A Work Domain Analysis of Patient Monitoring in the Operating Room

John R. Hajdukiewicz, D. John Doyle, Paul Milgram, Kim J. Vicente and Catherine M. Burns

Proceedings of the Human Factors and Ergonomics Society Annual Meeting 1998 42: 1038
DOI: 10.1177/154193129804201407

A WORK DOMAIN ANALYSIS OF PATIENT MONITORING IN THE OPERATING ROOM

John R. Hajdukiewicz[1,2], D. John Doyle[1], Paul Milgram[1,2], Kim J. Vicente[1,2], Catherine M. Burns[2]

[1]Institute of Biomedical Engineering
[2]Department of Mechanical and Industrial Engineering
University of Toronto, Canada

This paper presents a method for structuring the work domain of the anesthesiologist in the operating room, using Rasmussen's (1986) approach for work domain analysis. The goal of this research is to provide an integrated approach for patient monitoring by bridging the gap between physiological principles associated with the patient and clinical practice. Data were collected from literature reviews, discussions with anesthesiologists, operating room observations, and simulator sessions to develop the work domain representation. From this information, the work domain was structured using various levels of abstraction and decomposition, independent of any particular situation. Next, an analysis of the links between the operating room and the work domain was performed. The results indicated that this approach has useful insights for training and interface design. The approach provided a framework for representing the work domain as an invariant purpose-based structure for a constantly changing work environment.

Motivation

The effectiveness of patient monitoring in surgical anesthesia has become an area for debate and concern among researchers and medical personnel (Orkin, 1993). Recently, monitoring and therapeutic equipment in operating rooms have increased in number and complexity, largely in response to high demands for providing quality care in sicker patients. As a result, cognitive demands on the medical personnel, primarily anesthesiologists, have increased because of the associated additional monitoring and supervisory tasks in this highly dynamic environment (Orkin, 1993; Westenskow, 1993).

Many approaches have been proposed to tackle the above problem. Some designers have focused efforts on developing expert systems to manage patient data (e.g., Mora, Passariello, Carrault, & Pichon, 1993; Beneken & Blom, 1983; Fukui, 1987), while others have investigated different methods of integrating and displaying patient data (e.g., Thull, Popp, & Rau, 1993; Siegel, 1983). However, many of these approaches are limited because they primarily focus on clinical variables from current technologies. In general, they do not take into account the structure of the patient and the constraints that shape physiological behavior.

The objective of this paper is to present a method for structuring and analyzing the patient in the operating room, from the perspective of the anesthesiologist. The ultimate goal is to provide an integrated approach for patient monitoring by bridging the gap between the technical world of physiological principles and psychological world of clinical practice. This method is based on the tools of cognitive and systems engineering, and applies the approach for work domain analysis proposed by Rasmussen (1986). The results presented in this paper are part of a larger study conducted by Hajdukiewicz (1998) that analyzed the patient monitoring problem in the operating room.

Analytical Method

Data for this research were obtained from various sources (Table 1), incorporating an iterative cycle of scientific inquiry, similar to the data collection methods found in Xiao (1994) and Sharp (1996). The cycle started with developing an understanding of the patient and operating room environment through the review of textbooks, literature, and clinical manuals, and off-line discussions with anesthesiologists. These preliminary activities provided context for directed observations in the operating room and review of full-scope simulator sessions. From the observation activities, patterns became evident, and were recorded (e.g., notes and transcriptions). To end the cycle, these patterns contributed to a further understanding of the patient and operating room environment. Two cycles were performed, exploratory and focused. The exploratory cycle centered on understanding the work environment from a global perspective, and the focused cycle concentrated on particular aspects related to a chosen system that was monitored, the cardiovascular system.

The analysis involved integrating information from the data sources and performing a work domain analysis. Integration involved extracting confirmatory patterns from the data, and developing connections between physiological principles and clinical observations. In general, the review of paper sources (i.e., textbooks, literature, and clinical manuals) and off-line discussions with anesthesiologists provided greater contributions to the work domain representation. Operating room and simulator observations had a lesser impact, but provided insight into current medical practices.

