Using a Polygonal Display in a Mobile Anesthesia Monitor

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ABSTRACT

In this thesis we explore the possibilities monitoring the patient outside of the operating room using a mobile monitor. Anesthetists are responsible for the patient's wellbeing and carefully monitor their vital signs for irregularities. When the anesthetist is outside of the operating room they rely on assistants for monitoring. Providing the anesthetist with a mobile monitor can reduce human error by keeping the anesthetist informed outside the operating room, facilitating early detection and reducing biases during consults. Based on exploratory interviews with anesthetists a prototype was developed and tested in a diagnostic reasoning experiment. This resulted in several improvements in the design of the mobile monitor. In a second experiment we've pursued the possibilities of using a polygonal display in the mobile monitor for a quicker detection of complications.

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CHAPTER 1. INTRODUCTION

An anesthetist is responsible for delivering anesthesia to the patient during surgery. More importantly, the anesthetist is responsible for the wellbeing of the patient. This mainly consists of monitoring the patient before, during and after surgery and responding to any physiological changes in the patient that may be of harm. Part of the information is available by direct observation (e.g. monitoring the color of the patient's skin), but most information is observed from monitoring devices that display a variety of measured variables on a patient monitor.

Keeping track of all these variables and maintaining a complete mental model of the patient makes anesthesia a mentally demanding job. Fortunately not many complications occur because of the use of anesthesia. Death complicates five anesthetics per million given in the UK (0.0005 %) (Aitkenhead, Smith & Rowbothman 2007). There will always be a demand for delivering better patient care. Especially given the non-therapeutic effects of anesthesia there is little tolerance from patients and their families when a complication does occur that causes long lasting harm or death (Cooper, 1984).

It is important that when complications do occur they are detected as soon as possible. Monitoring and continuous vigilance allows for a greater period to respond before the complication grows in severity. Today's anesthesia monitors have automated alarms that sound when a value reaches a preset threshold, which in general is before a value reaches a potentially damaging level.

During long operations anesthetists can be responsible for two patients at once. In this setting is impossible to be constantly near the patient and monitor personally. Therefore a monitor that presents the patient's status outside of the operating theatre can improve patient healthcare.

In this thesis we will present a mobile patient monitor using a smartphone. The goal of this thesis is to answer two specific questions:

1) How can a mobile monitor improve patient safety
2) What is the best way to present the information from a patient monitor on a mobile device

Structure of the thesis

The thesis is divided into 5 parts: first we will give background information about the Job of the anesthetist and how current patient monitoring works in chapter 2. In Past Research (chapter 3) we'll give an overview of current patient safety in anesthesia and give a short explanation of how human errors emerge. State of the Art (chapter 4) consists of recent research directed at improving patient monitoring. Chapter 5 is the main part of the thesis and gives a description of the prototype, important design considerations and the results of the experiment concerning the prototype. Chapter 6 is aimed at answering the question if including a graphical display can improve the anesthetist's detection of complications.

CHAPTER 2. BACKGROUND

2.1 The job of the anesthetist

2.1.1 The Anesthetist

The job of an anesthetist consists of much more than the administration of anesthetics. Anesthetists prepare the patient for surgery and are responsible for the recovery afterwards (but this only takes a relative short amount of time). Most time is spent monitoring the patient during the operation, as they are directly responsible for the safety and well-being of the patient during the operation. Anesthetists therefore need to be able to make many short term decisions that can have very large consequences, they have to be able to work in teams and must be on the highest level of alert at all times.

Before starting the operation, the anesthetist should take careful consideration in the administration of the anesthesia by gathering all useful information about the patient, for example information about the current medical condition, any previous operations the patient may have had, allergic reactions to drugs etc. Besides using this information to accommodate to the patients baseline physiological state, it also plays an important role when complications do occur.

The administration of the anesthesia can happen in different ways, usually being inhalation and intravenous injection. Anesthesia can be local (a specific body part), regional (particular region of the body, such as the lower half of the body) or general (affects all areas of the body). In this thesis the word anesthesia refers to general anesthesia. Various anesthetics are used to block pain responses and relax the muscles. After the patient has been made unconscious an endotracheal tube is placed in the trachea to support the patient's airway management and facilitate ventilation of the lungs. Anesthesia usually causes a loss of a regular breathing and stops protective reflexes such as coughing and gagging. The anesthetist can decide at what speed (respiratory rate) a mix of oxygen, air and anesthetic vapours are being pumped in and out of the patient.

During the operation the anesthetist carefully monitors the patient. A patient can lose too much blood or get an allergic reaction, which can lead to discomfort after the operation, injuries or even death. There is also a natural tendency of the body to (over)compensate to the surgical activities, which can cause a physiological imbalance in the patient. For example, pain in the patient can cause a dangerously high heart rate. This can be suppressed by the anesthetist through administration of certain anesthetics.

Some information about the state of the patient is directly available to the anesthetist, for example skin color. However, most information comes from monitoring devices, displaying each measured variable on a single monitor (for example heart rate or blood pressure). Today's anesthesia monitors have automated alarms that sound when a value reaches a preset threshold, which in general is activated before a value reaches a potentially damaging level.

When a complication does occur it is important that it is detected as early as possible. Effective monitoring and continuous vigilance are extremely important as it allows for a greater period to respond before the complication grows in severity. This also means that the anesthetist sometimes has to act before coming to a full diagnosis of the complication. They also have to manage situations not caused by the anesthetic itself, but by the patient's medical state or the surgical procedure. The anesthetist has the authority to stop the surgical procedure if he or she feels the patient's health is at a risk.

After surgery the patient is taken to the recovery room, where the patient is monitored carefully by the nurses and the anesthetist to make sure the transition from an anesthetized state to an awakened state goes smoothly. Residual sedative can cause some problems and there is still the possibility of an allergic reaction or upper airway obstruction.

2.1.2 The Anesthesia assistant

Multiple eyes are better than one (J. Cooper, Long, & Newbower, 1982). Thus the job of an anesthesia assistant mainly consists of monitoring the vital functions of the patient, assisting the anesthetist with the intubation and checking of the equipment. The assistant's job also consists of analyzing and diagnosing the situation, providing anesthetic care and communicating with the patient. Because many of these tasks overlap with the tasks of the anesthetist good collaboration and communication is crucial.

The Dutch hospitals work with a *two-table system*, which means that anesthetists can be responsible for two patients in different operating rooms simultaneously. This gives the anesthesia assistant much more responsibility as they are monitoring the patient when the anesthetist is not around. Depending on the level of education of the assistants the anesthetist can leave the theatre and let the assistant work under remote supervision.

2.2 Current patient monitoring in Anesthesia

The anesthetist uses a patient monitor which displays the measured variables (fig. 1). There is also a monitor on the ventilator (fig. 2), but this mostly displays machine settings like respiratory rate and O2 percentage. These values do not change unless the anesthetist adjusts them.

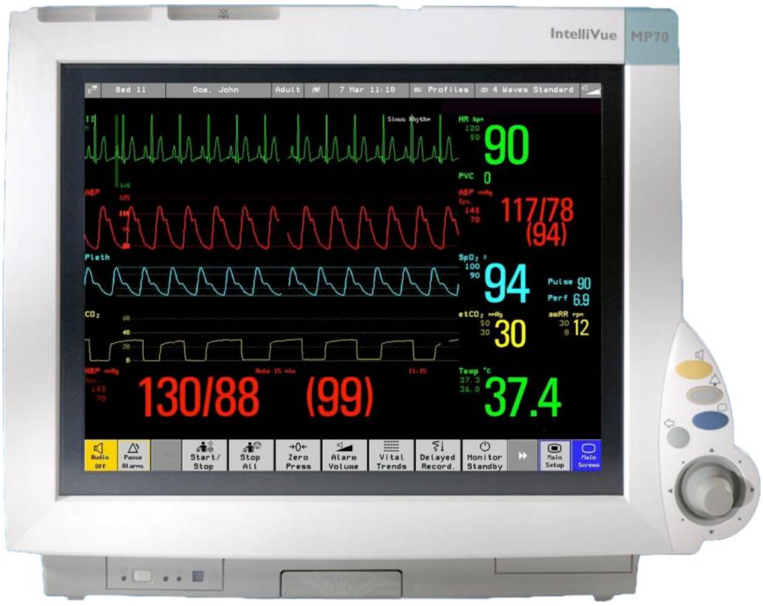


Fig. 1 Patient monitor

Fig. 2 Ventiliator

2.2.1 Anesthesia patient monitor

The anesthetists of the UMCG use the Philips MP-70 IntelliVue monitor for monitoring the patients (fig. 1). The monitor is highly adjustable: users can change alarm limits, colors, variables and the size of the curves. Most anesthetists will leave these settings to their default to avoid confusion, with the exception of the alarm limits. The monitor can also display trends of certain variables in a line graph. The use of this option is a matter of preference, as some anesthetists don't use it at all.

2.2.2 Values presented on anesthesia monitors

Heart rate

Heart rate is the number of heart beats per minute (bpm) and is usually measured by placing electrodes on the chest. Heart beats produce a small electrical signal (ca 1 mV) that is amplified and processed to a frequency reading. A heart rate can be too fast (tachycardia) or too slow (bradycardia). A rapid heart rate can be an indication of very serious complications like hypovolemia (decreased blood volume), pain or heart failure. This makes heart rate the most important vital sign to monitor and is usually made audible throughout the operation.

A steady state heart rate varies much between patients: a regular heart rate of 55 can be normal for some patients and be a critical situation for others. However a normal sized adult would have a regular heart rate of 75 and values below 50 and above 110 would be considered critical.

Oxygen saturation

Oxygen is carried to tissues by binding to hemoglobin molecules in the blood. Oxygen saturation is a percentage of the maximum oxygen that the blood could carry. A hemoglobin molecule can carry a maximum of four oxygen molecules. If a hemoglobin molecule only carries three, it would be carrying only 75% of its maximum capacity.

On a patient monitor, oxygen saturation is displayed as SPO2 and is measured by a pulse oximetry. This is a probe attached to the patient's finger, toe or ear lobe and measures the red and infrared light that is transmitted through the tissue. How much light is absorbed by the hemoglobin depends on how saturated it is with oxygen. As blood is normally saturated with 95 to 100% oxygen, a saturation falling below 95% would be considered critical.

Expired CO2

Expired CO_2 is the amount of CO_2 that the patient exhales after air has been driven into the lungs by the ventilator machine. Values below 3.3 kPa (kilopascal) and above 5 kPa are considered critical. This could mean a mechanical problem (for example with the ventilation) or that the body is unable to transport the necessary amount of CO_2 to the lungs.

Tidal volume

Tidal volume (vt) is the amount of air that is driven into the lungs of the patient by the ventilator machine and exhaled again. It is calculated in millimeters per kilogram. A patient weighing 70 kg normally has a vt of 420-560 ml. Respiratory rate is usually set to 12 breaths per minute.

Blood pressure

Blood pressure is the force that is applied to the artery wall surface when the heart pumps blood through the body. Blood pressure is measured non-invasively by placing a cuff around the upper arm where the blood pressure in the arteries is related to the cuff pressure needed to occlude blood flow. Because the cuff has to inflate and deflate slowly measurements are only done only every few minutes.

In certain situations (for example very sick patients) an invasive blood pressure monitoring technique is preferred. Invasive blood monitoring uses an arterial canula and provides new blood pressure values with every heartbeat. This is useful with very sick patients or when heavy blood loss is expected. However placing an arterial canula can be the cause of some serious problems, like blood loss, nerve damage, infections and various other complications. Though these complications do not happen often they are serious enough to only use an arterial canula when there are strict indications.

Blood pressure readings consist of two numbers: the maximum (systolic) pressure and the minimum (diastolic) pressure that is exerted on the walls of the blood vessels. A patient's systolic blood pressure of 120 mmHg (millimeters of mercury) and diastolic blood pressure of 80 mmHg is denoted as 120/80. Average blood pressure for an adult will range from 111/65 to 140/90.

2.2.3 Curves presented on anesthesia monitors

ECG

The ECG (fig. 3) is one of the simplest, yet very important ways of monitoring the patient. Electrodes are placed on the patient that monitor the natural electrical activity of the heart. The ECG delivers information about the heart rate, cardiac rhythm and can help with the detections of several heart complications. One of the downsides of the ECG is that it is easily disturbed by other electrical equipment, like electrosurgical devices that produce high voltages to 'burn' tissue in the surgical wound.

Fig. 3 ECG

Plethysmogram

The plethysmogram (fig 4.) is a visual representation of the pulse oximetry that is used to measure the oxygen saturation. However on a plethysmogram it represents the amount of blood that pulsates in the finger. Because blood that is being pumped around takes some time to reach its destination the peaks of the plethysmogram are a little delayed from ECG.

Fig. 4 Plethysmogram

Capnogram

A Capnogram is a graphical representation of the measured CO_2 in the patient's exhaled air. When air goes into the lungs the CO_2 concentration in the air is almost zero, hence the lower baseline of the curve. A capnogram can be used to detect deviations in breathing and technical malfunctions of the ventilator.

