THE APPLICATION OF THE ECOLOGICAL INTERFACE DESIGN APPROACH TO NEONATAL INTENSIVE CARE MEDICINE

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Ecological interface design techniques were used to first model and then develop an interface to help clinicians assess tissue oxygenation in a neonatal intensive care unit. Several challenges were encountered during this work. The abstraction hierarchy model structure that was used has limitations in this environment. The first limitation concerned the depth of knowledge that was available. Tissue oxygenation is a complex, and not totally understood process. Furthermore, it is truly distributed in nature. Both these limit the level of detail that could be included in the system model. Second, in this environment the sensor suite is very limited and is defined a-priori. Therefore, many of the variables that were identified as important in the abstraction hierarchy model are impossible to measure. Despite these limitations, the interface that resulted from the abstraction hierarchy model compared favorably to the existing interface in a simulated clinical environment.

INTRODUCTION - INTENSIVE CARE MEDICINE

> Error is inevitable. Whereas in the more forgiving circumstances of "normal" life, learning from one's mistakes is usually a beneficial process, in the control rooms of chemical or nuclear power plants, such educative experiences can have unacceptably catastrophic consequences.
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> - J. Reason, 1988, p. 8.

Although this quote refers to an industrial process control environment, the same holds true for the practice of medicine. Clinicians are required to make many time critical decisions and carry out critical actions in an environment where human errors can have catastrophic consequences. This is particularly true of intensive care medicine where often "heroic medical management" is required if patients are to survive [Abramson, 1980]. Furthermore, human errors do occur in this environment. One study reported that more than 60% of all incident reports in a medical-surgical intensive care unit were caused by human error [Abramson, 1980].

In many ways the supervisory control environment of industrial settings (e.g., nuclear power plants, chemical processing plants, etc.) are similar to the environment of an Intensive Care Unit (ICU). In both environments people are forced to make time-critical decisions that can have catastrophic consequences if they are not correct. People in both environments must also deal with large uncertainties, leading to a similar problem solving behavior that is typically cyclical in nature [Albert, 1988, Gaba, 1994, Rasmussen, 1986]. There has been a considerable amount of research devoted to understanding these industrial settings, in an attempt to develop systems that aid operators' decision-making. This is not the case for the ICU environment, the evolution of ICU monitoring systems is just starting. ICU monitoring is currently dominated by the single-sensor-single-indicator mode where each sensor has its own display. The goal of this work is to determine if work modeling and interface design techniques, originally developed for industrial environments, can be successfully applied to an ICU environment.

The Development Experience

This section contains a brief overview of the steps taken in the development of the ecological decision support system for the assessment of tissue oxygenation in a Neonatal Intensive Care Unit (NICU) environment. The problems that were encountered and their solutions are discussed.

A structured field study was used to create a model of tissue oxygenation that is relevant to neonatal intensive care medicine. Rasmussen's Abstraction Hierarchy (AH) was used as the model structure. The first challenge that had to be addressed was the identification of the proper levels of abstraction for the AH model. Initial attempts were made to use the levels that had been defined for other domains [Rasmussen 1986, Vicente 1992]. It was quickly determined that these were not appropriate. To identify the relevant abstraction layers, it was necessary to examine the "states of knowledge" that the clinicians used to communicate with each other.

During this field study the phrases and terminology that were used by the clinicians to communicate with each other were recorded. These phrases were then placed in a list and ordered from abstract to concrete. Where possible, means-ends relationships were also used to order the list. Figure 2, is part of the list of concepts and phrases that were recorded during the focused field study. Terms were then grouped into broad categories that are related in a means-ends manner. These groups became the abstraction levels used for the rest of the modeling.

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	Balances	
23.	fluid build up problem with his lungs	Balances
24	electrolyte imbalance	
25.	Balancing between blood clot formation and bleeding	
26.	Fluid balance	
27	carefully track the amount of fluids ins & outs of the infant	
	Trending (Time gradient - indication of state of balance)	
28.	team was trending BP	
29	detect trends	
30.	temperature graphs	
31.	blood pressure of the infant dropped	
32.	de-accelerations in fetal heart rate	
33.	inspired oxygen concentration was being gradually reduced	
	Processes:	
34.	Ventilation	Processes
35.	Oxygenation	
36.	attempts to oxygenate	
37.	clotting mechanisms of the blood	
38.	weaning	

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Figure 2. A portion of the ordered list of "states of knowledge".

Based on this analysis, five levels of abstraction were identified. They are listed below:

- *Purpose*: homeostasis: maintain internal environment
- *Balance* : to maintain the internal environment the supply and demand for nutrients must be balanced.
- *Processes* : the process that connects the chambers that are in balance. Process correspond to regulated flows of oxygen.
- *Transport, Storage, & Control* : the components that make up the processes, and the storage chambers.
- *Physical form:* the actual arrangements and interconnections of the various body sub-systems

Figure 3 depicts the abstraction levels that where identified and the goal-means relationships that exist between them.