Data Source	Description	Data Collection Activities	
		Exploratory Cycle	Focused Cycle
Textbooks, Literature and Clinical Manuals	• Reviewed theoretical foundations of physiological concepts, processes and models for representing the work domain • Reviewed case studies of procedures and critical events	• Reviewed general concepts related to physiological processes of the body, the operating room environment, and tasks of the anesthesiologists	• Attention centered on understanding cardiovascular monitoring, in context, from a physiological and clinical point of view • Reviewed case studies for critical events affecting the cardiovascular system from Gaba Fish, & Howard (1994) and Muravchick (1991)
Off-line Discussions with Anesthesiologists	• Interviewed practitioners about their work environment • Practitioners asked to critique the work domain representation developed • Conducted in a relaxed environment, away from the operating room	• 1 expert anesthesiologist interviewed regarding general aspects of the work domain	• 2 expert anesthesiologists interviewed regarding specific aspects of the work domain, related to cardiovascular monitoring
Operating Room Observations	• Observed anesthesiologists interact with the work domain, and asked general and specific questions about the work environment • Conducted at the Toronto Hospital (Toronto, Canada) over a 2 year period	• 2 surgeries observed with 1 expert anesthesiologist: liver transplant and lobectomy	• 5 surgeries observed with 4 expert anesthesiologists, focusing on cardiovascular monitoring: prostatectomy, open heart surgery, removal of bowel obstruction, laparoscopy, and orthopedic surgery
Simulator Session Observations	• Observed full-scope simulator sessions used for training medical staff in teamwork and crisis management • Conducted at the Canadian Simulation Centre for Human Performance and Crisis Management (North York, Canada) over a 2 year period	• 3 simulator sessions with different expert anesthesiologists were observed without transcription	• 9 simulator sessions with different expert anesthesiologists were observed, of which five were reviewed and transcribed • Scenarios with cardiovascular events were chosen: advanced cardiac life support, acute hemorrhage, anaphylaxis, total spinal

Table 1: Data collection activities for work domain analysis (adapted from Hajdukiewicz, 1998).

Work Domain Representation

The development of the work domain representation is highly dependent on how the work domain is defined within the work environment. In the case of the operating room, the primary focus of attention is the patient, who is monitored and controlled throughout the surgery. For this reason, the patient was chosen as a work domain of the anesthesiologist. Figure 1 illustrates the relations between the work environment (operating room), work domain (patient), and subsets of the work domain (body systems) (Hajdukiewicz, 1998).

The work domain representation is shown in Figure 2, utilizing the dimensions of abstraction and part-whole decomposition for the whole body and a focused subset of the body, the cardiovascular system (Hajdukiewicz, 1998). This representation was adapted from the work domain levels described in Rasmussen (1986), by using the structure and terminology found in the medical literature and observed in clinical practice. For example, the physical form and function levels of abstraction corresponded to human anatomy and physiology, respectively. Information gathered from the data collection process was used to complete the details of the representation (i.e., filling in the matrix with the work domain variables).

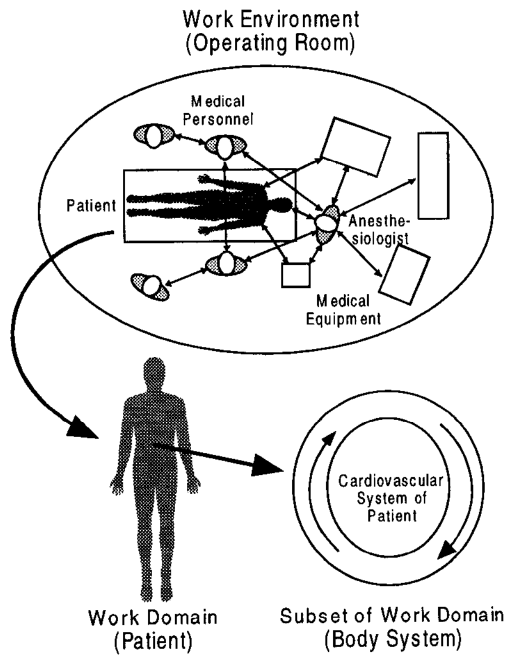

Figure 1: Relations between the work environment, work domain, and subsets of the work domain (adapted from Hajdukiewicz, 1998).