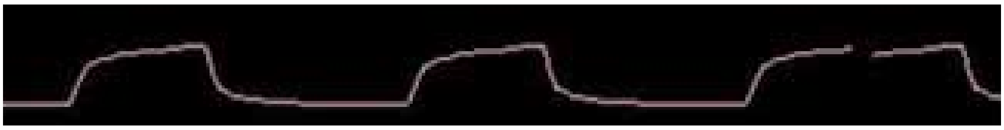


Fig. 5 Capnogram

Ventilation pressure

In an spontaneously breathing patient the muscles in the diaphragm, the abdominal wall and between the ribs contract and expand the chest cavity, causing air to enter the lungs. When under general anesthesia the muscles are relaxed and a certain amount of pressure is needed to move air into the lungs. The anesthetist can choose from two ways of ventilating the patient: pressure-controlled and volume-controlled. With press-controlled ventilation the amount of pressure is fixed and the tidal volume depends on the compliance of the lungs. With volume-controlled ventilation the machine pumps a fixed volume of air into the lungs, creating an airway pressure that depends on the compliance. The pressure can be monitored using the ventilation pressure graph. It also contains the expiration pressure (PEEP) and the inspiration pressure (PAW).

Fig. 6 Ventilation pressure

CHAPTER 3. PAST RESEARCH

3.1 Improving safety in anesthesia

3.1.1 Complications

Deaths caused by anesthesia has been a popular research topic over the past decades. Impressive improvements in safety largely decreased mortality rates that were caused by anesthesia. For example, a connector design that prevents a gas hose or cylinder to be connected to the wrong site. Though the numbers vary somewhat, several studies from the United Kingdom, The Netherlands, Australia and other countries show a current mortality rate of one death per 200,000-300,000 of anesthesia administered, while the mortality rate in the 1980s was around one death per 5000 anesthetics (Arbous et al., 2001; Bracco et al., 2001; Lienhart et al., 2006; Rowbotham, D & Smith, 2007; Runciman et al., 1993). However this number does not apply to patients with a compromised health status, where the risk of dying increases to around one death per 10,000-15,000 and has been roughly unchanged for the past twenty years (J.B. Cooper & Gaba, 2002; Lagasse, 2002).

Of course improving safety in anesthesia is not just about lowering the risk of dying. A variety of injuries may result from administration of anesthesia. Some examples are dental injury, peripheral nerve injury and postdural puncture headache. Though mortality data is widely available, for morbidity they are lacking. Thus for most injuries it remains unclear if, and with how much, the estimated risk of occurrence has dropped (Botney, 2008). Besides physical discomfort, injuries can also cause anxiety, phobias and post-traumatic stress disorders in the patient (Bacon, Morris, Runciman, & Currie, 2005).

The huge gains in anesthesia can be attributed to a wide range of improvements. New monitoring techniques such as capnography and pulse oximetry allowed for earlier detection of common anesthetic risks. Fiberoptic bronchoscopes, laryngeal mask airways and various special-purpose tools allowed for better management of difficult patient airways (Botney, 2008). Besides having better tools at their disposal the decrease in mortality rates was also accomplished through the widespread adoption of practice guidelines (Kohn, Corrigan, & Donaldson, 2000), for example dealing with patients that have particular clinical problems such as diabetes.

Most anesthesia-related complications are related to irregular heart rate (arrhythmia), a rapid change in blood pressure (hypotension) and various problems with the ventilation of the lungs (Rowbotham, D & Smith, 2007). Risk factors are age, medical condition and the use of cigarettes, alcohol and drugs.

The huge improvements in anesthesia safety are seen as a great success and are even considered an example for various other fields (Lanier, 2006). Yet there is always a demand for even better patient care. Especially given the non-therapeutic effects of anesthesia (the patient will not get any better from the anesthesia itself) there is little tolerance from patients and their families when a complication does occur that causes long lasting harm or death (J.B. Cooper, 1984). Such complications can also affect the mental health of the anesthetists themselves, as suicide rates among anesthetists are more frequent than among most other specialties (McNamee, Keen, & Corkill, 1987).

3.1.2 Human Error

There was an early realization that human actions were a main cause of anesthetic morbidity and mortality and not the drugs themselves. This resulted in a strong focus on research to improve anesthesia safety by preventing human errors (Botney, 2008). But what defines as a human error? Human error is not synonymous with blame, as the errors are often made by highly motivated and experienced people that performed their job as well as expected (D. M. Gaba, 1989). What does classify as human error differs on the context and the taxonomy used as there is no universally agreed classification (S. J. Wheeler & Wheeler, 2005). In the anesthesia literature the most popular is a distinction between slips, lapses and mistakes.

The distinction between slips and lapses are subtle as they both involve errors made in an automated process that does not require conscious control or problem solving. A slip is an action that did not occur as planned (Rasmussen, 1982), for example writing the wrong year in a date shortly after New Year. A lapse is a memory failure, forgetting to do a certain action in a sequence. With slips and lapses the desired goal was correct, but the execution failed.

A mistake is an error that resulted in an action that led to an unwanted outcome. The execution may go as planned, but the selected goal was inadequate to begin with, for example an anesthetist makes a bad diagnosis and the patient receives the wrong treatment. Mistakes can be split in rule-based mistakes and knowledge-based mistakes.

Rule-based mistakes are errors in applying the correct heuristics (are rules of thumb Chapter 3.2.3 Decision Making). This can either be applying a good rule to the wrong situation or simply applying a bad rule. Knowledge-based mistakes are mistakes that were made when heuristics don't apply (because of the encounter of a new situation) and online reasoning is required. Online reasoning is highly error prone because of three reasons: 1) conscious thought is a limited resource, 2) the mental model of the situation can be incorrect, and 3) it is very susceptible to the confirmation bias (favoring features of the world that support the hypothesis) (Reason, 2005).

Cooper was the first to apply critical-incident analysis to errors and mishaps in anesthesia. Critical-incident analysis was already successfully applied on military aviators, a field that has many basic similarities to the practice of anesthesia (D. M. Gaba, Howard, & Small, 1995). They found that human error was at least partially responsible for critical incidents in 70% of the cases, though there is rarely one cause for an incident (J B Cooper, Newbower, & Kitz, 1984). This resulted in a variety of strategies to prevent or detect critical incidents, such as additional training, improvements in equipment design, the use of alarms and various other organizational improvements (S. J. Wheeler & Wheeler, 2005).

More recent reports of human error in anesthesia give an even higher number of human errors in anesthesia incidents. Though the results vary somewhat there is agreement that human error is involved in 70-80% of the cases (Webb et al., 1993) and is very similar to numbers found in many other domains (Reason, 2005). The Australian Incident Monitoring Study (Webb et al., 1993) looked at 2000 anesthetic incidents. They found a wide variety of contributing factors to human error, with the most important being misjudgment (16%), failure to check equipment (13%), fault of technique (13%), inattention (12%), haste (12%) and inexperience (11%).

3.2 Cognitive processes of the anesthetist

In order to better understand how human errors emerge, a good understanding of the basic principles of human cognition is indispensable. In this section we'll first discuss attention and awareness to better understand why slips and lapses can occur, even in well-trained anesthetists. Second, an overview of the decision making process of the anesthetist during complex decisions, to better understand how mistakes are made.

3.2.1 Attention & vigilance

Attention plays an important role in understanding human errors. It is inattention that can drive an anesthetist to the accidental administration of the wrong drug, while attention to the alarm signals make him realize the mistake and correct it. Attention allows us to selectively concentrate on one aspect of the environment and ignore other things (Schwid & O'Donnell, 1992). Fatigue influences attention negatively and when attention is low, mistakes are more easily made.

One important aspect of attention is vigilance. An anesthetist must remain alert and watchful for extended periods of time when monitoring the patient's vital signs. During long operations there is a probability that vigilance decreases, resulting in longer reaction times to visual and auditory alarms (Howard et al., 2003).

When a critical situation emerges, it is essential for the anesthetist to be able to completely concentrate on finding a solution. However it is still important that the anesthetist is able to detect other dangers that may emerge. Even during complex tasks the anesthetist regularly scans the environment for relevant and new clues (St. Pierre, Hofinger, & Buerschaper, 2008). The mechanism that allows the anesthetist to do this is called background control and happens without any conscious planning. Factors like stress and level of confidence reduce background control.

Loeb (1994) studied why changes in monitored patient vital signs were detected earlier during the maintenance phase than during the induction phase. His conclusion was that the higher workload during the induction phase results in less glances at the displays. He suggests that competing demands may even be a more major cause of lower situation awareness (seen next paragraph) than fatigue. The results also showed that anesthetists usually looked several times at the monitor before detecting an abnormal value, which suggests that most of the time anesthetists only focus on certain variables.

3.2.2 Situation awareness

Situation awareness (SA) is used to describe the operator's awareness of changes to the environment. Being situational aware is often accompanied with the feeling of being in control of the situation. Endsley (1995) identified three stages in situational awareness: what is happening and where (perception), which events really matter (understanding), and what could happen next (prediction).

Attention plays an important role in creating and maintaining SA. The detection of all the relevant objects, parameters and events requires the conscious allocation of attention. SA is maintained by scanning the environment at regular intervals, which is done during background control. Measuring SA is somewhat tricky, as people are not always aware of what they are aware of, or what they are not aware of.

Situation Awareness has been intensively studied in aviation, but less in the anesthesia domain. Gaba (D. M. Gaba, 1992a) identified that situation awareness anesthesia was equally important in the anesthesia domain. In his cognitive model of the anesthetist's problem-solving behavior he shows how SA can be mapped (fig. 7) (D. M. Gaba et al., 1995). The perception stage plays part in observation, verification of observation, problem recognition, allocation of attention, and prioritization components of the model. The understanding stage is referred to in the model as problem recognition. The prediction stage is mapped on predictions of future states. Gaba also sees the ability of reevaluation as an important aspect of situation awareness, which is brought forth by the loop of observation, decision, and action.

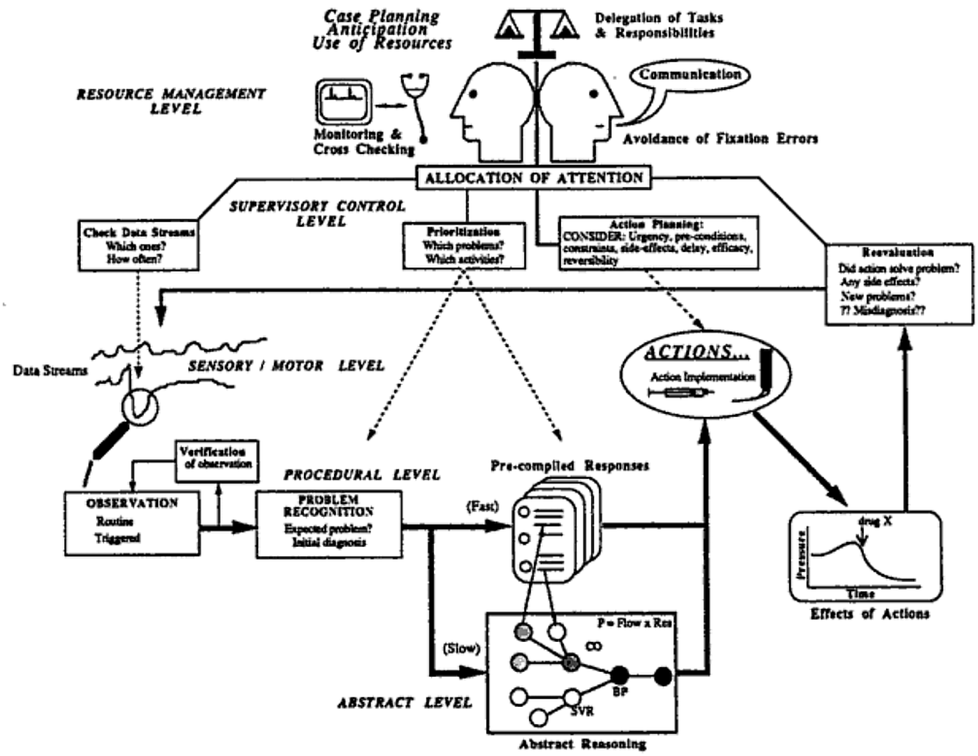


Fig. 7 Model of the dynamic decision making process in anesthesiologists (D. M. Gaba et al., 1995)

Gaba identifies three situations where SA plays an important role. The first is the *detection and interpretation of situational cues*. These cues can be very subtle, for example an anesthetist hears a surgeon mumble to a nurse that she needs to set up a second blood suction system. This should trigger the anesthetist to look for signs of excessive blood loss. The second is *adapting to an evolving situation*: when a situation produces an unexpected outcome quick reevaluation of the state of the patient is needed to still come up with a coherent view of the situation. Here flexibility is of the essence, as the anesthetist not only needs to apply knowledge in various ways, but also needs to be flexible enough to disregard previous held beliefs. The last situation is where *special elements of knowledge* have to be utilized, for example when a possible diagnosis alters because of a specific patient history.

3.2.3 Decision making

Decision making is a complex mental process that results in the selection of an option from a number of alternatives. Decision making is typically characterized as having a relatively long time to make the decision and dealing with uncertainty (Wickens, Gordon, & Liu, 2004). The field of anesthesia is involved with *dynamic* decision making, as the environment is also complex and susceptible to change (D. M. Gaba, 1992b).

