Journal of Biomedical Informatics 44 (2011) 425–431

Contents lists available at ScienceDirect

Journal of Biomedical Informatics

journal homepage: www.elsevier.com/locate/yjbin

Deviations from protocol in a complex Trauma environment: Errors or innovations?

Kanav Kahol [a,b,*], Mithra Vankipuram [b], Vimla L. Patel [c], Marshall L. Smith [a]

[a] *Simulation and Education Training Center, Banner Good Samaritan Medical Center, Phoenix, AZ 85016, USA*
[b] *Human Machine Symbiosis Laboratory, School of Biological and Health Systems Engineering, Arizona State University, Tempe, AZ 85287, USA*
[c] *Center for Cognitive Informatics and Decision Making, School of Biomedical Informatics, University of Texas Health Science Center, Houston 77030, USA*

ARTICLE INFO

Article history:
Received 15 August 2010
Available online 13 April 2011

Keywords:
Errors
Innovations
Complexity

ABSTRACT

Protocol standardizations are important for consistent and safe practices. However, complex clinical environments are highly dynamic in nature and often require clinicians, confronted with non-standard situations, to adjust and deviate from standard protocol. Some of these deviations are errors which can result in harmful outcomes. On the other hand, some of the deviations can be innovations, which are dynamic adjustments to the protocols made by people to adapt the current operational conditions and achieve high accuracy and efficiency. However, there is very little known about the underlying cognitive processes that are related to errors and innovations. In this study we investigate the extent to which deviations are classified as errors or innovations, as a function of expertise in a Trauma setting. Field observations were conducted in a Level 1 Trauma unit. A total of 10 Trauma cases were observed and collected data was analyzed using measures that included customized activity-error-innovation ontology, time-stamps and expertise of the team members. The results show that expertise of the caregivers and criticality of a patient's condition in critical care environment influence the number and type of deviations from standard protocol. Experts' deviations were a combination of errors and innovations; whereas the novices' deviations were mostly errors. This research suggests that a novel approach must be taken into consideration for the design of protocols (including standards) and compliance measurements in complex clinical environments.

1. Introduction

Healthcare systems are complex systems with non-linear interactions and dynamic emergent behavior [1]. From the initial days of simple doctor-patient relationship, healthcare today has expanded to include a multitude of factors that increase the complexity of the system. This is true at various levels of healthcare wherein multitude of people interact with other people and in recent times a myriad of complex technology. The presence of such dense and interrelated network structure of interactions between these entities makes operations in complex networks often intractable. This can be seen when tracking activities and workflow in critical care environments such as emergency departments and Trauma centers. From an intervention perspective, the issue of intractability makes design, implementation and evaluation of the intervention difficult. Poorly implemented interventions could adversely affect patient safety. Consequently, interventions in complex environments need to be understood at a fundamental level to ascertain how to successfully implement interventions and ensure that these interventions will improve patient safety.

A class of interventions that has proven to be very useful in complex environments is protocols. Protocols serve as a means to accomplish complex tasks by dividing them into simpler observable units. Typically, protocols suggest a sequence of these atomic tasks and define the criteria for success. Most clinical procedures can involve several steps and having a protocol helps in standardizing the steps and ensuring that all steps are completed. The utility of protocols is assessed using checklists, a tool that has proven to be a very effective in the management and control of processes in complex environments [2]. Checklists help in several ways to ensure quality and safety and have become an easily implementable method to avoid errors. Duane et al. [3] assessed the effect of a protocol for Central Venous Line (CVL) placement on blood stream infections (BSI) and patient outcome in a Trauma Intensive Care Unit (ICU). It was found that the protocol, when supported by a nursing checklist, reduced BSI incidence rates and minimized the length of stay in the Trauma ICU. In addition to having a positive impact on clinical outcomes, protocols and checklists aid in reducing costs incurred by the clinical unit. Semel et al. [4] performed a decision analysis of the implementation of a protocol checklist in a US hospital for a 1 year time period. It was found that checklist

* Corresponding author at: Human Machine Symbiosis Laboratory, School of Biological and Health Systems Engineering, Arizona State University, Tempe, AZ 85287, USA.

E-mail address: kanav@asu.edu (K. Kahol).

1532-0464/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.jbi.2011.04.003

implementation could generate cost savings after enabling the avoidance of five major complications (assuming a baseline complication rate of 3%). Protocols and checklists enable institutions to reduce costs by avoiding expensive medical errors and consequently improving the quality of patient care.