Level of Decomposition

Level of Abstraction	Whole Body	System	Organ	Tissue	Cell
Purposes	Homeostasis (Maintenance of Internal Environment)	Adequate Circulation, Blood Volume, Oxygenation, Ventilation	Adequate Organ Perfusion, Blood Flow	Adequate Tissue Oxygenation and Perfusion	Adequate Cellular Oxygenation and Perfusion
Balances	Balances: Mass and Energy Inflow, Storage, and Outflow *	System Balances: Mass and Energy Inflow, Storage, Outflow, and Transfer *	Organ Balances: Mass and Energy Inflow, Storage, Outflow, and Transfer *	Tissue Balances: Mass and Energy Inflow, Storage, Outflow, and Transfer *	Cellualar Balances: Mass and Energy Inflow, Storage, Outflow, and Transfer *
Processes	Total Volume of Body Fluid, Body Temperature, Supply: O_2, Fluids, Nutrients, Sink: CO_2, Fluids, Wastes	Circulation, Oxygenation, Ventilation, Circulating Volume	Perfusion Pressure, Organ Blood Flow, Vascular Resistance	Tissue Oxygenation, Respiration, Metabolism	Cell Metabolism, Chemical Reaction, Binding, Inflow, Outflow
Physiology		System Function	Organ Function	Tissue Function	Cellular Function
Anatomy			Organ Anatomy	Tissue Anatomy	Cellular Anatomy

* Balances include: Water, Salt, pH, Electolytes, O_2, CO_2

Level of Abstraction	System	Sub-system	Organ	Component
Purposes	Adequate Circulation and Blood Volume			
Balances	Cardiovascular System: Mass Inflow, Storage, and Outflow	Pulmonary and Systemic Systems: Balance Mass Flows; Mass Inflow, Storage, Outflow, and Transfer	Organ Vascular Network: Balance Mass Flows; Mass Inflow, Storage, Outflow , and Transfer	Vascular Components: Balance Mass Flows; Mass Inflow, Storage, Outflow, and Transfer
Processes	Circulation, Volume, Fluid Supply and Sink	Pulmonary and Systemic Circulation (Pressure, Flow, Resistance) and Volume, Fluid Supply and Sink	Cardiac Output, Organ Circulation (Pressure, Flow, Resistance), Fluid Supply and Sink from each Vascular Network	Circulation through Vascular Components (Pressure, Flow, Resistance), Vascular Blood Volume, Fluid Supply and Sink
Physiology	Cardiovascular System Function	Pulmonary and Systemic System Function	Cardiac Function (Heart Rate, Rhythm)	Atrial and Ventricular Function; Arterial, Arteriolar, Capillary, Venule, Venous Function
Anatomy			Cardiac Anatomy	Vascular Anatomy

Figure 2: Work domain representation of the human body. The lower part represents a subset of the human body in detail, the cardiovascular system (adapted from Hajdukiewicz, 1998).

In Figure 2, the abstraction hierarchy is on the vertical axis, outlining the various means-ends relations of the human body, with familiar references for medical practitioners. The lower levels include the anatomical and physiological structures, which represent the available resources and component functions in the body. The higher levels include the purposes of the work domain. Changes in configurations of anatomical structures propagate bottom-up to affect manifestations at higher levels of abstraction. The purposes of the work domain propagate top-down, providing reasons for its function.

The part-whole decomposition is on the horizontal axis, depicting the organization of the body. Traditionally, the human body has been organized according to the functional taxonomy noted by Sherwood (1993). At the bottom of the decomposition (right-hand side) are cells with specialized functions. The cells are aggregated up the decomposition structure (moving left) to form tissues, organs, body systems, and finally the whole body. This provides a unified framework for the organization of structural components of all body systems for the medical domain.