Decision making lies on a continuum from an informal to a more analytical approach (Croskerry, 2005). The analytical approach is systematic, and involves more cognitive control. The informal approach is heuristics, or rules of thumb that the anesthetist applies. In Gaba’s model of *the dynamic decision making process in anesthesiologists* (fig. 7) the heuristic and the analytical approach are depicted as the procedural level and the abstract level. The procedural level contains problem recognition with precompiled response, allowing a fast corrective response as there is no abstract reasoning taking place. This is a crucial anesthetic skill as the exact diagnosis may be still unknown. The abstract level contains abstract reasoning and is a much slower process.

There are over 40 biases documented that somehow can influence the diagnostic process (Croskerry, 2005). Decision making can be divided into three phases and cognitive biases can occur in any of them: (1) Receiving and using cues, (2) Hypothesis generation and selection, and (3) action selection.

The first stage involves perceiving cues and sending it to working memory. Most of the biases are involved with limitations of the working memory. For example, the limited number of cues that an anesthetist can pay attention to, or seeing the first cues as more important (anchoring heuristic).

In the second stage, hypothesis generation and selection, the cues are used to form differential diagnoses by retrieving information from long-term memory. Hypotheses that have been considered recently or more frequently are more easily retrieved. This can make it more troublesome to come up with the correct hypotheses for more unusual complications and can also lead to wrong estimates of frequency of occurrence. The frequency of occurrence is sometimes estimated by cognitively assessing the ease of retrieval (availability heuristic).

In the third stage, plan generation and action choice, the possible actions at a selected hypothesis are retrieved from memory. Just as hypothesis generation, action generation is also susceptible to the availability heuristic.

Chapter 4. State of the Art

4.1 Alarms

Alarms are used to support the anesthetist in monitoring the patient's vital functions. An audible alarm alerts the anesthetist to look at the monitor, where the variable that activates the alarm blinks to become more salient. Alarms are activated when a variable exceeds a preset threshold and continues to sound until the anesthetist brings the variable to normal levels, adjusts the threshold or silences the alarm.

Ideally an alarm should detect all life-threatening situations and does so well before these situations occur. However the more sensitive the alarms are set, the higher the rate of false alarms. False alarms can occur because a variable goes beyond a preset threshold but is of no clinical relevance. It can also occur because of errors in the measurements, for example when a patient is being moved in another position and an instrument gets disconnected.

The current rate of false alarms in critical care monitoring is up to 90% and has not changed over the past 20 years (Imhoff & Kuhls, 2006). False alarms distract the nurses and physicians from their current task and a high frequency can lead to frustration. Some even go so far as silencing the alarms outright or changing the alarm settings to a level that is unlikely to be exceeded (Block, Nuutinen, & Ballast, 1999). The staff may become desensitized to the alarms, in which case the alarms are no longer consciously registered. There is also the problem of induced stress in the attending physician by the continuous sounding of alarms (Griffith & Raciot, 1992).

Various methods from the field of artificial intelligence have been suggested to make the alarms "smarter". These include knowledge-based methods, machine learning, neural networks, fuzzy logic, and Bayesian networks (for an overview see Imhoff & Kuhls, 2006). Though these methods are very promising they fail to satisfy the strict medical requirements. Even though fewer but better auditory alarms can improve patient safety, from a manufacturers perspective detecting all critical events is still more important (Edworthy & Hellier, 2005). At present there is no alarm algorithm that has proven to be as comprehensive as the existing alarm systems.

4.2 Monitors

Within the fields of aviation and nuclear power plant control it has been shown that information displays fitted to the task at hand lead to a reduction in errors (Allnutt, 1987). Many valuable lessons from these fields can also be applied to anesthesia displays, but as Drews & Westenskow (2006) point out, there are some extra challenges to overcome: (1) a nuclear power plant is designed to be monitored and patients are not, (2) relationship between the physiological variables is not always clear, (3) there can be a difference between the monitored values and the real patient status as the monitored values are approximates, (4) what are normal and abnormal physiological variables can differ between patients and contexts.

Yet there is a high demand for improvement in the current display, which has basically been left unchanged for the past 20 years (Botney, 2008). Almost all displayed variables on the current patient monitors are single sensor, single indicators and are presented as a number on the screen. Because there is no integration of information the anesthetists have to mentally integrate the information themselves. This places a high demand on the cognitive resources of the anesthetists and limits the resources that are available for other tasks.

Integrated monitors

The alternative is to use a display that integrates information, thus demanding less cognitive resources. As humans are very good at detecting symmetries (Wagemans, 1998), most integrated displays use symmetrical shapes to indicate the normal state of the patients. Any deviations from normal are easily detected as the shape becomes asymmetrical. For example (Jungk, Thull, Hoeft, & Rau, 2000) visualized the oxygen supply as a square, integrating oxygen content in the blood and cardiac output (Fig 8).

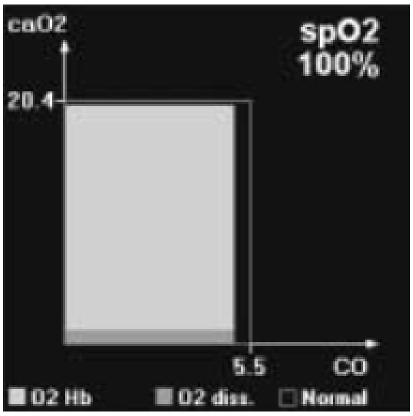


Fig. 8 Visualization of the oxygen supply with oxygen content in the blood on the y-axis and cardiac output on the x-axis (Jungk et al., 2000)

(Gurushanthaiah, Weinger, & Englund, 1995) used a polygon to display six patient variables as one figure. When the polygon is filled the patient's state is normal. They compared the polygonal display with a numerical display and found it shortened detection times by 15%. The polygon is further discussed in chapter 6.

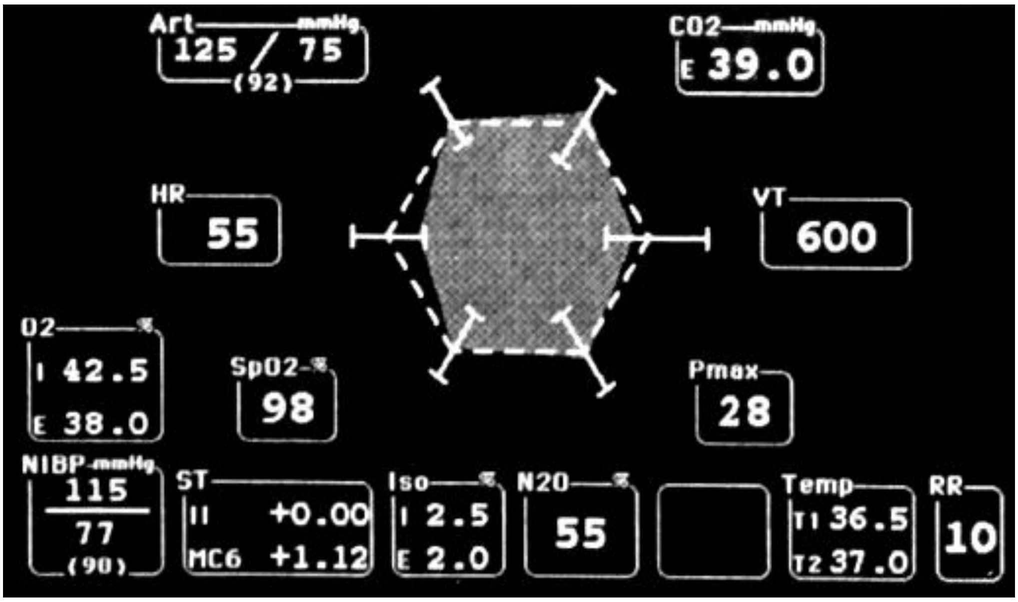


Fig. 9 Polygonal display (Gurushanthaiah et al., 1995)

It is sensible to integrate the variables that have some sort of physiological relations. For example, (van Amsterdam, 2010) stacked heart rate on top of blood pressure (fig. 10) because it depicts the level of anesthesia. A too low anesthesia level is an indication that the patient may be in pain, resulting in an increase in heart rate and blood pressure. A too high level of anesthesia and the opposite occurs, which is also undesirable.

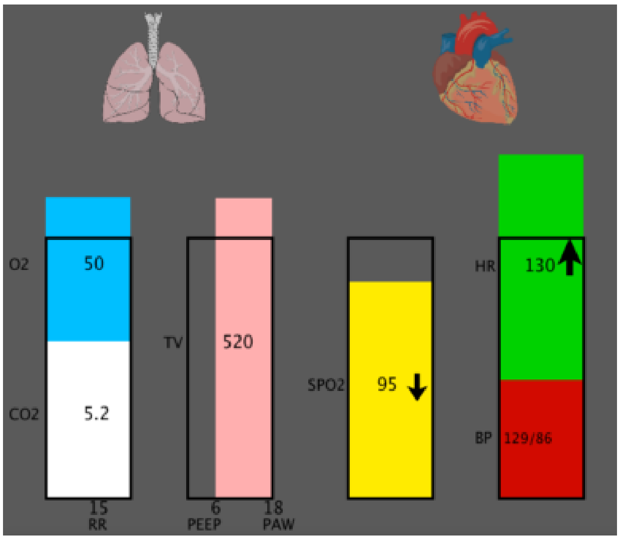


Fig. 10 Metaphorical Anesthetis Interface (van Amsterdam, 2010)

Drews & Westenskow (2006) provide a literature review of the data displays in anesthesia. Almost all of the reported graphical displays show improvements in detection, diagnosis, or treatment. However, Drew & Westenskow point out that many of the studies also show some serious limitations and methodological problems.

Many of the studies showed a low number of subjects and not testing the displays in a controlled enough fashion. The methods used varied greatly between studies: ranging from static pictures to dynamic simulations. It is not clear if all of these methods generalize equally well to the real world. Especially given that most of the test settings only mirrored a partial task, whereas a clinical setting involves multitasking.

Finally, none of the displays have showed to be effective in improving detection, diagnosis *and* treatment. This is important because all of the three processes are highly interwoven. Blike et al. (Blike, Surgenor, & Whalen, 1999) acknowledged that trend curves such as ECG and arterial blood pressure remain irreplaceable for now and that graphical shapes can only give an overview of the patient's state and hints to a possible diagnosis.

4.3 Decision Support Systems

A decision support system (DSS) is a system that aids the decision making process. When a complication occurs the anesthetist is faced with a large problem space. A DSS in the anesthesia domain can help guide the anesthetist by providing possible diagnoses with the probabilities that it is correct. It can then help with the selection of the appropriate action. For example, (Pott, Johnson, & Cnossen, 2005) tried to raise the SA of the anesthetists by presenting up to five different diagnoses.

Current DSS's developed for the anesthetist are still very experimental. The number of diagnoses that the current DSS's can detect is limited, and there is no clear consensus around the logical rules (the rules under which a certain diagnosis is given) that should be used. Another limitation is that they do not have access to information about external events.

Chapter 5 Mobile Monitor

In our current study we focus on the possibilities of monitoring the patient's vital functions on a smartphone. It is not until recently that by technological innovations phones have become suitable for this task. Several of these innovations are an increase in screen size and resolution, faster processor speeds for handling data, and longer wireless connectivity due to better batteries.

Because this is a very exploratory research where we rely a lot on the anesthetists input, we've put a strong focus on building a prototype implementation of a mobile monitor, strongly based on input from anesthetists. We felt that we would get the best input if they had something to actually interact with and could see the results of their ideas. The design of the prototype is discussed in the first part of this chapter and ties together *Chapter 3 past research* with preliminary interviews done with the anesthetists. The second part of this chapter consists of a pilot experiment that was done with the prototype.

5.1 Designing the prototype

To come up with the gist of the prototype we've set up a preliminary interview with a group of anesthetists and anesthesia assistants about using a mobile monitor. The questionnaire was set up to give answer to two main questions: (1) in what situations can a mobile monitor help to improve patient healthcare and (2) how should the patient information be presented on a mobile monitor. We've also asked about any drawbacks that they could think of or any additional features that they would consider useful. The results are presented as a summary below.

5.1.1 Situations where a mobile monitor can be beneficial

Before starting on the functionality we have to identify the situations in which a mobile monitor can be beneficial. From the preliminary interviews two major benefits were identified when using a mobile monitor: keeping aware of the patient status when not in the operating room and having all the information available when presented with a consult.

1) Periodically checking up with the patient

The anesthetist is not always in the operating room. In Dutch hospitals where the anesthetist can be responsible for two patients simultaneously it's simply not possible to be in the second operating room. There are operations in which the anesthetist is simply not allowed to walk constantly in and out of the operating room in fear of risking unnecessary infections to the patient. In such situations the only way for the anesthetist to keep informed of the status of the patient is by contacting the anesthesia assistant, who is assigned to only one operating room at a time. It is their job to keep the anesthetist informed and alarm them if the patient's situation deteriorates.

There are some disadvantages to this approach. A delay is inevitable between the start of a patient deterioration and moment the anesthetist is informed. Even when the anesthetist gets alarmed they first have to observe the situation, recognize the problem and select the appropriate action, before they can start treatment.