Agencies, such as the American College of Surgeons (ACS), the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) and the American Board of Surgery (ABS) have recognized the importance of protocols and standardizations. ABS, for example, have made training in Advanced Cardiovascular Life Support (ACLS) and Advanced Trauma Life Support® (ATLS®) protocols mandatory for general surgery certification [5]. In addition, recent initiatives by the Department of Human Health Services have supported efforts on standardizations and the use of information technology to develop protocols [6].

Much research on medical errors attempts to identify error as deviations from some known standard [7–9]. While an error being interpreted as a deviation may be true, the converse need not necessarily be accurate. In fact, it is possible that a deviation from a protocol may be an innovation designed to maximize patient safety. The identification of such cases is critical to the evaluation and improvement of existing protocols. In addition to protocol management, it is important for novice clinicians to identify such cases and adapt existing protocols to the situation at hand. While understanding the importance of standards is part of good clinical practice and should be grasped effectively, knowing when to deviate from the protocol can indicate flexibility and adaptability that is important in assuring good and safe decisions. It can accordingly be problematic if our education system and our management structures advocate following standard protocols alone, failing to acknowledge that students also need to learn how to handle complex problem solving that is outside the boundaries of "standard solutions". A example of such a complex problem is that of the emergency landing of US Airways flight 1549 in the Hudson River – a situation in which the pilots made good decisions about following some protocols but departing from others [10]. In this paper, we seek to explore the relation between errors, innovations, protocols and expertise in complex critical care environments.

From a cognitive perspective, error, innovation and effectiveness of protocol is intimately linked with expertise of the clinicians. Patel et al. studied the relationship between task difficulty and expertise [11]. The authors employed semantic analysis and found that experts were able to use well developed knowledge base and superior reasoning strategies in clinical reasoning. Groen and Patel [12] in another publication isolated the reasoning process that physicians go through when diagnosing a clinical case, using techniques to identify knowledge structures. They showed that in medicine, experts tend to follow a top-down reasoning strategy wherein reasoning from a hypothesis to account for the case data, which seemed anomalous when compared to other domains. This is an important finding from the perspective of studying errors and innovations. In other domains wherein experts tend to gather data and assemble hypothesis, there is scope for significant amount of trial and errors. On the other hand, in clinical decision making, experts more often than not utilize a top-down approach to decision making. It has been shown that this methodology when combined with experience driven cognitive constructs results in experts making fewer errors compared to novices. It is plausible that when experts do deviate, they are more likely to be innovations.

Another aspect of cognition that needs to be accounted for is the capability of a clinician to generalize given data into correct diagnosis. Cognitive research in medicine [13] has shown that clinicians can generate different levels of mental representations, from the very specific to the very general. The critical factor in determining generality is typically the degree of high level expertise of the clinician, namely, specialized or specific expertise (i.e., knowledge of a particular sub-domain of medicine, such as endocrinology or cardiology). Higher-level representations are generated by these more expert clinicians, whereas lower-level and more detailed representations are typically generated by novices, or more commonly, intermediate level clinicians (e.g., senior medical students, recent graduates, and residents).

This condition points to the ability of experts to apply generic rules to a given case, giving them extra cognitive resources to apply innovations and limit errors. Research has shown that experts as a result of their practice, learn to associate individual items in working memory with the contents in long term memory, which result in the development of conceptual organizations in memory called retrieval structures [14]. An expert can use these retrieval structures to provide selective and rapid access to long term memory. On the other hand novices seem to occupy their working memory and long term memory resources in the details of the case (due to the lack of mature retrieval structures) which may be irrelevant. In such type of workload, it may be challenging to innovate and depending on the workload, one may make extensive errors as is in the case of complex environments. In fact, research confirms that a key element of retrieval structures is their use by experts to eliminate irrelevant information [15] freeing working memory for innovative thinking.

In general the literature on clinical expertise, gives clues into the underlying mechanisms of the relationship between errors and innovations. One area of research that has explored the mechanisms of innovations is cognitive basis of creativity [16]. This field explores the cognitive basis underlying creative thinking and reasoning. It identifies conditions that lead to creation and innovation and is based on the hypothesis that creativity is supported by pre-invention structures and the explanation structures in experts. This is a very intriguing model for creativity and cognition but its relevance to complex domains such as Trauma may be limited. In general, the theories from creativity tend to focus on free thinking approach wherein timeliness of creativity is not a big factor. On the other hand, in complex environments such as Trauma or critical care, timeliness of decision making may fundamentally alter the innovation process and it is important to study the mechanisms underlying errors and innovations separately.

