

PATIENT MONITORING SYSTEMS FOR EFFECTIVE PATIENT MANAGEMENT IN THE ICU: FRIEND OR FOE?

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Technology design is arguably the biggest foe in the ICU. Several researchers have attempted to integrate ICU information to reduce the cognitive burden on clinicians. However the abstraction-decomposition (ADS) framework increasingly used for modelling the ICU work domain has been subject to question in this context. This paper proposes an alternative framework based on the Viable Systems Model and the Recognition Primed Decision model from naturalistic decision theory. By acknowledging the biological nature of patient systems, the limitations of sensed data, the role of effector technology and the importance of diagnoses in patient management, it is anticipated that technology will become more friend than foe in the ICU.

Patient monitoring (PM) technology of the single sensor, single indicator type commonly found in Intensive Care Units (ICU's) is a critical source of clinician overload and decision making error. While human factors and usability issues related to the representation of information are contributing factors, the underlying assumptions and models used to design this technology also contribute. Until these issues are addressed, PM technology will remain more foe than friend to nursing and medical staff working in ICU's.

This paper reassesses the three main elements comprising the ICU work domain, re-evaluates the essential characteristics of each and proposes an alternative framework for modelling the ICU as a work domain.

Most discussions of technological design for use in ICU's begins with a description of the ICU work domain. Figure 1, pulls together the elements that are discussed.

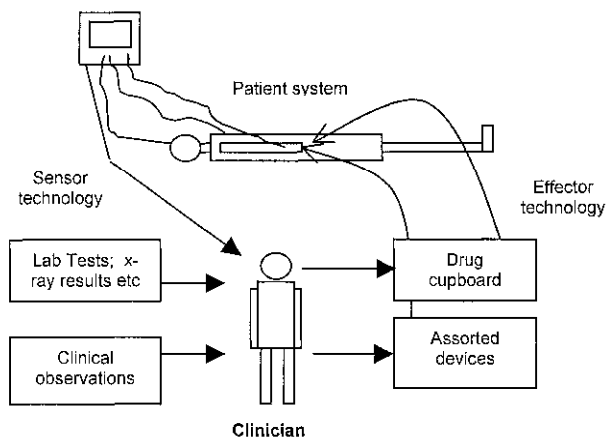


Figure 1. Typical representation of an ICU workdomain

The ICU work domain is typically represented as having three elements:

1. The patient is illustrated as the system to be controlled.
2. Sensor technology presents information to clinicians about internal patient states, while effector technology, is used by clinicians to effect changes in patient states.
3. Clinicians integrate diffuse sources of information using it to plan and implement appropriate intervention activities and therapeutic modalities.

The following sections discuss each of these elements in terms of modelling assumptions or challenges.

PATIENTS – THE SYSTEM UNDER CONTROL

Researchers such as Sharp, (1996) and Hadjukiewicz, (1998) have recognised the need to integrate patient information, thus reducing this burden on clinicians. Information displays developed by these researchers have focused on making visible the underlying structure and function of ICU patient systems. Structure and functions have been modelled using the Abstraction-Decomposition Space (ADS) formalism of Work Domain Analysis (WDA) within the Cognitive Work Analysis (CWA) approach (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999).

However, the ADS approach on which these displays are based may not be appropriate when applied to physiologically deranged ICU patients. This is not to say that the ADS approach is inappropriate to physiologically optimised (Roizen, 1994) patients admitted to Operating Rooms. The two patient groups are different and may therefore require different modelling approaches.

Miller and Sanderson (2000) have proposed Beer's (1981) cybernetic Viable Systems Model (VSM) as an alternative WDA formalism for modelling ICU patient systems. The VSM describes biologically entities as recursive systems. As is shown in Table 1, each recursive level is defined by its own anatomical structures, physiological processes and intrinsic control systems as represented by control system boundaries. The inclusion of control systems within the recursive model acknowledges the biological entities capacity for self-regulation and self-organisation.

Biological control systems serve to manage state variety according to Ashby's Law of Requisite Variety (Beer, 1981). Pathophysiology occurs when the variety at one level cannot be accommodated within that level or by higher order control systems. In relation to the CWA framework, the VSM serves the same function as a traditional WDA in that it describes the central part of the field upon which clinician interventions are made.