The upper part of the Figure 2 represents the entire human body as the work domain. The lower part focuses on the cardiovascular system, a subset of the human body, at the levels of decomposition pertinent to cardiovascular monitoring for the purposes of maintaining adequate circulation and blood volume. It is important to note that this representation is independent of any specific patient condition, type of surgery, medical equipment and personnel, and organizational factors. This characteristic is useful because the representation may be used as a tool for problem solving in all circumstances, including unanticipated events.

The development of this representation builds on previous work in medical domain analysis (e.g., Sharp, 1996; Xiao, 1994; Rasmussen, Pejtersen, & Goodstein, 1994). The representation provides greater detail in defining the structure of the patient in the operating room with a unified framework, independent of any particular situation.

Interactions between the Operating Room Elements and the Patient

The elements in the operating room, primarily medical personnel and equipment, interact with the patient during the surgery (Figure 1). These elements are discussed with reference to the operating room, how the work domain representation may be utilized in formulating strategies for patient monitoring and control, and how connections with the structure may be obtained.

Medical Personnel

During the operation, the patient is monitored and controlled by medical personnel, who have varying goals, objectives, and obligations. The personnel have responsibilities that focus their attention to various parts of the work domain structure. To illustrate this concept, two main areas of responsibility regarding the work environment are considered: the surgical aspect and supporting anesthesia.

From the observations conducted in the operating room, the surgical team concentrated primarily on the lower levels of abstraction and at the organ and tissue decomposition levels during the operation (e.g., modifying the patient's current anatomical structure to meet particular objectives). On the other hand, the anesthesiologist and anesthesia assistants were observed to generally concentrate at the higher levels of abstraction and a broader range of decomposition levels, ensuring the patient was safe during the operation. Some parts of the work domain were also noticed to overlap, requiring coordination and sharing of tasks among the operating room personnel. In allocating roles and responsibilities onto the work domain structure, informational and control requirements (as defined by the work domain variables) begin to emerge.

Medical Equipment

During the operation, medical personnel use equipment to determine and control the patient's state. This equipment acts as an interface between the anesthesiologist and the patient, where information is received regarding the patient's state and actions are performed to control certain aspects of the work domain.

In monitoring the patient during the operation, the anesthesiologist uses equipment that sample patient variables in order to assess the patient's clinical status. However, most of the variables, as outlined in the work domain representation, are not directly available from the work environment. Some of the available variables indirectly map onto various parts of the work domain (e.g., electrocardiograph trace), while others require analytical methods to estimate their values (e.g., systemic vascular resistance estimated by pressure difference in systemic system divided by cardiac output). The work domain representation provides a framework for organizing monitored information from this dynamic work environment.

Discussion

The work domain analysis performed in this paper resulted in a few insights regarding the work domain.

(1) First of all, each patient is different in the operating room, requiring varying strategies for monitoring and control. Some of these differences include state of health, age, sex, size, and types and progression of diseases. As a result, it is very difficult to incorporate specific monitoring and control protocols for all possible situations due to this variability. However, there are similarities in the general anatomical and physiological structures (and their purposes) of patients, which are modeled in the work

domain representation. This representation contributes to an understanding of the patient's situation, useful for problem solving in the dynamic operating room environment.

(2) Secondly, the ability to access the patient is critical for monitoring and controlling the patient's status in the operating room. However, this access is highly constrained in the work environment, limiting the anesthesiologist in the tasks that can be performed. Strategies for accessing the patient may be devised by using the work domain representation with connections to medical equipment. An example is integrating redundant information from various sources (e.g., heart rate on monitor with patient's pulse rate), thus minimizing uncertainty in the patient's status.

(3) Thirdly, the anesthesiologist shares the work domain (i.e., patient) and coordinate actions with the surgeon and other medical personnel. Attention is focused primarily at the higher levels of abstraction and decomposition.

The following points summarize some of the implications of this research:

(1) Because the work domain was modelled independently of any particular situation, this representation can contribute to the definition of requirements for monitoring technologies. The work domain variables can be prioritized with other forms of analysis (e.g., study of control tasks, monitoring strategies, social organization within the work environment, and medical personnel competencies), to further narrow the requirements.

