Designing User Interfaces for Smart-Applications for Operating Rooms and Intensive Care Units

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Abstract. Today's physicians and nurses working in operating rooms and intensive care units have to deal with an ever increasing amount of data. More and more medical devices are delivering information, which has to be perceived and interpreted in regard to patient status and the necessity to adjust therapy. The combination of high information load and insufficient usability creates a severe challenge for the health personnel with respect to proper monitoring of these devices respective to acknowledging alarms and timely reaction to critical incidents. Smart Applications are a new kind of decision support systems that incorporate medical expertise in order to help health personnel in regard to diagnosis and therapy. By means of a User Centered Design process of two Smart Applications (anaesthesia monitor display, diagnosis display), we illustrate which approach should be followed and which processes and methods have been successfully applied in fostering the design of usable medical devices.

Keywords: Smart-Applications, Safety Critical Systems, Healthcare, User Interface, OR, ICU.

1 Working Conditions in ORs and ICUs

Backhaus and Friesdorf ([1], p.45, translation by the authors) describe the "megalopolis" intensive care unit (ICU) "as an unmanageable set of hoses, cables and wires interconnected with at least an equal amount of sensors, instruments, devices or any other technical equipment. Right in the middle, the »patient« agonisingly made stationary by the equipment that is required to keep him alive" (Fig. 1). These circumstances describe both the situation in ICUs and in operating rooms (ORs). The assembled multitude of technical support systems creates highly complex and highly dynamic working conditions for the attending physicians and nurses (in the following summarized as health personnel).

As a general rule, patient monitors are the central constituent of this environment. They measure and log vital signs (e.g. heartbeat, blood pressure, breathing and anaesthetic gas concentration levels), and thus form the basis of a reliable monitoring of the patient. Patient monitors are used for anesthetized patients in ORs and ICUs as well

T. Gross et al. (Eds.): INTERACT 2009, Part II, LNCS 5727, pp. 684–695, 2009.

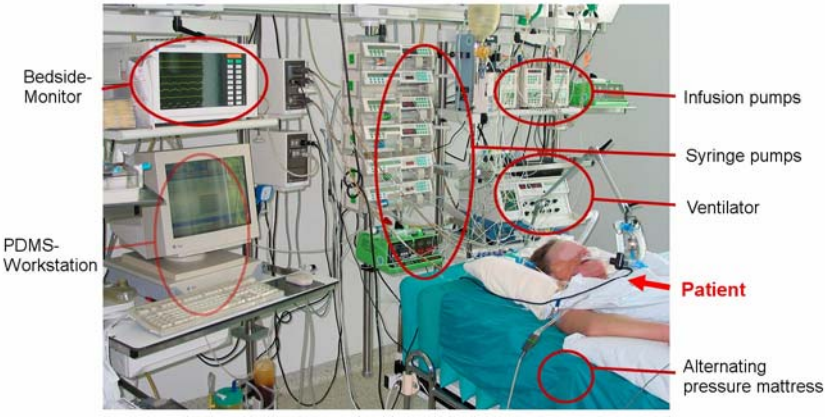

Fig. 1. Patient embedded between technical equipment on a modern ICU

as for conscious patients in general wards and allow health personnel to quickly diagnose and react on critical patient conditions. The interaction with medical devices is often difficult and cannot be effective without a huge amount of previous knowledge. Furthermore the medical devices from different manufacturers often vary in their operating philosophy. Patient monitors for example often have different controls/keys with a different layout. Thus nurses often have to adapt to a different handling while going from one patient to another or interacting with various devices (e.g. ventilator, patient monitor and syringe pump) at one patient. Obradovich and Woods [2] and Wears and Cook [3] show that these devices often suffer from bad usability. This deficiency is of particular importance because the workload of many users in the medical domain does not give them enough time to carry out in-depth examinations of these technical devices [4]. Health personnel often refuse to change visual settings of devices because they fear that they could end up with an even worse layout and not being able to change it back.

But even if every specific device would be ergonomically designed, numerous problems will only manifest themselves in the interaction with other devices in a certain working context. Some of the problems emerge from divergent design principles. In addition, there is insufficient interconnection and integration within the various devices compiling the patient monitoring system assembly (Fig. 1). This forces users to type in identical data into different devices, or to read a measurement at one device and type it into at another device. Taking these situations into account, the lack of acceptance for these devices is hardly surprising.