SENSORS AND EFFECTORS

Sensors

As illustrated in Figure 1, the patient system is only one component within the ICU work domain. Thus, the VSM does not describe the complete set of tools that ICU clinicians (nurses and doctors) have. A complete representation must include a mapping between the patient system and the cognitive and physical resources available.

Sensor technology encompasses all instrumentation used to provide access to internal patient physiological dynamics. Instrumentation includes devices such as electrocardiographs, devices for measuring blood pressure, radiological tests, laboratory tests and so on. Sensor technology is not usually viewed as part of the work domain itself, but is a means for acquiring information it.

Reising and Sanderson (1996; 2000) describe some practical limitations of sensory technology. These include:

1. Sensor unavailability. Many physiological functions and processes cannot be sensed because they are not well understood. Medical knowledge continues to evolve and still has much to uncover. In addition technological sensors that providing access to certain functions and processes may not yet exist.
2. Sensor unreliability. Unreliability may arise from the characteristics of the technology itself, for example, it becomes damaged, wears out or is not properly calibrated. Unreliability also arises because the patient system reacts with sensors as in the case of blood clot formation at the tip or in the inner lumens of cannulae.
3. Parameters are often derived from lower order sensed parameters, which may be suspect or prone to influences that become obscured. The following equation which describes oxygen consumption is a case in point:

$$VO_2 = (CO \times Hb \times 1.34)/10 \times (SaO_2 - SvO_2)$$

where: CO = Cardiac output is itself derived from other parameters

Hb = measured haemoglobin (mg/dl)

1.34 = the amount of oxygen (ml) carried by 1 gm of haemoglobin

SaO₂ = the % saturation of oxygen in arterial blood

SvO₂ = the % saturation of oxygen in venous blood

In addition a number of other limitations can be identified that are specific to the ICU. These include that:

1. Parameters may not always be measurable at intervals appropriate to their natural rate of change. Cardiac output measurement via the commonly used thermodilution method, for example, involves a somewhat convoluted and potentially hazardous procedure that is performed on a routine basis or per perceived need.
2. The majority of parameters measured in the ICU are level or state variables (Forrester, 1971). Rate variables—essential components within control feedback loops—are rarely calculated.
3. Technologically sensed information is not the only information available to clinicians. Information is also available via the clinician's own sensory apparatus. The effect of this was brought home in Sharp's (1996) study where physician subjects engaging with a simulated NICU scenario "wanted to see the infant and to make observations that were not provided" (p.160).

Thus the physiological information available to clinicians is not presently capable of representing the whole of patient system or even specific functional parts with great accuracy or completion. Available information merely transforms the 'black box' patient into a relatively 'muddy' one. Much about patient states remains hidden or suspect.

Despite technological limitations measured parameters are important, though single measurements are rarely of concern. Most important are patterns of movement in parameters over time, and parametric movement relative to other metrics eg heart rate with blood pressure with oxygen saturation. Although some sensor technology includes printing functions most of this information must be integrated on a paper based patient observation chart.

Effectors

Effector technology represents the arsenal of therapeutic technologies available to clinicians as they act on the patient system. This technology includes pharmaceutical agents (drugs) and devices such as mechanical ventilators, haemofiltration set ups, aortic balloon pumps etc.

Effector technology serves two main purposes. It provides a means for:

1. Delivering therapeutic support. For example a mechanical ventilator is used to support respiratory function when a patients own respiratory efforts do not meet physiological demand
2. Acting on the patient system in order to gain information about the state of the system.

Reporting results for monitoring in simulated NICU scenarios, Sharp (1996) noted that "many physicians wanted to take actions to correct the situation" (p.160). A clinician's ability to act on the patient system has therapeutic motivations, but is also akin to 'poking the black box' in order to see whether expected reactions occur or not.

Challenging the patient system using effector technology also provides information about the 'robustness' of physiological systems. For example, a patient with a closed head injury will typically have an intracranial pressure (ICP) sensor insitu to measure pressure within the cranial vault. Interventions such as tracheal suction stimulate coughing which raises ICP. The time taken for ICP to return to its pre-suction level is an indicator of the degree of cerebral swelling. This strategy is also employed when fluid is administered to assess circulatory dynamics or renal function and in procedures such as glucose tolerance testing.

Current PM systems do not adequately support clinicians in tracking the physiological effects of interventions. It is therefore difficult to determine whether phenomena such as parametric oscillations are the result of internal physiological processes or clinician intervention eg drug over followed by under dosing.

