different forms and descriptions of attention, in this section the focus lies on vigilance

Vigilance is the ability to remain alertly watchful for extended periods of time and to react to rare and accidentally occurring stimuli (St. Pierre et al., 2008). During World War II this phenomenon was initially studied in radar monitors (Mackworth, 1948). Mackworth found that the level of vigilance was often lower than desired and that it dropped steeply after half an hour of watch. These results were also replicated in a research with industrial inspectors (Harris & Chaney, 1969). The decrease in vigilance is known as vigilance decrement (Wickens & Hollands, 2000).

Monitoring patients in anaesthesiology is a vigilance task (some societies of anaesthesia even have it integrated into their maxim: v*igila et ventila* (stay vigilant and ventilate) (St. Pierre et al., 2008)). Some operations can take hours and vigilance can become a problem. Weinger and Englund (1990) studied a range of factors influencing monitoring performance and vigilance in anaesthesiologists and discerned three general categories: the environmental component, the human component and the equipment component.

Environmental components that may decrement the level of vigilance are temperature and humidity, environmental toxicity, ambient lighting and workplace constraints (e.g., the arrangement of equipment). Clinical information for example is gained primarily visually, by looking at the patient or monitors. Monitor glare caused by non-diffused lighting could seriously impair vigilance (Weinger & Englund, 1990).

The human component consists of human error (see section 3.1.2.), interpersonal and team factors and other personal factors like fatigue, workload and stress. Several tools have been created to assess the human component (Loeb, 1993; Loeb, 1994; Weinger et al., 1994). For example, Loeb (1993, 1994) found higher response times for the detection of abnormal monitor values and more missed monitor events during induction (a time of high workload) than during maintenance. However not every task impairs vigilance, according to the study of Slagle and Weinger (2009) reading during the maintenance period of the operation doesn't impair vigilance.

The third category Weinger and Englund (1990) discerned, the equipment category concerns mainly human factors principles and the design of equipment which will be discussed in chapter 3.3. Maintenance and good calibration of equipment leads to trustworthy equipment and aids vigilance.

In addition to being vigilant it is also important for the anaesthesiologist to know what is going on in the operating room. This situation awareness will be discussed next.

3.2.2. Attention – situation awareness

In order to plan or problem solve effectively in dynamic, changing environments (e.g. the operating room), people must have a relatively accurate awareness of the current and evolving situation (Wickens & Hollands, 2000). Situation awareness plays a role in a variety of situations and it has been extensively studied in aviation. For example: the tragic case of the airplane flying into a mountain in Columbia.

The two pilots were in a rush to land the plane because of a delay. When cleared for landing, they entered a wrong beacon into the Flight Management system which caused the plane to turn away from the runway. For one minute neither of the two pilots noticed this change of course. When the pilots detected that they were on the wrong path they had difficulties determining their location relative to an important radio beacon. After several minutes the pilots turned the aircraft towards the desired path. However, while solving the problem they lost awareness of their distance from the terrain around them. An alarm sounded and the crew attempted an immediate climb away from the terrain. However they were unsuccessful because they failed to notice that the speed brakes, designed to aid the airplane in losing lift, were still deployed. Impact occurred a few seconds later. This accident occurred because the pilots lost situational awareness of their geographic location relative to the terrain and the state of the aircraft (Endsley & Strauch, 1997). Situation awareness includes knowing what actually happens and what information is present in the actual situation, what the actual events signify and in which directions the situation could evolve (Endsley, 1995; St. Pierre et al., 2008). This concept is also applicable in domains such as anaesthesia. According to Gaba, Howard and Small (1995), anaesthesia and aviation share a lot of characteristics such as dynamism, complexity, high information load, variable workload and risk.

Anaesthesiologists work within a complex sociotechnical system, where the problem space is large and the number of relevant factors that anaesthesiologists (and system designers) need to take into account is enormous (Pott, Johnson, et al., 2005). St. Pierre et al. (2008) state that in order to develop and maintain situation awareness in these situations, people first have to construct a situational image (their term) of the current situation by detecting all objects, parameters and events that might be relevant. In order to keep this situational image up to date it has to be updated regularly and the perceived elements have to be assessed with respect to their relevance. Endsley (1995) described the role of situation awareness in aviation as the three levels shown in figure 6. According to Endsley the first level contains perception of the elements in the current situation. The

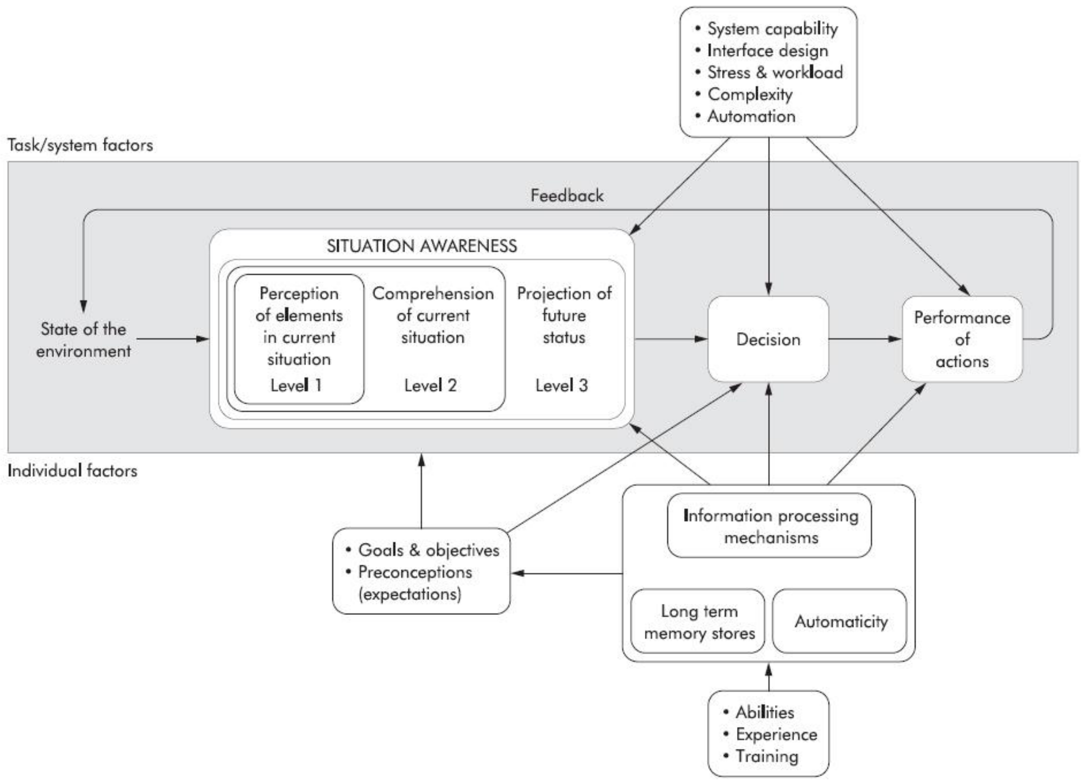


Figure 6. Model of situation awareness in aviation (Endsley, 1995).

second level contains understanding what these elements signify in the current situation. The third level is to use level 1 and 2 to predict a future state. In figure 6 the role of situation awareness in the overall decision-making process is shown. Several major factors influence situation awareness: an individual's capabilities, the design of the system and the individual's objectives and preconceptions. Vigilance explained in the previous chapter would for a large part fall under what Endsley (1995) described as the first level of situation awareness.

Gaba et al. (1995) integrated situation awareness in their model of the problem solving behaviour of

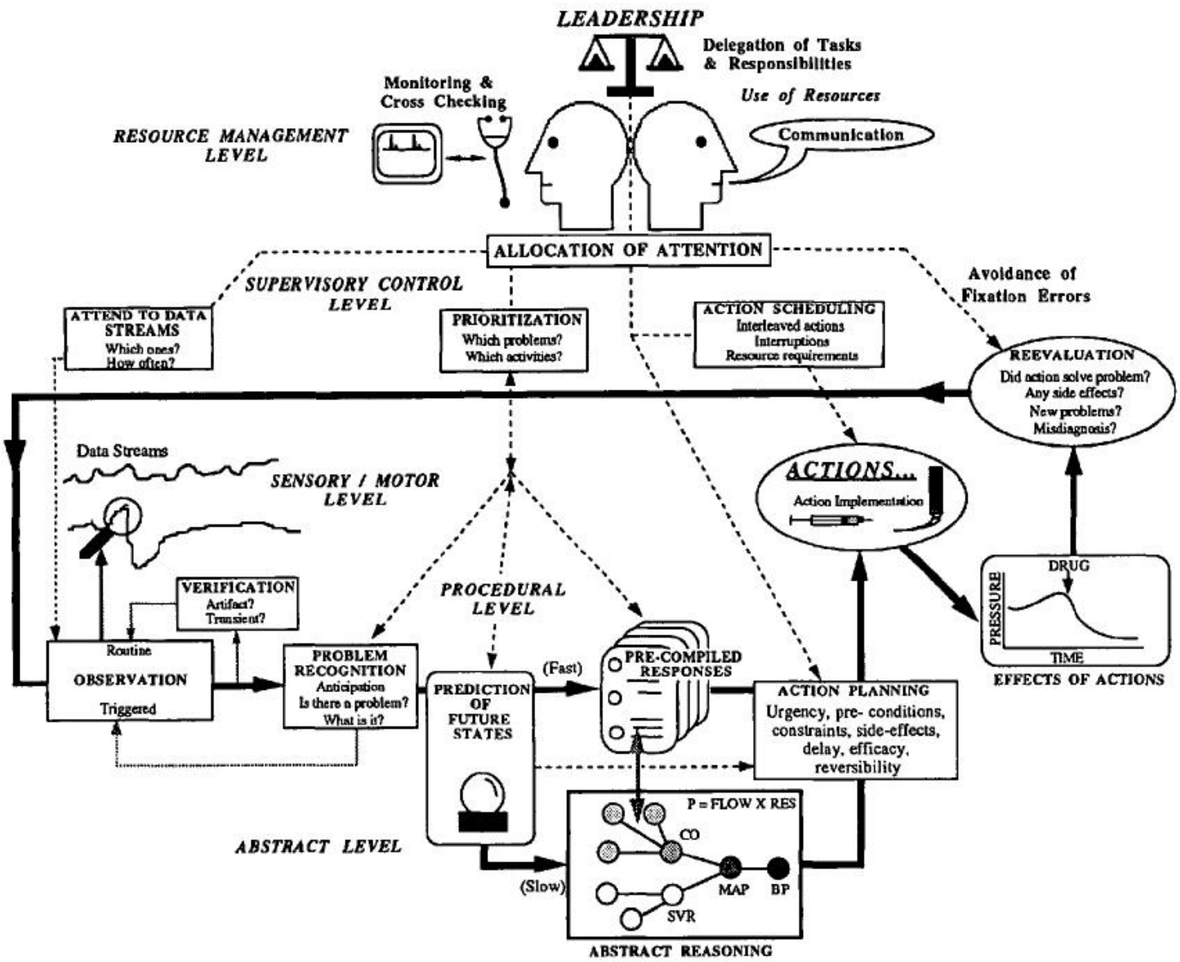


Figure 7 A cognitive process model of the anaesthesiologist's problem-solving behavior (Gaba et al. 1995).

anaesthesiologists.

The model, shown in figure 7 incorporates models of Klein (1989), Rasmussen (1986) and Reason (1990). It shows five levels of mental activity adapting to Rasmussen (1983). The five levels consist of a sensory / motor level, a procedural level, an abstract level, a supervisory control level and a resource management level. According to Gaba et al. (1995) the latter two levels are responsible for situation awareness. Supervisory control concerns allocation of attention, prioritization of tasks and scheduling of actions. Resource management concerns the mobilization and utilization of available resources, the distribution of workload and communication with others. There is a rapidly iterating loop of observation (where vigilance plays a crucial role), data verification, problem recognition, fast pre-compiled responses and slow abstract reasoning. Based on these steps the anaesthesiologist arrives at action planning and evaluates the outcome. Then the process starts all over. Situation awareness in the model of Gaba et al. (1995) is similar to situation awareness in the model of Endsley (1995). Observation matches with the first level of Endsley, verification and problem recognition with the second level and prediction of future states with the third. Using their model, Gaba et al. (1995) analysed key aspects of situations and recommended training including: practice in scanning instruments, explicit training in allocating attention (using games), and enhanced training in situation assessment and on pattern matching. This specialized training could benefit situation awareness and therefore patient safety. Like in aviation training, training is done using a simulator.

3.2.3. Decision making

Situation awareness is a part of problem solving. Other parts of problem solving are diagnostic reasoning and decision making. Clinical reasoning, medical problem solving, diagnostic reasoning and decision making are all terms used in a growing body of literature that examines how clinicians make clinical decisions (Patel & Arocha, 2004). In anaesthesiology, Cooper, Newbower, & Kitz,(1984) found that 33% of incidents with a substantial negative outcome were caused by judgmental errors. These errors in which the action represents a bad decision, arise from lapses in training or poorly developed decision making skills (Cooper, 1984). The results underline that decision making is an important subject in improving safety. Croskerry (2005) conducted a survey asking 30 medical professionals about the last time they read a journal article or book explicitly about decision making and how important they thought decision making was in their practice. Unanimously they answered that decision making is indeed very important, but 80% had not read anything on the topic since residency training. Croskerry argues that this is caused by the prevailing research position in medicine that perceives clinicians as purely objective and rational hypothesis testing individuals who weigh every factor and who are not influenced by environmental factors. However in anaesthesiology it has been shown that anaesthesiologists use other forms of decision making. For example DeAnda et al., (1990) observed mostly the use of pattern matching without careful deliberation. This type of decision making would fit into the pre-compiled responses of the model of (Gaba et al., 1995).