1.1 Stress and Habituation Effects

Numerous studies (cf. [5] for a review) document that the cognitive system of humans is generally not well adapted to monitoring activities. The errors occurring in monitoring tasks are mostly a consequence of the high attentional load, caused by the enormous amount of information and the large number of signals that have to be processed. In the case of health personnel using monitoring devices, Coiera et al. [6] found evidence for the following three possible types of errors: (1) Users see the information

on a monitor, but they are not interpreting it. (2) Users concentrate on a very small amount of the data and ignore relevant information. (3) If users are tied up with performing a complex task, they avoid spontaneously addressing themselves to another task. Thus severe problems are sometimes detected too late.

It has been shown however that an adequately designed device can support the human information processing considerably in relation to monitoring tasks. Parasuraman et al. [5] emphasise the possibility of exploring the system behaviour, whereas Norman [7], recommends that the system should communicate its internal control decisions to the user.

1.2 Users in Healthcare as a Challenge

As in every design task that needs to incorporate the wide experience and expertise of users, the quality of the system design is directly dependent on how effective clinical expertise can be fed into the development process and applied to the product. The characteristics of this medical field are: the comprehensive education of the users, a language that is hard to understand for the medical laymen, as well as the far ranging legal requirements set by regulatory authorities. Due to the well known limitations in expressing expertise simply questioning the health personnel is not very promising [8] [9]. Many well established methods of user and task analysis like in situ observations and interviews or even usability tests are almost impossible to accomplish, because of the jeopardy of life and limb for at least some of the parties concerned. The everyday working life of health personnel is largely beyond the realm of experience of designers and developers. Therefore, it is a challenge to devise the design requirements that follow from this process and to turn these into an adequate design.

There are additional factors that make it difficult to optimise the design for a specific user group. For example, in Switzerland or France anaesthetic nurse specialists can (under the supervision of an anaesthesiologist) apply narcoses, whereas in Germany the application of a narcosis is mandatorily done by anaesthesiologists. This differentiation occurs from country to country, but also within each country, hospital, and even hospital ward when allocating tasks between medical specialist und clinical nurse specialists. This leads to the situation that persons with the same occupational title and the same job description take on different responsibilities, e.g. in adjusting the dose of the medication or adjusting the parameters of the respirator. Therefore, it is difficult to make generalisations from single observations or interviews in order to design one system for a certain user group.

1.3 Decision Support in Medical Devices Systems

When patients stay in ICUs and ORs they are often in critical conditions. Therefore, in some cases, the health personnel have to arrive at decisions very quickly. Nevertheless, depending on situation and case, they have to take up to 65 to 100 parameters spread over several devices into consideration [10]. Hecker and Hölscher [11] show that it takes a lot of effort for the health personnel to monitor this multitude of distributed information and parameters on the devices and – in case of an alarm – to efficiently identify the causes and react accordingly. To cope with the immense data volume on ICUs and ORs, decision support systems are currently being discussed

[12]. According to [13], [14], and [15] it is expected that these systems can increase the quality in healthcare by improving the performance of the health personnel, by enhancing patient safety, by saving time, and by cutting down treatment expenses at the same time.

However, there are great challenges for introducing decision support systems in the medical domain. Particularly the acceptance of a system by the users is often an issue [14]. The central question asks how a system could be integrated in the existing workflow. It not only has to be compatible with the existing hardware, but it has to be technically mature und updateable [14]. Mueller et al. [16] state that comprehensive analyses have to be carried out before one can integrate these systems into the workflow. Kawamoto et al. [17] specify this request and give three preconditions to advance the application of decision support systems in clinical practice: (1) decision support has to be provided automatically as part of clinician workflow, (2) decision support has to be delivered at the time and location of decision making, and (3) the system has to provide actionable recommendations. Applications that are designed in order to meet these preconditions are in the following referred as *Smart Applications*.

In summary, decision support systems seem to have the potential to improve the situation in the ICUs and in the ORs. The question remains: How can one design medical devices that achieve both a high degree of usability and a widely acceptance by the health personnel? In the following section we present two examples how the early involvement of users can help to deal with these challenges.

