

Infusing Healthcare with Resilience

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Abstract. Resilience engineering strives to build the adaptive capacity of systems that is essential to continue operations in the face of substantial challenges. The healthcare enterprise provides a compelling opportunity to consider *resilience* as a desirable trait of systems. Clinicians, from physicians to nurses and technicians, are a source of resilience and develop and rely on artifacts from status boards to information systems and equipment to perform cognitive work. While information technology (IT) systems have been promoted as a means to improve patient safety, current information systems and equipment systems are brittle and erode resilience instead of contributing to it. Based on a five-year study funded by the Agency for Healthcare Research and Quality, we present a concept for an infusion device interface that would contribute to resilience.

Resilience and its engineering

The ability of any system to adapt to a changing environment relies on a deep understanding of the system, what it does, and what it cannot do. Systems that are poorly configured for change are said to be *brittle* (Sarter, Woods and Billings, 1997). By contrast, systems that are designed to be adaptable and to withstand challenges and return to normal with minimal decrement in performance are said to be *resilient* (Hollnagel, Woods, and Leveson, 2006). Resilience can be seen in action because it is made visible by the way safety and risk information are used.

Resilience is more than a simple set of resources because it involves adaptation to varying demands and threats that are brought on by the continuing negotiation among competing economic and workload pressures (Nemeth, 2009). As Figure 1 shows, these can pressure an organization's operating point (represented by the encircled dot). Depending on the circumstances, the operating point can be caused to shift toward the boundary of acceptable performance (Cook and Rasmussen, 2005) and prospective failure.

Resilience is an active process that implicitly draws on how an organization or society can organize itself and promises to replace traditional notions of risk assessment by shifting attention to a *prospective* view that anticipates future events that may challenge system performance. The ability to foresee and adapt to changing conditions increases the system's ability to survive despite

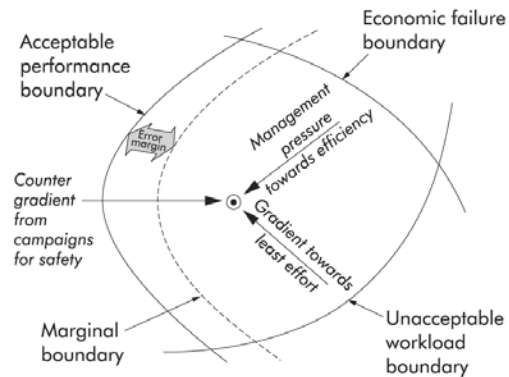


Figure 1. Influences on a system's operating point (Cook and Rasmussen, 2005)

variations in its environment. Adaptation and restructuring make it possible for an organization to meet varying, even unusual, demands.

Resilience engineering (RE) focuses on the ability of an organization to cope with, and recover from, unexpected developments. Rather than a focus on a system's productive capacity, RE can be used to assess and enhance the ability of an organization to adapt in order to meet challenges. With roots in complexity study (Carlson and Doyle, 2002) and cognitive systems engineering (Hollnagel and Woods, 2005), RE seeks to create and maintain systems that can cope with and adapt to complex, dynamic, and changing environments. RE acknowledges the inability to specify all possible threats to a system and system responses. Instead, it provides methods and tools to manage safety and productivity.

This paper addresses issues related to healthcare information and communications technology (ICT) at the system level. It also shows how the most widely-used IT-controlled device, the infusion pump, can be developed to support operators who must cope with a complex, fluid, uncertain work domain.

Healthcare context

Health care patients require coordinated, uninterrupted care that is provided by multiple distributed care providers, as well as the coordination and integration of many functions and specialized areas of knowledge over time. However, the "cottage industry structure...of the national healthcare delivery system" results in "disconnected silos of function and specialization" (Reid, *et al*, 2005:12-13). As a result, connectivity, integrated care, and coordination are inadequate nationwide at all stages of illness treatment and expose patients to the risk of harm. An estimated 60 million patients in the U.S. suffer from two or more chronic conditions and are particularly affected by the disconnection among clinical care specialties. Transitions into, through, and out of departments and clinics create opportunities for *gaps* in the continuity of care (Cook, Render, and Woods, 2000). In each transition, information is both required and generated. Information that may not be available, may be inaccurate or outdated, or misinterpreted can pose a risk of harm to the patient from insufficient preparation, diagnosis, treatment, and follow-up. The separation and specialization of functions in care facilities allows for gaps in care continuity to occur.