When presented with unfamiliar problems or problems that do not respond to the typical procedural responses anaesthesiologists have to switch to abstract reasoning. There many different theories of diagnostic reasoning. According to Croskerry (2009) all of these approaches can be roughly divided into two main groups, the intuitive and the analytical approach. The intuitive approach leans heavily on the experience of the decision maker and uses reasoning that depends on inductive logic (deriving a general conclusion from a set of particular statements). According to the intuitive approach experienced decision makers recognize overall patterns in the information and act accordingly. Typically these decisions are made under uncertainty because not all information is present and they employ heuristics or mental shortcuts (Tversky & Kahneman, 1974). Decisions in the intuitive approach may be made very quickly (Croskerry, 2009). The analytical approach takes place under more ideal circumstances where there is a greater availability of resources resulting in less uncertainty. Decisions made under these circumstances are more rational (Croskerry, 2009). Gaba et al. (1995) do not explain the process of abstract reasoning in their model of decision making, but it seems to fit with the analytical approach. Norman (2005) states that conceptual knowledge of basic science may be used more often in anaesthesiology than in other medical fields. Reasoning in areas such as anaesthesiology and critical care management is very different from other fields of medicine, resembling in part the vigilance of the aircraft pilot and in part the fine 'tweaking' of a complex non-linear system that one sees in an expert mechanic (Norman, 2005).

Heuristics and biases

In many instances of complications the anaesthesiologist will initially try a pre-compiled response. A pre-compiled response is a treatment response which was used numerous times in the past. The anaesthesiologist knows the risks and benefits of the treatment and has seen the response it normally generates (Weingart & Wyer, 2006). The fast pre-compiled responses are used when rapid action is needed and are based on heuristics. Heuristics are rules of thumb, intuitions, abbreviations, simple judgements and short cuts (Croskerry, 2005). Important heuristics for anaesthesiologists are the representativeness heuristic and the availability heuristic (Kremer, Faut-Callahan, & Hicks, 2002). The representativeness heuristic causes people to think that the probability that "A" belongs to a given class "B" is directly related to the degree to which "A" resembles "B". The anaesthesiologist would be judging for example the probability that shortness of breath originates from cardiac versus pulmonary failure (Kremer et al., 2002). The availability heuristic refers to the ease with which instances or occurrences can be brought to mind (Tversky & Kahneman, 1974).

While heuristics lead to quick decision-making when necessary, they may also lead to cognitive biases (Croskerry, 2005; Wickens & Hollands, 2000). For example the confirmation bias: experimental data suggests that people in general are overconfident in their state of knowledge or beliefs. People are primarily looking for information that confirms their current hypothesis and are not seeking information that supports an opposite conclusion (Wickens & Hollands, 2000). Another well-known problem in anaesthesia is anchoring, which is the tendency not to deviate from an early diagnosis. Anaesthesiologists sometimes have a tendency to bias their belief revisions in favour of an initially chosen hypothesis (Wickens & Hollands, 2000).

While the above description of heuristics and biases seems to paint a pessimistic picture of the decision-making of anaesthesiologists, heuristics enable a decision maker to adapt to situations where the decision maker must work rapidly and cannot afford to invest a large amount of mental effort or time to consider all the possible hypotheses (Wickens & Hollands, 2000). Heuristics are often used because most of the time they do lead to a correct, or at least satisfactory outcome. In order to minimize the negative aspects of heuristics, practitioners need to be trained in decision making and to be aware of the dangers of heuristics (Gaba, 1992; Klemola & Norros, 1997, 2001; Norman, 2005). In addition, crisis management manuals (containing protocols for specific situations) are developed to support decision making (Bacon, Morris, Runciman, & Currie, 2005; Runciman et al., 2005).

3.3. Technical aids

Another way to improve safety is to improve the equipment of the anaesthesiologist. In the following paragraphs we will take a look at a variety of state-of-the-art technical solutions developed to aid the anaesthesiologist in his work. This can among other things be done by improving situation awareness, reducing workload and supporting decision-making. First the use of alarms and the auditory modality will be discussed. After that an overview of decision support systems and monitors will be given.

3.3.1. Alarms & auditory displays

Auditory attention is different form visual attention in several ways. First, the auditory sense can take input from any direction, and thus there is no need to actively scan the environment. Second, most auditory input is transient (Wickens & Hollands, 2000). In other words, a sound is heard and then it ends, while most visual information is more continuously available. Auditory alarms are particularly useful when attending to other things, at least when these alarms are not false or going off too often. Alarms are cheap and easily fitted. An anaesthetic workstation filled with several pieces of apparatus may produce 20 or more alarm sounds (Edworthy & Hellier, 2005). The success of alarms is dependent on their sensitivity and specificity as well as of the staff responding to them (Schoenberg, Sands, & Safran, 1999). A sensitive alarm will go off sooner and more often, than a less sensitive alarm. A sensitive alarm will miss less critical situations, but may cause more false alarms. A more specific alarm may alarm for a single situation, a less specific alarm for a range of situations. For many alarms these three factors are not optimal, in a study by Block and Schaaf (1996) it was shown that in 81% of the auditory alarms going off there was no risk to the patient. These alarms were false alarms or alarms indicating there was a change outside a default limit. This high level of non-critical alarms results in anaesthesiologists ignoring alarms, silencing alarms or increase boundaries to avoid the alarm going off at all. Watson, Sanderson and Russell (2004) found that anaesthesiologists responded to only 3.4% of all auditory alarms An ideal alarm system would only warn when appropriate; the sounds would be standardized according to function, sounds should reflect the urgency, false alarms would be rare rather than common and learnability would be given proper consideration (Edworthy & Hellier, 2005). To approach this ideal several systems have been designed. For example, Ballast (1992) designed an alarm system that responds to changing values instead of boundaries being violated. Since the goal of anaesthesiologist is to keep his patient stabile, this seems a good way to prevent missing slow changes (Simons & Rensink, 2005). Ballast (1992) also suggested a visual cue instead of an annoying on-going alarm signal. Despite ideas such as Ballast's, there has been little progress for the last 20 years in the field of alarm systems, most alarms are still simple threshold alarms (Imhoff & Kuhls, 2006). Threshold alarms indicate a change outside a pre-set limit. A threshold alarm going off does not always signify a critical event and is sensitive to artefacts (for example caused by surgical activity) causing a variable momentarily moving outside the pre-set limit.

Auditory displays

Another way of exploiting the characteristics of the auditory modality is by using auditory displays. Presenting auditory information redundant to information on visual displays may allow offloading of some visual workload to the auditory channel (Seagull, Wickens, & Loeb, 2001). For alarming this seems valid. However Seagull et al. (2001) did not find significant improvements in monitoring performance when visual information was made redundant by introducing sounds representing a heartbeat and breathing. An example of an implementation of an auditory display that made it into the current operating room is variable tone pulse oximetry, in which the pitch depicts the saturation (Sanderson, Watson, & Russell, 2005). For example: when saturation drops, pitch of the sound drops. Another sonification in the current operating room is that of the heart rate, which is presented by a beep for every heartbeat. Sonification has disadvantages in an already noisy operation room. Other sounds may mask the auditory displays and anaesthesiologists may fail to notice slow changes if no auditory standard is provided. This makes visual backup or other cues essential (Sanderson et al., 2005). According to Seagull et al. (2001) using redundant auditory displays is not beneficial nor detrimental to monitoring. Still sonification is useful for detecting changes when the anaesthesiologist is not watching the monitor.

3.3.2. Decision support systems

One way to support anaesthesiologists is to warn them when a parameter is outside a pre-set limit as with alarms discussed in the previous section. Another way is to actively support the decision making process with a clinical decision support system (DSS). Any computer program designed to help healthcare professionals make clinical decisions is called a clinical decision support system. Musen, Shahar and Shortliffe (2006) divide DSS into three groups. First of all there are tools for information management, for example database systems with descriptions of complications. Second there are tools that provide patient-specific recommendations and finally there are tools for focusing attention. Most of the DSS work in anaesthesia falls in the last two categories. For example a system that provides only relevant information (de Graaf, van Den Eijkel, Vullings, & de Mol, 1997) or systems that provide explanations for abnormalities (Krol & Reich, 2000; Pott, Cnossen, & Ballast, 2005; Pott, Johnson, & Ballast, 2006; Pott, Johnson, et al., 2005). An important drawback of DSS is the fact that they only integrate measured patient data. They are not able to take external cues like surgical activity or the colour of the patient's face (a blue colour may indicate a breathing problem) into account.

3.3.3. Monitors

As discussed earlier, situation awareness is a key ingredient in preventing and dealing with complications. Therefore it is important to facilitate the situation awareness of the anaesthesiologist. Providing the anaesthesiologist with patient information which is easier and faster to interpret than the standard monitor and provides a complete picture of the patient's condition, should increase the anaesthesiologist's situation awareness and reduce the time needed to make interventions (Drews & Westenskow, 2006). The standard monitor described in chapter 2 is an instance of a single-sensor, single-indicator display (for each sensor there is value present on the monitor). This display requires clinicians to observe and mentally integrate the variables measured by independent sensors. This is difficult, effortful and time consuming (Drews & Westenskow, 2006). In this paragraph some alternatives will be discussed.

Contemporary attempts of new display designs have been characterized as metaphor graphics, configural and emergent features displays, or ecological displays. All share the goal of showing higher-order physiological functions or states by graphically configuring lower-level measures in a manner that makes the higher level properties emerge (Sanderson et al., 2005).

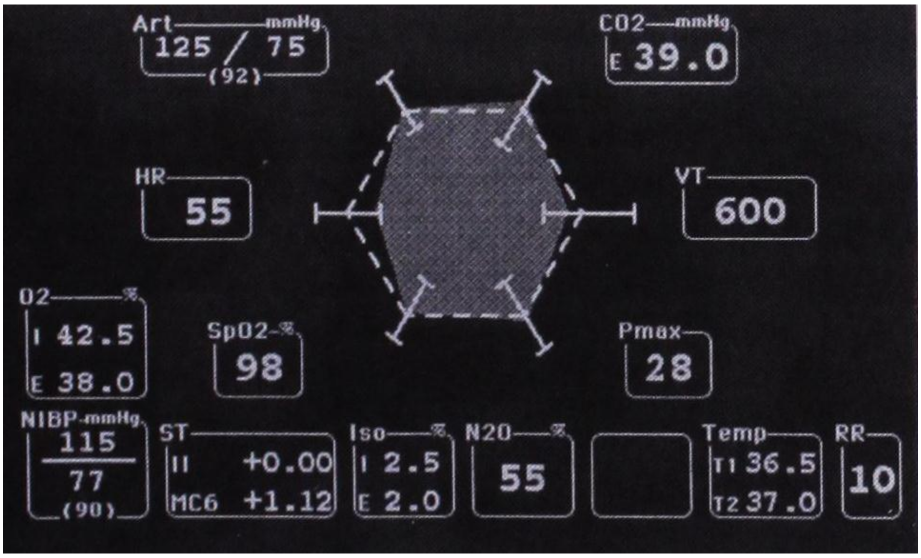


Figure 8 Polygon display of Gurashantaiah et al. (1995)

Cole and Stewart (1993) built a rectangular display to display tidal volumes and respiration rate as the height and width of a rectangle. Using this rectangle display anaesthesiologists were able to interpret respiratory status twice as fast as width a tabular display. Michels, Gravenstein and Westenskow (1996) used similar rectangles that integrated 30 measured variables. Of four tested events, two were detected faster and three were identified faster. Jungk, Thull, Hoeft and Rau (2000) and Blike, Surgenor and Whalen (1999) used a similar approach. However in recent studies using the rectangular display, this advantage was not replicated (van Amsterdam, 2010; Hooff & Cnossen, 2010). Other research includes research on displaying trends (Kennedy et al., 2009) and the use of hexagons (Fig. 8) (Gurushanthaiah, Weinger, & Englund, 1995) adapted from nuclear power plant control systems (Woods, Wise, & Hanes, 1981). This monitor provides the user with an added emergent feature: symmetry. When one the variables deviates from its ideal value it disturbs the symmetry which causes it to stand out, in other words to emerge (Christopher D Wickens & Hollands, 2000). Gurushanthaiah et al. (1995) found faster detection times in their experiment using anaesthesia residents and non-clinicians. Interestingly the polygon is one of the very few designs that actually found its way into the operating room (Drews & Westenskow, 2006).

The optional polygon display on the Ohmeda Modulus CD anaesthesia machine turned out to be used only rarely and was since then removed from next-generation workstations. There are several reasons that could have contributed to the failure of the polygon display. A more general reason identified by Daniels & Ansermino (2009) is the lack of usability testing to ensure real-world applicability. Other problems were identified by Drews & Westenskow (2006) among them scaling, significant change in some variables was less perceptible than a significant change in others. According to Drews and Westenskow (2006) it did not support the diagnostic process of the anaesthesiologist, for a diagnosis more detailed information was necessary. However when switching to another view is fast this does not have to be a problem. Finally the arbitrary placement of the variables was an issue. An important design principle is that related variables should be displayed in proximity of each other (Barnett & Wickens, 1988).The design principle was violated by the design. For example: saturation and end-tidal CO_2 are related, but were not in each other's vicinity.

4. Current study

The previous chapter describes only a part of the enormous amount of research that has been done in the field of anaesthesiology. Human error is linked to many anaesthesia related mishaps. One of the most important factors in reducing human error is improving situation awareness. The various improvements proposed for the anaesthesia monitor have, while promising, not yet found their way to monitors currently used in the operating room.

Even if a new monitor is successfully implemented it is impossible for anaesthesiologists to continuously watch the monitor due to the 'two table system' in the Netherlands. In the Netherlands anaesthesiologists may be responsible for two operating tables at any given moment. This is made possible by highly trained nurse anaesthetists. However the anaesthesiologist is still the one in charge and responsible for the well-being of the patients. When attending to multiple patients situation awareness becomes even more important. Therefore a more flexible means of monitoring could be beneficial for situation awareness. Using smartphones for this task seems to be a very promising way of aiding the anaesthesiologist in his day-to-day work. It enables the anaesthesiologist to check the status of patients while not being present in the operating room. Up till now little research has been done on the use of smartphones in the medical domain. This by itself is not surprising since the smartphone is a relatively new phenomenon. Park and Chen (2007) showed in a study among doctors and nurses that the intention of using a smartphone in medical settings is primarily based on the perceived usefulness, and to a smaller extend, the perceived ease of use of the device. Leijdekkers and Gay (2006) belong to the few researchers that describe an implementation of smartphones in the medical domain. They built a prototype smartphone application for heart patients which in combination with wireless biosensors, is able to alert physicians when complications arise. However the authors have not yet tested the prototype with real subjects.