2 Designing Smart Applications

In the first example, the Anaesthesia Display „SmartPilot“, the challenge was to turn a scientific lab prototype into a product that supports anaesthesiologists in administering anaesthesia. The prototype uses mathematical models to calculate the concentration at the effect site and the resulting effect. This is based on statistical distributions. Based on drug dosage and patient traits the most probable course of drug concentration and resulting effect is displayed. The mathematical models also predict those values for the future. As the prototype displayed much information, which was not familiar to most anaesthesiologists, it was not very useful to them. Important requirements for a display were self-explainability and – especially in the case of real time data – allowing fast interpretation. The aim was to change the design of the display accordingly.

The second example is a Diagnosis Display, which in case of an alarm gives suggestions for the underlying cause, based on a multivariate analysis of the measured vital signs (blood pressure, heart rate, oxygenation, etc.). The focus of this research project was to study how diagnoses as well as their reliability can be displayed adequately and how such a system needs to represent itself to be considered as support by the users (and not e.g. as paternalism).

The two examples have been designed in a User Centered Design process. The process started with observations of the workflow, workplace and overall behaviour of 8 (SmartPilot) respectively 6 (Diagnosis Display) users in their everyday environment at work. Interviews with further health personnel completed the insights. Based on the results mock-ups for the devices have been created that were iteratively

improved in dialogue with health personnel at different hospitals. As a next step prototypes have been implemented and tested in usability tests. The samples for the tests included 5 physicians and 4 nurses (Diagnosis Display) respectively 10 anaesthesiologists (SmartPilot). Finally an improved prototype of the SmartPilot has been tested in a simulator study with a high fidelity patient simulator with another 10 anaesthesiologists.

2.1 Anaesthesia Display "SmartPilot"

Both projects have in common, that new features are to be made available. To succeed it needs to be understood, how those features fit into the daily routine of the users, and to what extent they are already represented in their minds and working procedures. Self evidently, anaesthesiologists take into account how drugs distribute in the patient's body and which effect they cause. But to do so, they use rather heuristics because accurate calculations are almost impossible without technical support. Intra-operative awareness and pain result from low drug dosages and adverse effects like hemodynamic shock and breath depression are caused by high dosages. All of them can result in increasing healing time and/or permanent damage. The aim is to reduce the workload and to support the personnel to apply the adequate procedure.

First observations in ORs showed that anaesthesiologists do not want an additional device to be monitored at their workplace. Anaesthesiologists often work in crowded

Fig. 2. Anaesthesia workplace in an OR

places, virtually in the middle of an equipment park consisting of anaesthesia machine, patient monitor, syringe pumps, warming therapy devices and more (Fig. 2). It seemed reasonable to add information the anaesthesiologist needs to track anyway to detect changes in the patient's state to the new display. This way the most important information is available in one place (the new "SmartPilot" display) and should only require looking at the other devices like anaesthesia machine, patient monitor, syringe pumps etc. to explore parameters in more detail or to adjust drug administration or change other settings.

As a simplified description of their major goal of work the interviewed anaesthesiologists could agree to the following statement: "anaesthesiologists want to keep the hemodynamic signs of the patient stable in adjusting the depth of anaesthesia to the changing pain level resulting from the surgery". In the mathematical models, the depth of anaesthesia is calculated as a probability to tolerate noxious stimuli. To allow the anaesthesiologist to stick with his mental models, this calculated anaesthetic depth was displayed with the most important hemodynamic parameters on a shared time scale (Fig. 4, lower right side). This allows putting the calculated effect into perspective based on hemodynamic reactions.

The drug dosage as well as the calculated concentration at effect site is displayed accordingly. That allows the anaesthesiologists to see the coherence of drug dosage, concentration at effect site, calculated effect, and observable effect on patient at a glance. That also helps to relate the individual patient to the standard, as described by the models. In a next step these findings were realized as sketches and discussed and revised iteratively with the help of several anaesthesiologists (Fig. 3).