The present research, to our knowledge, is one of the first to study to examine the cognitive basis of innovation mechanisms in experts in medicine. The following section provides the required background for understanding the concepts of innovation (and errors) and their classification.

2. Analytic framework

Fig. 1 describes a hierarchical schema for deviation classification in Trauma. This schema was developed based on field observa-

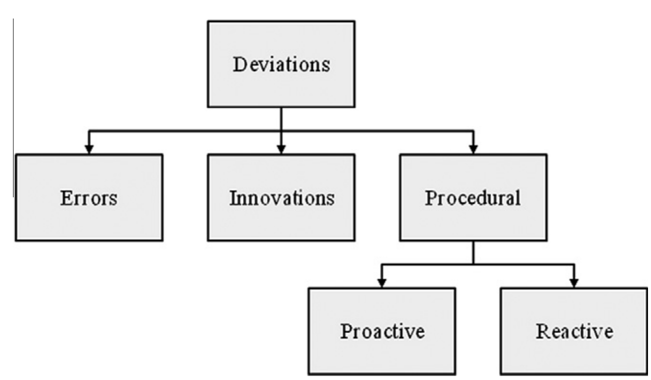

Fig. 1. Classification of deviations in Trauma based on observation data from [17].

tions done in December 2009 at the Level 1 Trauma center at Banner Good Samaritan Hospital in Phoenix, Arizona. Each of the key components of the classification is discussed below.

2.1. Identification of deviations

Deviations could be broadly defined as steps performed that are not on an accepted pre-defined protocol. For the analysis of deviations in Trauma, the most appropriate guideline or protocol available is the ATLS protocol [17]. It is mandatory that this protocol be followed in every Level 1 Trauma center for accreditation purposes. Research has shown that ATLS protocol is a very effective protocol in improving the quality of care in Trauma centers across USA [18] and is overseen by the American College of Surgeons. The key steps in the ATLS protocol are as follows [17],

(i) *Primary survey* – Assess the Airway, Breathing and Circulation (ABC) of the patient and secure the same. Perform Disability assessment and control Exposure and the Environment. This is the ABCDE of Trauma management.
(ii) *Secondary survey* – Complete a detailed, head-to-toe examination and obtain AMPLE (Allergies, Medications, Past history, Last eaten information and Events leading to Trauma) history from patient.
(iii) *Definitive diagnosis and management* – Provide a treatment plan and discharge or transfer patient from Trauma.

Table 1
Key steps in Initial Assessment and Management ATLS Protocol adapted.

ATLS – Initial Assessment and Management Protocol
(A) Primary survey assessment of ABCDE's
1. Airway with cervical spine protection
2. Breathing
3. Circulation with control for external hemorrhage
4. Disability with brief neurological evaluation
5. Exposure/environment
(B) Resuscitation
1. Oxygenation and ventilation
2. Shock management, intravenous lines, warmed Ringer's lactate solution
3. Management of life-threatening problems identified in the primary survey is continued
(C) Adjuncts to primary survey and resuscitation
1. Monitoring
a. Arterial blood gas analysis and ventilator rate
b. End-tidal carbon dioxide
c. Electrocardiograph
d. Pulse oximetry
e. Blood pressure
2. Urinary and gastric catheters
3. X-rays and diagnostic studies
a. Chest
b. Pelvis
c. C-spine
d. Diagnostic peritoneal lavage (DPL) or abdominal ultrasonography
(D) Secondary survey, total patient evaluation: physical examination and history
1. Head and skull
2. Maxillofacial
3. Neck
4. Chest
5. Abdomen
6. Perineum/Rectum/Vagina
7. Musculoskeletal
8. Complete neurologic examination
9. Tube and fingers in every orifice
(E) Adjuncts to the secondary survey
1. Computerized tomography
2. Contrast X-ray studies
3. Extremity X-rays
4. Endoscopy and ultrasonography
(F) Definitive care
(G) Transfer

Table 1 details the steps (in sequence) of the protocol. A deviation is marked if a step that is on the ATLS protocol is skipped, an extra step is performed or if a certain task is performed out of order. Typical deviations from the protocol include failure to perform a log roll (key step in protecting the spine during assessment), or a resident making an error by omitting steps or in some cases, adding unnecessary steps. In the following sub-sections, we provide definitions for the various types of deviations that were observed in this study.