Following the research in literature, presented in chapter 3, we decided to focus on creating a prototype smartphone application for anaesthesiologists. The smartphone application enables anaesthesiologists to access the information on the monitor at any time while on duty.

The aim of this study is to answer two questions:

- *How can a mobile monitor help to provide better healthcare?*
- *What design considerations have to be taken into account when designing a mobile monitor for anaesthesiologists?*

Before designing a prototype mobile monitor, several pilot studies were conducted. These pilot studies resulted in a number of 'guidelines' for the design of the mobile monitor. Based on these initial 'guidelines' a mobile monitor prototype was build and tested using a diagnostic reasoning experiment. This experiment served two purposes. First of all, since reasoning in anaesthesiology seems to be very different from other fields of medicine it is interesting to learn how anaesthesiologists reason when using a mobile monitor. Secondly the experiment will lead to the discovery of weak points in the design which may be improved. In chapter 5 the pilot studies and the design of the prototype will be presented. The diagnostic reasoning experiment is described in chapter 6 and a discussion of the results in chapter 7.

5. Mobile monitor

In this study the aim is to develop a new mobile monitor for anaesthesiologists. The mobile monitoring system is a new way of patient monitoring in anaesthesia. Therefore pilot studies were conducted to identify important design considerations. In these studies we interviewed several anaesthesiologists about the principle of monitoring patients using a smartphone and initial design ideas. Following the interviews we designed a prototype which was evaluated by anaesthesiologists and intensive care nurses.

5.1. Pilot interviews

Initially five resident anaesthesiologists of the UMCG were interviewed (see Appendix A for the Dutch questions and potential monitor layouts). The anaesthesiologists were interviewed about the pros and cons of a smartphone anaesthesia monitor, about display configurations, display designs from earlier studies, alarms and other design implications. The answers are summarized below and divided into four categories: attitude towards a mobile monitor, display configurations, alarms and other suggestions.

Attitude

The attitude towards the idea of mobile monitoring was overall very positive; only one anaesthesiologist responded negative towards a smartphone monitor. This respondent stated that an anaesthesiologist should always trust his co-workers completely and a mobile monitor was therefore superfluous. Other possible disadvantages mentioned by the respondents include safety of patient data (patient data might fall in the wrong hands) and anaesthesiologists going to their office during operations.

Another point stressed by several respondents concerns the applicability of a mobile monitor. To diagnose a patient more information than presented on a monitor is integrated. A diagnosis based on a monitor alone is considered impossible or at best irresponsible. An interesting note on this is that all respondents indicated that they would not be irresponsible themselves, but their colleagues might. Perceived advantages include, convenience and preservation of the two table system.

Display configuration

When the respondents were asked about display configurations, the overall consensus is that it should resemble the standard monitor described in chapter 2 with ECG, heart rate, plethysmogram, saturation, capnogram, end tidal CO_2, ventilation pressure curve and tidal volume or peak airway pressure. Various graphical displays from earlier studies were presented and of these various examples the polygon monitor using symmetry got the most positive reactions. Concerning colours schemes, the anaesthesiologists agree that it should match the colours of the standard monitor. For the polygon monitor no preference was given.

Respondents agreed that the minimum amount of information needed to assess the patient’s state is given by the variables and curves presented in section 2.2.2. In addition to the variables also their trends are considered important.

Alarms

On the topic of alarms the opinions of the anaesthesiologists differ. Some respondents want no false alarms at all, because they consider alarms as a disturbance. In their opinion alarms should only go off when the situation is critical. Other respondents want to be alarmed as often as possible, because they deem it important to be aware of every change.

Settings for the alarms should thus be highly customizable. It should be possible to set different alarms for different patients and situations, so setting them should be easily done. Participants noted that alarms should be accompanied with vibration of the smartphone and the location of the patient (which operating room). Alarm sounds should be optional. Other suggestions include colour coded alarms for different levels of urgency.

Other suggestions

In addition to standard alarms the participants were asked about suggestions for new kinds of alarms. One participant suggested including trend alarms. Trend alarms are interesting when the margins of change in variables are small or when it concerns children. Another respondent suggested placing a panic button in the operating room. When nurse anaesthetists need help or experience a crisis situation they should be able to simply press a button to warn the attending anaesthesiologist on his smartphone. Finally it is considered valuable if information about drugs administered to the patient is accessible on the mobile monitor.

Preliminary conclusions

From the preliminary interview we derived several important considerations for designing a prototype smartphone monitor. In summary the responses indicate a positive attitude towards the concept, the standard as well as a polygon monitor is regarded as an option. The minimum amount of information presented is a combination of ECG, heart rate, plethysmogram, saturation, capnogram, end tidal CO_2, ventilation pressure curve and tidal volume or peak airway pressure. The opinions on alarms differ and could be customizable to ensure broad acceptance.

The mobile monitor should present the anaesthesiologist with a simple tool to check on a patient's status when not present in the operating room. The mobile monitor may increase situation awareness outside the operating room. A mobile monitor seems also a very informative tool when asked for a consult, which happens often. Multiple times a day supervisors are called by younger anaesthesiologists for their opinion on a situation. In this case the anaesthesiologist asking for assistance will describe the patient status and the variables on the monitor. This description contains filtered information susceptible to, for example, the anchoring and confirmation bias (Kremer et al., 2002; Christopher D Wickens & Hollands, 2000). Most experienced nurse anaesthetists and anaesthesiologists in training have a diagnosis in mind when calling for help. Unintentionally they may neglect giving information that doesn't support their hypothesis. By introducing a smart phone monitor the supervisor will have access to the unfiltered information and is less influenced by a potentially biased view. Other potential advantages are early detection of complications, shorter conversations, learning the current patient status while rushing to the operating room and monitoring nurse anaesthetists and supervised anaesthesiologists from a distance.

5.2. The prototype

Based on our initial findings and results from earlier studies we designed an interface with three screens: the standard layout, a trend screen and a polygon screen. This prototype was programmed for a HTC Desire HD smartphone using the Android programming language (Google, 2007) and the Flot Javascript library (Laursen, 2007). In the next section each screen will be described. In the fourth section also a description is given of potential new ways of alarming and a simple way of setting alarms.

5.2.1. Standard layout

Following the preliminary conclusions presented in section 5.1., we chose to include a standard layout. The standard layout includes the variables presented in section 2.2. Figure 9 shows the 'classic' view and the names of the presented variables. The colour scheme is identical to the scheme currently used at the hospital in which the experiment was conducted. The names of variables are presented on the monitor in the operating room, but the smartphone screen is a lot

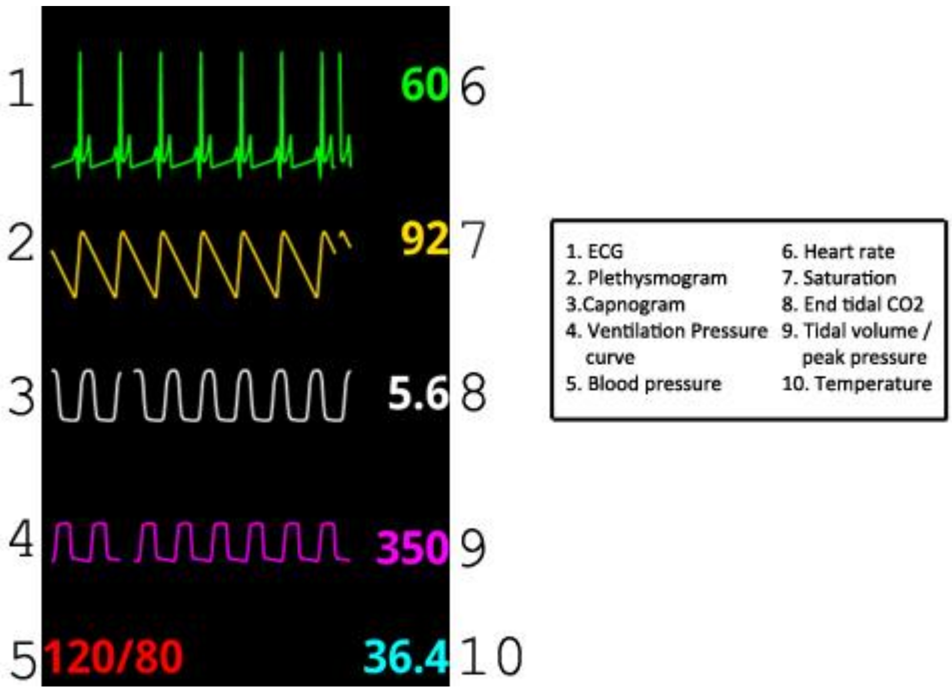


Figure 9 Classic view

smaller. To prevent the screen from getting cluttered we omitted the names of the variables.

5.2.2. Trends

In the trend view (Figure 10), trends for the main variables are visualized. In the current implementation the trend view shows how the variable has changed during the last ten minutes. All colours are matched with the classic view, except for the blood pressure. Because blood pressure consists of two variables (systolic and diastolic pressure) we chose different colours. Blue and orange

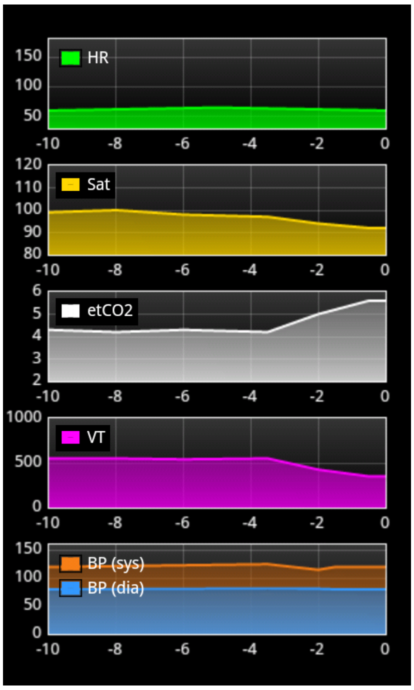


Figure 10 Trend view

were chosen because they are distinguishable by people with different types of colour blindness.

5.2.3. Polygon

The polygon view is based on the polygon by Gurushanthaiah et al. (1995). Drews and Westenskow (2006) observed that the polygon view is not suitable for making diagnoses, but it is very effective for detecting abnormalities (Gurushanthaiah et al., 1995). When the polygon matches the white hexagon all values are acceptable. The study of Gurushaanthaiah et al. (1995) shows that

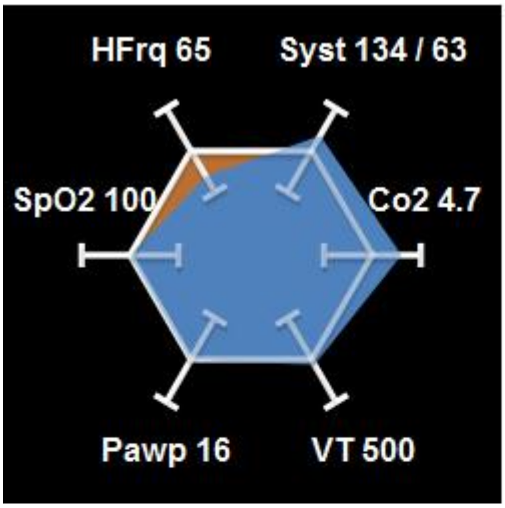


Figure 11 Polygon view

when values change, the shape will distort and the change is quickly and accurately detected. The polygon used in this study differs from the polygon of Gurushanthaiah et al. (1995) in several ways. First of all, following the advice of a senior anaesthesiologist the placement of the variables was altered. Heart frequency and blood pressure together represent the circulation and are placed on top. Saturation and end tidal CO_2 give information on the gas exchange and are placed the middle. At the bottom we placed peak airway pressure and tidal volume together. They give information about the ventilation of the patient.

The colour scheme ensures a good distinction of shapes. The inner background of the hexagon is coloured orange to improve saliency when a value drops. The white extending lines represent paths over which a vertex of the hexagon moves. Both ends of the line represent the upper and lower alarm limits for the specific variable.

5.2.4. Alarms

Setting realistic alarm limits is crucial for sensible alarms. However, a sensible limit can differ greatly for different patients and types of operations. It is expected that a simple and fast way of setting alarms could improve usability and the acceptance by the anaesthesiologists. First of all a simple and fast setting of alarms may encourage anaesthesiologists to use them. Secondly, since opinions differ on the number of alarms an anaesthesiologist accepts, simple and fast setting of alarms may decrease unwanted alarms.

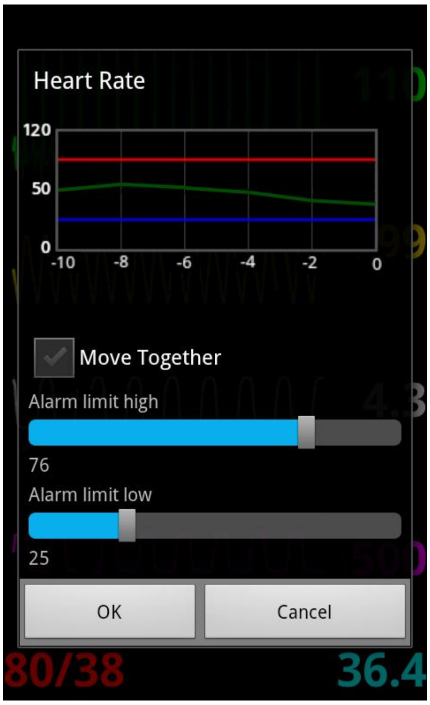


Figure 12 Setting alarms

The touchscreen of a smartphone enables user to set an alarm in a very intuitive way. For example: to set an alarm for heart rate, a user touches the heart rate variable and an overlay screen appears (figure 12). It shows the trend for the heart rate of the last ten minutes together with an upper and a lower limit. By dragging the bar labelled 'Alarm limit high' the user moves the upper limit, which is visualized by a red line. The same goes for the lower limit which is visualized by a blue line. With two simple movements an alarm is set. By checking the 'move together' box the user ensures that the lower limit moves with the upper limit and vice versa.