In summary, the knowability of patients' states is limited and the relationship between sensed data and effector intervention is complex and is not a one-to-one mapping.

However, despite the 'muddy box' nature of ICU patients and the uncertainty inherent in this, approximately 70% of patients admitted to ICUs are discharged. In some cases this percentage has been reported as being as high as 88% (Gopher et al, 1989). This is achieved in the context of ICU admission of patients who would otherwise die if left in a regular hospital unit.

CLINICIANS – INTEGRATORS OF MUDDY BOX INFORMATION

Despite inevitable capacity limitations, clinicians integrate large volumes of changing information. The integrative framework is the patient diagnosis A diagnosis is a constellation of observed clinical manifestations that

medical consensus agrees represents a unique pattern of pathophysiological dynamics.

Diagnoses are presented in pathophysiological textbooks as formal generalisations that represent the body of current medical research knowledge, informed speculation and experience.

A diagnosis typically includes descriptions about the following.

- The contexts that trigger deranged patient states. These contexts are represented as a typical patient history eg of smoking; trauma; infection; family history of... etc.
- The anatomical elements involved in and at various stages of a pathophysiology trajectory. A disease state is rarely isolated to specific anatomical structures but tends to affect many structures over its course.
- The physiological logic (the 'whys') underlying processes that comprise a pathophysiological trajectory. Processes that exceed their control boundaries tend to trigger other pathophysiological processes in an escalatory manner.
- Control processes as descriptions of physiological state aberrations.

Thus diagnoses describe dynamic pathophysiological trajectories. They are not static, context independent states.

In day to day clinical practice a diagnosis is also a high-level working hypothesis which is progressively elaborated upon, confirmed, refuted or modified on the basis of observed physiological change. Differential diagnoses are successively ruled out until a definitive diagnosis is made.

A diagnosis is a conceptual tool—a template that focuses a clinician's expectations about what is likely to happen, where within the patient system, and over what time scales (minutes, hours, days, weeks...).

The ability to make an accurate diagnosis depends first on clinicians learning formalised general patterns of pathophysiological trajectory. From this basis, day to day diagnostic decision making is one of recognising patterns of physiological behaviour and matching these to diagnostic templates.

Expectations, goals, cues and actions are key elements within Klein's (1998) Recognition Primed Decision (RPD) model. The central power of a diagnosis is its ability to cue refutable expectations. Expectations enable the development of short, medium and longer term patient management goals. Goal achievement is monitored by the use of sensory data cues. Sensed data patterns, goals and expectations within a diagnostic framework, inform intervention actions given the therapeutic resources available. The anticipated outcomes from intervention are then compared against the initial expectation which may be reconsidered.

Klein's (1998) basic RPD model is shown in Figure 2. The present paper argues that diagnostic trajectories described in pathophysiological text books represent the formalised experience of the medical-nursing profession. Diagnoses cue expectancies, from which plausible goals are developed and tested against relevant cues which suggest typical actions. Practice refines these skills.

Klein (1998) does not claim that the RPD model leads to faultless decision making even among experts and cites several factors that 'get in the way' of decision making accuracy eg:

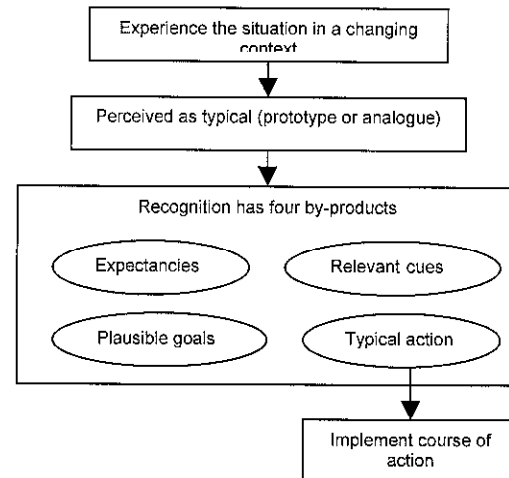


Figure 2. Klein's (1998) Recognition Primed Decision model

1. Stressors such as time pressure, which limit ability to gather information, disrupt ability to sort and prioritise and which distract from the task at hand.
2. Uncertainty as a consequence of missing information, unreliable information, ambiguous or conflicting information, excessively complex information.