(2) The representation may also serve as a template for assessing monitoring technologies within the operating room (i.e., determination of how well the displayed variable maps onto the work domain structure).

(3) The work domain representation may be a useful tool for assessing the patient before, during, and after the operation. Most surgical patients have "faults" in their body systems, requiring interventions to manage or solve the problem. Some examples include disease processes that have affected system structure and function (e.g., cardiac disease), and trauma cases (e.g., severe hemorrhage). The proper assessment of body functions and anticipation of complications (e.g., depressed organ function due to anesthetics) are crucial for planning monitoring and control strategies, to minimize risk to the patient during the operation.

(4) There has been a recent trend in medical schools to train physicians using case-based learning. The work domain representation, as a structure that unifies anatomy, physiology, and functional purposes, may be used as a template for assessing hypothetical cases and formulating solutions.

Acknowledgements

The authors would like to thank Dr. D. John Doyle and the staff at The Toronto Hospital, and Dr. Matt M. Kurrek at the Sunnybrook Health Sciences Centre for their assistance during the data collection process. In addition, we would like to acknowledge support from the Natural Sciences and Engineering Research Council of Canada for this research.

References

Beneken, J. E. W., & Blom, J. A. (1983). An Integrative Patient Monitoring Approach. In J. S. Gravenstein, R. S. Newbower, A. K. Ream, & N. T. Smith (Eds.), *An Integrated Approach to Monitoring* (pp. 121-131). Boston: Butterworths.

Fukui, Y. (1987). An Expert Alarm System. In J. S. Gravenstein, R. S. Newbower, A. K. Ream, & N. T. Smith (Eds.), *The Automated Anesthesia Record and Alarm System* (pp. 203-209). Boston: Butterworths.

Gaba, D. M., Fish, K. J., & Howard, S. K. (1994). *Crisis Management in Anesthesiology*. New York: Churchill Livingstone.

Hajdukiewicz, J. R. (1998). *Development of a Structured Approach for Patient Monitoring in the Operating Room*, Unpublished M.A.Sc. Thesis, University of Toronto, Toronto.

Mora, F. A., Passariello, G., Carrault, G., & Pichon, J.-P. L. (1993, December). Intelligent Patient Monitoring and Management Systems: A Review. *IEEE Engineering Medicine and Biology Magazine*, 23-33.

Muravchick, S. (1991). *The Anesthetic Plan: From Physiological Principles to Clinical Strategies*. St. Louis: Mosby Year Book.

Orkin, F. K. (1993). Patient Monitoring in Anesthesia as an Exercise in Technology Assessment. In L. J. Saidman & N. T. Smith (Eds.), *Monitoring in Anesthesia* (pp. 439-455). Boston: Butterworth-Heinemann.

Rasmussen, J. (1986). *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering*. New York: North-Holland.

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive Systems Engineering*. New York: John Wiley and Sons, Inc.

Sharp, T. (1996). *Progress Towards a Development Methodology for Decision Support Systems for use in Time-Critical, Highly Uncertain, and Complex Environments*, Unpublished Ph.D. Dissertation, University of Cincinnati, Cincinnati.

Sherwood, L. (1993). *Human Physiology*. (2nd ed.). New York: West Publishing Company.

Siegel, J. H. (1983). Integrated Approaches to Physiologic Monitoring of the Critically Ill. In J. S. Gravenstein, R. S. Newbower, A. K. Ream, & N. T. Smith (Eds.), *An Integrated Approach to Monitoring* (pp. 41-57). Boston: Butterworths.

Thull, B., Popp, H.-J., Rau, G. (1993). Man-Machine Interaction in Critical Care Settings. *IEEE Engineering Medicine and Biology Magazine*, 42-49.

Westenskow, D. R. (1993). Alarms. In L. J. Saidman & N. T. Smith (Eds.), *Monitoring in Anesthesia* (pp. 475-490). Boston: Butterworth-Heinemann.

Xiao, Y. (1994). *Interacting with Complex Work Environments: A Field Study and a Planning Model*, Unpublished Ph.D. Dissertation, University of Toronto, Toronto.