Smart alarms

In addition to simple threshold alarms, smart alarms can be incorporated. For example several variables can be derived in multiple ways. Heart rate is typically derived from the ECG, if a sensor sticker lets loose it is important to warn personnel in the operating room, so this will trigger the alarm. This is less important for the anaesthesiologist outside the operating room. Because heart rate can also be derived from pulse oxymetry the system is able to verify that the patient is in fact fine and the system will not trigger an alarm on the smartphone. This type of alarms will reduce non-critical alarms and therefore reduce the nuisance caused by non-critical alarms.

5.2.5. Organization of the screens

Different views of the prototype and a new way of setting alarms are presented in the previous paragraphs. The prototype will be implemented on a smartphone. The anaesthesiologist needs to interact with the smartphone to access a particular screen. Therefore it is important to explain how the screens are organized and explain how the user interacts with the prototype. As mentioned in the previous section tapping a variable accesses the alarm settings menu. By making a swiping motion on the screen the user can switch from one view to another. This enables the anaesthesiologist to access information very quickly without cluttering a single screen with information.

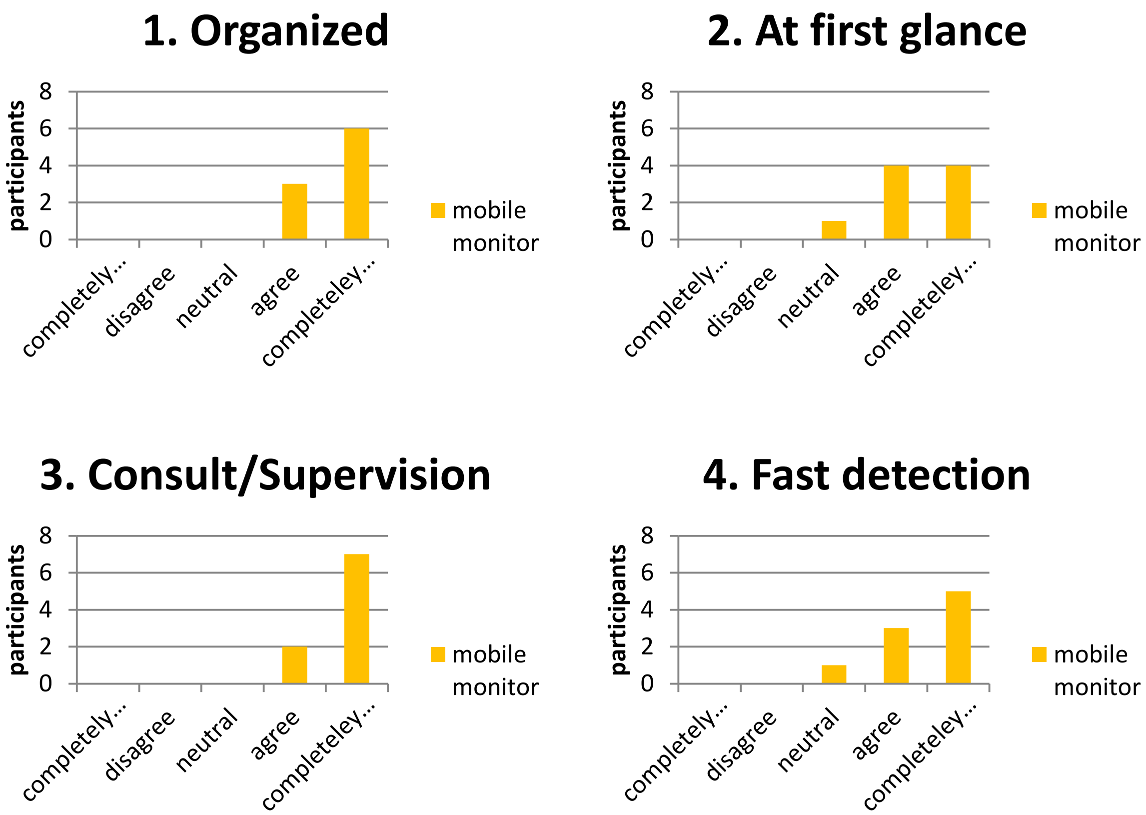
The mobile monitor consists of three slots next to each other. A slot contains one view and only one slot can be viewed at once. The polygon monitor is placed in the left slot. While responsible for a patient the polygon view facilitates the detection of complications. With a single glance the anaesthesiologist is able to see if the patient is stable. By making a swiping motion from right to left over the screen the view is changed to the classic view in the middle slot. This screen enables the anaesthesiologist to interpret the curves and with another sweep the trends in the right slot are accessed which allow the anaesthesiologist to see how the patient's status changed over time.

5.3. Results - user experience

The mobile monitor with the standard layout and trend information was used for the diagnostic reasoning experiment (see chapter 6). The polygon monitor was used in another experiment which is described in Moes (2011). After both experiments, participants were asked to give their opinion on the monitors using questionnaires. The questionnaires contained scaling – and open questions about the layout and the perceived usefulness of the monitors. For the scaling questions a 5-point Likert-scale ranging from 'completely disagree' to 'completely agree' was used (see appendix B and C for the questionnaires in Dutch). The results of the questionnaire concerning the standard layout and the trend information as well as those collected after the experiment of Moes (2011) concerning the polygon will be discussed next.

5.3.1. Standard monitor and trends

The participants in the diagnostic reasoning experiment received a questionnaire after using a prototype without the polygon (detection was not part of the experiment).



Graphs 1,2,3,4 – 1: Layout of monitor is organized, 2: I know the patient's status at first glance, 3: The monitor is useful for second opinions/consults/supervision, 4: The monitor enables fast detection of complications outside the operation room

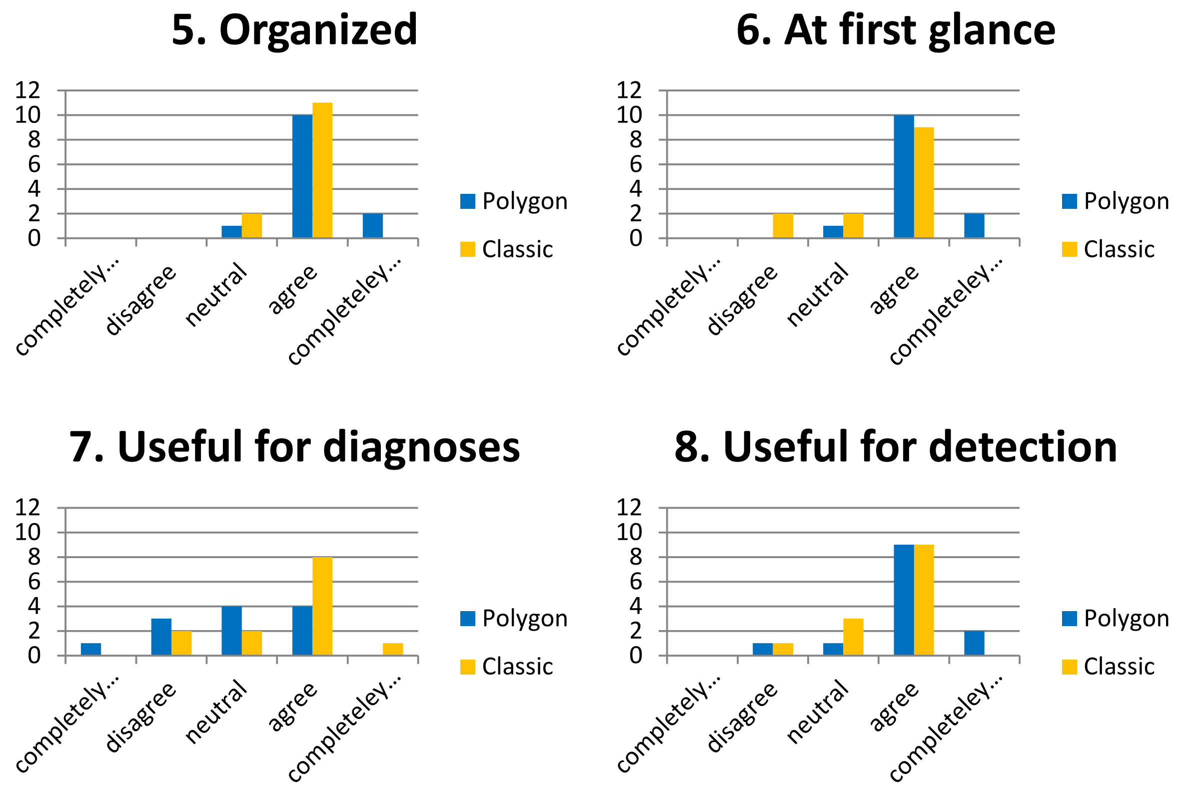
The experiment was done by nine anaesthesiologists (6 male, 3 female, mean age = 43.7 yr; sd = 11.3; mean experience = 13.0 yr; sd = 11.8 yr). Six out of nine are current smartphone owners.

Overall the participants had a very positive attitude towards the mobile monitor with just the standard layout and trend information. All participants thought the mobile monitor was organized well (graph 1). Most participants stated that they could identify the patient's status at first glance. One participant responded neutral (graph 2). All participants considered the use of the monitor for supervision and consults useful (graph 3). When asked if the monitor facilitated detection of complications outside the operating room, most participants agreed and one was neutral (graph 4).

The participants were also asked to comment on the monitor to identify strong and weak points. Trend information was considered to be a very valuable feature. Also the fact that the prototype uses the same colour scheme as the monitor in the operating room was appreciated. Missing peak airway pressure and respiratory rate were considered weak points. The length of time over which the trend information was visible (now 10 minutes) was perceived too short. One participant found the ECG hard to interpret with high heart rates. Finally it would be beneficial if information on blood loss and administered medication would be accessible, according to one participant.
Eight out of nine participants would use the mobile monitor if it was available, one participant was neutral.

5.3.2. Polygon

The participants of the experiment of Moes (2011) received the questionnaire after finishing the experiment done on a laptop with the polygon view and the classic view.



Graphs 5,6,7,8 – 5: Layout of monitor is organized, 6: I know the patient's status at first glance, 7: The monitor enables fast diagnosis, 8: The monitor enables fast detection

The participants were thirteen intensive care nurses (1 male, 12 female). A large part of their job is to monitor patients and alarm physicians when complications arise. Therefore their opinion about the polygon is very valuable.

Participants considered both monitors organized but were more positive about the polygon monitor (graph 5). A similar opinion is found for the theorem: "I know the patient's status at first glance" (graph 6). The results considering the monitors as an aid for diagnosis (graph 7) match the ideas of Drews & Westenskow (2006). Participants state that the polygon does not support the diagnostic process as well as the classic monitor. However participants were more positive about the polygon than the 'classic' monitor for detection (graph 8).

In addition to the scaled responses, participants were free to comment on the weak points of the design of the polygon. Two participants suggested different positioning of the variables. One participant suggested putting heart rate on the top right and taking the variables from the classic monitor (top to bottom) and placing them clockwise on the hexagon. Another suggestion was placing the 'important' variables (words of the participant) on the right side of the polygon. Asking which variables the participant meant was impossible since this questionnaire was anonymous. Other commentary included improvement of saliency by letting the shape change colour when an alarm limit is violated and showing the curves. One participant was concerned about the dependency on the set alarm limits. When finally asked if the intensive care nurses would like to use the polygon in their day to day work, one participant said no, five were neutral and seven responded positive.

6. Diagnostic reasoning experiment

The aim of the experiment is to learn how an anaesthesiologist reasons about a case when using a mobile monitor. Learning which information is important using another technique than interviewing anaesthesiologists could point out extra design considerations and lead to improvements of the mobile monitor. In addition the experiment gives an insight into diagnostic reasoning in anaesthesia in general.

The goal for the subject was to recognize complications. Subjects were given the new prototype as described in chapter 5. In addition to the mobile monitor, subjects were allowed to ask questions to one of the experimenters who acted as a nurse anaesthetist in need of assistance. The polygon screen was left out since it is developed for detecting complications. This leaves a mobile monitor with the classic and the trend view. Six different cases were presented to the anaesthesiologist. During a case the patient status did not change. However an illusion of a dynamic setting was created by using moving curves for the electrocardiogram, plethysmogram, capnogram and ventilation pressure curve. The dynamic setting should increase realism.

6.1. Method

6.1.1. Subjects

Nine anaesthesiologists of the University Medical Centre of Groningen (UMCG) participated in the experiment. Six male, three female (mean age = 43.7 yr; sd = 11.3; mean experience = 13.0 yr; sd = 11.8 yr). Six out of nine are smartphone owners. All subjects were recruited during relative “quiet” moments of their work. Subjects were doing paperwork, just finished their shift or were supervising a stabile patient. If necessary, care for their patient was transferred to another anaesthesiologist enabling the subjects to finish the experiment without being called back to the operating room.

6.1.2. Stimuli and apparatus

In the experiment six patient cases were presented to the subjects. Each case consisted of a location (which operating room), a description of the patient and the operation so far. The cases used in the experiment were chosen by an experienced anaesthesiologist.

In table 1 the six cases are presented. The cases can be subdivided in two groups: cases with airway related complications and cases with circulation related complications.

Table 1. Experimental complications

Cases	Airway / Circulation
Circulation failure	Circulation
Embolism	Airway
Hypoventilation	Airway
Hypovolemia	Circulation
Problem of the lungs	Airway
Tension pneumothorax	Airway

Below a specific description of each case is given with a ‘screenshot’ of the classic and trend screen of the mobile monitor.

Circulation failure: Serious circulation failure (shock) with an unknown cause.