The situation is different when the anesthetist is able to periodically check on the patient's status using a mobile monitor. First, potentially dangerous situation may be detected earlier. There are various reasons why attention and vigilance of the anesthesia assistant may drop, for example fatigue. Thus having the anesthetist also checking up on the patient is not necessarily redundant. Second, we discussed earlier that situation awareness plays an important role in problem recognition. Being away from the patient lowers the anesthetist's situational awareness. Time passes and the last state of the patient may not come as vivid to mind as when the anesthetist left the room (of course the patient's condition can also change). The lower the SA of the anesthetist the more time is needed to observe the situation and recognize the problem.

2) Consults

When an event occurs that needs some sort of intervention it is not always necessary or possible for the anesthetist to go back to the operating room immediately. The anesthesia assistant may also be capable of solving the problem himself, but depending on the situation he will contact the anesthetist for a consult or affirmation. The assistant provides the information to the anesthetist to make the final decision.

It is important that the assistant provides all the relevant information. However, the assistant can simply not have enough experience to detect all the relevant changes. Also, when calling for an affirmation or consult the assistant may already have some sort of diagnosis in mind. Many biases are possible to influence the process, for example the confirmation bias. The confirmation bias is a tendency of people to favor information that confirms their hypothesis. The assistant may (unconsciously) provide the anesthetist the information that is in support of his own diagnosis only.

5.1.2 Design of the mobile monitor

Another part of the preliminary interviews was focused on the functionality of the application. A complete copy of the normal patient monitor seemed unwise for two reasons: The space on a mobile phone is rather limited and displaying all the information would make the display somewhat cluttered. Second, the task of remotely monitoring a patient is somewhat different from monitoring the patient in the same room. Thus some adjustments might be useful to make the display better suited for this task.

As discussed earlier we've identified two possible uses for a mobile monitor. In the first use the mobile monitor is merely a tool for detection: keeping the anesthetist aware of the current state of the patient. However when an anesthetist is called for a second opinion the mobile monitor needs to be a tool to support diagnosis. The display of a standard patient monitor needs to be suited for both detection and diagnosis. Because a mobile monitor is highly interactive it can have separate views for detection and diagnosis. It is not necessary that all the information is presented on a single screen.

From the preliminary interviews it became clear that the main display should contain a minimal amount of necessary variables to detect that there is something wrong. Mainly because the space on a mobile phone is limited, but also because when something is going wrong, the anesthetist should head back to the operating room as quickly as possible.

5.1.3 The use of graphical displays for detection

During the interviews we also discussed the option to use a graphical display as an alternative to presenting the variables as with the patient monitor. Graphical displays have shown a reduction in recognition time of complications (Drews & Westenskow, 2006). In the previous chapter we've discussed that the acceptance of graphical displays is low because they do not fully support the diagnostic process. From the interview it became clear that this is less of a problem for the mobile monitor because it is intended to be used mostly as a detection tool. If needed, changing the display to support diagnostic reasoning is very easy.

Another problem with integrated displays is that they have not been tested enough in a controlled fashion (Sanderson, Watson, & Russell, 2005). Implementing integrated displays in real life clinical settings is difficult because it should never compromise patient safety. In contrast, when implementing a graphical display in a mobile monitor the anesthetist can have firsthand experience and still be safely warned by the anesthesia assistant if anything is left unnoticed.

But what would be the best graphical display to use on a mobile monitor? Perhaps this depends more on personal preferences and the anesthetist should decide themselves how to display the data. After all, in contrary to the patient monitor a mobile device is only used by the anesthetist. In the next chapter we will further discuss integrating a polygonal display in the mobile monitor (Gurushanthaiah et al., 1995).

5.1.4 Mobile monitor as a tool to support diagnostic reasoning

When the anesthetist is called over the phone for a consult, a diagnostic reasoning process starts in the anesthetist. We have discussed in the previous section that the current graphical displays are not very well suited for diagnostic reasoning, therefore a more traditional presentation of the curves and variables are in place. Having access to more information is usually better, as long as the anesthetist has no problem finding the necessary information. If not all the information fits on one screen most anesthetists preferred keeping the important information grouped together and placing other variables on a separate screen.

Trend information was considered a very useful tool for diagnostic reasoning and detecting complications. When variables are changing very steadily in one direction a larger trend may become unnoticed. Displaying graphical trend information can make them more aware of the change. On the standard patient monitor displaying the trend information is optional.

As mentioned before one of the possible pitfalls when consulting over the phone is the confirmation bias. Therefore implementing a decision support system that presents other possible diagnoses was considered to be a useful feature.

5.1.5 The need for smarter alarms

Being able to set alarms on the phone is considered a useful feature by all the anesthetists. However as some pointed out, with the current alarm settings the rate of false alarms is too high to make it practical. Human actions can be triggers for alarms, for example when a patient is repositioned on the operating table, monitoring signals may be disturbed temporarily and cause an alarm state. In the operating room an alarm is easily verified by looking at the display, but a mobile phone has to be taken out of the pocket first. When the anesthetist is busy with another patient such false alarms can be very distracting.

Thus smart alarms as discussed in Chapter 3 are not only an improvement, but a necessity if alarms are to be implemented on a mobile device. The smart alarms may not be as extensive in detecting critical situation as the regular alarm settings, but not using them can lead to two possible situations: first the anesthetist can find the alarms too distracting and turn them off completely and second, the alarms can distract the anesthetist when the seconds patient need his attention, thus compromising the safety of one patient over the other.

5.2 Prototype and user experiences

Based on the design considerations and the preliminary interviews we constructed a prototype of a mobile monitor for the android operating system. The smartphone used for testing and development was a HTC Desire HD. The smartphone was programmed to become a mobile monitoring device. The telephone function of the device was not used. We tested the prototype with 9 anesthetists (mean age: 44, 3 females). Six were familiar with the use of smartphones.

We presented the prototype to the anesthetists in a setting that was similar to a real consult. The anesthetist had to assign a diagnosis to six different complications by using the mobile monitor and asking questions to the experimenter. How well the subject performs in this task is not our primary interest and for more details and a further analysis of the diagnostic reasoning task see Doesburg (2011).

We were interested in three things: first, the experiences of the subject using the device in a somewhat realistic setting, second, observing how the subjects interact with the device (is it easy enough to use?), third, what information that is currently not on the screen is indispensable for a correct diagnosis and how that influences the usefulness of the device.

5.2.1 The prototype

The final prototype consisted of three screens (fig. 11):

Standard display

The most important curves and numeric variables were put on a single display. The trends that are displayed are from top to bottom: ECG, plethysmogram, capnogram and ventilation pressure. The numeric variables are: heart rate, oxygen saturation, expired CO_2, tidal volume, blood pressure and temperature. The display very much mimics the standard patient monitor display as the relative placement of the variables and trends are the same. All other variables were left out to make it less cluttered. The colors of the variables were the same as on the normal patient monitor.

Trend information

The screen showed the trend of the past ten minutes and contains the trend information of the following variables: heart rate, oxygen saturation, expired CO2, tidal volume, and blood pressure (systolic and diastolic in one display).

Switching between screens was done by swiping the finger across the screen. Swiping from left to right brings the user to the screen to the left of the current screen, swiping from right to left brings them to the screen to the right. Other functionality such as alarms was not implemented.

Polygonal display

For the quick identification of complications a polygonal display was included that is based on the graphical display by (Gurushanthaiah et al., 1995). The use of this display is further discussed in chapter 6.

Fig. 11 The three screens of the prototype. From left to right: standard display, trend information and polygonal display.

5.2.2 User experiences

After the subjects had assigned a diagnosis to the six complications we asked questions about their experience with using the device. The results of this evaluation are presented as a summary below:

Trend information was considered the most useful feature. All anesthetists considered the displays to be well organized. Eight anesthetists found the mobile monitor a useful asset, for both consults and detection, and would like to use the mobile monitor in their daily tasks.

Peak pressure and respiratory rate were the variables that were most missed. These are needed for a good interpretation of the tidal volume. Complications can occur over a period longer than 10 minutes, so there was a preference to make the trend information adjustable. Also the ECG was set to display 10 seconds at a time and made the ECG more difficult to interpret for the higher heart rates.

Blood loss and recently given medication were the items of information that were most frequently asked for. Normally when an anesthetist enters the operating room he first checks the variables on the patient monitor, followed by a look at the blood loss and administered medication. This information is sometimes necessary to interpret the situation correctly (for example: is the recent rise in blood pressure a symptom or caused by medication used by the assistant?).

5.3 Conclusion & discussion

From the input of the anesthetist we constructed a prototype to give anesthetists hands-on experience with a mobile monitor. The results show that the anesthetists from the experiment consider a mobile monitor a valuable addition to their daily practice and that the prototype meets their expectations.

However the results also show that it is very important to consider the different situation in which the mobile monitor is being used compared to the traditional use of the standard patient monitor. When the anesthetists are out of the operating room they are busy with other tasks (even if on coffee break) and should not be unnecessarily disturbed. This means that there should go considerable thought in the way that alarms are implemented on the device.

But maybe a bigger problem is that information about external events is missing. In some situations the anesthesia assistant is allowed to provide medication without consult. It is not always apparent from looking at a mobile monitor if the change in variables is a symptom or caused by medication. The main purpose of the mobile monitor is to get the anesthetist into the operating room earlier when something goes wrong, not to make the anesthetist go to the operating room unnecessary.

But a mobile monitor also opens up many new possibilities because it is a personal device that doesn't need to be shared. This allows for the use of new ways of presenting information, smarter alarm functionality and other support tools for diagnostic reasoning which would not be possible on the patient monitor. In the next chapter we'll discuss one of those additional features that could be implemented on a mobile monitor: a polygonal display for faster detection of complications.

CHAPTER 6 POLYGONAL DISPLAY

6.1 Introduction

This chapter tries to answer the question whether including a graphical display on a mobile monitor can improve the anesthetist's detection of complications. Compared to the patient monitor a smartphone has some characteristics that make it particularly suitable for the inclusion of a graphical display. For example, interacting with a smartphone is much easier because you don't have to walk over to the device. This makes it unnecessary to support both detection and diagnosis of complications in one display, because the display can be changed much quicker.

The graphical display that we included in the mobile monitor is a slightly modified version of the polygonal display by Gurushanthaiah, Weinger & Englund (Gurushanthaiah et al., 1995). This display was selected because it provides an almost complete picture of the patient status in a single graphical shape. It is also the only display that has been implemented clinically. However, its implementation in the Ohmeda Modulus CD anesthesia machine was short-lived because of two problems.

The first problem was the way the variables were presented on the display. The polygonal consisted of six spokes, representing each of the six variables. If the patient's state was normal the shape filled up to form a polygon. However, the scaling of the variables was not adjustable. This resulted in a difference in interpretation between the variables because the same change in size of a spoke was more critical for some variables than for others.

The second problem was that the polygon was considered by the users to be only suited for the detection of complications because it lacked information that was available on the standard patient monitor. The Ohmeda Modulus CD had a different page for numerical values and waveforms, but the user had to walk over to the device to change it (Drews & Westenskow, 2006).

The first problem is easily avoided by allowing the anesthetist to set the scaling of the variables themselves. It can also be made easier by using the alarm limits as the scale. This makes interpretation of the figure the same even with different patients, because the image shape is always relative to what are considered the critical values. The second problem is not really a problem anymore if the user accepts that the display is only intended to be used for the detection of complications. After a distortion in the polygon is detected the user can quickly change the page to a display more suited for the diagnostic reasoning process.

The setting used in the experiments done by Gurushanthaiah differs somewhat from a real-life situation: First, Gurushanthaiah had the subjects monitor only one simulated patient at the same time. In real life the anesthetist does not have the time to keep his attention constantly on the monitor. Second, in Gurushanthaiah's experiment the subjects had to respond when a variable changed and indicate in what direction. Although the detection of changes is important, it is not necessarily true that a faster detection of changes also leads to an earlier detection of complications. Third, the display which the polygonal display was compared against was a numerical display that is not representative for the current patient monitor used in most hospitals (fig. 12). The placement of the variables was different and the curves (ECG etc) were not included in the display.

Because of these objections we have set up a new experiment in which we tried to answer the following question: does a polygonal display have a more positive effect on detection time of complications compared to the standard patient monitor? We hypothesize that complications will be detected faster with the polygonal display compared to the classic monitor.