Failures in care continuity, the inability of care settings to handle surges in care demand, failure to keep track of patients, and equipment that disorients and induces error are all evidence of brittle healthcare systems. Health care systems that are designed to adapt to care demand are more likely to be resilient. As a goal-directed organization of resources (Rouse, 2004:139), the healthcare enterprise can be expected to operate with some degree of cohesion. That is, care services that are needed would be provided to those who need it by those who offer it. This would allow the interaction of various organizations to pursue a common goal: the improvement of health.

As in other high hazard settings, expertise (Feltovitch, Ford, and Hoffman, 1997) in healthcare is the ability to know what is—and what is not— important. Healthcare activities rely on the acquisition, portrayal and analysis of therapeutic and diagnostic information as an integral part of individual patient care. The daily work of the clinician requires representations that serve as a map of the ever-changing territory of work that must be successfully navigated (Rasmussen and Pejtersen, 1995:132). What information is represented, and how it is represented, depends on the individual and group cognitive work that it is intended to support. Individual elements of information vary enormously in the length of time that they remain reliable, and their weight depends a great deal on their context. The need for accurate, timely information also exists at the unit level, such as the operating room (OR), intensive care unit (ICU) and emergency department (ED), where the technical work of unit planning and management directs who will get care, what type of care will be provided, and when it will be provided.

IT Support for clinical cognitive work

Complex systems, including information systems, have been developed as a means to improve efficiency and reliability across a spectrum of commercial and institutional applications. Worldwide annual purchases of software and services by organizations and governments have reached an estimated \$1 trillion. (Charette, 2006: 43) Even at this significant size, evidence shows that efforts to respond to real world requirements are problematic across many sectors.

Medical informatics is the application of information technology to healthcare, which includes components that range from device control/display interfaces, decision support systems, artificial intelligence, electronic medical records, information retrieval, outcomes assessment, and telemedicine. Information technology has been employed to improve efficiency and reliability for healthcare's blunt (management) end. More recently, it has been touted as a means to improve patient safety at its sharp (operator) end. Initial indications for the success of this notion are sobering. For example, the UK's National Health Service effort to create a national electronic medical record is over four years late, with projected costs are around \$23.5 billion that are well beyond the original \$4.3 billion estimate, and is nowhere near ready (Charrette, 2006).

Figure 2 represents the current state of IT support for clinical healthcare cognition. Care providers exist in an information ecology that includes the patient, other clinicians, devices, information systems, and physical artifacts. In this work setting, care providers attend to individual patients using their own observation, consultant views, and patient self-reports. They direct and monitor therapeutic and diagnostic equipment (shown in the lower portion of Figure 2). Such devices have recently been connected to communication networks to “push” significant information to clinicians and related systems. They consult and often develop cognitive artifacts such as paper charts, orders, and status boards (Nemeth, *et al.* 2006). They request and synthesize data from a

variety of information systems and departments (shown in the upper portion of Figure 2). All this happens in the context of caring for multiple patients who each have unique needs and care trajectories that must be planned and coordinated.