2.1.1. Deviations as errors

We define error as any deviation that potentially impacts patients and their treatment outcome negatively. Some examples of errors detected in the data gathered from Trauma include:

- Clinician is not present in the Trauma room when the patient arrives.

Treatment of a Trauma patient is a time critical activity that requires preparation for efficient implementation. Delay in arriving for the Trauma reduces the time the clinician has to prepare for the Trauma case. Such an error reduces Trauma efficiency and, in worst case, can potentially have negative clinical outcomes.

- Clinician staples a patient's wound inaccurately causing the clinician to redo one or more staples.

Such errors in psychomotor performance often occur due to the time critical and expertise-driven nature of the complex environments. Clinicians may make such errors due to the added cognitive pressure. These type of errors have been reported in literature [19] and lead to the clinician deviating from the protocol to rectify the error.

- The Trauma team fails to perform a log roll when examining the spine of the patient.

The log roll ensures that the patient's cervical neck and spine is protected during secondary assessment. Failure to perform the log roll could potentially compromise the patient's spine and nervous system. Consequently, it is considered to be an erroneous deviation.

2.1.2. Deviations as innovations

Innovation can be defined as a deviation from the protocol that may positively affect the patient's outcome. Innovations, that are properly validated and generalize, can potentially become part of the protocol that it initially deviated from. Some examples of innovation include,

- The clinician prioritizes secondary examination of the patient to address time critical aspects of the patient's treatment.

The ATLS protocol allows for clinicians to adapt the processes to a specific patient. However, there are times when clinicians need to deviate even within the broad framework to care for his/her patient. Penetrating injuries to the chest, for example, are given higher priority than head and maxillofacial examination during the head-to-toe survey of the patient to ensure that conditions of pneumothorax or hemothorax (chest cavity compromised by air or blood, respectively) are detected early. This type of innovation, which can be understood as *dynamic innovation,* is quite common but presents an important challenge for judging compliance.

- An attending physician suggests that the patient's arm could be taped up as they anticipate problems a patient may have during a required X-ray scan.

This is an anticipatory innovation wherein an expert based on previous experience can predict the possible outcomes of an action and can provide preventative or supportive inputs.

- The attending physician shares an innovative method for a procedure for treating the patient that has not yet been validated.

This is a knowledge based innovation. Experts are adept at learning from new sources and are capable of carefully testing new procedures and *innovations*. These types of innovations can potentially be dangerous if implemented by novices but experts can devise a careful plan, roll out and test new methods in a controlled manner.

2.1.3. Proactive and reactive procedural deviations

During classification of deviations based on preliminary data gathered, it was found that a large number of deviations were neither errors nor innovations as defined above. Some examples include,

- Resident pauses when conducting the primary survey in order to ask the patient to co-operate.
- The Trauma nurse, reacting to a patient vomiting, moves over help the patient clean up.
- A Trauma nurse anticipating a patients' arrival, requests the Radiology technician to insert the X-ray apparatus below the patient's sheets, prior to patient arrival.

All three cases are neither errors, nor innovation as they do not directly impact patient outcomes but rather are actions demanded by dynamic nature of the complex environments. The first two deviations mentioned above are examples of clinicians performing procedural steps in reaction to patient-specific actions. These classes of deviations are termed *Reactive Procedural Deviations*. The last case is a procedural action requested proactively by the Trauma nurse to improve the efficiency of the Trauma case. Hence, this class of deviations is called *Proactive Procedural Deviations*.

Using the analytic framework defined above, deviations were identified using ATLS protocol for "Initial Assessment and Management". The following were the specific questions we attempted to answer through analysis of the deviations,

Question 1: How often do the Trauma team members deviate from the Advanced Trauma Life Support protocol?
Question 2: When clinicians deviate, what are the types of deviations made?
Question 3: How do these types of deviations vary with the experience (level and type) of the members of the clinical team?

3. Methods

3.1. Site description

The field observations for this work were conducted in Banner Good Samaritan's Trauma unit, one of 6 Level 1 Trauma centers in the Phoenix metropolitan area. Approximately 3000 patients are treated annually in this five bed unit. The Trauma center has dedicated hospital resources for the management of Trauma patients throughout all aspects of care, including initial evaluation and resuscitation, acute care and rehabilitation. In addition, the Trauma unit collaborates with surgeons from neurosurgery, cardiothoracic, vascular, orthopedic, plastics, ophthalmology, urology and internal medicine departments to provide the required care for incoming patients. The Trauma team (present during every shift) includes 1 Trauma resident, 2 Trauma nurses, 1 Trauma attending, 1 anesthesiologist, 1–2 juniors residents, 1–2 medical students, and radiology and lab technicians.