Patient: Male (63), heart infarction in 2007.
Medication: Beta-blockers, sintrom and metformine.
Procedure: hemicolectomy because of a colon carcinoma.
Other: pre-operative Hb=5.4. Kidney and liver function is normal.

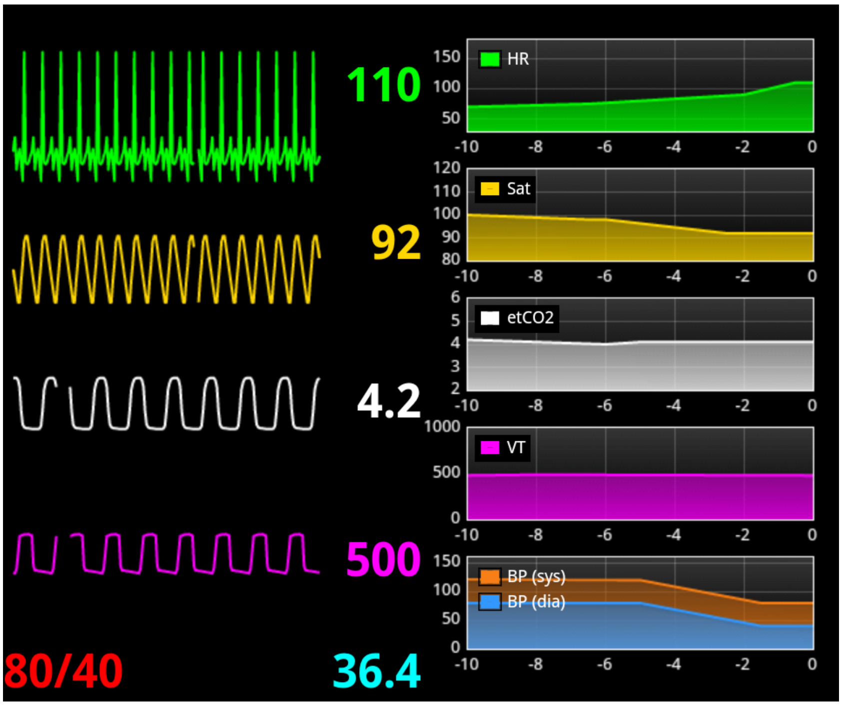


Figure 13 Circulation failure

Embolism: A cloth (thrombus), tumour tissue or an amount of air entered the circulation and blocks the lung vessels. This leads to an unexpected blocking of the blood circulation and gas exchange. The lungs may become more rigid.

Patient: Female (43) with a genetic predisposition for ovary and mammary tumours.
Medication: -
Procedure: Laparoscopic removal of the ovaries.
Other: During the procedure a tumour is found, which cause the procedure to be difficult and slowly progressing. The surgeon is considering switching to a classical laparotomical approach.

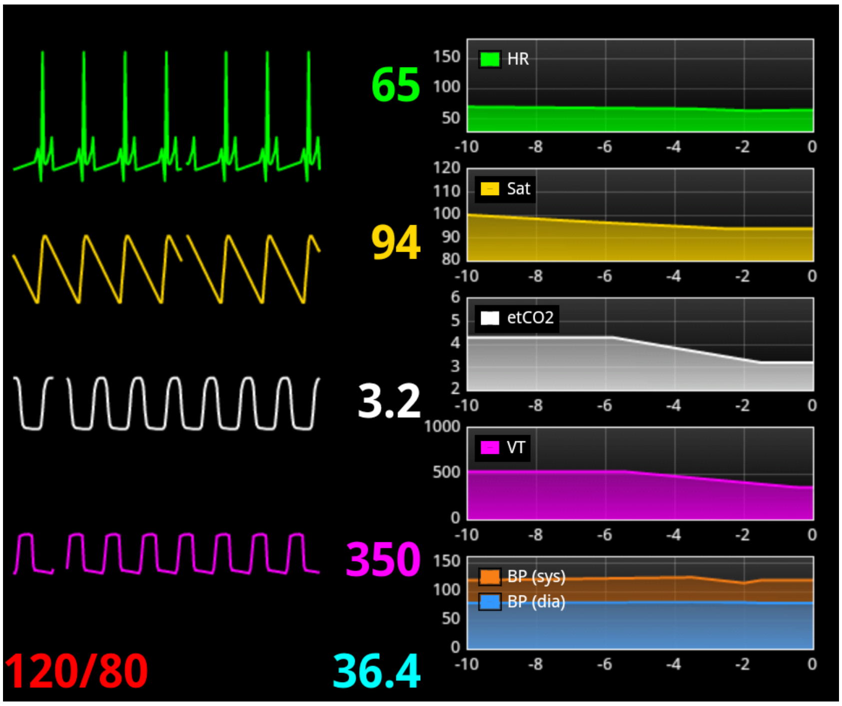


Figure 14 Embolism

Hypoventilation: Tidal volumes are low, but ventilation pressure is normal. Patient is probably difficult to ventilate.

Patient: Healthy young patient.
Medication: -
Procedure: Osteotomy of the lower jaw.
Other: No specific problems.

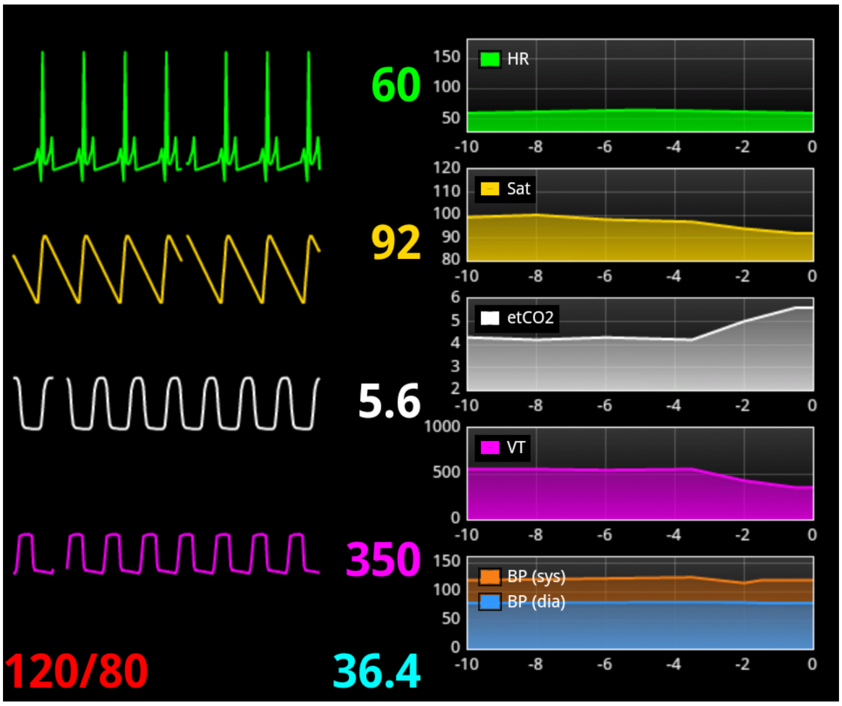


Figure 15 Hypoventilation

Hypovolemia: Failing blood circulation and a low blood volume in the heart caused by lack of fluids or blood loss. The first few minutes the body will compensate the blood pressure and CO_2 by vasoconstriction (constriction of the vains) in 'less important' organs.

Patient: Man (73).
Medication: Sintrom (this medication stopped 4 days prior to the operation) and Metoprolol for paroxysmal atrial fibrillation.
Procedure: Revision of whole hip.
Other: Removing old prosthesis was difficult. Orthopaedist is preparing placement of the new hip.

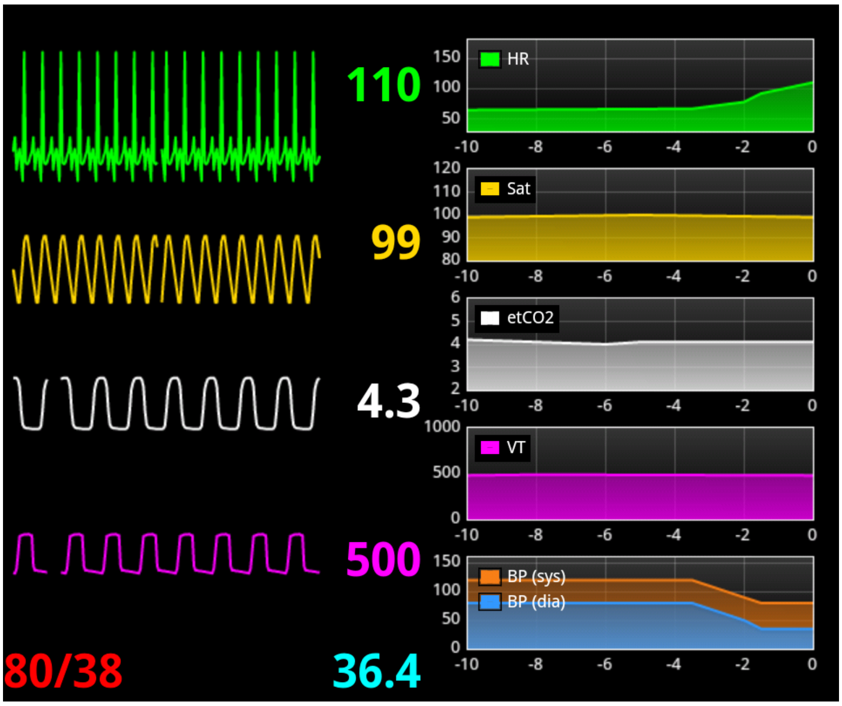


Figure 16 Hypovolemia

Problem of the lungs: Ventilation pressure is the same, but tidal volume dropped. End-tidal CO_2 is normal. Ventilator pressure has been raised to prevent hypoventilation

Patient: Male (28) motorcycle accident.
Medication: Pulmicort and salbutamol for asthma.
Procedure: Complicated fracture of the lower leg.
Other: When arrived at the hospital patient was hemodynamically stabile. Some concussion on the thorax, but a thorax scan showed no problems. Surgeon has been working for two hours, progress is slow.

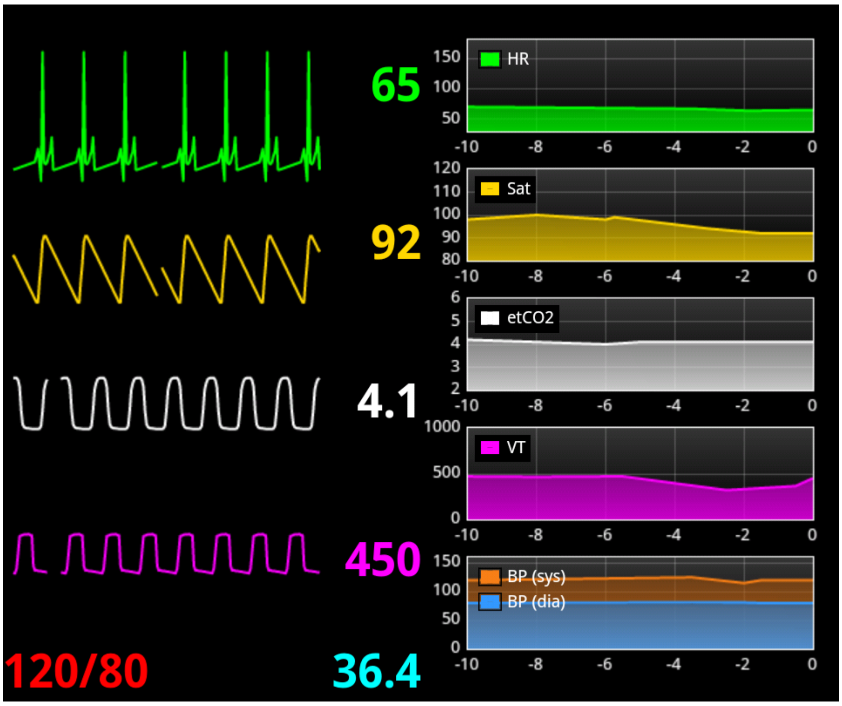


Figure 17 Problem of the lungs

Tension pneumothorax: A spontaneous, traumatic, or iatrogenic (caused by medical procedures) lung damage causes air to flow in chest cavity (pneumothorax). With every breath more air flows into the cavity. The trauma has valve characteristics preventing air from escaping (tension pneumothorax).

Patient: Male (54) with pancreas tumour.
Medication: Metropolol for hypertension and pulmicort for COPD.
Procedure: Removal of tumour from the upper abdomen.
Other: Kidney function is mildly disturbed. First blood gas measurement was ok. Patient has an

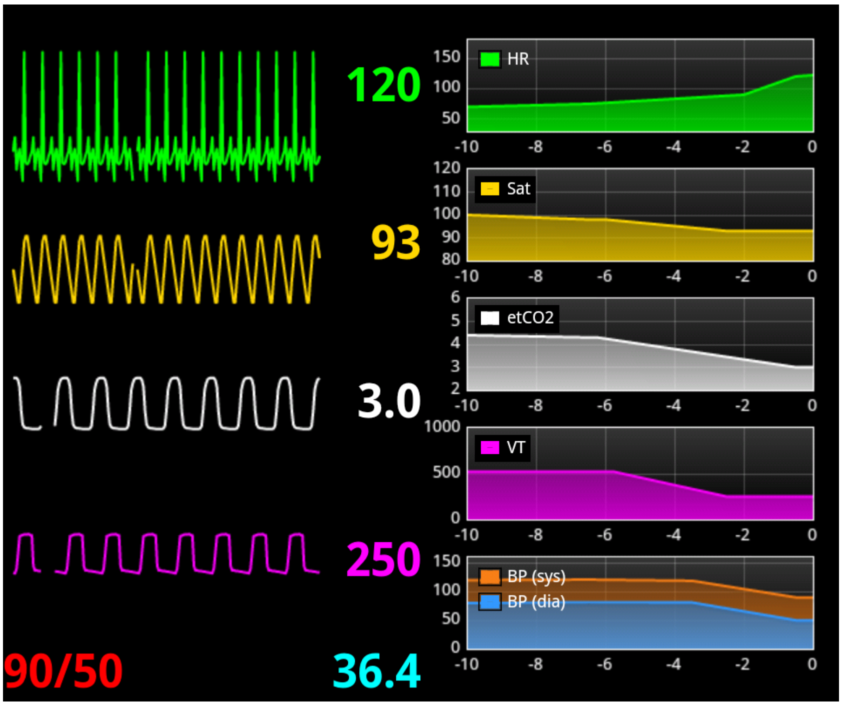


Figure 18 Tension pneumothorax

arterial line and central venous pressure line.