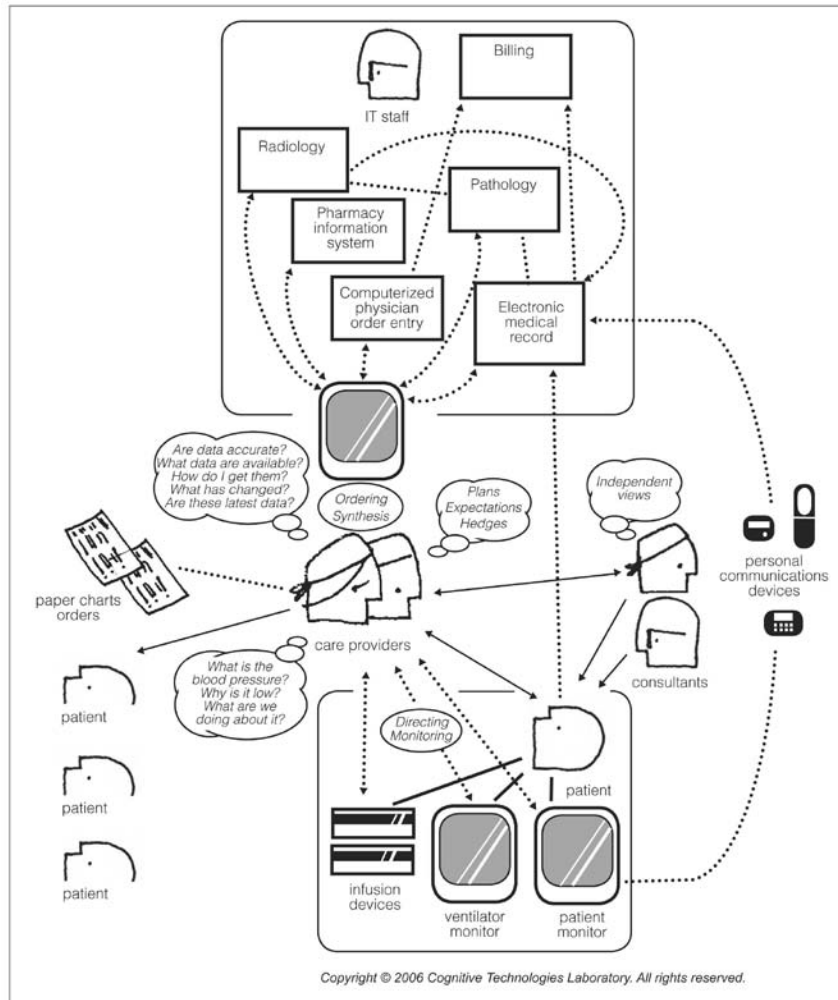


Figure 2. An Acute Care Information Ecology
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Three elements in this ecology serve as an example of the current state of support for care provider cognition: medical records, decision aids, and medical devices.

Medical records. Electronic versions of *medical records* (EMR) attempt to make the large amount of information that they contain useable. Despite these efforts, clinicians find the EMR is a poor match for the kinds of cognitive work that they must perform. This mismatch arises from increasing reliance on the medical record to support billing for clinical activity, configuration of records to assist billing and not clinical purposes, difficulty in locating critical information among the vast amount of information that the record contains, and the inability to use the record for important clinical activities such as the comparison of data. Now that it no longer serves a clinical role, clinicians have resorted to performing additional work to create their own informal solution:

the sign out sheet (Wears and Perry, 2006). Each shift, clinicians list each of the patients on a unit along with critical items of information that are related to their condition and care.

Decision aids. Clinical *decision aids* (shown in the upper portion of Figure 1) have sought to help physicians synthesize complex considerations into rule-based guidance on patient care decisions. Berg (1997) describes how such computer-based approaches to support clinician cognitive work have attempted to create rule-based aids for patient medical care decisions. Decision support systems need to be constantly monitored to determine whether their suggestions fit a particular case. Also, the number of branching points may become so great to accommodate exceptions that the system is impossible to use and maintain (Ash, Berg, and Coiera (2004:108). The failure of this approach demonstrates that decision making under clinical conditions is far more complex and less tractable than proponents of these early systems believed. Clinical decision support systems' effect on practitioner performance and patient health remain as inconsistent as they were 15 years ago. (Garg, Adhikari, McDonald, Rosas-Arellano, *et. al.*, 2005). Relatively few clinical decision support systems (CDSS) are in use after their introduction over 25 years ago (Kaplan, 2001).

Medical devices. Equipment such as infusion pumps increasingly feature complex control and display interfaces. Even highly experienced clinicians who have used infusion devices for years get “lost in menospace” when they perform even the simplest tasks (Nunnally, *et.al.* 2004). Collections of such complex devices occur in acute care, particularly the intensive care unit (ICU).

Obstacles to healthcare IT resilience

Clumsy automation. Medical information systems, electronic medical records, decision aids, and devices all suffer from being what Weiner (1989) termed *clumsy automation*. Systems that are clumsy, or poorly designed for human use, do not aid but rather impede cognitive work. They add new communication and coordination tasks to an already burdensome workload. Practitioners must develop coping skills including “work-around” procedures in order to adapt to the software system shortcomings. The systems are hard to operate, which induces errors. The net effect is to erode clinical effectiveness and patient care quality. The failure of clinical IT flows in part from developers' “disregard for the ways in which people organize their work coupled with a disdain for the ordinary resources on which they rely....” (Heath and Luff, 2000:3-4) It also results in part from healthcare's persistent underinvestment in technologies such as IT, as well as the failure to take advantage of engineering-based systems design, analysis, and management tools such as human factors research. (Reid, *et.al.*, 2005:15, 31, 63).

No user research agenda. Success in understanding ambulatory healthcare safety at the system level starts with actual patient and information flow. This is *work as done*. Failure to understand what Rouse (1998) terms “the current situation” undermines efforts to understand enterprise opportunities, threats, and crises. Those who do not understand *work as done* must rely on presumptions about what operators do. This is *work as imagined*. Healthcare systems that are based on *work as imagined* allow gaps in continuity, resulting in inadequate patient care.

Underinvestment. Information and its exchange are crucial at the patient, unit, organization, and environment level. Yet cost and political pressures force developers to minimize the time and effort that is expended to produce systems for clinical use. Complex systems exceed the ability of their creators to understand them and are installed and operated without benefit of testing. Without

testing or risk management, developers have no way to know what may go wrong or why. (Charette, 2006: 46-48) The device and system shortcomings that result create multiple problems for healthcare. Hospitals resist system adoption due to cost-benefit mismatch, rapid obsolescence, and time the systems divert from caring for patients. (Freundheim, 2004) Systems that are intended to improve on healthcare performance and patient safety are now perceived to create new forms of unintended adverse outcomes. (Koppell, Metlay, Cohen, *et. al.*, 2005) Heeks, Mundy and Salazar (1999:2) contend that “many—even most—health care information systems are failures.” The estimated costs of information systems alone for each large hospital are about \$50 million, yet the overall benefits and costs of hospital information systems have rarely been assessed. When systems *are* evaluated, about three quarters are considered to have failed and provide no evidence they improve the productivity of health professionals. (Littlejohns, Wyatt, and Garvican, 2003)

IT misperceptions. Recent developments have made ever greater amounts of data related to patients available to clinicians. Data availability, however, does not equal data utility. In order to be useful, data must be easy to manage so that it supports clinical cognitive work. This simple statement belies the depth and complexity it involves. Misperceptions about user-device interaction have substantial consequences for clinical work. Infusion devices and computerized physician order entry (CPOE) systems provide an example. Husch, *et.al.* (2005) contend that dose-related error reduction relies on interfacing infusion devices with other systems that deal with the use of medications such as the electronic medical record, computerized physician order entry, bar code medication administration and pharmacy information system. Such systems may be beneficial, but they can also suffer from difficulties such as being unable to handle marginal conditions that are a regular part of patient care. For example, CPOE relies on a centralized computer system to track and manage the provision of medication. CPOE is intended to create a continuous connection from physician, to pharmacist, to nurse. The approach is intended to reduce causes of medication error by improving the reliability and accuracy of health care system performance. While information systems can improve on some difficulties, they can also introduce others. Indeed, Koppel, *et.al.* (2005) report that clinicians at one major acute care facility perceive their CPOE system to have problems related to data entry, and lack confidence in this clinical system’s reliability. Recent studies implicate CPOE systems as a cause of adverse drug events (Nebecker, *et al*, 2005), pediatric mortality (Han, *et. al*, 2005), and erroneous test ordering (Rosenbloom, *et. al.*, 2005)

The trend toward reliance on complex devices and systems at healthcare’s sharp end can be expected to increase. For example, Breslow, *et. al.* (2004) suggest that the use of remote monitoring by intensivists, also referred to as *telemedicine*, can improve clinical and economic outcomes at hospitals. The intention for such systems is to link one intensivist to multiple remote ICUs by computer-supported data links. The control center-style workstations that intensivists use to interact with remote locations can be expected to force greater reliance on displays for the purpose of intra- and inter-group collaboration. A different approach to the development of IT support for clinician cognitive work would start to contribute to healthcare system resilience at the sharp end.

Designing From User to System

The creation of better equipment and information systems makes it easier for workers to anticipate future opportunities and problems ahead of time. Indeed, Butler and Gray (2006) have suggested

IT as a means to improve mindfulness in the face of complex technologies and surprising environments. How can IT systems be created so that they adapt to the fluid, variable clinical healthcare work setting?

In the context of research, design and development, the role of design has the responsibility to link the adaptive power of people as goal-directed agents to technological capability (Alexander, 1977). People actively manage the dynamic characteristics of their work place by drawing on a deep knowledge of their work domain to create and use artifacts (Blumer, 1986). Workers create cognitive artifacts (Hutchins, 2002) in physical (order forms, checklists, schedules) and digital (equipment control and display interfaces, information) form to aid their cognitive work. Prior work has shown how these artifacts can be used to understand (Xiao, *et al.* 2001) and derive design guidance for IT systems to support such work settings, because the artifacts embody only the essential elements of a work domain. This makes it possible to pursue a design approach from the user to the system. How can IT systems be configured in order to support such an approach? Klein, *et.al.* (2004) propose traits that IT systems need in order to participate in a highly adaptive human work domain such as clinical healthcare :

- 1) Fulfill the requirements of a Basic Compact to engage in “common grounding” activities—an agreement to facilitate coordination, to work toward shared goals, and to prevent team coordination breakdowns
- 2) Able to adequately model other participants’ actions *vis-à-vis* the joint activity’s state and evolution—Able to coherently manage mutual responsibilities and commitments to facilitate recovery from unanticipated problems
- 3) Be mutually predictable—The mental act of seeing ahead, with the frequent practical implication of preparing for what will happen.
- 4) Be directable—Able to deliberately assess and modify others’ actions as conditions and priorities change.
- 5) Able to make pertinent aspects of their status and intentions obvious to their teammates —Make targets, states, capacities, intentions, changes, and upcoming actions obvious
- 6) Able to observe and interpret signals of status and intentions—Able to signal and form models of teammates.
- 7) Able to engage in negotiation
- 8) Enable a collaborative approach
- 9) Able to participate in managing attention
- 10) Help to control the costs of coordinated activity

The ability to be resilient relies on a deep understanding of the work domain; acute and ambulatory care, in this instance. Human factors (Nemeth, 2004) and cognitive systems engineering methods (Woods and Roth, 1998) make such understanding possible and are integral to resilience engineering. Methods including observation, interviews, work domain analysis, and cognitive task analysis can be used to reveal essential features (semantics) of work domains, and how operators engage and overcome obstacles. Each of these methods link functional meaning and material purposes to physical processes and material form through system abstraction-decomposition (Rasmussen and Pejtersen, 1995) in the same way that “what to how mapping” (Carlock and Fenton, 2001) builds a strong link between requirements and design parameters.

Complex medical devices have not been obstacles to effective healthcare. The real obstacle has been to understand the complex operations of health care systems in which sophisticated medical devices exist. This suggests the use of complex healthcare devices and systems should be to represent the relevant aspects of work domains as the problem space in which practitioners work. The means to discover relevant aspects, or domain semantics, is available in the social sciences and engineering; specifically cognitive psychology, sociology, and human factors. The study of real world work requires methods that are able to understand it. Human factors study examines how experts develop and use cognitive artifacts as a way to deal with real world problems. This yields insight into what truly aids expertise. Understanding clinical decision making will open the door to know how to best convey information to clinicians, and how clinicians will be able to make better decisions. For example, improvements to cognitive aiding can make critical information such as pharmacological and blood-related data available when and where it is needed in a format that is best suited to clinical use. This can only come about through the work of well-qualified researchers in cognition. Our studies using cognitive systems engineering (see, for example, Nemeth, Kowalsky, Brandwijk *et al.* 2008 ; Nemeth, Nunnally, O'Connor, *et al.* 2005 ; Nemeth, O'Connor, Klock, *et al.* 2006), have revealed how clinician initiatives to fill care continuity gaps. We have also demonstrated how a well-founded understanding of clinical cognitive work can be used to guide IT system development. Both make it possible for health care organizations to adapt or reorganize in response to demand; to be *resilient*.

An Example of Building Resilience

Most infusions in U.S. hospitals are now provided by infusion pumps , making this device the most widely used IT-controlled equipment in the acute care environment (Hunt-Smith, *et al.* 1999). As Figure 3 indicates, these are opaque systems that offer poor feedback and low observability, and

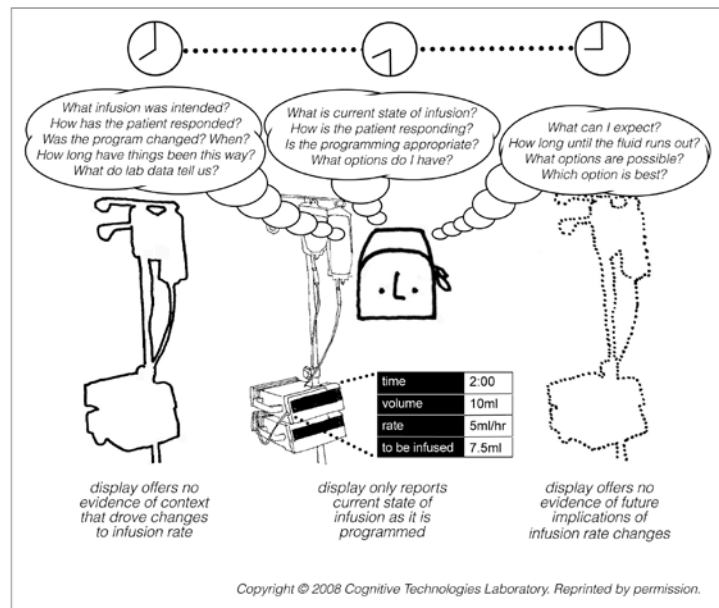


Figure 3. Clinician and pump information mismatch
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undermine resilience and increase brittleness. Pumps just provide current state descriptions. Clinicians, the physicians, nurses and technicians who operate the pumps cannot know what happened, or what will happen even though all three are crucial to patient care.

This display concept shown here is based on findings from a five-year study funded by the Agency for Healthcare Research and Quality (Nemeth 2004). The concept demonstrates how an infusion pump interface can provide information about device display and control through time, showing operating history, current state, and implications for the future. Including context information makes it possible to interpret device behavior in terms of its clinical use.

In this theoretical (yet typical) example, Figure 4 shows the system state for a pediatric patient who is receiving an infusion of dextrose that was started at 08:07 and is programmed to be completed at 10:07. At the current state (09:10), the infusion is about halfway completed. The infusion is paused for a procedure, resumed, and reprogrammed to make up the difference.

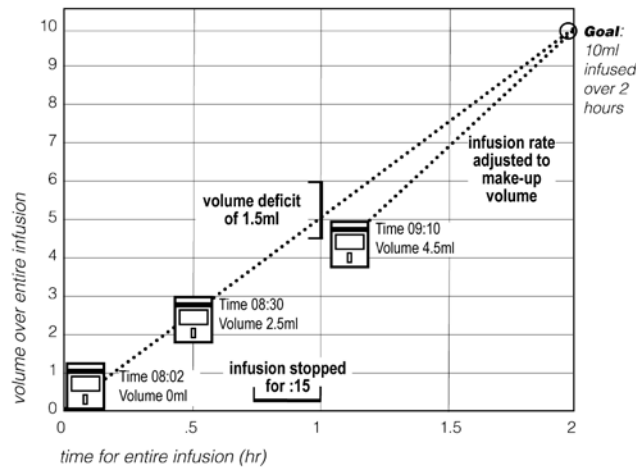


Figure 4. Pediatric dextrose infusion volume infused over time
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The display in Figure 5 shows volume/time (rate) parameters, current and recent system status, and the expected course of the infusion if current program settings are maintained. The device controls remain fixed in the display center, while the data scroll from right to left as time passes. A “thumb wheel” control at lower center would make it possible for a clinician to control the rate of infusion. Moving the control up or down would adjust the rate to various settings. Values for each variable would change to show the implications of a rate change. After evaluating the various options and their implications, the clinician could select and enact a new rate. Only then would the rate change.

The graphic representation makes it possible for clinicians to use pattern recognition to determine how infusions are programmed and progressing. Alphanumeric characters provide values for discrete variables that are necessary for accuracy.

As a predictive display, a clinician can recognize dose-limit errors that plague current infusion displays that are programmed using only numbers. Additional information (indicated by “i” symbols) can be displayed that coincides with the treatment timeline. For example, the “i” at the

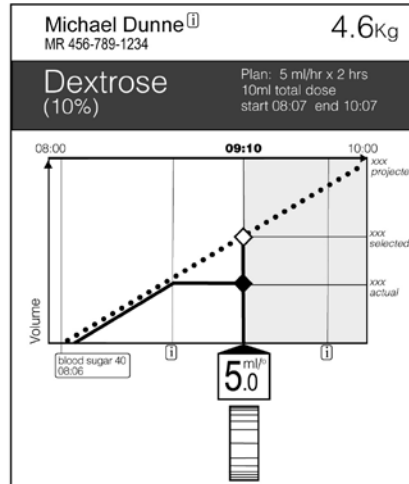


Figure 5. Infusion interface concept to improve resilience
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lower left indicates blood glucose test results that were reported at 08:06. This overlay of therapeutic activity with results makes it possible for the clinician to make more informed decisions about patient care. The interface concept reflects many of the 10 traits identified by Klein, *et al.*, (2004) for IT to serve as a team player, making it better suited to work jointly with clinicians. Making clinical and programming information explicit makes team coordination easier and prevents coordination breakdowns. Figure 6 shows how the display would change through time as it displays past, current and anticipated states. In this case, the display is shown at 0830, 0900, and 0910.

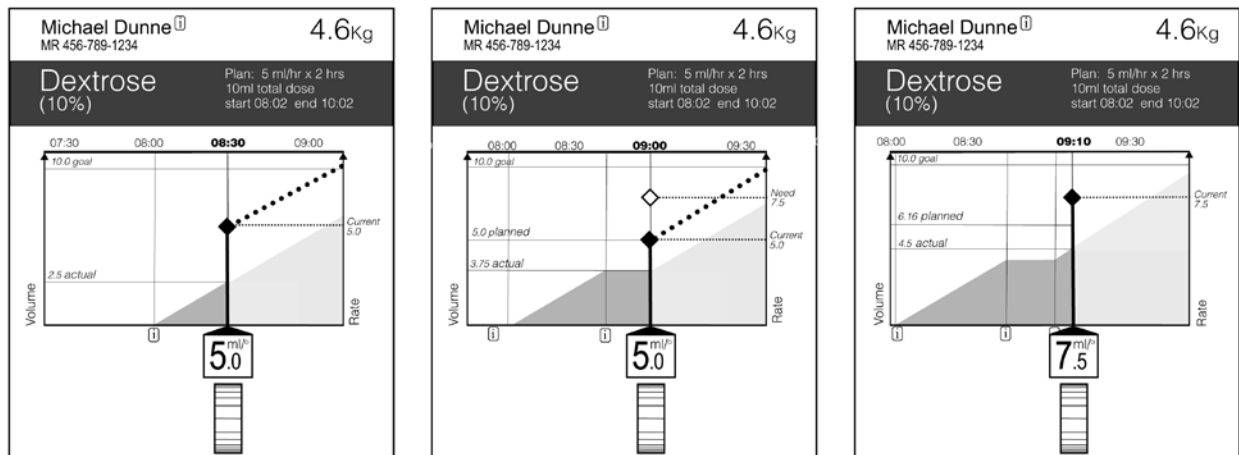


Figure 6. "Infusion" state at 0830, 0900, and 0910
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Providing past, current, and anticipated states and making connections with related data, such as lab results, makes it easier to recover from unanticipated problems. Showing projected values helps clinicians see ahead and prepare for what will happen. Controls make it possible to explore contingencies before committing to a final decision. This enables the clinician to evaluate multiple options and make decisions. Integrating controls with displayed information makes it possible to

deliberately assess and modify programmed infusion actions as conditions and priorities change. The combination of graphic and alphanumeric information makes pertinent aspects of the device target, status, capacities, programming intentions, and upcoming actions obvious to members of the clinical team. These are the kinds of observable and controllable traits that would improve IT support for health care, and help to build system resilience.

Conclusion

Current research on resilience seeks to clarify how resilience works, where it comes from, and what factors facilitate or impede it. These and other active steps can improve the ability of healthcare systems to respond adequately to increasing demands and avoid an accumulation of discrete well-intentioned adjustments that can detract from organizational efficiency and reliability. This makes the difference between organizations that inadvertently create complexity and miss signals that risks are increasing, and those that can successfully manage high hazard processes.

Durable improvements to reliability, efficiency and safety can only come through sustained, deep looks into the actual work that operators perform. Human factors methods enable those who perform research in any application to discover essential features (semantics) of work domains, and to gain insight into operator behaviors as they negotiate those features. Results from such research can contribute to improved resilience in enterprises beyond healthcare. This includes the development of criteria to quantify risks in the work domain, and tools such as information and communication technology (ICT) to support operator cognitive work.

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