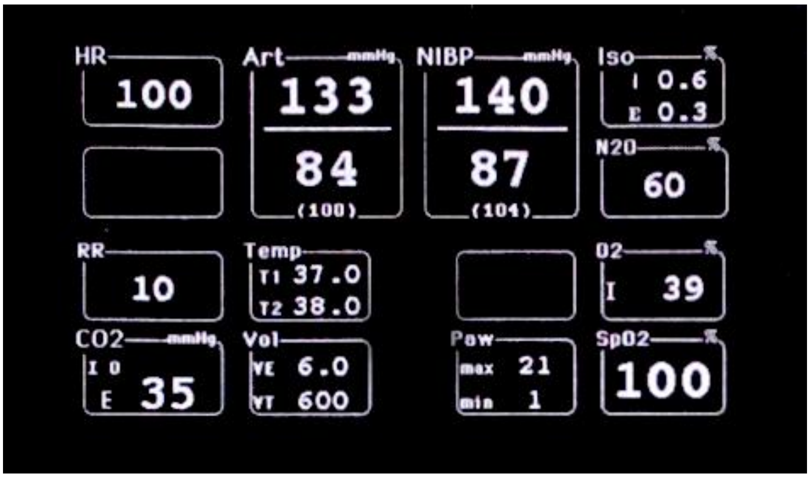


Fig. 12 The numeric display used in Gurushanthaiah's experiment (Gurushanthaiah et al., 1995)

In our experiment the subjects needed to monitor multiple simulated patients. The displays were updated in real time and complications could occur in any of them. We measured their response time for when they felt that: 1) they had the feeling that there was something wrong with the patient and 2) some sort of intervention was needed.

6.2 Methods

6.2.1 Subjects

A total of 13 nurses from the neurological intensive care unit at the University Medical Center Groningen (UMCG) participated in the experiment. Nurses from the neurological intensive care department were recruited instead of anesthetists because they were more easily available and monitoring patients is also part of their job. The main difference is that a nurse will generally only alarm the attending physician instead of starting treatment personally.

6.2.2 Stimuli and apparatus

Although the goal of the experiment was to compare displays for a mobile device, for the experiment itself a simulation of the displays was run on a laptop. The simulation was build in JavaScript in combination with PHP and MySQL

Nine patient monitors for 9 different patients under narcosis (male, age 40) were presented at once to the subjects (fig. 13). There were 9 displays to divide their attention, because in a real-life setting the anesthetist or nurse does not have the time to keep their attention constantly on one monitor. The nurses of IC are used to monitor multiple patients, but generally not more than four.

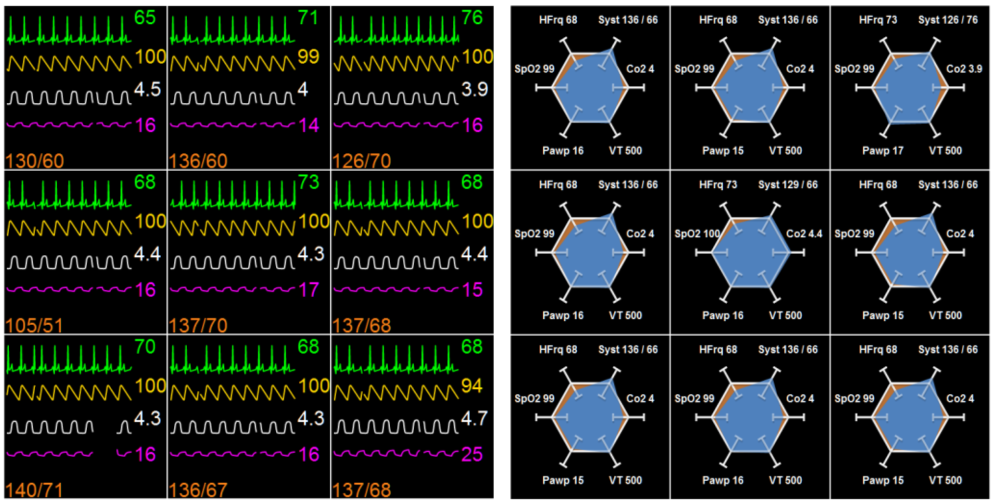


Fig. 13 Screenshot of the experiment with the classic display (left) and polygonal display (right).

Two datasets of nine scripts were composed that contained the course of the variables for the monitors. A script lasted 15 minutes and every 5 seconds the patient variables were updated. Every script started with different patient variables for a stable patient and with every update the variables changed within a range that should not give any cause for concern.

At some point in a script a complication could start to occur and the variables changed in a direction that does give cause for concern. The start point of a complication varied to make sure the complications were spread out over the run of the experiment. A complication lasted on average 4 minutes and 20 seconds and at the end of a complication the monitor went blank for 15 seconds, after which a new patient was displayed.

In a set of nine scripts there were two scripts that contained only one patient (no complication), two scripts that contained two patients (the first with a complication the second without) and five scripts that contained three patients (the first two with a complication the third without). Thus all scripts ended with a patient without a complication.

Six different types of complications were included in the scripts. The scripts were created on a patient simulator in the UMCG skills lab. The complications that were used in the experiment were:

Pain

Pain is caused by insufficient anesthesia depth and thus the patient experiences pain. This results in an increased heart rate and blood pressure.

Hypotension

Hypotension is an abnormally low blood pressure.

Hypoventilation

Hypoventilation occurs when the ventilation is inadequate. Problems with ventilation are mostly caused by misplaced or kinked endotracheal tubes. This results in an increase in CO_2 and peak airway pressure (Pawp), but a lowered saturation.

Lung problem

The lungs are not working properly. Saturation drops and peak airway pressure increases.

Tension pneumothorax

This occurs when air goes through a punctured lung into the pleural space. This causes an increased peak airway pressure and heart rate and a lowered blood pressure, saturation and CO_2.

Circulation failure

Circulation failure is when the cardiovascular system is unable to supply the cells of the body with enough oxygenated blood (also known as shock).

Table 1. the variables that increase (+) or decrease (-) in a complication

	Variables				
Complication	Heart rate	Blood pressure	CO2	PAWP	Saturation
Pain	+	+			
Hypotension		-			
Hypoventilation			+	+	-
Lung problem				+	-
Tension pneumothorax	+	-	-	+	-
Circulation failure	+	-	-		-

The classic display (fig. 14) showed five patient variables (heart rate, saturation, expired CO2, peak airway pressure and blood pressure (systolic and diastolic)) and four curves (ECG, Plethysmogram, Capnogram and Ventilation Pressure). The colors of the variables and curves were the same as the patient monitors used in the UMCG. Because the subjects were already familiar with the patient monitor, variable names were not included for the classical monitor. The curves were generated based on the value of the variables. For example, the curve of the ECG was generated based on the current heart rate and therefore there were no changes in the ECG other than the distance between the peaks.

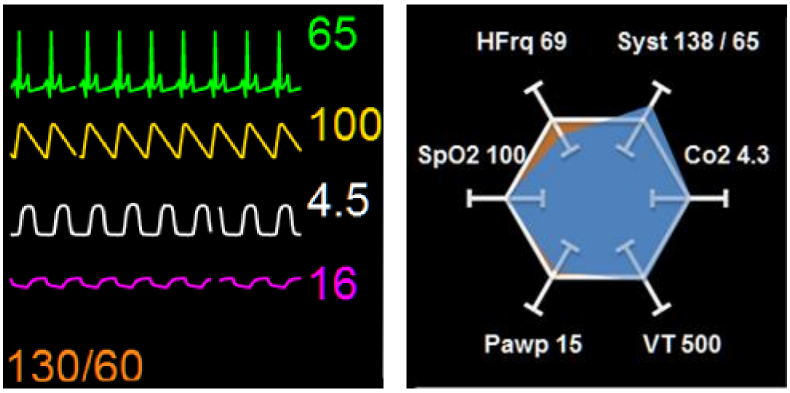


Fig. 14 classic display (left) and polygon display (right) that were used in the experiment

The polygonal display only showed the patient variables (no curves) and was made out of a single shape in which each variable was presented as a vertex (fig. 14). The corresponding vertex changed proportionally according to the value of the variable. Thus if a value increased the vertex moved outward and vice versa. How much the vertex increased or decreased depended on the alarm limits that were set for the variable. The borders of the line running through the vertex were based on the lower and upper limit of the alarms. Thus if all variables were precisely in the middle of the lower and upper limit the figure was completely filled up to a form a hexagon. If a variable deviated from this center the shape was distorted. The abbreviation and value of the variables were presented at the outer end of the vertex.

Table 2 shows all the variables and their alarm limits. It should be noted that SPO2 has no upper limit (the maximum value is 100), but because the maximum value of 100 is desirable, the upper limit is set to 105 to make sure that a value of 100 still fell in the middle. For blood pressure only the systolic pressure is used as a vertex and the diastolic pressure is displayed numerically next to it.

There were no alarms that went off in the displays. Alarms draw the attention to the display where something is going wrong, while we are interested in how well complications are detected for the graphical aspect of the displays only.

Table 2. Alarm limits

Variables	Lower limit	Upper limit
Heart rate	55	90
Blood pressure (systolic)	50	130
Blood pressure (diastolic)	80	160
SPO2	95	-
CO2	3.5	5.0
PAWP	12	20

6.2.3 Experimental design

The experiment took place in a quiet room near the intensive care unit on a laptop. At the start of the experiment the subjects were given instructions in the form of a powerpoint presentation with verbal explanation. The subjects were instructed to monitor nine patients at the same time. They were told that changes could occur on some of the monitors during the experiment and that they had two tasks: 1) indicate when they had the feeling that something was going wrong with the patient but intervention was not (yet) needed and 2) indicate when the situation became so troubling that they would alarm the attending physician. Although these criteria are somewhat subjective it more closely resembles the task of monitoring the patient remotely on a mobile monitor than the recognition of complications, which was done in other experiments with anesthesia displays (van Amsterdam, 2010). It was the general opinion of the anesthetists that if a complication occurs, the anesthetist should head back to the operating room instead of looking at the display figuring out what is going wrong.

6.2.4 Measures

Input was registered by pressing the numpad key that corresponded with the monitor on the screen. By pressing the key one time the subjects indicated that something was going wrong and the background of the monitor went from black to slightly red. By pressing the key a second time they indicated that they would alarm the attending physician. This made the background change to a brighter red (fig 14). Pressing a key on the numpad did not influence the script, which was played out completely. A short demonstration of 1 minute was given before the start of the experiment. The experiment consisted of two trials of 15 minutes: one with the normal patient monitor (classic display) and one with the polygonal display. At the end of the experiment the subjects had to complete a questionnaire about their experiences with the two displays.

Response times were measured from the moment the complication started for both tasks. Each subject was presented with both the displays and the datasets. Therefore each subject was randomly assigned to one of the four display-dataset ordering combinations. The results consist of the response times, the number of incorrect responses and the questionnaire that was presented to the subjects at the end of the experiment.

There are two different response times: the response for the indication that there is something wrong (response 1) and for calling the attending physician (response 2). Because the results differ strongly between complications they are presented separately. Because there are multiple comparisons an alpha level of 0.004 is used to maintain a familywise error rate of 0.05. All p values are cited without correction for multiple testing. The data was analyzed using a one-way ANOVA.

The incorrect responses consist of responses that were too early (false positives) and failure to detect a complication within the duration of the script (false negatives). The false positives are responses that occur during the startup time of a complication. These were not included in the ANOVA.

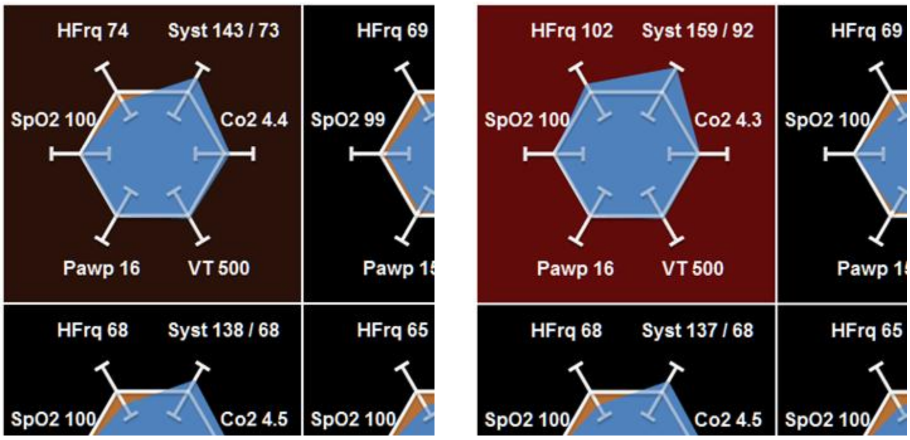


Fig. 15 Demonstration of how the background colors change. The first response (the feeling that there is something wrong) on the left and the second response (calling the attending physician) on the right.

6.3 Results

31 out of 168 responses are too early (false positives) for the classic display and 22 out of 162 for the polygonal display (fig. x). 31 out of 168 complications are missing (false positives) for the classic display and 17 out of 162 for the polygonal display (fig. x).

The mean response times for indicating that there is something wrong are presented in fig. 18. The mean response times for calling the attending physician are presented in fig. 19. The displays are compared for each complication separately because there is a large difference in the length of the complications and thus in the mean response times.