At Banner Good Samaritan's Trauma center, patients are treated by the Trauma team with the resident acting as the Trauma team leader. The resident treats the patient under minimal supervision of the attending Trauma surgeon. In each case, out of the two Trauma nurses, one nurse acts as the primary nurse assisting the resident, while the other Trauma nurse takes charge of documenting activities. Therefore in each Trauma is dealt with a core team that includes 1 PGY3/4 level resident, 1 PGY1/2 level resident, 1 Trauma attending, 1 (primary) Trauma nurse and 1 technician (radiology).

Trauma nurses supporting the Trauma leader are experienced registered nurses (RNs) with 5–10 years of critical care experience. A total of 36 residents complete a 2 month Trauma rotation in the 3rd–4th year of their residency program.

3.2. Study description and methodology

This study was approved by the Institutional Review Board and the informed consents were obtained from the participants on each encounter. Field observations were gathered by one researcher over a period of 3 months from December 2009 to February 2010. Trauma cases that occurred between 9 am and 9 pm (Monday–Thursday) were observed. The researcher logged observations using an automated data collection tool run on laptop using Microsoft Windows® XP operating system. The software automatically time-stamps all observations entered into the system. In this manner, observations were gathered unobtrusively. Clarifications about the events that occurred were obtained from clinicians between Trauma events.

Within the time period specified, a total of 10 Trauma cases were observed with seven attending Trauma surgeons (experts) and seven Trauma residents at the PGY1 (novices) and PGY3 (intermediate expertise) level, each. The Trauma cases were of two types – Trauma A and Trauma B. At the Trauma center in Banner Good Samaritan Health System, Trauma A refers to high criticality cases that require the presence of an anesthesiologist, while Trauma B cases are those cases that are classified as low criticality. Out of the 10 cases observed, eight cases were classified as Trauma B and two as Trauma A cases. The ATLS protocol for Initial Assessment and Management was utilized to assess these cases for deviations. Irrespective of the type of the cases, all steps of the Initial Assessment and Management Protocol are required to be followed by the core Trauma team. This allows for a valid comparison between the 10 Trauma cases.

The analysis of the data was performed by researchers in collaboration with an expert Trauma clinician (an attending). Deviations identified (through consensus) are classified as errors, innovations or procedural deviations based on the classification methodology described in Section 2. The data set was then analyzed using statistical means and interpreted to answer the questions outlined in Section 2. We employed independent group *t*-test to find differences between number and types deviations in Trauma A and Trauma B cases. A *p*-value of $p < 0.05$ was accepted as statistically significant.

4. Results

4.1. Question 1 – how often do Trauma team members deviate from the Advanced Trauma Life Support protocol?

The results are presented as mean (μ) ± standard deviation (σ). Fig. 2 depicts the mean deviations that occurred in the 10 Trauma

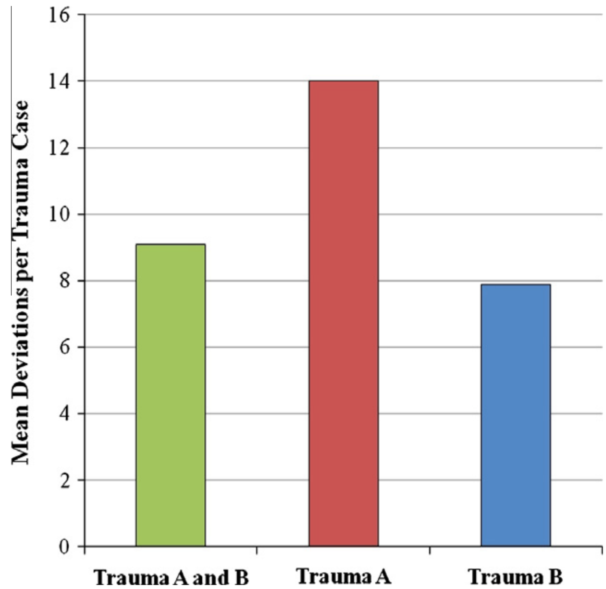

Fig. 2. Mean deviations per Trauma case.