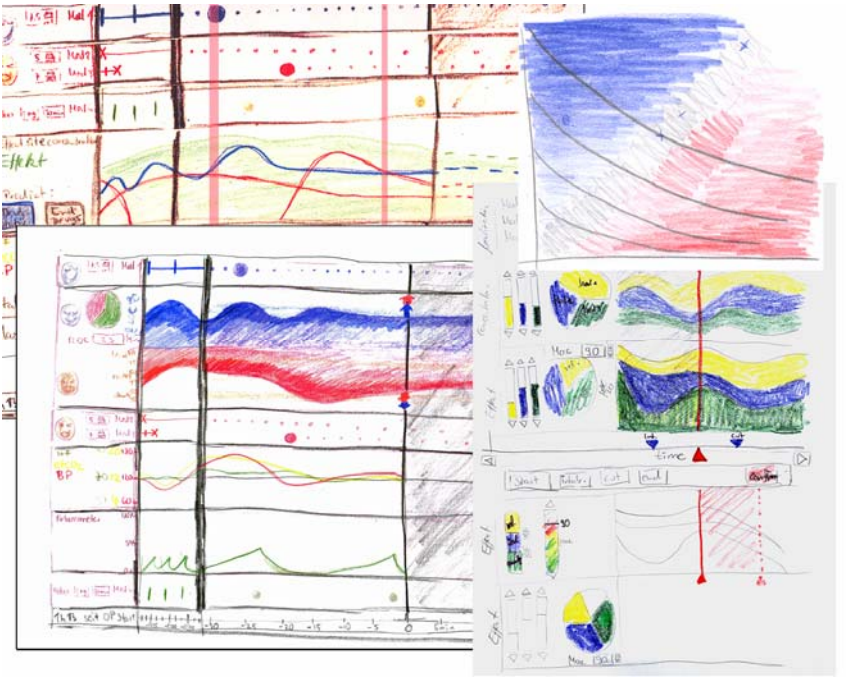

Fig. 3. Sketches which were iteratively discussed and improved with anaesthesiologists

Fig. 4. "SmartPilot" Prototype state of December 2007

In the next phase a functional prototype was developed and formal usability studies have been conducted. In the end, a display evolved which includes the most important vital signs as deviation from a norm, the combined effect of analgesic and hypnotic drugs as a graph as well as an index which was deliberately developed for this display to quantify the anaesthetic effect (Fig. 4). Furthermore, the concentration of each drug at effect site is displayed in relation to the according dosage. In relating the vital signs as an indicator for the current patient state with the calculated drug concentrations, the anaesthesiologist is able to relate the drug reaction of the individual to the norm. All information is displayed on a shared time scale to simplify the contextual interpretation. On this time scale additionally events like "skin incision" can be marked. As SmartPilot combines measured variables with model based calculations, it is crucial to visually separate the two. Therefore all vital signs are in a separate box, all calculated drug concentrations, and the indices BIS and NSRI also have a single box each.

2.2 Diagnosis Display

During the design process of the Diagnosis Display one central question was how the reliability of a diagnosis can be communicated to the user. This question occurs because it is rarely possible that an expert system can derive a diagnosis that is absolutely certain. Additionally some steps of the physicians' workflow (e.g. finding out what favours a diagnosis) are not supported when the plain diagnosis is displayed. Eventually theses actions may be even hampered. Thus the system should be designed in a way that "overtrust" or "undertrust" problems can be avoided [18]. Actually the