The experienced anaesthesiologist who created the cases also provided a wide range of questions and answers for each case. This enabled the experimenter to answer questions like “What do you hear when you listen to the lungs?” or “How much fluid has been given?”. In the event that a subject asked a question without a prepared response, the experimenter answered that the question could not be answered.

Apparatus

The experiment was done with a HTC Desire HD smartphone with a 4,3-inch glossy SLCD touchscreen with a resolution of 800 x 480 pixels. The smartphone was running the prototype as presented in paragraph 5.2. A case was selected by tapping an icon with the name of the operating room. The experiment was recorded using an Olympus VN-240PC digital voice recorder.

6.1.3. Instructions

At the start of the experiment participants were asked for their permission to record the experiment. It was emphasized that the recordings would be used only for this experiment and would be anonymous. They received a very brief instruction on the use of the smartphone and were told that one of the two experimenters would play the role of a nurse anaesthetist calling and asking for help. The phone conversation was simulated, the experimenters sat opposite of the subject. The second experimenter took notes. The total duration of the experiment was between 30 and 40 minutes.

Subjects were instructed to diagnose each presented case, using the description given by the experimenter, the information on the mobile monitor, questions and by proposing actions (see also the full Dutch instructions in appendix D). Subjects were also instructed to think out loud.

A case started by telling the subject in which operating room the patient was. The subject would then navigate to the appropriate operating room using the corresponding icon on the smartphone. The experimenter would describe the case as presented in paragraph 6.1.2. After which the subject would start thinking out loud.

6.1.4. Order of presentation

The cases were presented in the same order for every subject (shown in table 2). A case was ended by the experimenter. The case was ended when a subject committed to a diagnosis, had no alternative hypothesis or was stuck in the reasoning process.

Table 2. Order of the cases

Order of the cases
1. Hypovolemia
2. Hypoventilation
3. Problem of the lungs
4. Circulation failure
5. Embolism
6. Tension pneumothorax

6.1.5. Measures

During the experiment all conversation was recorded. The verbal protocols were analysed for quantitative data (questions and proposed actions) as well as for qualitative data (patterns in reasoning). In addition to the recording a questionnaire using a 5-point Likert-scale ranging from ‘completely disagree’ to ‘completely agree’ was used to determine if a scenario was realistic, simple and likely (see appendix E for the questionnaire in Dutch).

6.2. Results

Due to technical issues one participant was presented with only four of the six cases. This participant was removed from the quantitative data to eliminate differences due to the different number of cases seen by the participant.

6.2.1 Quantitative data

There is a large variety in the number of questions and proposed actions per subject (Table 3 and 4). Participant 5 asked with twenty questions almost three times more questions than participant 2 with seven questions. A smaller, but similar difference is found for the proposed actions. Differences in age, experience or gender could not account for these results. DeAnda et al. (1990) performed an experiment with simulated critical incidents and found a high variability in performance. Some participants made many mistakes and some none. DeAnda et al. (1990) suggest differences in personality as an explanation for differences in response times and number of errors when attending to complications. This may also be the case in our experiment.

Table 3. Totals per question and per subject

Question per subject	#1	#2	#3	#4	#5	#6	#7	#8	Total
Blood loss	3	2	2	2	2	3	3	2	19
Ventilator pressures	1	2	2	2	3	4	1	2	17
Amount of fluids			1	2	2	2	1	2	10
FiO_2			1	1	3	1	1		7
PEEP			1	2	1	2	1		7
Anaesthesia meds				3			2	1	6
ECG abnormalities		2	2		1				5
Pressure recently changed	3		1			1			5
Hb				1	1	2			4
Urine amount					2		1	1	4
BIS			1	1	1				3
CVD			1		2				3
Sweaty					1	1			2
Weight of patient	1		1						2
Anaesthesia meds given	1								1
Breathing frequency						1			1
Duration of operation	1								1
Glucose					1				1
Temperature change		1							1
Tube blocked				1					1
Total questions	10	7	13	15	20	17	10	8	100

Table 4. Totals per action and per subject

Action per subject	#1	#2	#3	#4	#5	#6	#7	#8	Total
Listen to lungs / heart	4	3	5	4	4	2	3	5	30
Raise FiO_2 / 100% O_2	2	2		1	2	1	2		10
Increase ventilator pressure	2		1	1	1	1			6
Administer Voluven		2	1	1		1			5
Ventilate manually		3					1		4
Aspirate tube	1	1					1		3
Fentolyn			1				1	1	3
Give aerosol	1			1	1				3
Increase PEEP					1		2		3
Check machine		1		1					2
Measure blood gasses			1	1					2
Place CVD					1			1	2
Administer red blood cells					1				1
Check spirometrics	1								1
Listen to mouth	1								1
Thorax scan					1				1
Total actions	12	12	9	10	12	5	10	7	77

Looking at the cases in Table 5 it becomes apparent that anaesthesiologists sometimes require different information to reach the same conclusion. For example in the case of Hypovolemia one anaesthesiologist did not ask about blood loss, she ruled out ECG abnormalities and diagnosed Hypovolemia on the basis of the mobile monitor alone.

Table 5. Totals questions per scenario

Questions per case	Hypovolemia	Hypoventilation	Problem of the lungs	Circulation failure	Embolism	Tension pneumothorax	Total
Blood loss	7			8		4	19
Ventilator pressures	1	7	2	1	3	3	17
Amount of fluids	4			6			10
FiO_2	1	4			2		7
PEEP		2	2		2	1	7
Anaesthesia meds	2		1	2		1	6
ECG abnormalities	2			3			5
Pressure recently changed		1	3		1		5
Hb	3			1			4
Urine amount			1	3			4
BIS	1	1		1			3
CVD				1		2	3
Sweaty				2			2
Weight of patient			1	1			2
Anaesthesia meds given				1			1
Breathing frequency		1					1
Duration of operation				1			1
Glucose				1			1
Temperature change	1						1
Tube blocked		1					1
Total questions	22	18	10	35	8	11	100

At first sight no apparent pattern in the questions or actions per subject can be seen. For the questions and actions per scenario (Table 5 and Table 6) the pattern seems also a bit random. However when the number of questions and actions are grouped for airway and circulation related complications (see Table 1) a pattern seems to emerge (Table 7 and Table 8).

Table 6. Total actions per scenario

Actions per case	Hypovolemia	Hypoventilation	Problem of the lungs	Circulation failure	Embolism	Tension pneumothorax	Total
Listen to lungs / heart		5	7	4	6	8	30
Raise FiO_2 / 100% O_2		3	4		3		10
Increase ventilator pressure		3	1	1	1		6
Administer Voluven	2			2		1	5
Ventilate manually		2	1		1		4
Aspirate tube			3				3
Fentolyn			3				3
Give aerosol			3				3
Increase PEEP		1			2		3
Check machine		2					2
Measure blood gasses						2	2
Place CVD				2			2
Administer red blood cells	1						1
Check spirometrics			1				1
Listen to mouth		1					1
Thorax scan			1				1
Total actions	3	17	24	9	13	11	77

Table 7 shows that blood loss, the amount of fluids given, Hb and ECG abnormalities are typically important for circulation related cases. On the other hand ventilator pressures, Oxygen concentration (FiO_2), PEEP and changes in ventilator pressures are asked typically in airway related complications. Four times blood loss was asked for in an airway related complication. Table 5 shows that all four times were in the tension pneumothorax case. This can be explained by looking at the monitor view for tension pneumothorax (Fig. 18). The monitor shows in addition to airway related problems (low SpO_2, low $etCO_2$ and low tidal volume) an increase in heart rate and a dropping blood pressure, the monitored variables indicate problems both in the airway and in the circulation.

Table 7. Total questions per group

Questions per group	Airway	Circulation	Total
Blood loss	4	15	19
Ventilator pressures	15	2	17
Amount of fluids	0	10	10
FiO_2	6	1	7
PEEP	7	0	7
Anaesthesia meds	2	4	6
ECG abnormalities	0	5	5
Pressure recently changed	5	0	5
Hb	0	4	4
Urine amount	1	3	4
BIS	1	2	3
CVD	2	1	3
Sweaty	0	2	2
Weight of patient	1	1	2
Anaesthesia meds given	0	1	1
Breathing frequency	1	0	1
Duration of operation	0	1	1
Glucose	0	1	1
Temperature change	0	1	1
Tube blocked	1	0	1
Total questions	46	54	100

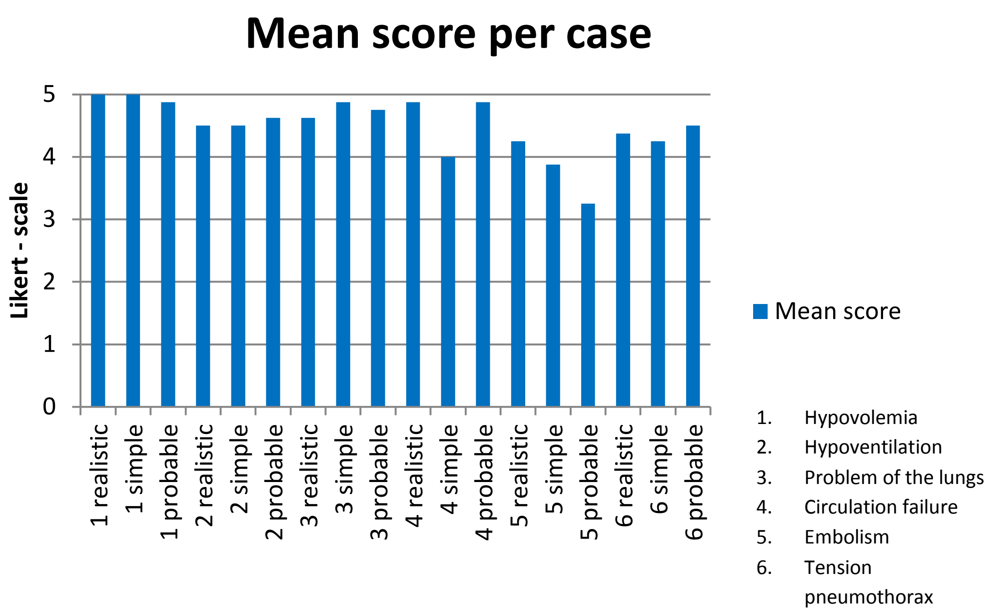
Table 8 shows the importance of auscultation (listening to lungs / heart) for airway related complications. Also raising the Oxygen concentration, raising ventilator pressures, manual ventilation and other ventilator related actions are asked in the airway complications. For circulation problems the administration of Voluven® is typical. Asking to increase ventilator pressure in a circulation problem seems unnecessary, but the reason to do this was sound. Subject 1 wanted to rule out pulmonary oedema. This is a rational idea, since a circulation failure can be caused by a disturbed gas exchange in the lungs. Table 8 also indicates that most actions are proposed for airway related cases.

Table 8. Total actions per group

Actions per group	Airway	Circulation	Total
Listen to lungs / heart	26	4	30
Raise FiO_2 / 100% O_2	10	0	10
Increase ventilator pressure	5	1	6
Administer Voluven	1	4	5
Ventilate manually	4	0	4
Aspirate tube	3	0	3
Fentolyn	3	0	3
Give aerosol	3	0	3
Increase PEEP	3	0	3
Check machine	2	0	2
Measure blood gasses	2	0	2
Place CVD	0	2	2
Administer red blood cells	0	1	1
Check spirometrics	1	0	1
Listen to mouth	1	0	1
Thorax scan	1	0	1
Total	65	12	77

6.2.2. Questionnaire

Graph 9 shows the results of the questionnaire considering the different cases. For each case subjects were asked to rate how realistic, simple and probable the presented case was. Graph 9 shows overall high mean scores for all complications, except for the embolism case. The embolism case was considered more difficult and less probable than the other cases.



Graph 9 - Mean scores over 5 point likert-scale (1 completely disagree – 5 completely agree) concerning realism, difficulty and probability of each case

7. Discussion

This study represents the first study on the use of mobile monitoring in anaesthesia. In this study a prototype of a smartphone-based mobile monitor was developed that displays patient data in several ways. Following pilot studies a prototype with three screens was built. It consists of a polygon screen which supports detection of abnormal values, the currently used monitor and a trend screen which allows the anaesthesiologist to track patient variables over time.

In a diagnostic reasoning experiment the prototype was tested to gain an insight in the diagnostic reasoning process the mobile monitor needs to support.

This chapter presents the discussion of the experimental results. In paragraph 7.1 we discuss the results of the diagnostic reasoning experiment. Paragraph 7.2 focuses on the consequences of the results for the design of the mobile monitor and in paragraph 7.3 conclusions and ideas for further research on mobile monitoring are presented.

7.1. Diagnostic reasoning experiment

The results showed that anaesthesiologists may use different information to reach a similar conclusion. Every anaesthesiologist is searching for relevant information and is trying to see the "big picture", this fits in the general framework of situation awareness (Pott, Johnson, et al., 2005).

