Decision support in anaesthesia monitoring

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Abstract

Ever since the first anaesthesia was administered, a very important subject of research in anaesthesia has been the improvement of patient safety. An important result of this research has been the advent of new monitoring devices. Partly because of these new devices the anaesthetist has to manage large amounts of data during his task. This is one of the reasons why most incidents in anaesthesia involve human error. The research we will present in this paper, is part of a project that was started to develop methods for supporting the anaesthetist in his task. In this paper we will propose a research method that should lead to a thorough understanding of the anaesthesia process. A number of approaches are presented to model the anaesthesia process, along with a number of methods that can be used to test the validity of the model. Finally a method is discussed to identify where things go wrong and what kind of support the anaesthetist needs to prevent this.

Introduction

Ever since the first reported anaesthesia procedure in 1847 and the first reported death during anaesthesia in 1848, improving patient safety has been an important research topic. Both anaesthesia techniques as well as patient monitoring have been subject to a large number of improvements. In our research we concentrate on the monitoring task of the anaesthetist.

Monitoring patient condition serves two purposes in anaesthesia. If we look at the normal anaesthesia process as a manual feedback control loop, monitoring the patient is the anaesthetist's feedback in this process. The other purpose of monitoring is to detect process deviations. A deviation process or incident is any event causing a change in patient physiology or equipment behaviour that exceeds the limits of normal process variability.

Observation of the patient and the surgical procedure he is going through, was and is an essential part of the monitoring process. However, during the last two decades more and more monitoring devices have become available to continuously monitor a large number of patient functions (parameters). In the early 80's every monitoring device was in a separate unit with its own display and user interface. This resulted in a monitoring setup which was very difficult to survey. In the late 80's and early 90's, monitoring equipment has become available that integrates all monitoring modalities in one device. These devices have one integrated display for all measured variables and one user interface to control alarm and display settings. Although data-acquisition and data-display are integrated now, data processing is still done separately for every parameter. The anaesthetist must therefore continuously monitor between 2-10 measured physiological signals and between 10-30 features extracted from these signals. The only support he gets in this task are a number of high and low limit alarms on the feature values, of which he should set the limits himself. Clinical research shows that as little as 3% of all alarms triggered represent a problem with the patient (Kestin et al, 1988). Therefore most anaesthetists ignore or disable most alarms. This means that the anaesthetist has to work with large amounts of data offered to him, without any support to manage them.

The anaesthetist uses the data offered to him to obtain information about the status of the patient. This information is used to decide whether intervention is necessary, and if so what kind of intervention. Means of intervention are: administration of drugs in different dosages, infusion of different kinds of fluids and blood with different infusion rates, and changing administration of anaesthetic gases and oxygen. All together there are about 50 different controls which can be adjusted or applied individually as well as combined with each other.
Considering the complexity of the anaesthetists task described above, it is not surprising that recent research shows that 75% of all incidents involve human error (Chopra et al, 1992). Chopra's study was based on voluntary significant observation reports. A significant observation was defined as "any deviation, however minor, from acceptable safe practice or working condition". For patients in good condition administering anaesthesia is a routine task. Human error probability for routine tasks for a trained operator is in the order of $10^{-3}$ (NRC, 1975). Reliable reports on incident rates in anaesthesia are not available. There is however some research based on voluntary incident reports. The problem of underreporting that is inevitable in this kind of research can be accounted for by using expert judgement. Research based on this method shows an overall incident rate of $2\times10^{-3}$ for healthy patients (Paté-Cornell, 1994). From this we may conclude that incident rate is in the same order of magnitude as human error probability.

One approach to improve patient safety is to improve anaesthetist performance by training and organisation of the entire workspace. This will however hardly affect the $10^{-3}$ error probability for routine tasks. To improve performance in this respect it is better to support the anaesthetist in his task in order to minimise the effects of the errors he is destined to make.

Support can be offered in a number of different ways ranging from automation of subtasks (like automatic control of blood pressure) to complete support of the anaesthesia task. The research being described in this paper is part of a project that is started to find ways to support the anaesthetist in his monitoring task with the goal to improve patient safety. If we want to be able to justify the means of support we want to offer, a thorough analysis of the anaesthesia monitoring process is necessary. The project goals can be formulated as follows:

- Develop methods to automate a number of basic data and information processing tasks, using advanced automatic signal processing and pattern recognition algorithms.
- Try to acquire a thorough understanding of the anaesthesia monitoring task in terms of data and information processing and the process of decision making, in order to identify how the anaesthetist should be supported.

In this paper we will concentrate on the second project goal. If we analyse this goal we can identify three different issues that should be tackled. To acquire understanding of the anaesthesia monitoring task we will have to build some kind of model to describe it. If we have build a theoretical framework, which we want to use to identify and solve practical problems, it will have to be validated. Only if we have such a valid model of the anaesthesia monitoring process it will be possible to identify where things can go wrong. In short this comes down to the following research issues:

- Construction of a model that describes data, information and activity flow in the anaesthesia process for both normal and deviation processes.
- Development of a method to test the validity of the model that is build.
- Identification of the monitoring tasks for which support is needed, based on the validated process model.