The single sensor, single indicator technology commonly found in ICU's exacerbates these problems because it requires active information gathering and integration. Sensed data is not linked in any conceptual way to the patient system or its pathophysiology. Thus technology is arguably the central foe in the ICU context.

Improving the design of patient monitoring technology requires a modelling framework that:

- Highlights missing information thus making these gaps visible.
- Maps sensed data to the level of physiological recursion to which it pertains, so that technological designers and clinicians know what the data is telling them in relation to patient system processes and functions.
- Facilitates the display of sensed information in ways that make underlying patterns (up, down and oscillatory trends) and parameter associations visible.
- Allows clinicians to explicitly link diagnostically based expectations and therapeutic action outcomes with sensed data that would confirm/refute or support the effectiveness of these.

THE PROPOSED VSM/RPD MODEL AND ITS IMPLICATIONS

Table 1 is an attempt to integrate the VSM with the RPD models to create a space that describes the relationships between patient pathophysiology, available technology and conceptual resources.

The columns in Table 1, represent the levels of recursion in the VSM. Each level includes the anatomical structures, physiological processes and control boundaries (normal values; normal ranges; non-lethal and lethal ranges where these are known) relevant to each level of recursion.

In the ICU context recursive levels are arranged from lowest to highest level to reflect the nature of

pathophysiology that propagates up through levels of recursions as higher order control systems become overwhelmed by variety generated from within lower levels.

The RPD model is reflected in the rows below the VSM. The 'diagnosis' and associated expectations describe anticipated pathophysiological progression in terms of the anatomical structures and physiological processes affected over time. As stated, much of the data sensed by technology reflects level variables within control feedback loops. Thus sensed parameters can be mapped against the control boundaries at associated levels of recursion. When represented in a user interface the difference between control boundaries and sensed data provides information about the magnitude of derangement within recursions. The state of control parameters at higher levels of recursions provides information about the extent to which these systems are managing lower level variety.

An ADS based WDA makes visible the constraints afforded by the structure, function and resources available within a work domain. The VSM/RPD model is a substitute for the ADS when the assumptions underpinning ADS do not apply (Miller & Sanderson, 2000). The VSM/RPD model does however achieve the same end. By appropriately mapping technologically sensed data to the recursive levels to which these pertain gaps are made visible. Effector technology mapped to the recursive levels to which these pertain makes the opportunities for intervention visible.

The inclusion of diagnostically based expectations make visible means-ends relations across the patient system (the "Why-What-How arrows), for example "I have this expectation (what), derived from a diagnostic template

(why), which I will confirm by setting this goal (how)"; "I will monitor this data (what), because I have set this goal (why), which I may achieve using this effector (how).

The VSM/RPD involves diagnoses as the integrative framework for understanding the 'black box' patient. This means that the design of technology is not driven a priori by the patient system but is also driven by the cognitive and perceptual activities undertaken by clinicians. The VSM/RPD therefore incorporates the next phase in CWA, that of Cognitive Task Analysis, (Rasmussen et al, 1994; Vicente, 1999). The over-riding purpose of clinician intervention in the ICU is to prevent the escalation of pathophysiological dynamics while also promoting a return of the patient system back towards its homeostatic state. The kinds of strategies that might be employed include to:

1. Remove a pathophysiological trigger eg via antibiotics.
2. Hold the trajectory to its current level of recursion eg via the administration of vasopressors (eg adrenaline).
3. Support physiological dynamics at higher levels of recursion eg initiate mechanical ventilation to support respiration even though it has not yet failed.

Successful intervention is dependent on the clinician being able to see where a pathophysiological trajectory is within the recursive structure, and the state of control system variety both across and within the recursive structure.

A user interface that supports these strategies by making visible the underlying structure of deranged patients and resources available for intervention will be a most decided friend in the complex decision environment that is the ICU.

Table 1. The proposed VSM/RPD Model

	VSM				
	Recursion 5 (Lowest level)	Recursion 4	Pathophysiological trajectory Recursion 3	Recursion 2	Recursion 1 (Highest level)
Anatomical structures	...	...	...	...	...
Physiological processes	...	...	...	...	...
Control boundaries	...	...	...	...	...
Diagnosis (Why)					
Expectations		What			
Goals	Why		How	Why	
Cues (sensed data)	What				What
Actions (effectors)	How				How

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