The reasoning observed in the experiment will be discussed using the popular model of Gaba et al. (1995) (see also paragraph 3.2.2). In the experiment the model of Gaba et al. (1995) is entered at the supervisory control level at the "attend to data streams" –block (see Fig. 19). In this block subjects listened to the description of the experimenter and accessed the mobile monitor. The subjects then entered the "observation"-block, in this stage subjects looked at the standard monitor screen and the trend screen and entered the loop of observation, verification and problem recognition. In this loop the anaesthesiologist integrates the information on the monitor with the oral description and recognizes a problem. In the loop subjects often explicitly categorized the problem very early in the protocol as an airway or circulation problem. For example:

"Everything points to a problem with the ventilation.."-subject 1

"I observe a dropped saturation, dropping in time with the tidal volume. So there is a ventilation problem." – subject 2

"At first sight it is some form of shock" -subject 8

The observed categorization is also seen in the results section presented in chapter 6. Questions and proposed actions fit with the category of the complication. The categorization is an example of the representativeness heuristic (Tversky & Kahneman, 1974). No errors resulting from the use of the heuristic were observed. This heuristic is also used often by clinicians in other fields (Kremer et al., 2002).

According to the model of Gaba et al. (1995) the subjects would enter the next block: the prediction of future states. However no explicit evidence is found in the verbal protocols. The next step is a pre-compiled response or abstract reasoning. Only few pre-compiled responses were observed in the verbal protocols. For example:

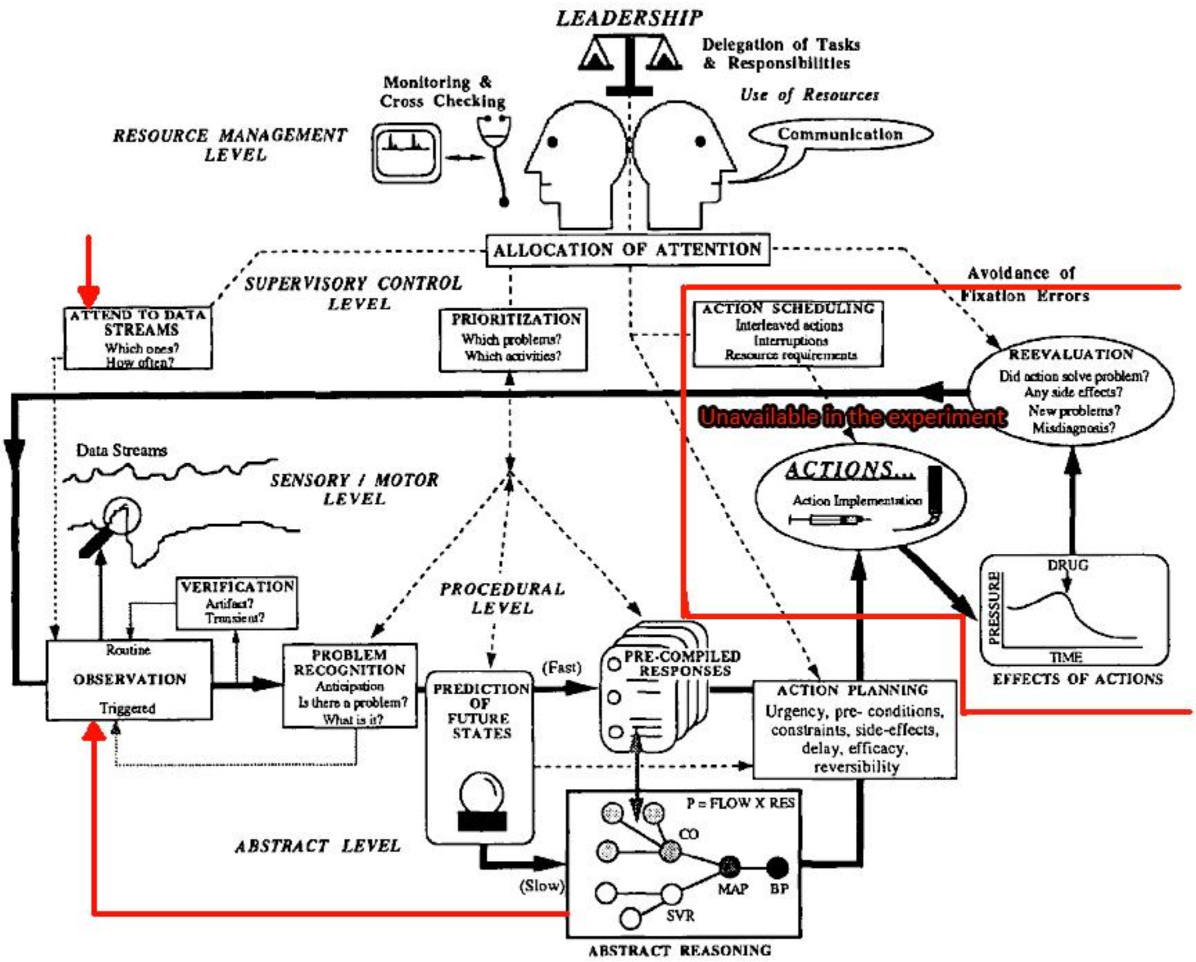


Figure 19 Adapted model of problem-solving behaviour of Gaba et al. (1995)

"Possibly a low Hb, so it would advise to give some Voluven, check the blood and see how the patient reacts."- subject 3

"Ehm I would give 100% Oxygen and see if it helps.." – subject 5

The above verbal protocols also illustrate the uncertainty associated with the intuitive decision making strategies presented by Croskerry (2009).

Subjects were instructed to think out loud, this and the experimental setting (subjects were not able to treat patients in the experiment) may have promoted the use of abstract reasoning and may explain the few observations of pre-compiled responses. During abstract reasoning, subjects derived likely conclusions from a limited amount of information and tried to test them. For example:

"..patient has Asthma, which may cause bronchospasm. So I'll listen, what do I hear?" – subject 8

"So this caused by too much fluids or something is wrong with the heart. If you listen what do you hear?"- subject 4

This is a form of abductive reasoning (Peirce, 1955). Abductive reasoning is a combination of inductive reasoning and deductive reasoning. As seen in the protocol bronchospasm is general conclusion from a set of specific variables (induction) and this in combination with additional information is used to deduce a specific and more certain conclusion. To gain more certainty the subjects asked questions as seen in the results of chapter six which constitutes a switch from abstract reasoning to observation. This is seen in de adapted model in Figure 19. The questions asked are vulnerable to the confirmation bias. Subjects actively sought information to confirm their hypothesis and not information that supported an opposite conclusion.

When subjects arrive at a conclusion, subjects are in the action planning stage of the model (Fig 19). The action planning stage is the final stage reached in the experiment since subjects were not able to treat patients and observe the results of their treatment. The verbal protocols are clearly only a partial representation of what subjects where thinking of, but give an insight in the diagnostic process the mobile monitor needs to support. The verbal protocols also show how reasoning in the experiment differed from the model of Gaba et al. (1995). The difference may be caused by the setting of the experiment. Subjects were forced to take a step back to the observation-block since they were not able to perform actions to test hypotheses. However switching from abstract reasoning to observation may also be done in the operating room.

The model of Gaba et al. (1995) fits relatively well with the observed reasoning in the experiment. This is not unexpected since the model is very general. This generality may also explain the popularity of the model since it easy to fit observed reasoning to the model. The consequence is that the model explains little of what is really happening in the diagnostic reasoning process.

Realism of the experiment

In general the anaesthesiologists agreed on the urgency of the case and the diagnosis. Graph 9 shows mean scores for the questionnaire about the cases and shows and overall agreement that the cases were realistic, simple and probable. This realism is also illustrated by the verbal protocols. Several subjects indicated that they wanted to go to operating room and see the patient with their own eyes. For example:

Subject 4: “I would want to take a look at the patient. . If possible..”

Experimenter: “This is not possible, you are stuck in an elevator”

Subject 4:”Then I would be screaming by now”

2 minutes later.

Subject 4:”Ok, now I would climb out of the elevator, because this patient needs help”

There was no specific case subjects wanted to see with their own eyes. Different subjects, mentioned returning to the operating room in different cases.

For the embolism case (case 5) the mean values in graph 9 for probability and simplicity are somewhat lower than for other cases. This case was special since subjects did not agree on the urgency of the case. Two subjects would accept the values in the embolus case and would wait and see what happens while others were considering aborting the procedure. Besides their opinion, no other similarities between the subjects were identified. The difference may be caused by differences in personality. Some anaesthesiologists may wait longer before treating and wait to see if the patient stabilizes by himself, while others may correct every abnormality in the patient's variables.

7.2. Design consequences

Overall the questionnaires (see paragraph 5.3.1) showed that the attitude of anaesthesiologists towards using a mobile monitor was very positive. Following the observations in the diagnostic reasoning experiment and the results of the several questionnaires, a number of improvements and limitations of the mobile monitor were identified.

7.2.1. Improvements

The improvements on the mobile monitor can be divided into three groups: missing variables, information not currently measured and layout improvements.

Missing variables

Missing variables that are measured in the operating room such as ventilator pressures, FiO_2 and PEEP should be added based on the frequency subjects asked for this information. In addition it may be useful to include the trend of the set ventilator values. This will enable anaesthesiologists to see the adjustments on the machine that are done in the operating room.

Information not currently measured

Subjects frequently asked for information that is currently not measured automatically in the operating room. Rather it is observed by looking at the patient, looking at the containers with blood and urine and listening to the lungs. In the current operating rooms anaesthesiologists log everything they do and every change in the patient's status they perceive. When this is logged electronically into a database, the mobile monitor may access this information and display blood loss, urine production, administered drugs etcetera. Like anaesthesiologists, nurse anaesthetists and supervised anaesthesiologists use heuristics and may be biased. In the current situation a nurse anaesthetist or supervised anaesthesiologist may neglect to mention certain information when consulting the anaesthesiologist by phone due to biases. Anaesthesiologists using the mobile monitor will be able to form their own 'picture' of the patient status and are less vulnerable for the effects of untold information.

Listening to the heart and lungs is by far the most proposed action in the diagnostic reasoning experiment. But is also bigger challenge to automate. However there are techniques being developed that may enable including auscultation in the mobile monitor. De Vos and Blanckenberg (2007) build a system that uses neural networks to classify heart sounds into normal (innocent) and pathological classes. Chauhan, Wang, Sing Lim, and Anantharaman (2008) used a Mel frequency cepstral coefficient (MFCC) to deduce representative features from heart sounds and used a hidden Markov model (HMM) to classify these sounds. Classifications generated by such systems can be sent to the mobile monitor. Another option is to send an audio stream to the mobile monitor to which the anaesthesiologist could listen using the smartphone's speaker or a headset in noisy environments.

Layout improvements

Subject indicated a few issues considering the layout of the mobile monitor. According to their comments the trends currently shown on the monitor are too short. Subjects indicated that a history of 30 minutes would be better. Also the resolution of ECG was considered too low. This may be caused by the standard waveform used in the experiment. Despite this, displaying a curve full-screen when selected by the user may benefit the detection of abnormalities in the curve's shape.

7.2.2. Important considerations

The mobile monitor aids the anaesthesiologist in several ways. The polygon screen is designed for fast detection of complications and the classic screen and trend information aid the diagnostic process by enabling anaesthesiologists to perceive the elements in the current situation and thus facilitating situation awareness. The mobile monitor diminishes the effects of biases from nurse anaesthetists and supervised anaesthesiologists calling for help and allows fast interpretation because the caller does not need to explain what can be seen on the monitor.

Therapeutic actions like increasing ventilator pressures or administration of medication will not be included in the mobile monitor. The goal of the mobile monitor is detection of complications and supporting the diagnostic process of the anaesthesiologist outside the operating room. The data should trigger the anaesthesiologist to return to the operating room or should be used for consulting. Any treatment should be done by the anaesthesiologist or other qualified personnel in the operating room.

It is important to consider potential consequences of implementing the mobile monitor. The mobile monitor may alert the anaesthesiologist while on a break. If anaesthesiologists are disturbed often during breaks this is in violation with health and safety regulations which dictate that a break should be undisturbed. When a break is disturbed it is no longer a break and the effects of resting will be diminished. Suspending all alarms during the break will ensure an undisturbed break. If the situation turns critical a nurse anaesthetist may press an alarm button which overrides the 'pause-mode' of the mobile monitor and turns the alarms back on. Another potential consequence of the mobile monitor is that anaesthesiologists will spend less time in the operating room, because the monitor enables them to monitor the patient from elsewhere in the hospital. It is important to stress that the mobile monitor should trigger the anaesthesiologist to go to the patient and failure to do so should be corrected.

Several studies focussed on the use of decision support systems (DSS) in anaesthesia (Gohil, GholamhHosseini, Harrison, Lowe, & Al-Jumaily, 2007; de Graaf et al., 1997; Krol & Reich, 2000; Pott, Cnossen, et al., 2005). It is interesting to research the effects of including a DSS in the mobile monitor. A proper DSS facilitates diagnosing, but may be used as an excuse not to return to the operating room.

7.3. Conclusion and further research

In this study it is shown how a mobile monitor implemented on a personal smartphone may increase situation awareness outside the operating room. It enables anaesthesiologists to detect changes in the status of the patient and aids the diagnostic process outside the operating room. The effects of biases which cause nurse anaesthetists and supervised anaesthesiologists to neglect mentioning certain variables are diminished by the mobile monitor. In addition it may decrease time necessary to comprehend the current patient status.

Before implementing the mobile monitor, further research of the improved mobile monitor is recommended. The focus of these studies should lie on the use of the complete mobile monitor in realistic settings. It is considered important to learn the effects of the proposed improvements on the diagnostic process outside the operating room. Furthermore these studies will give valuable information on how the mobile monitor is used in the day-to-day work of anaesthesiologists. In addition further research may provide more evidence for the adjusted model of Gaba et al. (1995) and may help to further specify parts of the model.

Future experiments should incorporate better (virtual) patients to increase realism. The patients should react to therapeutic actions and patient variables should dynamically change over time. Also the effects of including a decision support system in the mobile monitor is considered worthwhile.

There is a great potential for mobile monitoring in anaesthesia and hopefully such systems will be introduced in hospitals in the near future.