Models of tissue oxygenation physiology at each of these abstraction levels were then created. This was accomplished by referencing physiology texts and discussions with physicians. These models captured the constraints that govern the behavior of the system at each level of abstraction and enable the identification of the variables important for system understanding. Structured interviews with physicians were used to verify the accuracy and completeness of the model

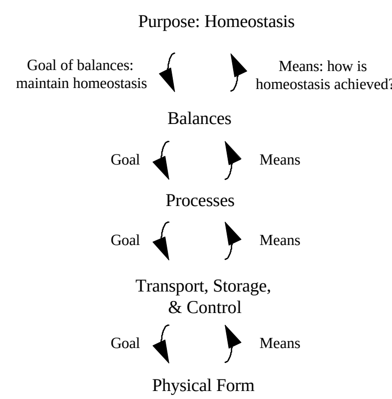

Figure 3. The identified abstraction levels and the goal-means relationships.

The next step was to map the abstraction hierarchy model onto an ecological interface. Several challenges were encountered at this stage. First, the physiology of tissue oxygenation is an extremely complex and highly interconnected process. It is also distributed in nature, the physician must be concerned about the oxygenation of every cell in the body. These issues lead to several limitations with decision support systems that are based on this type of model structure. First, in other environments that are less complex and better understood, an abstraction hierarchy model of the environment can directly support many different analytical problem-solving strategies. People in these environments can use "searching" type techniques where individual paths through the model are explored in an attempt to identify and diagnosis the cause of the problem. These problem-solving techniques are not that powerful in this domain.

Although physicians can use functional relationship to focus in on a specific physiologic subsystem (e.g., it is a respiratory disease) they can not continue decomposing the system to a level where they can identify a fundamental root cause of the problem. Therefore, this type of analytical problem solving is not a major component of diagnostic strategies used by physicians, and this aspect the abstraction hierarchy is not applicable to this environment.

The second issue that limits the usefulness of the abstraction hierarchy in this environment is the fact that the sensors set is defined a-priori. There are relatively few sensing devices available in this environment. Furthermore, the distributed nature of the system makes the placement of these sensors important. For example, the abstraction hierarchy identifies the capillary blood PO_2 (partial pressure of oxygen in the blood) as an important variable in this system, however, this is significant throughout the body, measurements at a particular point gives limited information about the PO_2 in other parts of the body.

In summary, there are limitations to the use of the abstraction hierarchy as the basis of decision support systems in this environment. However, the abstraction hierarchy was a useful tool to help identify a unified set of concepts, at different levels of abstraction, that the physicians use during clinical problem solving. This is the role that the decision support system will fill, it will aid the physicians in forming these concepts based on the underlying data streams that are available. Furthermore, the structure of the abstraction hierarchy will provide the basic structure for the information presentation. How this is achieved is discussed below.

The sensor limitations were addressed as follows. Typically, based on an abstraction hierarchy analysis of a system, sensors would be placed at the appropriate places. This is not possible for this environment, the sensor suite is defined a-priori. This led to a situation where many of the variables identified as important in the abstraction hierarchy modeling could not be directly measured. For example, the abstraction hierarchy identified the partial pressure of oxygen at the mitochondria of every cell in the body as an important variable. Obviously, this can not be measured.

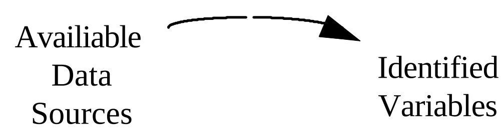

Figure 4. Mapping available data sources onto identified variables.

To address this problem an inventory of data sources was created. This set was then mapped on the set of variables identified by the abstraction hierarchy model of tissue oxygenation, as shown in Figure 4. Four cases were encountered, listed in Table 1.

Direct Mapping:	Some of the identified variables were sensed, for these variable the sensed value was used.
Analytical Mapping:	Some of the identified variables where a direct mapping was not available an analytical model existed that could be used to derive values for the unobservable quantities.
Heuristic Mapping:	For other variables there were no direct of analytical mapping existed a heuristic map was used. These relationships between observable and unobservable variables were qualitative and subjective in nature. They were identified based on discussions with physicians.
No Mapping	Some identified variables, no mapping between observed quantities and the identified variables were found that were robust.

Table 1. Classification of mappings between identified variables and measurable parameters.

EMPIRICAL EVALUATION

Overview

A 2 x 3 x 2 repeated measures factorial design with one within-subject factor (interface type) and two between-subject factors (expertise, order). There were two levels for the interface type, the existing interface, and the EID interface. The expertise factor had three levels, based on the experience of the subjects. They corresponded to residents, fellows and attendings. A total of 16 subjects participated in the study. Due to the limited number of scenarios available and the desire to reduce variability, the subjects experienced each scenario twice, once with one interface, and once with the other. This made the order in which the subjects experienced the interfaces important, since the subject may learn something from their first experience that they apply to the second. This was accounted for by including an order factor. Four scenarios were developed that depicted common acute clinical situations, they were treated as replicates in the experimental design.