In the following sections we will discuss possible approaches to tackle each of these issues.

**Analysis**

In the introduction we briefly touched on terms like data, information and decisions. Since these are the key subjects of investigation we will briefly illustrate how these concepts are interrelated. In general we can draw the chart in figure 1.

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DATA       DATA               INFORMATION     INFORMATION               DECISIONS
data processing          information processing
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*Figure 1 Relations between data, information and decisions*
The relations illustrated in figure 1 are almost trivial but form the basis for any model of information and data flow, and decision making in the anaesthesia monitoring process. The anaesthetist has access to a lot of data which are only part of which is relevant in a given situation. One could say that he is continuously processing data to obtain information about relevant aspects of the condition of the patient. Based on this information he decides what should be done to change or maintain the current patient state.

We already stated that the anaesthesia process can be divided into two important states. The normal process and the deviation process. We will start with a description of both states.

**Normal process**

One of the main causes of the complexity of the anaesthesia control process is that the variables to be controlled cannot be measured directly. The most important variables to be controlled during anaesthesia are tissue oxygenation and depth of anaesthesia (sufficient reduction of pain sensation and consciousness). There are no means of measuring these parameters directly in a way that is practically feasible. This means that controlling patient state, even under normal conditions, requires a lot of data and information processing by the anaesthetist. We could say that the anaesthetist builds an internal model of the patient and the anaesthetic delivery system based on knowledge, experience and a large amount of data about the patient. This model is used to continuously estimate the state of the patient in terms of adequacy of tissue oxygenation and anaesthesia. Most of the anaesthetist's activities are directed to the optimisation of these two aspects of patient state. This is what we will call the normal process flow.

**Deviation process**

Events causing large variations in the two control variables mentioned can occur during normal process flow. Only if an incident occurs a deviation process is initiated. In this context an incident is an event that causes a substantial change in the physiology of the patient or a problem occurring somewhere in the delivery of anaesthetic gasses or medication. This results in a mismatch between the data coming from the patient and the internal model of the anaesthetist. This is what we will call a deviation process. After detection of the mismatch or the event itself, the anaesthetist will try to diagnose the problem. If he can identify the problem, the anaesthetist will try to correct it. During this process the internal model will be used to diagnose and solve the problem and it will be continuously adjusted. If the problem cannot be corrected he will try to bring the patient in the best possible state given the problem that occurred. In this case he will also use and adjust the internal model of the patient during the process. If the new internal model is build, the process switches back to the normal state. If either the deviation is not detected in time, the wrong diagnosis is made, or the new internal model is wrong, the mismatch between the internal model and the real process will continue to exist. This can eventually lead to patient injury. If this happens the incident has evolved into a critical incident.

In the introduction we argued that it is impossible to prevent incidents from occurring. We could however try to prevent an incident from developing into a critical incident. We therefore want to support the anaesthetist in detecting a possible mismatch between his internal model and data coming from the patient.

In the next section we will describe a number of different process models and discuss their value for our research based on a number of requirements we will place upon them. We will also present a number of different methods to test a theoretical model. Finally we will give an indication of how we could identify steps in the process where things can go wrong.

**Methods**

The methods we will discuss in this section are not yet in a definite form. We only want to describe a number of possible approaches to acquire some insight in the anaesthesia process.

**Model**

If we want to offer support to the anaesthetist by automatic data and information processing, we should have detailed understanding of how the monitoring task is carried out by the anaesthetist himself. We can try to model the anaesthesia process in terms of information and data flow and processing. If this (set of) model(s) can be tested and validated, it can be used to identify which task can and should be done by the computer and which tasks are better left to the anaesthetist. Based on the foregoing we can formulate a number of requirements the model(s) should meet. These requirements are listed below:
• The model(s) should cover all data and information processing aspects of the anaesthesia monitoring and control process.

• The model(s) should cover the normal process, the detection of deviations, as well as the deviation process.

• The model(s) should be consistent with the most recent views on human cognitive processes.

• Data and information flows should be modelled in such a way that all transformations performed on them are explicitly described.

• The model(s) should define the sequence in which the information and data processing tasks are carried out.

**Dynamic decision making model**

The first model we will discuss is the model developed by Gaba (1994). He models the thought processes of anaesthetists as they administer anaesthesia and respond to perio-operative problems. This model is illustrated in figure 2. It was developed for both normal and deviation process flow. It also incorporates current views on human cognitive modelling. However, data and information flows are not explicitly modelled. Furthermore there are a lot of actions described in this model without a clear place in the sequence of events. Especially the supervisory control level and the resource management level contain a lot of actions without a clear place in the execution flow. Another problem of the Gaba model is that there is no explicit transition from the normal process to the deviation process. This model can be very useful to describe the process in a comprehensive way. However, if we are interested in specific information and data processing tasks a more specific model is needed. We therefore believe that for our purpose this model is not appropriate. If we would like to use it significant changes to it would be necessary.