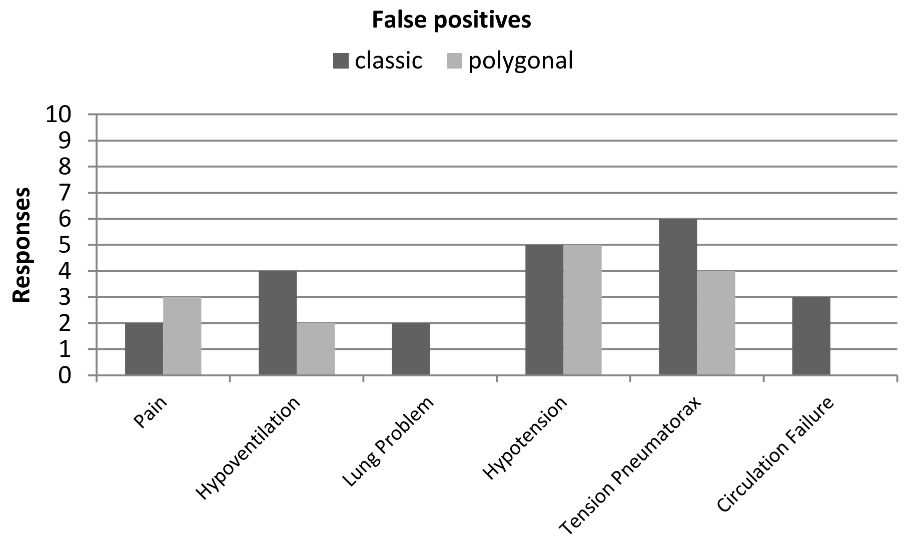


Fig. 16 Number of false positives (responses that were too early) for each complication

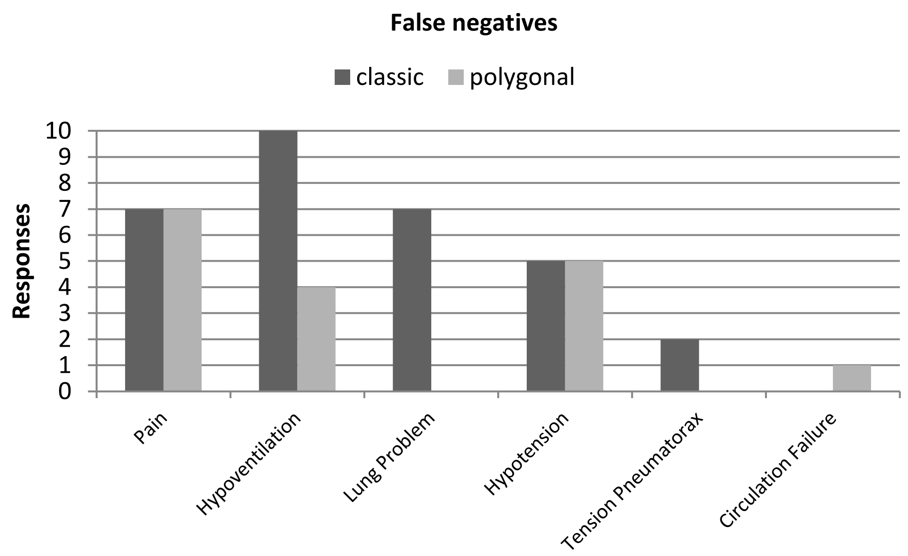


Fig. 17 Number of false negatives (complications that were missed) for each complication

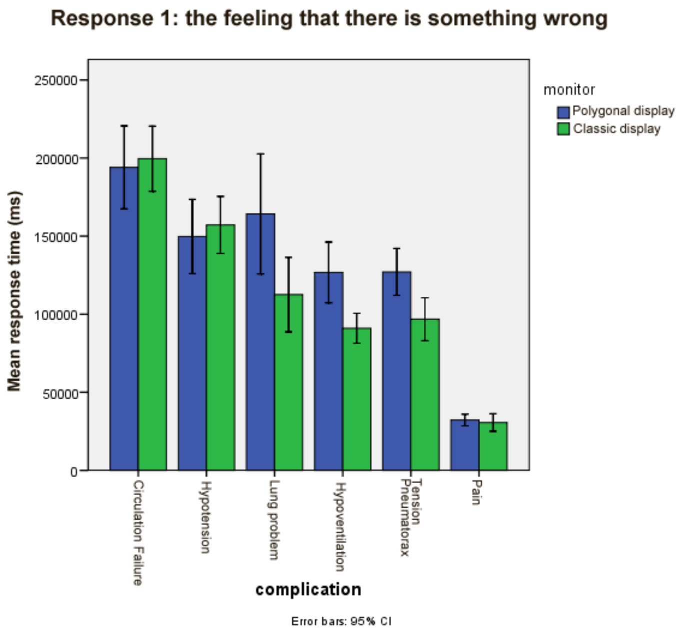


Fig. 18 Mean response time for indicating that there is something wrong

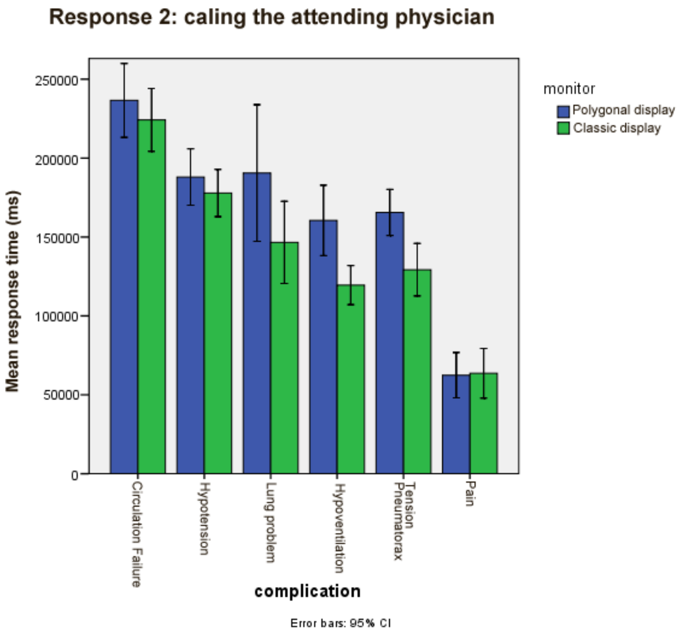


Fig. 19 Mean response time for indicating that the attending physician should be called

Pain

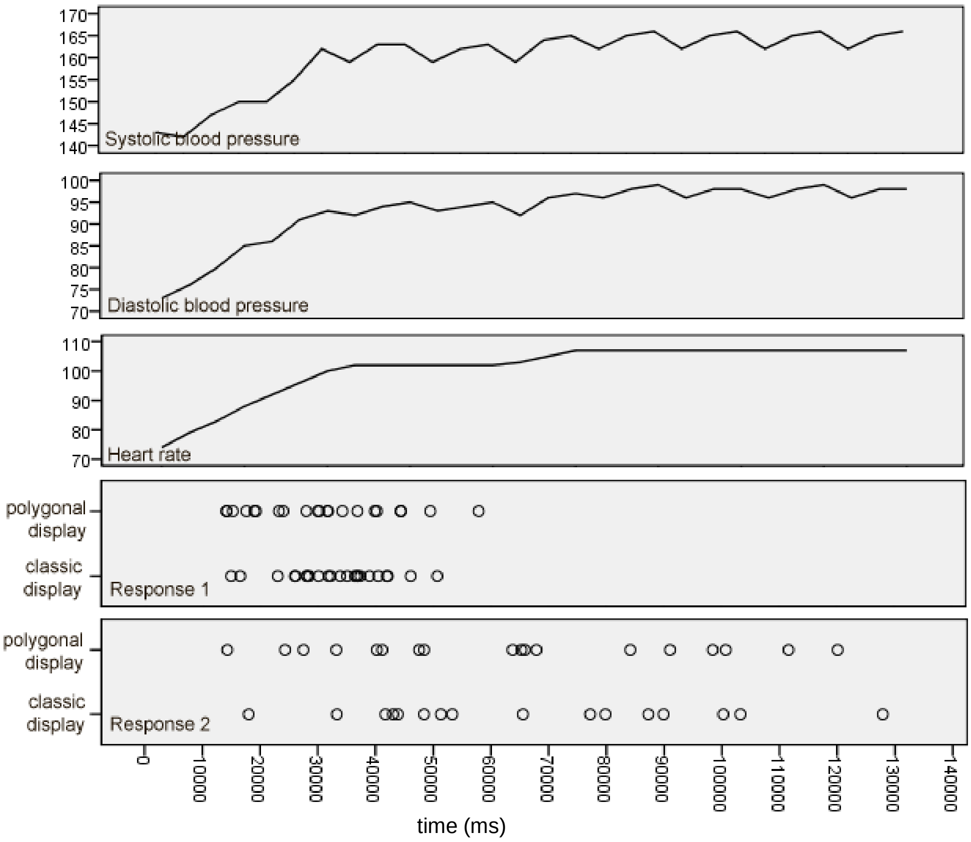


Fig. 20 Responses for the complication pain and the values of the affected variables at the time of the response (response 1=indicating that there is something wrong, response 2=calling the attending physician).

For the classic display a total of 2 responses out of 30 are too early and 7 out of 30 complications were missed. For the polygonal display 3 responses out of 30 are too early and 7 out of 30 complications are missing. For the first response (having a feeling that there is something wrong) there is no significant difference in reaction times between the classic display (mean = 32.59 s, sd = 20.75 s) and the polygonal display (mean = 30.90 s, sd = 29.49 s), F(1,22) = 0.27, p = 0.609. For the second response (calling the attending physician) there is also no significant difference in reaction times between the classic display (mean = 61.415 s, sd = 20.75 s) and the polygonal display (mean = 64.75 s, sd = 29.49 s), F(1,18) = 0.09, p = 0.77.

Hypoventilation

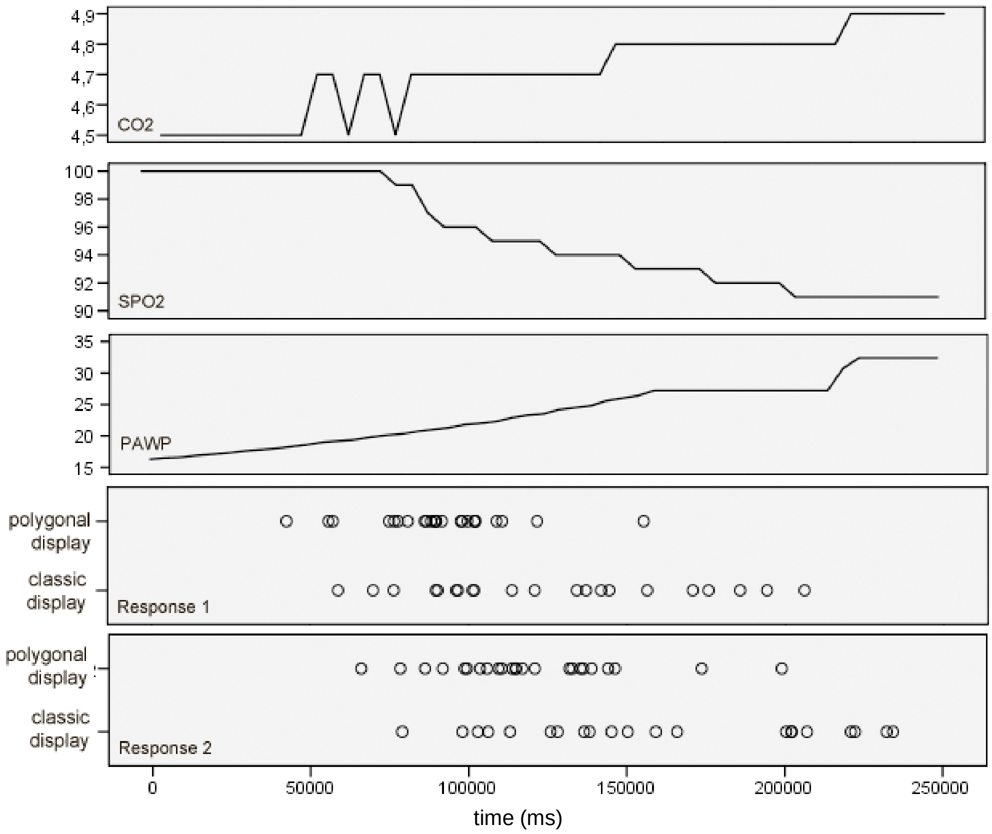


Fig. 21 Responses for the complication hypoventilation and the values of the affected variables at the time of the response (response 1=indicating that there is something wrong, response 2=calling the attending physician).

For the classic display a total of 4 responses out of 30 are too early and 10 out of 30 complications are missing. For the polygonal display 2 responses out of 30 are too early and 4 out of 30 complications are missing. For the first response (having a feeling that there is something wrong) there is a significant difference in reaction times between the classic display (mean = 125.60 s, sd = 27.31 s) and the polygonal display (mean = 91.03 s, sd = 12.19 s), $F(1,21) = 15.85$, $p < 0.001$. For the second response (calling the attending physician) there is also a significant difference in reaction times between the classic display (mean = 162.36 s, sd = 42.54 s) and the polygonal display (mean = 119.54 s, sd = 38.31 s), $F(1,21) = 10.16$, $p < 0.004$.

Lung Problem

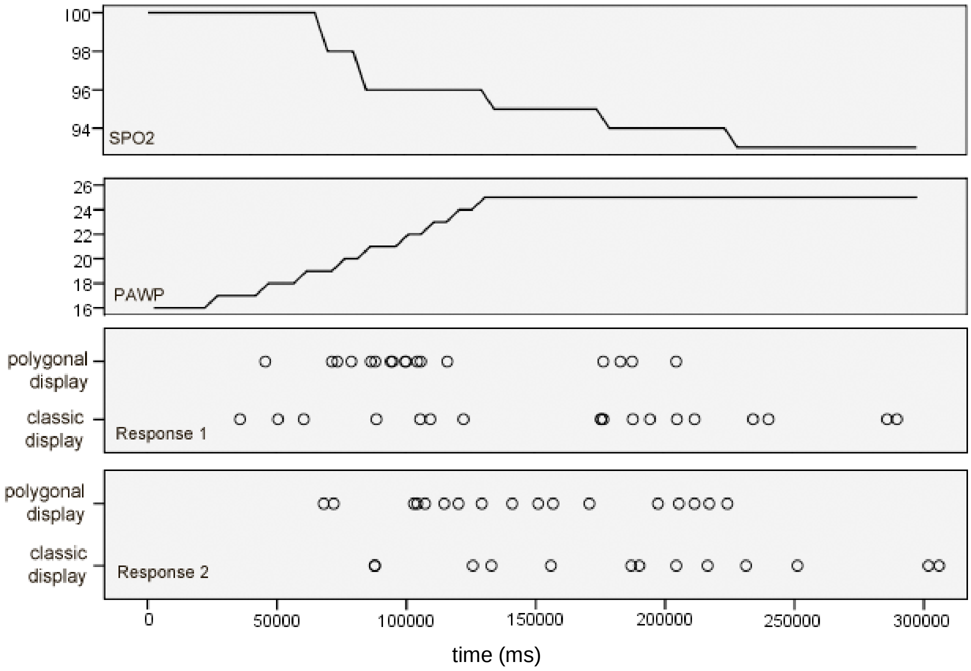


Fig. 22 Responses for the complication lung problem and the values of the affected variables at the time of the response (response 1=indicating that there is something wrong, response 2=calling the attending physician).

For the classic display a total of 2 responses out of 24 are too early and 7 out of 24 complications are missing. For the polygonal display 0 responses out of 21 are too early and 0 out of 21 complications are missing. For the first response (having a feeling that there is something wrong) there is no significant difference in reaction times between the classic display (mean = 151.25 s, sd = 70.33 s) and the polygonal display (mean = 108.33 s, sd = 25.23 s), $F(1,22) = 3.96$, $p = 0.06$. For the second response (calling the attending physician) there is also no significant difference in reaction times between the classic display (mean = 183.72 s, sd = 62.40 s) and the polygonal display (mean = 142.04 s, sd = 24.05 s), $F(1,20) = 4.52$, $p = 0.05$.

Hypotension

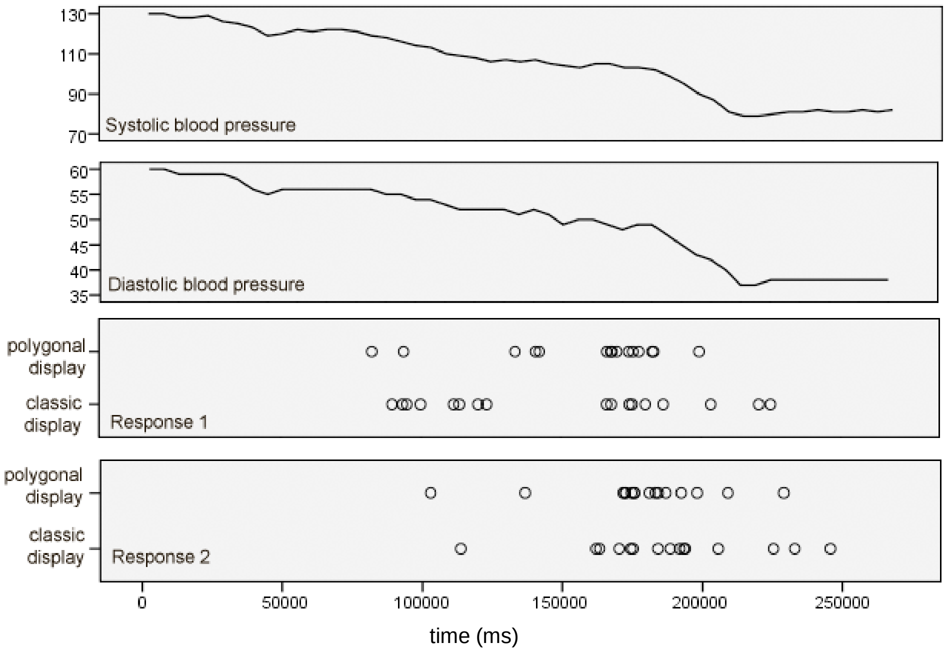


Fig. 23 Responses for the complication hypotension and the values of the affected variables at the time of the response (response 1=indicating that there is something wrong, response 2=calling the attending physician).

For the classic display a total of 5 responses out of 30 are too early and 5 out of 30 complications are missing. For the polygonal display 5 responses out of 30 are too early and 5 out of 30 complications are missing. For the first response (having a feeling that there is something wrong) there is no significant difference in reaction times between the classic (mean = 151.60 s, sd = 42.74 s) and the polygonal display (mean = 151.41 s, sd = 38.22 s), $F(1,21) = 0.00$, $p = 0.99$. For the second response (calling the attending physician) there is also no significant difference in reaction times between the classic display (mean = 183.72 s, sd = 62.40 s) and the polygonal display (mean = 187.26 s, sd = 34.74 s) and the polygonal display (mean = 173.49 s, sd = 28.74 s), $F(1,21) = 10.08$, $p = 0.31$.

Tension Pneumothorax

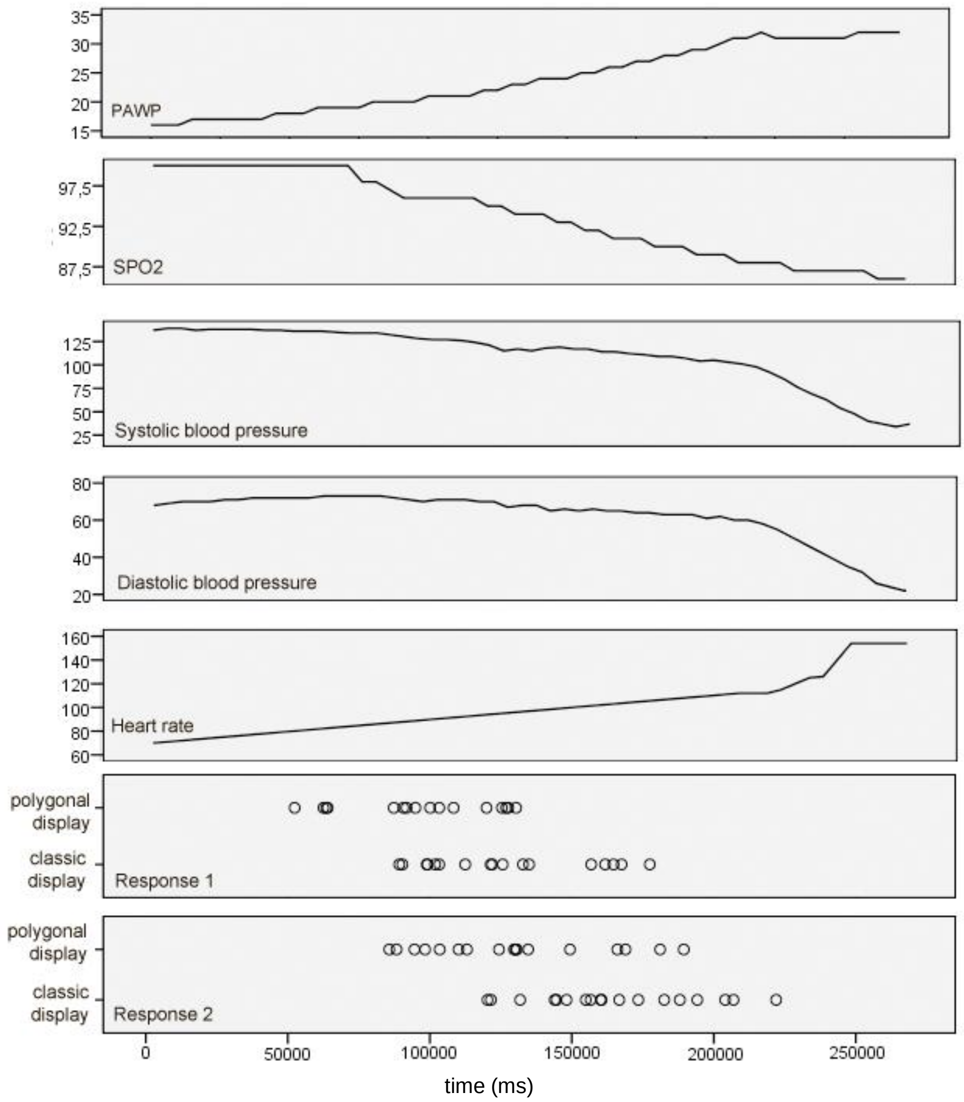


Fig. 24 Responses for the complication tension pneumothorax and the values of the affected variables at the time of the response (response 1=indicating that there is something wrong, response 2=calling the attending physician).

For the classic display a total of 6 responses out of 30 are too early and 2 out of 30 complications are missing. For the polygonal display 4 responses out of 30 are too early and 0 out of 30 complications are missing. For the first response (having a feeling that there is something wrong) there is no significant difference in reaction times between the classic (mean = 129.48 s, sd = 27.03 s) and the polygonal display (mean = 100.50 s, sd = 25.12 s), $F(1,21) = 9.82$, $p = 0.01$. For the second response (calling the attending physician) there is also no significant difference in reaction times between the classic display (mean = 183.72 s, sd = 62.40 s) and the polygonal display (mean = 167.77 s, sd = 27.50 s) and the polygonal display (mean = 131.82 s, sd = 27.48 s), $F(1,21) = 9.82$, $p = 0.01$.

Circulation failure

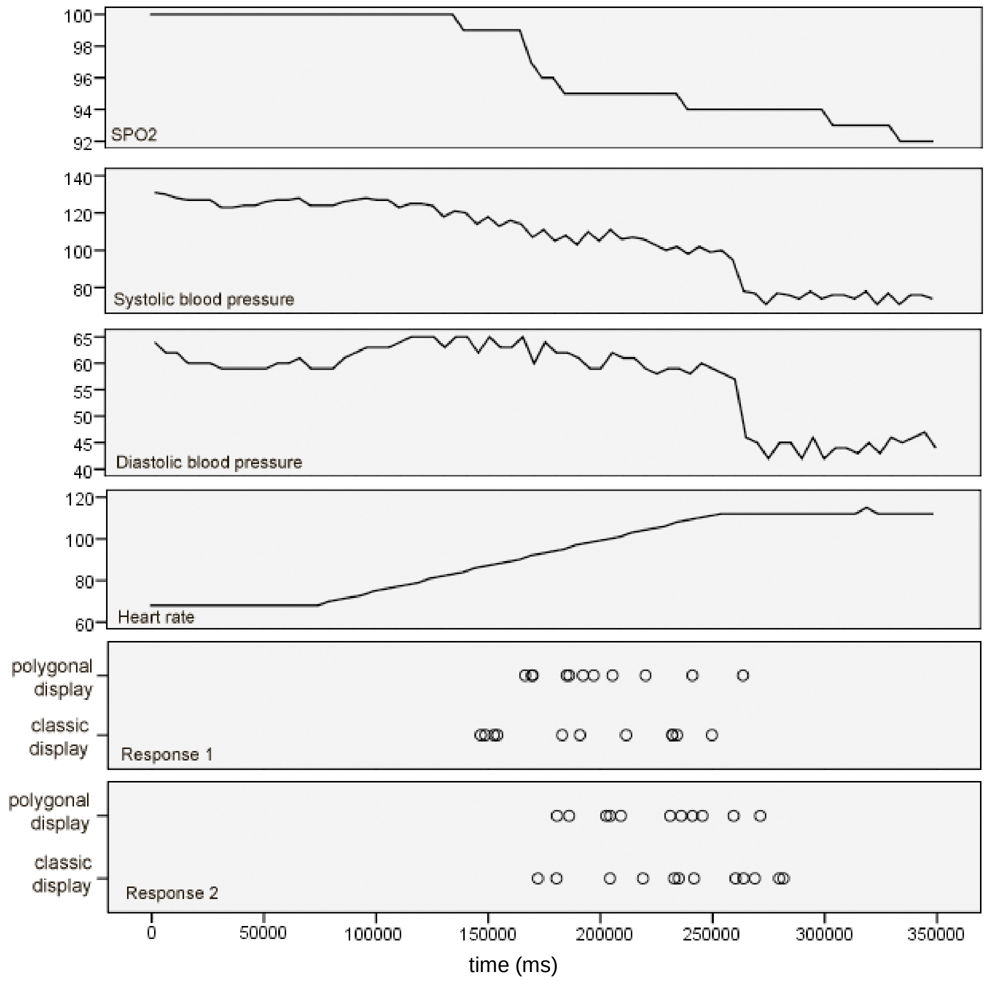
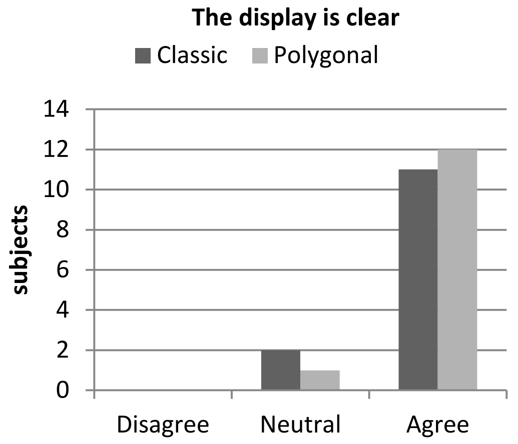


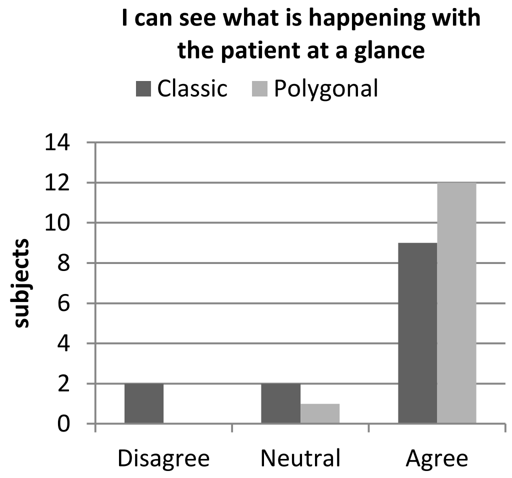
Fig. 25 Responses for the complication circulation failure and the values of the affected variables at the time of the response (response 1=indicating that there is something wrong, response 2=calling the attending physician).