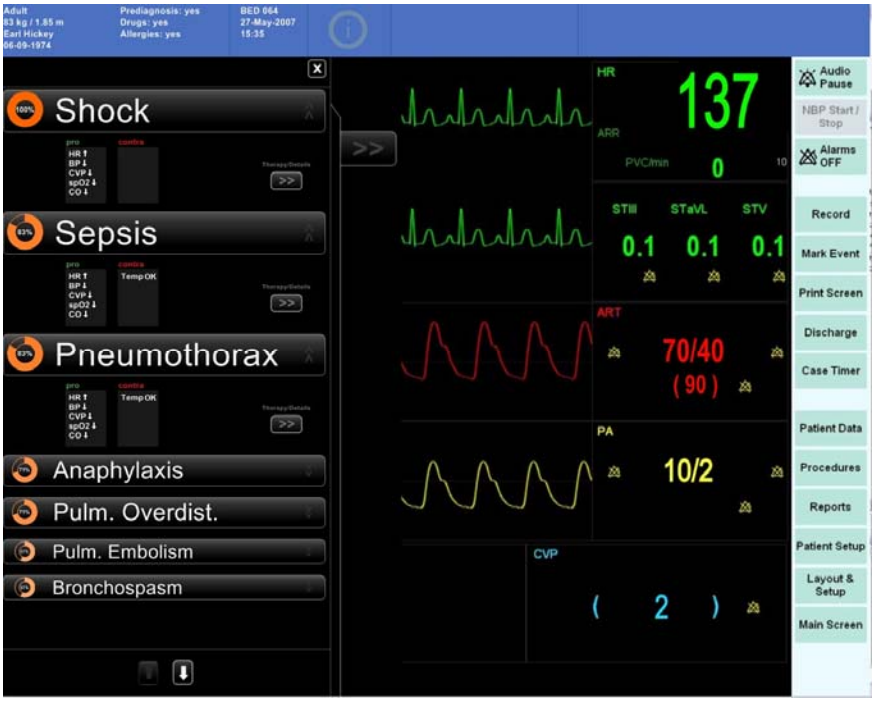

Fig. 5. Diagnosis Display with proposed diagnoses. The validity and reliability of a diagnosis is communicated by the orange segments of circles and by variations in font height and size.

results of usability-tests and interviews showed that the knowledge of a diagnosis' reliability is crucial for many participants. Furthermore, a visual presentation of the reliability is preferred over a numeric one. A numeric presentation usually stands for a high grade of accuracy that cannot be guaranteed in most cases. The validity and reliability of a diagnosis can be communicated by coloured geometrical shapes (orange segment of circle) and variations in font height and size. Numeric expressions like a percent value are only provided additionally (Fig.5).

Another important aspect was the acceptance of the Diagnosis Display. As Berner and Moss [13] point out, systems are particularly accepted, if the user is able to understand how the device works and how diagnoses are calculated. The extent of decision support can affect the acceptance as well. Several physicians (as participants in the usability-test) commented on certain drafts of the Diagnosis Display that the decision support would be too extensive. They said that the display shows trivial diagnosis and information that they already know for sure in this situation. Some nurses however considered this information as useful. A few physicians agreed and commented that the display would be useful for certain situations (e.g. admission of a patient, cognitive overload, education). This discrepancy shows that it is essential to focus on certain users and situations when a decision support system like this is introduced. The assumption is underlined by the following finding: The majority of the physicians consider the display as an inspiration and source for their own decision

Fig. 6. Diagnosis Display with the possibility to add clinical observations

making process. They would like to see lots of information and diagnosis on the display. The majority of the nurses however are primarily interested in symptoms, not diagnoses, because these symptoms trigger the nurses' treatment activities, without the prior involvement of a physician. E.g. one nurse stated: "diagnoses are not important for me".

The interviews and tests show that physicians and nurses are critical about additional devices at the workspace. In fact, a good integration into an existing device and the ability to communicate with other devices is required. Here the Diagnosis Display was integrated into a patient monitor to provide information at the point of care (Fig. 6). Asked about the integration the majority of the participants said that the Diagnosis Display should only be visible on demand. They wanted to keep the monitor they are used to as their primary device for supervising. However they expected some kind of notification when the Diagnosis Display has new information for them.

The participants also criticised that the display can only use parameters that are measured by devices. If the display needs to reproduce the process the physicians go through, clinical observations of the patient (e.g. tearing, sweating) are missing. This information is very important for the physicians. As a solution these observations can now be chosen from a list and affect the calculation of a diagnosis when using the display (Fig. 6). However these observations often must be entered into a Patient Data Management System too. This conflicts with the precondition that users do not want additional work with the Diagnosis Display. Therefore these clinical observations

should be synchronized between the Diagnosis Display and the Patient Data Management System.

2.3 Conclusion from the Case Studies

One major challenge in the design of the Anaesthesia Display "SmartPilot" and the Diagnosis Display is to implement the support feature without suffering complacency or overtrust (as described above). The display needs to be designed in a way requiring the users to make use of their expertise despite all support. This necessity was mentioned by some of the participants of the usability tests as well. They frequently noted that especially inexperienced colleagues need to be challenged to learn diagnosing or administering anaesthesia appropriately and effectively.