Figure 5 depicts the display that corresponded to the existing method of data presentation. It closely resembles the current interface in place in the NICUs. It consists of individual instrument readings, a table of recent blood gases, physical findings, and case notes. Figure 6 is the ecological decision support system's interface. Both interfaces include the physical findings and the case notes windows. They are included on both interfaces to make the simulation more realistic.

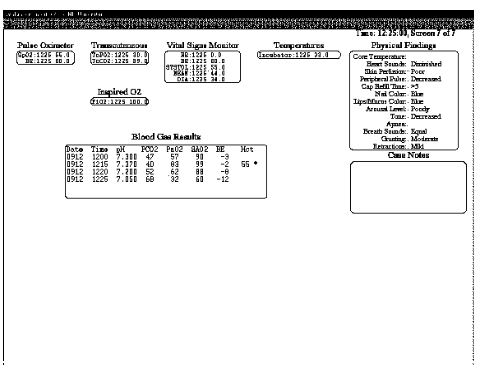

Figure 5. Existing interface.

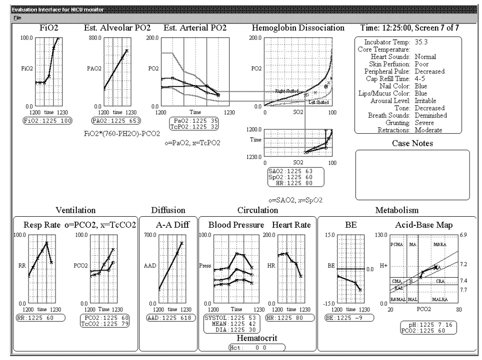

Figure 6. Ecological interface.

Immediately following the last time slice of the scenario, physicians were asked to select 5 diagnosis from a list of 20 that best described the infant's state, they were asked to rank their choices (1=most likely, 5= least likely). The last time slice remained on the screen while the diagnostic form was completed.

Results Highlights

The accuracy of diagnosis was measured in several different ways. The first measure that was used simply classified the response as correct if the physician included the proper diagnosis in their list of potential diagnosis. The results of this comparison are shown Figure 7. This graph plots the percentage of times the correct diagnosis was included in the list of potential diagnosis (across scenarios).

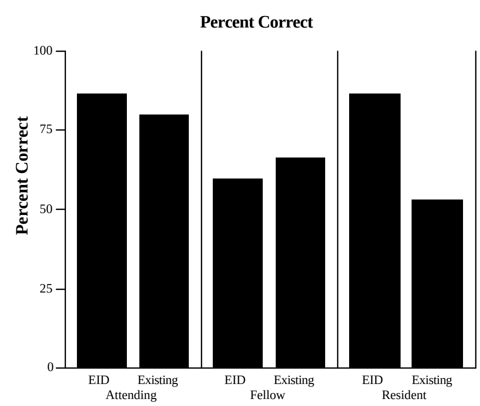

Figure 7. Percentage of correctly scored scenarios.

A four way ANOVA was run, with order, experience, subject, and interface as the controlled factors. A mixed model with nested and factorial factors was used. The dependent variable was the percentage of times the correct diagnosis was included in the list of potential diagnosis. Since the data are based on frequency counts, the data were first converted to percentage scores and then square root transformed. The resulting statistic ranged from 0 to 10, 10 corresponding to a perfect score.

Several factors where significant. First the subject within experience was significant, ($F(9,9) = 12.0829$,

$p \leq 0.0005$). This is not surprising, each individual is different. A significant difference was also seen in the between the interfaces ($F(1,9)=8.1008$, $p \leq 0.0192$). Physicians performed better with the new interface. The Interface x Experience interaction was also significant, as expected ($F(2,9) = 14.3877$. $p \leq 0.0016$). This effect was in the direction expected. <u>All residents (the least experience group) preformed better with the EID interface</u>. <u>Furthermore, only one subject out of the 16 preformed better with the existing (and more familiar) interface.</u>

DISCUSSION

Overall the development effort was successful. The resulting system was shown to improve the diagnosis in the simulated environment. Several issues were encountered during the development effort that resulted from the differences in the NICU work domain and the industrial work domain where EID is typically applied. First, the complexity of the patient far exceeds the complexity of any industrial process. The physiological systems that are the focus of diagnostic reasoning are both distributed in nature and are not fully understood. This greatly influences the problem solving strategies used by clinicians. Second, the sensor suite is defined a-priori and is very limited. Whereas in industrial application of EID, the abstraction hierarchy can be used to define sensor requirements, this can not be done in the NICU environment. Many of the physiological variables that are identified as important can not be measured. Clinicians do, however, use abstraction to deal with this environment. They do abstract higher order concepts from raw data streams presented to them in the NICU environment. These concepts are used in the clinical decision making process. This seems to be were a EID based system fits into this environment. A properly designed EID system can help the clinicians abstract meaning from the many raw streams of data that they are presented with.

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