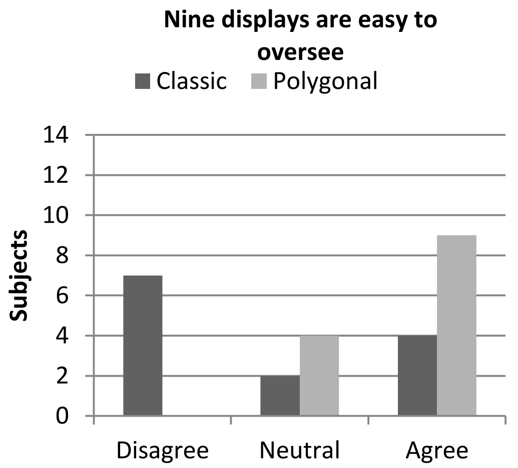
For the classic display a total of 3 responses out of 24 are too early and 0 out of 24 complications are missing. For the polygonal display 2 responses out of 21 are too early and 1 out of 21 complications are missing. For the first response (having a feeling that there is something wrong) there is no significant difference in reaction times between the classic (mean = 194.08 s, sd = 39.57 s) and the polygonal display (mean = 199.59 s, sd = 31.02 s), $F(1,20) = 0.13$, $p = 0.72$. For the second response (calling the attending physician) there is also no significant difference in reaction times between the classic display (mean = 236.58 s, sd = 31.02 s) and the polygonal display (mean = 224.24 s, sd = 29.68 s), $F(1,21) = 0.77$, $p = 0.39$.

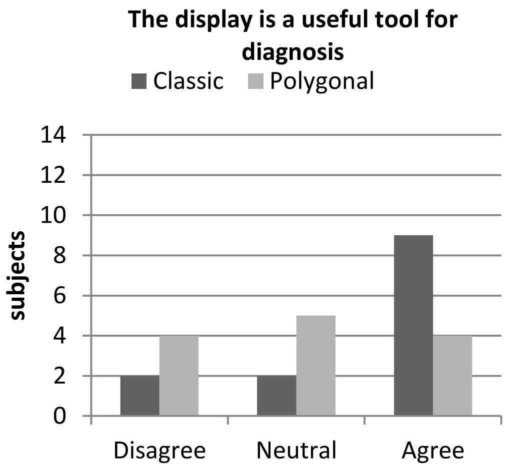
Questionnaire

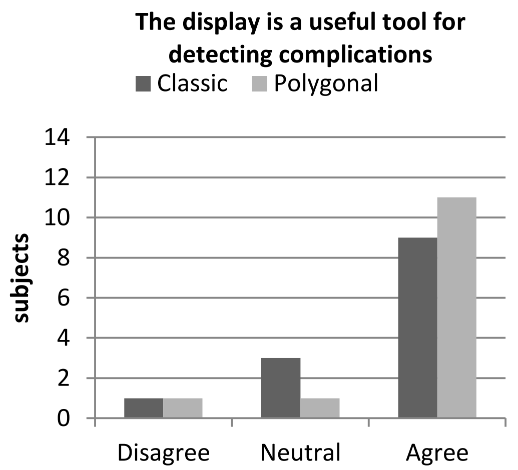
After the experiment the 13 subjects were presented with a questionnaire where they could rate each answer on a scale of disagree, neutral or agree. There were no strong differences except for *nine displays are easy to oversee* (9 agreed for the polygonal display versus 4 out for the classic display) and *the display is a useful tool for diagnosis* (4 agreed for the polygonal display and 9 for the classic display).

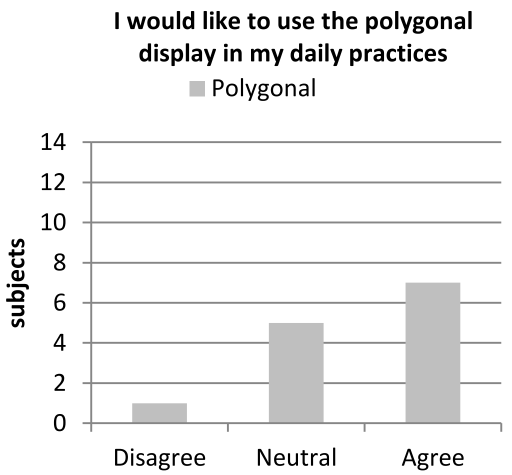












6.4 Discussion

The experiment was constructed to see if there's a difference in reaction times between the polygonal and the classic display in terms of detection of complications. The results only show a significant difference in the hypoventilation complication. However, medium to large effect sizes were also found in the complications tension pneumatorax and lung problem. This is interesting because these three complications are all involved in the respiratory system, whereas the other three (pain, circulation failure, hypotension), are taking place in the circulatory system.

One possible explanation for only finding an effect in these three complications is that the subjects were not familiar enough with the Pawp variable. During the introduction of the experiment some of the subjects needed a quick reminder of PAWP and its standard alarm limits.

As discussed earlier there were no alarms implemented on any of the displays. Thus the polygonal display has a large advantage for unfamiliar variables: the alarm limits are constantly visible through the edges of the figure, whereas on the classic monitor the subjects have to rely on their own knowledge of the alarm limits to interpret the value. Normally, when the alarm is triggered there is a beeping sound and the triggered variable starts to blink. The inclusion of information in a graphical displays that is not also available in the control display was found to be an issue with other experiments as well (Drews & Westenskow, 2006).

In all three complications that involved the respiratory system Pawp was the first indicator that there was something going wrong with the patient and therefore should be the main trigger for the response. This is especially shown by the lung problem complication where it reaches the alarm limit after 75 seconds, whereas the second variable SPO2 reaches the alarm limit after 130 seconds.

There is a large difference in the number of complications that were missed: 31 out of 168 for the classic monitor compared to 17 out of 162 for the polygonal display. However, when we only look at the three complications that did not involve the respiratory system the number of missed complications are basically the same for the classic and polygonal display: 12 out of 84 complications were missed in the classic display and 13 out of 81 in the polygonal display.

The relatively high number of missed complications (48 out of 330) is interesting and may be an indication that the task of monitoring nine patient monitors at the same time was too difficult. The questionnaire also indicated this: 7 out of 13 participants indicated that they found it difficult to oversee 9 patients at once on the classic display. However, it is somewhat surprising that none of the participants found it difficult to oversee 9 patients on the polygonal display, given that the performance for the polygonal display was not that much better.

The difficulty of the task is also shown by the distribution of the responses, which are typically scattered over the whole duration of the complication. Many of the response times are well beyond a patient's normal range of variables and in some cases the patient would even have died by then.

It is possible that the nurses of the intensive care are more familiar with circulatory changes than respiratory changes in their daily practices. This would suggest that the polygonal display is better suited for the detection of rare complications or when the observer is unfamiliar with normal values. When a wide variety of staff is monitoring the same patient it gives the attending physician some control over how the values should be interpreted.

Mobile monitor

The experiment was constructed to answer the question whether a polygonal display could be a useful addition to a mobile monitor for anesthetists. Therefore instead of focusing on recognition of complications the task was less specific and focused on detecting that there was something wrong. Although this criterion is somewhat subjective it represents the idea that the anesthetist should head back to the operating room instead of figuring out what is wrong. It is also because of this task that the experiment could be run with the nurses of the intensive care department, whose job is also focused on detection instead of recognizing the type of complication.

The questionnaire showed mainly positive feedback on using the polygonal display. 9 out of 13 participants found 9 polygonal displays easy to oversee (versus 4 for the classic display) and 7 of the participants would like to use the display in their daily practices (of course the opinions of the anesthetist might differ).

In conclusion: Purely based on of the response times there is no reason to see why a polygonal display would be a useful addition to a mobile monitor. The small differences found in reaction times can probably be attributed to the inexperience of the subjects with Pawp. However the somewhat poor performance also makes the suitability of the subjects for this experiment questionable. There are a relatively high number of false positives, false negatives and generally late responses that have a very strong influence on the mean scores and standard deviations. Anesthetists have a higher level of experience and may show different results. But even though the results show no clear difference between the polygonal display and the classic monitor there could still be a strong personal preference of the user to include a polygonal display.

CHAPTER 7 CONCLUSION

The goal of this thesis was to answer two specific questions:

1) How can a mobile monitor improve patient safety
2) What is the best way to present the information from a patient monitor on a mobile device

To answer these questions we conducted two experiments. In the first experiment we provided a prototype to the anesthetists to get hands on experience with a mobile monitor. The prototype was based on the past research of Chapter 3 and the results of a preliminary interview presented in Chapter 5. In Chapter 3 we discussed that the most important way of improving patient safety is reducing the number of human errors. In chapter 5 we identified two ways in which a mobile monitor can reduce the number of human errors: raising situation awareness and reducing errors because of incomplete information. A mobile monitor can raise situational awareness by keeping the anesthetist informed outside of the operating room. Providing the anesthetist with more complete information reduces the effects of biases that can influence a consult. We learned from the hands on experience that the anesthetists considered a mobile monitor to be a useful tool for the detection of complications outside of the operating room and for being more informed during consults.

The second question *what is the best way to present the information?* is also partly covered by the first experiment, but with a focus on presenting the information during a consult. We were interested if there were any limitations when using a mobile monitor. From the experiments it became clear that it is important to consider that the patient monitor does not provide all the necessary information to fully understand the state of the patient. Important information like past medication and blood loss are not included on the display. Missing this information can become a problem if this leads to uncertainty, making the anesthetist head back to the operating room unnecessary or distracts them when their attention needs to be with another patient. Therefore it might be necessary to include information that is currently not present on the patient monitor in the operating room.

In Chapter 4 we presented various other ways to display the patient data that were more suited for the detection of complications than the standard patient monitor. In our second experiment we tried to answer the question if a polygonal display is a better way of presenting the patient information for the detection of complications in a mobile monitor. We conducted an experiment with a polygonal display that resembled the situation of monitoring a patient from outside of the operating room. Although the results showed no clear benefits for including a polygonal display in a mobile monitor it probably is better suited for the detection of complications with more inexperienced observers. It would be interesting to test the polygonal display with a wider range of subjects that vary in experience level. The polygonal display is just one of the many ideas of representing patient information. Even though the polygonal display might not be best suited for a mobile monitor for anesthetists there might be other displays that are.

One aspect that has not been fully addressed in this thesis is the influence of a mobile monitor on the anesthetist's mental state. Increasing the safety of the patient that is being monitored from outside the operating room is a good thing, but it should not compromise the safety of the other patient that needs his current attention. Also, how does the anesthetist cope with this constant stream of extra information? Does a mobile monitor reduce or induce stress in the anesthetist? These are important questions that need to be answered before a mobile monitor should be implemented.

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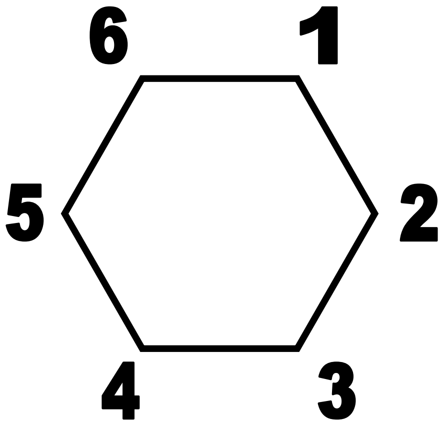
APPENDIX

A. Vragenlijst (in Dutch)

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

B. Questionnaire Anesthesisten

28-01-2011 versie

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?

____

____

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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?