**Figure 2 Complex model of dynamic decision making and crisis management in anaesthesiology (Gaba, 1994)**

**Deviations process model**

A totally different approach is to model the behaviour of the anaesthetist only for detection and occurrence of deviation processes. There are various models developed for this purpose (Gerdes, 1994; Rasmussen, 1987; Hale, 1987). We will discuss only the Glendon and Hale model which is illustrated in figure 3. The model gives a good description of the cognitive processes involved in detecting and controlling problems. Data and information flows however, are not incorporated in the model. Another limitation of the Glendon and Hale model is
that the normal process flow is not modelled. For the development of methods to support the anaesthetist, it is not possible to separate the detection of deviations from the normal process flow. This model could be useful only to identify where things can go wrong once a deviation is detected.

Figure 3 Behaviour in the face of danger (Hale, 1987)

Feedback control model

Another approach is to try to model the entire anaesthesia monitoring and control process as a feedback control system. In figure 4 a possible realisation of such a model is given. This is only a very elementary model to demonstrate the concept of such a model. One of the biggest shortcomings of this model is that it is very difficult to map the different elements in the model to human cognitive processes. Cognitive processes are often distributed over a number of elements or are only a small part of an element. This means that it will be difficult to identify where things can go wrong based on knowledge about human cognitive errors. Furthermore the model does not cover deviation processes. This could be incorporated in the model but problem solving is not really a control task. The model is suited to identify the kind of information used for each element, because information flows can be made very explicit. It is also possible to define a clear sequence of events. For detailed analysis of data and information processing a more detailed model will be necessary.

Considering the above it is clear that none of the approaches covers the entire anaesthesia process in sufficient detail. Therefore we will either have to take a deviation process model for the deviation process and a feedback control model for the normal process. We then also need a clear criterion for switching between these two models. We can also build a hybrid model combining the two models into one.

We have not discussed the possibility of a mathematical model of the process yet. In the past, attempts have been made to build a complete patient model. It seems however, that it is impossible to build a general mathematical model describing the entire process. We therefore choose a more qualitative approach that does offer the possibility to build a complete process model.
Model validation

If we have built a model or combination of models we can use a number of different methods to validate it. Each technique has its own advantages and disadvantages. We will discuss a number of methods with their pros and cons.

Observation

The first possible method is observation of the anaesthetist. This technique is very useful to obtain a preliminary impression of the validity of the model. The results of these observations can be used to adjust the model where necessary. A disadvantage of this technique is that it is time consuming and subjective. It is therefore not suitable for drawing general conclusions about the validity of the model. We can however use this method to get the final version of our model to which a more thorough method of validation will be applied.

Expert opinions

Another approach to validate the model are expert opinions. By confronting anaesthetists with either imaginary or practical cases, a detailed analysis of the monitoring process is possible. We can also get some insight in the relevance of different types of data and information in different situations. Finally, we can get a basic understanding of the cognitive processes involved in decision making. Since this is a time consuming form of data collection we can only interview a small number of anaesthetists most of which will be working in teaching hospitals. This method can be very useful to formulate hypotheses which can be tested on a large population of anaesthetists using questionnaires.

Questionnaires

The only possible method for larger scale data collection are questionnaires. This method is only useful if we have a number of hypothesis we would like to test. We can ask a large number of anaesthetists to judge a relatively large number of cases with different amounts of information presented within each case. The information to be presented and the cases to be judged will be based upon the knowledge from expert opinions research. This method can therefore not be done without the previously mentioned methods. If it is practicable to do this kind of research, we can reliably draw more general conclusions about the validity of our model.
The three methods together cover the entire validation process. It is not yet clear whether these methods are all feasible and practicable. If it is not possible to analyse the entire anaesthesia process in this way we can try to limit our research to very specific cases. This might be necessary to prevent that we drown in the data we will collect.

**Identifying sources of human error**

If we have a valid model with detailed information about the process of data and information usage and processing, we can start to investigate where things can go wrong.

**Incident analysis**

A possible source of data for human error investigations are incident reports collected for previous research. If we can map human errors in these reports to elements in our model, we can demonstrate where support is most needed and in what way. This will only work if the model we build is detailed enough to pinpoint places where errors can be made.

**Cognitive error identification**

Another source of human error identification is a more theoretical approach. We can use knowledge about possible errors in human cognitive processes to identify which processes in the anaesthesia monitoring task are likely to go wrong. This means that the model we build must be suitable for identification of errors in cognitive processes.

**Discussion**

In this paper we have tried to give a brief description of the problems we want to address in our project. We have presented a number of methods we could use to model the process we are investigating. We concluded that it is difficult to capture everything in one model. Although we will still try to find such a model, it might be sufficient to use two models next to each other to be able to model the different aspects of the process each in its own way. We also presented a number of different methods to test the validity of the model(s) used. Although it is not yet clear whether all of these methods will be feasible, we think that a hierarchical approach as presented above is optimal. The success of the incident analysis depends largely on the success of the other parts of the research. Even if a model can be build and validated, it is still not clear whether the available incident reports will contain the proper information for identification of elements in the model where things go wrong. For cognitive error identification the problem lies in the compatibility of the model and cognitive model theory. By taking into account these demands on the process model(s) it should be possible to achieve the goal mentioned in the introduction. We hope we can thus derive the specifications for a anaesthesia monitoring support system.

**References**