Both projects show, that it is crucial to the users to have those new features and information available in parallel to their standard working procedures. They want a system that is – at first – only observed whether it comes to the same conclusions. The decisions are at that time still made by the users themselves. Therefore with "SmartPilot" a product is developed which visualizes the distribution and effects of the drugs based on their dosage according to the underlying models. This is displayed in context of selected vital signs. The dosage of the drugs is carried out as usual by the anaesthesiologists at the anaesthesia machine and the syringe pumps.

The diagnosis display only exists as a research prototype and is meant as an optional component of a patient monitor. The user can turn the display on and off as he or she wishes, allowing to compare the results of the display with their own conclusions without any pressure to make use of it.

3 Designing Working Conditions Instead of Optimizing Devices

As these examples already show, it is crucial in the development of new medical devices to incorporate the lessons learned from the adversities found in clinical workaday life. If, for example, a user already has to monitor more devices than he or she is able to, adding a new device further increases this cognitive overload. Therefore, any new device added should replace at least one other device. If users are already displeased by typing in the same information into several devices, this problem has to be avoided when reengineering devices or developing a new class of devices. Ideally, users enter data into one task-oriented device, which then propagates the data into all other devices. A common standard[1] for the interchange of patient data is required to achieve this.

Another important lesson learned from both our case studies, is that users within a safety critical clinical environment have to act conservatively. Therefore, they tend to be critical towards innovative devices. This is because they cannot be sure that their expertise is considered and supported by the devices. Furthermore, they have to make sure that theses devices will not become a security risk for their patients. Ideally, the health personnel should be able to actively validate, whether the new system comes to the same conclusions as themselves, or analyse, why the device comes to other

[1] DICOM [19] shows that it is possible to establish a common data structure and communication protocol within the field of medical imaging.

conclusions. Depending upon whether the system has proved its value to the user, they can gradually utilize more of the functions of the device. Thus, they can gradually shift their way of working with the device in way that feels save to them. Particularly in support systems, it is of utmost importance that the systems themselves know their limits and can communicate these limits to the users [20]. Hence, an important question in regard to the Diagnosis Display is: How to visualize the reliability of a diagnosis to enable the users to avoid relying on the system when they should not? This holds particularly in the case, when the system itself does not have sufficient data or if the data is of questionable quality.

It is important to always leave the full freedom of decision over the medical device to the user. Every respirator offers the possibility to run the respiration manually. Every control loop at a syringe pump that automatically adjusts a given control variable, can be interrupted at any time and overwritten with manual settings. Last but not least, physicians want to see and touch their patients; they never rely merely on the patients' records when making decisions. Physicians are more willing to consider devices for diagnosis support if they can enter their clinical observations into the device, so that this data will be considered in the diagnosis computation by the device.

In developing medical devices used by nurses, it should be considered that both the competence, as well as the area of accountability of nurses differs sometimes highly from country to country, from hospital to hospital, and even from ward to ward. Some nurses with certain skills and responsibilities need to be informed about the general state of the patient to make qualified decisions about the patient's care. Other nurses work conclusively when instructed to do so, and otherwise, they carry out only assigned tasks of basic patient care. Developing products for such heterogeneous organisational application contexts is therefore a great challenge.

To disclose theses problems, restrictions and characteristics, it is important to involve the users early, repeatedly and consistently during the development process of the device. This way, the User Centered Design process leads – through early feedback, short iteration cycles and usability tests – to the understanding of context, interrelationships, work conditions, and problems of the target domain. As a result, this acquired knowledge can be used to design a better device suited well for its users, their tasks and their work contexts.

Acknowledgements. We want to thank all the participants of our usability-tests, simulator-tests, interviews, surveys, and workshops. We appreciate their willingness to critically reflect and discuss the new systems and for their patience to communicate their concerns to non-medics. Especially the physicians and nurses of the Universitätsklinikum Schleswig-Holstein, Campus Lübeck were very helpful in allowing us to look over their shoulders and observe them in ORs and ICUs. Last not least we are very grateful to Dr. Michael Imhoff, who provided us with photos of ORs and ICUs.

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