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Appendix

A. Questionnaire pilot (in Dutch)

Questionnaire Anesthesisten

28-01-2011 versie 0.5

Inleiding

Anesthesisten hebben te maken met een hoge cognitieve werkdruk. De anesthesist moet continu een real-time representatie vormen van de situatie van de patiënt. Hierbij wordt informatie geïntegreerd van de patiënt, verschillende apparatuur, en van de collega's.

Een manier om de veiligheid van de patiënt te vergroten is door de technische apparatuur van de anesthesist te verbeteren. Het ontwerpen van machines die rekening houden met de cognitieve beperkingen van de gebruiker valt onder het vakgebied van *Human Factors.* Het einddoel van *human factors engineering* is het aantal fouten te verlagen, de productiviteit te verbeteren en de veiligheid en comfort te verhogen wanneer mensen gebruik maken van het systeem.

Vanuit een human factors oogpunt is er nog genoeg ruimte over voor innovatie en verbetering op de anesthesieafdeling. Graag zouden we uw expertise willen gebruiken om een beter beeld te krijgen van de situatie.

Mobile Monitoring

Een van de ideeën om het de anesthesist makkelijker te maken is de monitor op een mobiele telefoon/tablet weer te geven zodat de patiënt op afstand in de gaten gehouden kan worden. Dit kan handig zijn bij lange operaties waarin de anesthesist niet continu bij de patiënt aanwezig hoeft te zijn. Daarnaast zou het een goede manier kunnen zijn om informatie te verstrekken bij het vragen om een second opinion.

Ook zijn er extra voordelen aan een mobile device verbonden zoals andere vormen van alarmfuncties: trilfunctie, ringtones, notificaties op het scherm. Het bekijken van de historie en persoonlijke weergaven behoort tot de mogelijkheden.

Wat vindt u van dit idee?

Wat ziet u als grootste voordeel van het gebruik van mobile monitoring?

- *Gealarmeerd worden*
- *Second opinions geven/ vragen*
- *Zekerheid, het constant kunnen checken*
- *Anders, namelijk…*

Ziet u ook nadelen?

Display

De huidige monitor biedt alle variabelen aan op één scherm. Sommige van deze variabelen zijn alleen nuttig in een bepaalde context of bij verandering. Omdat een mobiel een hogere mate van interactie heeft hoeven niet alle variabelen op één scherm zichtbaar te zijn.

Stel u zit in de koffiekamer. Welke informatie heeft u minimaal nodig om in 1 oogopslag de staat van de patiënt te kunnen beoordelen? En In welke vorm moet de parameter beschikbaar zijn: getal, histogram of andere suggesties? (zie lijst)

Opmerkingen:

Voor welke van de variabelen kan trendinformatie belangrijk zijn? (zie lijst)

Opmerkingen:

Heeft u bepaalde ideeën over hoe de schermindeling er dan idealiter uit moeten zien?

Zijn er bepaalde situaties waarin een specifieke niet-standaard weergave gewenst is? Zo ja welke en welke informatie moet er dan beschikbaar zijn?

Alarmen

Naast het weergeven van de informatie, behoort alarmeren ook tot de mogelijkheden. Dit kan op verschillende manieren:

- De weergave op het scherm kan veranderen:
    - knipperen
    - kleur
    - symbolen
- Een melding in tekst op het scherm
- Geluiden
- Trilfunctie

Wat zijn volgens u de potentiële valkuilen van een alarmeringssysteem op afstand en hoe zijn deze te ondervangen?

Welke van de variabelen hebben een alarm met een meer absolute grens en welke zijn meer relatief in een bepaalde context?

Hoe hinderlijk zijn vals positieve alarmen ten opzichte van de huidige monitor?

Hoe ziet het instellen van de alarmen er volgens u idealiter uit?

Heeft u zelf ideeën over nieuwe alarmen die u zou willen hebben?

Variabele	Direct zichtbaar	Trend	
SpO2	O	O	*Opmerkingen:*
Expired CO2	O	O	*Opmerkingen:*
Inspired O2	O	O	*Opmerkingen:*
Blood pressure	O	O	*Opmerkingen:*
PAW	O	O	*Opmerkingen:*
PEEP	O	O	*Opmerkingen:*
Heart rate	O	O	*Opmerkingen:*

Temperature	O	O	*Opmerkingen:*
Tidal volume	O	O	*Opmerkingen:*
Respiratory rate	O	O	*Opmerkingen:*
BIS	O	O	*Opmerkingen:*
Isoflurane	O	O	*Opmerkingen:*
Propofol	O	O	*Opmerkingen:*

Fentanyl	O	O	*Opmerkingen:*
Vecuronium	O	O	*Opmerkingen:*
Respiratory minute volume	O	O	*Opmerkingen:*
Blood loss	O	O	*Opmerkingen:*
Blood intravenous	O	O	*Opmerkingen:*
Fluids intravenous	O	O	*Opmerkingen:*
Urine loss	O	O	*Opmerkingen:*

Anders	O	O	*Opmerkingen:*

B. Questionnaire diagnostic reasoning experiment (in Dutch)

Experiment 2

Proefpersoonnummer: _______ Datum: ___-___-2011 Begintijd: ___:___ Eindtijd: ___:___

Specialisatie: _______________________ Geslacht: ___ Leeftijd: ___ Jaren ervaring: ___

Smartphonegebruiker: ___________ Opnamenummer: _________ Experiment Kai: _____

Scenario

1. ___________________
2. ___________________
3. ___________________
4. ___________________
5. ___________________
6. ___________________

Geef door middel van het inkleuren van een cirkel aan wat in hoeverre u het eens met de volgende stellingen.

Wat vond u van de mobiele monitor?	helemaal niet mee eens	niet mee eens	neutraal	mee eens	helemaal mee eens
De mobiele monitor is overzichtelijk	O	O	O	O	O
Ik zie in een oogopslag hoe het gaat met de patiënt	O	O	O	O	O
De mobiele monitor is een nuttig hulpmiddel bij second opinions / consulten / supervisie op afstand	O	O	O	O	O
De mobiele monitor is een nuttig hulpmiddel om buiten de OK complicaties snel te detecteren	O	O	O	O	O
Ik zou een mobiele monitor in mijn dagelijkse werkzaamheden willen gebruiken	O	O	O	O	O

Zou u iets willen veranderen aan de layout van de monitor? Denk hierbij aan de gekozen variabelen, de groepering van de variabelen, missende informatie, trends etc.

Zijn er dingen die u niet goed of storend vindt aan de mobiele monitor?

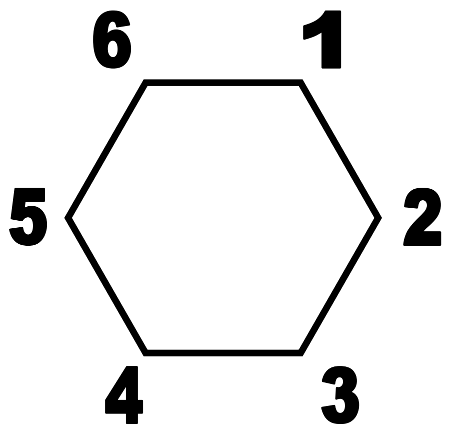
C. Questionnaire polygon (in Dutch)

Vragenlijst

Vraag 1

Onderstaand figuur geeft de zeshoek weer die bij het voorgaande experiment werd gebruikt. Vond u de plaatsing en de keuze van de variabelen goed?

- ☐ Ja
- ☐ Nee, … *(graag aangeven hoe het volgens u beter kan)*



1 ____

2 ____

3 ____

4 ____

5 ____

6 ____

Opmerkingen/ suggesties:

____

____

____

____

____

Vraag 2

Geef door middel van het inkleuren van een cirkel aan wat in hoeverre u het eens met de volgende stellingen.

	helemaal niet mee eens	niet mee eens	neutraal	mee eens	helemaal mee eens
Wat vond u van de zeshoek?					
De zeshoekdisplay is overzichtelijk	O	O	O	O	O
Ik zie in een oogopslag hoe het gaat met de patiënt	O	O	O	O	O
9 zeshoek displays zijn gemakkelijk te overzien	O	O	O	O	O
De zeshoek is een nuttig hulpmiddel bij het stellen van diagnoses	O	O	O	O	O
De zeshoek is een nuttig hulpmiddel bij het snel detecteren van complicaties	O	O	O	O	O
Ik zou de zeshoek in mijn dagelijkse werkzaamheden willen gebruiken	O	O	O	O	O
De volgende vragen gaan over de normale monitor					
De normale display is overzichtelijk	O	O	O	O	O
Ik zie in een oogopslag hoe het gaat met de patiënt	O	O	O	O	O
9 normale displays zijn gemakkelijk te overzien	O	O	O	O	O
De normale monitor is een nuttig hulpmiddel bij het stellen van diagnoses.	O	O	O	O	O
De normale monitor is een nuttig hulpmiddel bij het snel detecteren van complicaties	O	O	O	O	O

D: Instructions diagnostic reasoning experiment (in Dutch)

Instructies - diagnose experiment

Hartelijk dank voor uw medewerking aan ons onderzoek.

Het experiment waar u aan deelneemt, richt zich op het herkennen van complicaties door middel van de anesthesiemonitor weergegeven op een mobiele telefoon. Deze monitor is een enigszins versimpelde versie van de monitor in de OK. We stellen ons voor dat u in de toekomst een mobiele telefoon kunt gebruiken om de monitor van de patiënt te bekijken, zodat u de patiënt in de gaten kunt houden als u niet in de OK bent.
De bedoeling van dit experiment is te onderzoeken in hoeverre de mobiele telefoon gebruikt zou kunnen worden om buiten de OK de toestand van de patiënt te kunnen monitoren. Achteraf vragen we u daarom naar uw mening over de voor- en nadelen van het gebruik van zo'n “mobiele monitor”.

Procedure
Er zal een telefoongesprek worden gesimuleerd: u bent dienstdoend anesthesioloog, en bevindt zich buiten de OK. U wordt gebeld door een “anesthesiemedewerker” (gespeeld door de onderzoeker) die u om hulp vraagt tijdens een operatie wanneer de toestand van de patiënt zo verslechterd is dat hij uw hulp nodig heeft.

- We willen weten welke diagnose u als eerste te binnenschiet, gegeven enkel de beschikbare informatie.
- Vervolgens mag u vragen stellen om extra informatie in te winnen
- Tenslotte kunt u behandelingen voorstellen.

Indien u overstapt naar een andere hypothese is het erg belangrijk om dit te noemen.

We zijn met name geïnteresseerd in welke informatie u nodig heeft om de toestand van de patiënt snel in te schatten (dus bijvoorbeeld welke vragen u aan de anesthesiemedewerker stelt) en welke behandeling u overweegt en/of voorstelt. Het gaat dus om uw reactie in de eerste minuten van zo'n telefoontje. Zodra de onderzoeker genoeg weet, zal het scenario worden beëindigd en zal een volgende casus worden voorgelegd. In totaal krijgt u 6 casussen voorgelegd.

Het gaat er dus niet om om te kijken naar wat op langere termijn de effecten zijn van middelen die u eventueel zou willen toedienen, hoewel dat voor het stellen van de diagnose wellicht wel informatief zou kunnen zijn. U kunt overigens wel vragen welke middelen al gegeven zijn en wat daarvan de effecten waren.

We realiseren ons dat het waarschijnlijk is dat u in deze situaties allang zelf naar de OK was gespoed. Wij laten het aan uw fantasie over om een bepaalde reden te bedenken dat dit tijdelijk niet mogelijk is en u het volledig aan de anesthesiemedewerker over moet laten, al mag uw eerste reactie natuurlijk zijn: “Ik kom er ogenblikkelijk aan!”

Tot slot: We proberen met dit onderzoek meer inzicht te krijgen in hoe anesthesisten handelen en redeneren en hoe een mobiele telefoon nuttig zou kunnen zijn voor situaties waar u niet op de OK bent. Het experiment is op geen enkele wijze een persoonlijke toetsing van uw vaardigheden. We gebruiken juist met opzet extra complexe complicaties, waarbij het niet met zekerheid is vast te stellen wat het "correcte" antwoord is.

Graag willen wij uw reacties opnemen met een memorecorder. Alle opgeslagen informatie zal geanonimiseerd worden bewaard. Resultaten zullen anoniem en op groepsniveau worden gerapporteerd, zonder dat het tot individuele artsen terug te lijden zal zijn.

Monitor

Op de monitor ziet u …. <demo mobiele monitor>

Veel succes!

Afsluiting experiment

Afsluitend willen we u vragen om een enquête over de mobiele monitor in te vullen.

We willen u hartelijk danken voor uw deelname aan ons experiment. Dit onderzoek richt zich niet alleen op diagnostisch redeneren. Deze informatie willen we gebruiken bij het ontwerpen van een mobiel hulpmiddel wat ondersteuning biedt waar nodig.

E. Questionnaire cases diagnostic reasoning experiment (in Dutch)

	helemaal niet mee eens	niet mee eens	neutraal	mee eens	helemaal mee eens
Wat vond u van de Scenarios?					
Scenario 1 was realistisch	O	O	O	O	O
Scenario 1 was eenvoudig	O	O	O	O	O
Scenario 1 was waarschijnlijk	O	O	O	O	O
Scenario 2 was realistisch	O	O	O	O	O
Scenario 2 was eenvoudig	O	O	O	O	O
Scenario 2 was waarschijnlijk	O	O	O	O	O
Scenario 3 was realistisch	O	O	O	O	O
Scenario 3 was eenvoudig	O	O	O	O	O
Scenario 3 was waarschijnlijk	O	O	O	O	O
Scenario 4 was realistisch	O	O	O	O	O
Scenario 4 was eenvoudig	O	O	O	O	O
Scenario 4 was waarschijnlijk	O	O	O	O	O
Scenario 5 was realistisch	O	O	O	O	O
Scenario 5 was eenvoudig	O	O	O	O	O
Scenario 5 was waarschijnlijk	O	O	O	O	O
Scenario 6 was realistisch	O	O	O	O	O
Scenario 6 was eenvoudig	O	O	O	O	O
Scenario 6 was waarschijnlijk	O	O	O	O	O

Opmerkingen: