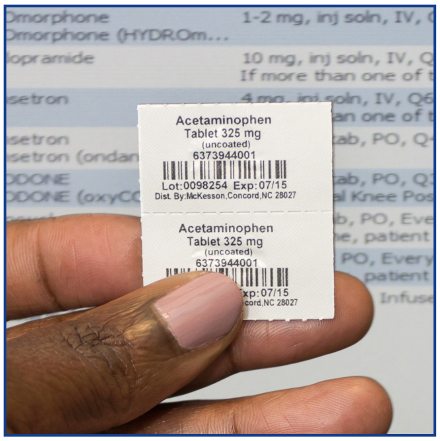
The Joint Commission
Journal on Quality and Patient Safety®

Improvement from Front Office to Front Line

August 2014
Volume 40 Number 8



"Jidoka allowed us to optimize the use of the BCMA technology, while maintaining the preferred human work flow, leading to decreases in both the number of safe practice violations and medication administration errors."

—Using Lean "Automation with a Human Touch" to Improve Medication Safety: A Step Closer to the "Perfect Dose" (p. 347)

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Conference Report

Resilience and Resilience Engineering in Health Care

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A system is *resilient* if it can adjust its functioning before, during, or following events (changes, disturbances, or opportunities) and thereby sustain required operations under both expected and unexpected conditions. Resilience is found in complex adaptive systems such as health care, which have specific features that encourage and require resilience. The study of health care resilience has the potential to expand the understanding and application of resilience concepts in health care and other safety-critical domains. Resilience makes a large but largely hidden contribution to patient safety. This article is a summary of the workshop *Ideas to Innovation: Stimulating Collaborations in the Application of Resilience Engineering to Healthcare,* held June 13–14, 2013, at the Keck Center of the National Academies in Washington, DC, sponsored by the University-Industry Demonstration Project of the National Academies and by the MedStar Health Research Institute. The meeting consisted of presentations from resilience experts and reactions from acute care safety practitioners. The goal of the workshop was to search for possible applications of resilience to health care, and to stimulate collaborations between academia, government, and industry stakeholders to pursue the application of resilience engineering in health care.*

The purpose of this article is to provide an overview of resilience and resilience engineering and to stimulate innovations in safety that might be produced by viewing health care safety through the lens of resilience engineering. Given the state of this emerging field, more robust tools in the application of resilience engineering to health care are needed.

What Is Resilience?

Resilience has been conceived as a feature of some systems that allows them to respond to an unanticipated disturbance that can lead to failure and then to resume normal operations quickly and with a minimum decrement in their performance.[1]

Resilience is important for those systems buffeted by combinations of usual and unusual demands; environmental disruptions; variations in staffing or other resources; information losses or corruptions; diffuse, varying, or conflicted goals; and, critically, incessant change. It is the resilience of these systems that gives them the ability to produce success despite conditions that could easily lead to failure—and that allows them to recover quickly and safely after failure. Current understanding of resilience is based on empirical observations of work domains. An example of resilience in action is shown in Sidebar 1 (page 377). In addition to emergency departments (EDs), studies have found resilience in operating rooms (ORs), ICUs, clinics and home care settings, air traffic control rooms, computer network operations centers, and military mission environments. Some resilience demonstrations from other domains are shown in Table 1 (page 377). Although different in many respects, these domains all involve high stakes and substantial risk—while workloads and operational tempos widely vary. The domains use complicated technology but also rely heavily on human experts for direction and control. Their operations are costly, resulting in constant economic pressure. Human work requires coping with complexity and uncertainty. Finally, these work domains exhibit continuous technical and organizational change.

Resilience is not simply success in the face of threat of failure. Although resilient systems can and do fail, they demonstrate a repertoire of behaviors, including qualitative shifts in performance in response to varying demands; purposeful, meaningful responses reflected by goal trade-offs; and a tenacity of efforts to respond effectively even when confronted by escalating demands or existential threats. Resilient systems dynamically forestall failure, mitigate failure in process, or redirect the failure pathway to make recovery easier, less disruptive, or less costly. For example, during the Fukushima Daichi nuclear disaster in March 2011, operators used the batteries from vehicles around the site to provide temporary power for control room instruments. They chose to organize work so that older operators were exposed to higher levels of radiation than their younger colleagues.[2]

* The National Academies Meeting Summary, "Stimulating Collaborations in the Application of Resilience Engineering to Healthcare," and the presentation videos from the workshop are available at http://www.ResilienceEngineeringHealthcare.com.

Sidebar 1. Resilient Response to Failed Drug-Dispensing Automation*

During a busy shift in the emergency department (ED), the automated dispensing units stopped working. The units displayed an unexpected error message ("printer not working" on a device without a printer) and were unresponsive to either keyboard or touchscreen entries. A severely bronchospastic patient needed immediate inhaler therapy. The nurses found an unused inhaler in a collection of medications intended for return to stock in the automated dispenser and used that in lieu of one formally dispensed for the patient. The pharmacy was contacted about the inoperative dispensing units. A pharmacist came to the ED and was unable to restore either unit to service. Working with the ED physician-in-charge, the nurses and pharmacists established a "runner" method of obtaining medications directly from the pharmacy. Physicians would write the names and doses of medications needed for patients on paper. Papers were gathered and taken to the pharmacy, where the medications were pulled manually from shelves and put into a bag. The bag was carried by the runner back to the ED, where the medications were distributed to nurses caring for the patients. A relay of two runners was employed in this way in the more than 45 minutes it took for the automated dispensing unit outage to resolve.

Resilience was expressed in the rapid assessment of the situation by the clinicians; the purposeful, focused intervention to obtain the critically important medication directly from an unusual source; and the anticipation of prolonged automation downtime that prompted the staff to establish an alternative for getting medications to the ED.

Ironically, although resuscitation drugs were immediately available from local "crash" carts, the medication needed to forestall the index patient's deterioration could be found only in the automated dispensing unit. With the automation broken down, the staff had the ability to treat a cardiac arrest but not the ability to prevent it.

The automated dispensing system was acquired mainly for inventory control and management of controlled substances. This system failure was eventually traced back to a subtle interaction between the provider order-entry function and a safety feature of the dispensing system in the context of a software upgrade. A similar failure occurred a few months later.

*Adapted from Perry SJ, Wears RL. Underground adaptations: Case studies from health care. *Cognition, Technology & Work.* 2012;14(3):253–260.

Table 1. List of Resilience-Demonstrating Events

1. Apollo XIII recovery after onboard explosion, 1970
2. US Marines retreat from Chosin reservoir area during the Korean War, 1950
3. Animal and plant ecological recovery following Mount St. Helens eruption, 1980
4. Crew response to Soviet submarine K-19 reactor leak, 1961
5. Controlled crash landing of UAL232 at Sioux City, Iowa, 1989
6. Power distribution management during the California power crisis, 2000–2001

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The presence of alternatives and the ability to assess situations and direct resources to achieve the higher-priority goals are key factors in resilience. The absence of either precludes resilience. A small-scale disturbance in a resilient system will be easily accommodated with little apparent effect. A large, important event will evoke a more dramatic response, but, in a resilient system, a dip in performance will be followed by rapid recovery. Highly resilient systems may even be able to recover from severe, existential disturbances, preserving critical resources against future needs and "live to fight another day."[3]

The opposite of a resilient system is a *brittle* one. Brittle systems are unable to accommodate even minor disturbances without ceasing to function. Large computer, electrical distribution, building, and even financial systems sometimes demonstrate brittleness, as demonstrated in the 2010 flash crash of the New York Stock Exchange.[4]

Resilience itself is "scalable," that is, it can be found across systems of different sizes. Although this is most obvious in dramatic, large-scale events, such as the medical response to a bus bombing (Case 4, Table 2, page 378), it can also be found in small-scale, routine situations, such as the handling of a "soft" emergency (Case 1, Table 2). Current interest in resilience focuses mainly on a narrow range of systems, from a few persons to an organization of perhaps thousands of people (for example, a military division). But some experts argue that resilience can be found in systems as small as individual cells or as large as ecosystems.[5] There is a strong technical basis for resilience found in complex, adaptive systems.[5–8]

One of the early resilience engineering theorists [and one of the authors], Hollnagel, identifies four related aspects of resilience: (1) monitoring or exploring the system's function and performance, (2) responding or reacting to events or condi-

Table 2. Examples of Resilience in Health Care

Case	Description	Event Scale	Activities	Notes
1	"SOFT" EMERGENCY SURGERY (1)* In the midst of a busy day, an "emergency" case is inserted into the sequence of cases without major impact on the schedule.	Very small	• Inquiry into specifics of the emergency case • Evaluation of current state of work in the OR • Negotiation of resource allocation	• Required multiple assessments • Resolved competing demands for resources • Made use of multiple degrees of freedom
2	AUTOMATED MEDICATION DISPENSING FAILURE (14) A software upgrade causes the automated dispensing unit in a busy ED to freeze without warning.	Small	• Recognition of the nature of the obstacle • Setup of informal back-and-forth pharmacy runner • Use of "stashed" drug supplies, "borrowing," and substitution	• Adapted organizationally to overcome technology failure • Reverted to manual system • Loss of ordinary accounting exchanged for speed of access to medications
3	ED IN "FREE FALL" (15) An influx of patients into the ED overwhelms the staff, leading to deviation from normal organizational protocols.	Medium	• Distribution of authority/responsibility • Forgoing of usual oversight • Work to recover ordinary operations	• Continued work in spite of loss of central organization • Used capacity reservoir in personnel
4	SUICIDE BUS-BOMBING (1) A bombing creates > 50 casualties, who are evacuated to hospitals and treated efficiently.	Large	• Direct care by senior clinicians in triage area • Dispersal of casualties to care locations • Self-mobilization of personnel taking on nonstandard roles • Dropping noncritical tasks (for example, paperwork)	• Entire facility involved • Repeated experience refined performance (learning) • Rapid return to "normal" operations

OR, operating room; ED, emergency department.
* Reference numbers, as listed starting on page 382.

tions, (3) anticipating or foreseeing future events and conditions, and (4) learning or reorganizing system knowledge (Table 3, page 379).[9] Together these provide a description of resilience in the context of human-scale complex, adaptive systems.

Examples of Resilience in Health Care

Examples of resilience include smooth integration of an emergency surgery into a busy OR schedule (Case 1, Table 2), the response to failure of automated dispensing equipment in the ED (Case 2), work around an overloaded ED (Case 3), and response to a suicide bus-bombing in an urban area (Case 4). Although these are quite different events, they all illustrate basic features of resilience.

In each of these cases, people seek to manage a temporary disturbance that manifests itself as a work disruption. The system possesses resilience if its configuration permits actors within it to effectively react to the disturbance by changing or trading off across goals. One trade-off, for example, would be the use of a more toxic antibiotic in a critically ill patient. Another would be the deliberate assignment of less competent staff to perform a procedure to permit the assignment of the more competent staff to a higher-priority or more complex procedure. At the moment of the disturbance, the flexible, adaptive element of the system lies mostly in the sharp-end workers—who call on their knowledge and experience to understand the disruption, anticipate immediate and future demands for performance, and shift work and work processes to meet those demands. To do this well requires a large and diverse fund of knowledge regarding their system's technical and organizational features, the sorts of things that are likely to happen and can happen, what resources are available, and what are the likely consequences of shifting resources in different ways. The fund of knowledge must be accessible and called to mind appropriately in the particular circumstances that comprise the disturbance. For example, in the soft emergency case (Case 1), the anesthesiologist "running" the OR is able to predict the likely duration of cases, knows the speed with which a patient can be brought to the OR from the ED, and knows the significance of the medical issues underlying the declaration of the case as an "emergency."

To manage the disturbance requires trading off across various goals. A hallmark of resilient systems is the presence of multiple interacting goals and the active selection of goals in the face

Table 3. Aspects of Resilience*		
Aspect	**Description**	**Example**
Monitoring	Scanning, listening, observing, attending to, examining the system operation over different time scales to understand the current state of the system	Being aware of the current use of operating rooms and the likely duration of the cases allows the coordinator to smoothly manage the "soft" emergency case (Case 1).
Responding	Acting or reacting, intervening, correcting, tuning, adjusting, tweaking, trading-off, sacrificing to achieve specific goals	Distributing authority to junior clinicians allows the ED in "free fall" to manage a patient surge (Case 3).
Anticipating	Projecting, foreseeing, looking ahead, forecasting, predicting, simulating within the system to understand likely and unlikely future conditions and events	Early setup of a runner system for drug requests and deliveries keeps the ED operating effectively over a long period (Case 2).
Learning	Incorporating, grasping, reviewing, studying experiences and integrating the resulting knowledge into structures available for future practice	Repeated experience with bus bombings promotes effective approaches to handling a bombing episode (Case 4).

ED, emergency department.
* Cases are summarized in Table 2.

of uncertainty. Typically, some goals are in conflict, and such conflicts must be resolved for resilience to come into play. For example, in the bus-bombing response (Case 4, Table 2), participants abandon most (but not all) routine paperwork to obtain the fastest possible response for multiple casualties. This allows immediate care of patients, which, in turn, creates potential problems and future work; for example, in establishing patient identification, tracing patients passage through the system, and resolving the paperwork left undone during the disturbance.

Although our attention is drawn to the drama of disturbance response, resilience is present in the system *before* the disturbance. The ability to deploy knowledge and trade off across goals depends, in turn, on the system's configuration and the opportunities that it provides. Particularly important is the presence of multiple "degrees of freedom" available to the people confronting the disturbance. In the "free fall" ED case (Case 3, Table 2) it was possible to provide high degrees of autonomy to each staff member so that he or she could work without the overhead effort needed to coordinate his or her activities with those who normally have authority. The presence of these individuals, their abilities, and the presence of local treatment equipment and medicines derive from systemic factors.

Recovery of Ordinary Operational Conditions

The return to normal operations is also an aspect of resilience, as illustrated, again, by the bus-bombing case (Case 4, Table 2)—the casualties from the bombing were managed quickly, and normal operations resumed within a few hours. Recovering lost capacity and restoring normal operations can be exceptionally difficult, particularly in computer-based operations, as in a medication administration record "knockout" case, which required "tricking" the computer by setting its internal clock back two days to reconstruct each patient's order history so that medication administration records would be complete and pharmacy billing would be passed to the accounting system.[10] Recovery itself is an expression of resilience.

Learning from Disturbances

Systems learn from disturbances and alter their configurations in response. For example, systems may learn how to anticipate and provide the facilities and supplies that might be needed by practitioners. Following the automated dispensing outage in Case 2 (Table 2), the configuration was changed to allow entry into the locked medication supply device in the event of a similar failure.

Resilience may be enhanced by repeated exposure to similar disturbances. The learning component of resilience (Table 3) includes incorporating past experience into future performances. In the bus-bombing case (Case 4, Table 2), the smooth performance resulted partly from experience with similar events during the preceding two years. It is also likely that many disturbances have common features that promote learning how to manage classes of disturbance. There may, for example, be more similarity between the disturbance features of a railroad mass casualty event and a building collapse than either has to a bus-bombing. Casualties from a bus-bombing appear at the triage locations within minutes of one another, while building-collapse and railroad accidents, which frequently involve many entrapped casualties, result in a slow but steady flow of casualties to triage. The ability to infer the implications of a particular type of event from previous experience may be crucial to response planning.

In general, resilience mitigates losses rather than achieving the usual successful performance obtained without a disruption. For each of the four cases in Table 2, the disturbance response involves sacrificing some goals in an effort to achieve others. Managing free fall in the ED is not anyone's notion of best care but reflects the deliberate acceptance of nominally suboptimal and even potentially hazardous approaches to distribute care under exceptional circumstances.

Learning appears to be sensitive to the frequency, severity, and variety of disturbances, so that when disturbances are common, significant, and varied, it is likely to be incorporated into formal work processes. When disturbances are widely spaced, learning may be mostly embodied in education and training. As disturbances become more variable and less predictable, more emphasis is placed on general capabilities, such as strength and agility, with which to address them.

Conversely, environments that present few surprises and maintain a constant tempo of operations may lose contact with the experience of resilience. Without opportunities to learn from disturbances, the value placed on resilience may fall. Maintaining the facilities, degrees of freedom, and expertise of operators may appear to be extravagances or even wasteful. Particularly in bureaucratic organizations, successful responses to disturbances may become unremarkable "ordinary" work, encouraging elimination of what appear to be unimportant capabilities or resources.

Resilience learning is systemic, involving incorporating experience with disturbances by humans but also incorporating experience in system configurations, resources, and artifacts that become the instruments by which resilience is brought to bear in other disturbances. Why is the ED—the setting for three of the four cases in Table 2—a good place to look for resilience? ED operations promote investments in resilience because circumstances there frequently call on resilience. The ED functions as a buffer between the external world and the rest of the hospital. This leads the ED to be exposed to a virtually unregulated flow of disturbances. The high rate and variety of disturbance exposure puts a premium on resilience. Disturbance management[11] is a primary element of ED practitioner training and culture. The activities in the ED are mainly confined to short-term patient evaluation and management, affording a limited time frame that makes "process tracing"—in which movement and communications are observed and analyzed—feasible for investigators.[12] The automated dispensing failure (Case 2, Table 2) shows how brittle technology leads practitioners to develop and rely on work rearrangements (sometimes called workarounds)[13] and novel strategies (for example, the hoarding of small amounts of a few medicines in a personal "stash").[14] Although neither facet of resilience is found only in EDs, conditions there make studies of resilience in EDs particularly productive.

Putting resilience into action often involves marshaling resources. Major disturbances, such as fires, building collapses, industrial accidents, and acts of war, result in sudden demands for attention in the ED and lead practitioners to go there. In the bus-bombing example, practitioners moved to the ED from around the hospital in anticipation of casualties. Such events also put a premium on fast responses, and the bus-bombing example shows how groups can forego various time-consuming administrative tasks when this occurs.

Finally, EDs can break down in interesting (albeit frightening) ways. These breakdowns can be catastrophic but are not necessarily so.[15] A resilient system performs better than a brittle one,[16] but being resilient does not mean being invincible. Although resilience is desirable, it may also be expensive. The ED is often at the crux of economic decision making in hospitals. Deciding how much to invest in resilience is a decision made under uncertainty. The ED is a potential laboratory for study of the interactions between money and resilience.

Factors That Enhance and Erode Resilience

Health care relies to varying degrees on resilience. The examples that we have provided demonstrate that resilience is an important contributor to successful outcomes in the ED. Studies of resilience are taking place in other areas, including ICUs and home care, where expressions of resilience are common, affirming the importance of resilience to responding to disturbances large and small.

Disturbances are common throughout health care, and education and training across the caring professions concentrate on recognizing, assessing, and responding to disturbances. Experience with disturbances leads organizations and firms to invest in resilience. Maintaining supply stocks and other resources, deliberately distributing authority and responsibility so that frontline workers have both the capacity and experience to act independently, and recognizing and aiding goal negotiation, are ways in which resilience is enhanced.

More difficult to assess and appreciate are what might be called the "slow factors." A nuclear power plant takes many years to design and build; bringing a new medical or nursing school to maturity may take as long. The knowledge and experience that contribute to expertise in worker cadres are developed and inculcated over the course of years or even decades. Cultural contributors that promote the kinds of values and inventiveness demonstrated at Fukushima are derived from cultural norms and practices developed over centuries. Resilient performances draw on these resources, which can be crucial at the moment of the disturbance. Although these factors may seem abstract or distant, preserving knowledge and expertise and effectively transferring this to next-generation practitioners is explicitly part of training organizations.

It is harder to identify and assess the factors that erode resilience. Optimizing economic returns may be a threat to resilience, particularly when contributors to resilience are misjudged as waste and eliminated, resulting in a more brittle system. In the United States and other countries, the narrow view of health care as a business may cause investments in resilience to be viewed as unnecessary. Management initiatives must be undertaken sensitively and carefully to avoid underappreciating the value of apparently nonproductive resources that are contributing to resilience potential, which might be otherwise misjudged as waste.[17,18] Because many of the details of work are tacit, poorly articulated knowledge, there is often a gap between the normative view of clinical work (what should be done) and the descriptive view (what actually is done). Privileging the normative view can easily lead to missing important, but latent, value, and this oversight might be discovered only much later, in the midst of a crisis. For example, the transformation of operations brought about by efficient information technology[19] can frustrate the coping efforts of practitioners to sustain operations in the face of disturbances.[10]

A related problem is the difficulty in assessing the quantity and quality of resilience present in a system. Although resilience is made apparent by the response to disturbances, it is not yet possible to gauge reliably how much resilience is present in a system or how resilience changes over time. Phenomena that are not easily converted to numbers receive less attention than those that are.

Our lack of requisite imagination about the range and nature of possible disturbances is similarly concerning. After accidents it is easy to recognize this lack of imagination. The Fukushima accident and the destruction of the shuttles *Challenger* and *Columbia*, for example, show the limits of our abilities to anticipate the full range of disturbances that will confront our systems. There is a stark contrast between the breadth of preparations during the US space program that paid off dramatically in the case of Apollo 13[20] and those that flowed from a shuttle program focused on providing routine transportation into space.[21]

Repeating similar disturbances promotes high levels of learning and investments in resilience (Case 4, Table 2). The converse also appears to be true: It is difficult to develop and sustain resilience if the rate of disturbance is low or the nature of disturbances varies widely. A busy urban ED is predictably unpredictable, and disturbances are common and varied in ways that test the resilience found there but also promote its development. We are struck by the many accounts of resilient performances that appear when ED workers talk with one another. (The workshop discussion provided examples of anticipating deteriorating conditions in specific patients, work tempo, and staff availability. The ability to foresee future bottlenecks and criticalities was cited as critical to managing work flows and achieving successful outcomes.)

Our limited knowledge about the factors that enhance and erode resilience may be taken as a road map for a broad research agenda. Discovering how (and how much!) resilience is modulated across a variety of medical settings is likely to be both challenging and exciting. Developing tools—both theoretical and empirical—for studying resilience in health care will take time and resources.

What Is Resilience Engineering?

Resilience engineering is the deliberate design and construction of systems that have the capacity of resilience. Resilient systems typically experience disturbances. Training practitioners to learn about the management of disturbances incorporates the learning process itself into the repertoire of practitioner skills. Resilience engineering might, for example, include creating opportunities for inexperienced practitioners to learn about trade-offs and consequences from deliberate exposure to disturbances.[21] We note that this type of learning requires substantial technical ability and judgment and may be mainly found near the end of apprenticeship, after the apprentice has the large fund of knowledge and experience needed to assess alternatives and probabilities. Long apprenticeship is itself now under strain.[22]

Because expressions of resilience involve trade-offs and sacrifices across goals, resilience can be engineered by ensuring that those making them are able to foresee the consequences of trade-offs and sacrifices and are able to undertake these actions. In medical and surgical practices—which, in contrast to nuclear power plants and similar engineered systems, have relatively flat technical and organizational structures—frontline professionals retain knowledge and authority to handle disturbances, in which they have opportunities to enact important trade-offs and sacrifices. The great variability across patients and situations requires vesting authority in practitioners. Clinicians are often called upon to assess risks and benefits of various courses of action under high time and consequence pressure. Helping them "play out" the consequences of choices, either via mental simulation[23] or via well-designed tools, is a potential avenue for engineering resilience in these settings.

It is clear that technology, workspace configuration, communications, and access to information all play important roles in resilience. Caring for the mass casualties of a bus-bombing, for example, makes heavy use of the ED as a physical place for clinical workers to congregate and move swiftly between patients. Portable imaging and laboratory technology provide near-real-time data. The presence of senior, experienced clinicians allows immediate decision making based on the best available clinical expertise. The ability to visualize critical resource availability (as, for example, displayed in Case 1, Table 2) can efficiently inform trade-offs and sacrifices. Understanding how these factor contribute to or erode resilience is an important area for further research.

Summary

Resilience is present in working systems and contributes substantially to operators' ability to respond to disturbances large and small. Although the study of resilience is in its early stage, many of the compelling examples of resilience in action come from health care. This is not a coincidence; disturbances are common, and the education and training of professionals emphasizes thoughtful, deliberate response to disturbances. Many environments in health care (such as the ED) serve as a liminal, buffering space between the predictable and orderly world of the hospital and the often tumultuous and unrestrained world outside it. Resilience examples are easily found here but resilience itself we believe to be ubiquitous across medical practice.

How is resilience created, sustained, and eroded? Research under way seeks to answer these questions. It is important to understand how resilience is affected by organizational and institutional change. We are sensitive to the need for means to gauge the quality and quantity of resilience in specific locations. We believe that resilience may be significantly eroded by a variety of mechanisms, particularly in systems under pressure. Investments in professional expertise, for example, are hard to sustain when the benefits that flow from them are difficult to measure and the acute need for the expertise is sporadic.

Finally, resilience does not invariably lead to success, and lack of resilience does not invariably lead to failure. Resilience may allow limited success in the face of severe disturbance, and the lack of resilience may lead to failure in the face of minor disturbance. The current exploration of resilience should prompt us to look more critically at success to build a more accurate picture of important systems in operation. The complex adaptive system that delivers care to patients is deploying resilience, mostly without being noticed. The surprising thing is not that there are so many accidents in health care but that there are not even more. Because our successes so regularly depend on it, finding ways to identify and enhance resilience is a critical need for patient safety. J

The conference was sponsored by the University-Industry Demonstration Partnership, Washington, DC, and the MedStar Health Research Institute, MedStar Health, Washington DC. The conference was planned and led by the National Center for Human Factors in Healthcare, MedStar Institute for Innovation, MedStar Health, Washington DC. This conference report reflects the views of the authors and not necessarily those of their institutions or the workshop sponsors. The authors gratefully acknowledge the presenters of the workshop, from whose sessions much of this content is based: Ann Bisantz, School of Engineering and Applied Sciences, University at Buffalo; Jeffrey Braithwaite, Centre for Clinical Governance Research, Institute of Health Innovation, and University of New South Wales; Joan Ching, Virginia Mason Medical Center; Cathie Furman, Virginia Mason Medical Center; Sorrel King, Josie King Foundation; Seth Krevat, MedStar Health; Christopher Nemeth, Applied Research Associates, Inc.; Barbara Pelletreau, Dignity Health; and Shawna Perry, Virginia Commonwealth University Health Systems and Virginia Commonwealth University.

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