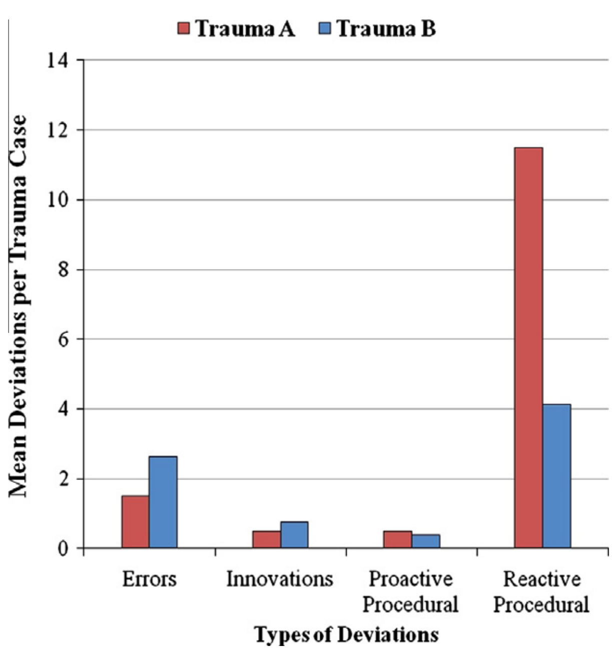

Fig. 3. Distribution of deviation and errors in two Trauma settings.

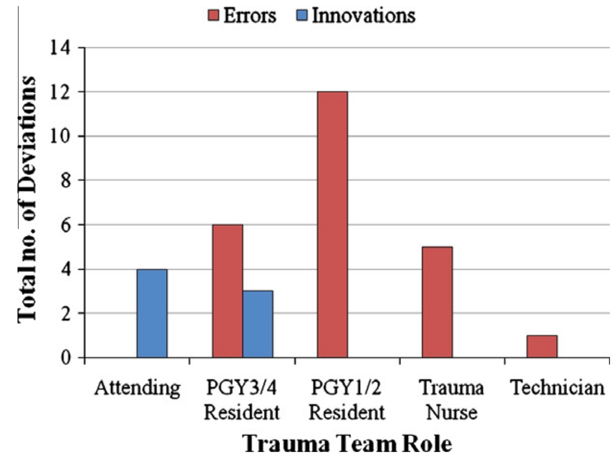

Fig. 4. Total number of deviations as a function of errors and innovation.

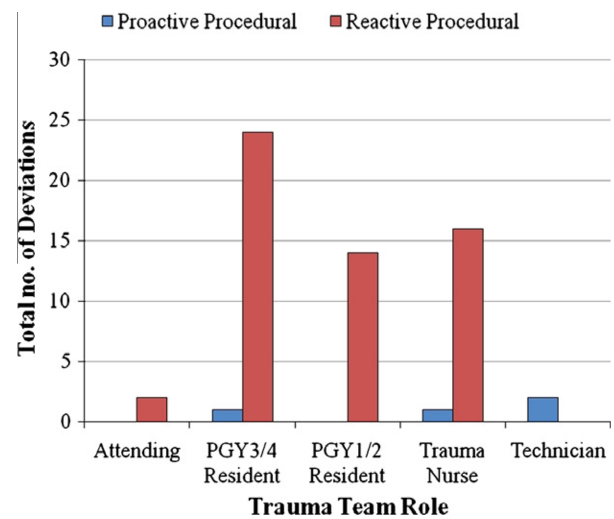

Fig. 5. Total number of deviations as a function of procedural deviations.

cases for: (i) Trauma A and Trauma B (9.1 ± 2.14), (ii) Trauma A (14 ± 1.41), and (iii) Trauma B cases (7.5 ± 2.79).

The mean number of deviations in Trauma A cases were higher compared to the mean deviations in Trauma B cases. Typically, Trauma A cases involve unstable and unpredictable patients. Consequently, the Trauma team makes relatively a larger number of deviations to adapt to the dynamic situation at hand.

4.2. Question 2 – when clinicians deviate, what are the types of deviations made?

Fig. 3 shows the distribution of: (i) errors (Trauma A: $\mu = 1.5 \pm 1.06$, Trauma B: $\mu = 2.63 \pm 1.1$), (ii) innovations (Trauma A: $\mu = 0.5 \pm 0.35$, Trauma B: $\mu = 0.75 \pm 0.7$), (iii) proactive procedural deviations (Trauma A: $\mu = 0.5 \pm 0.35$, Trauma B: $\mu = 0.38 \pm 0.37$), and (iv) reactive procedural deviations (Trauma A: $\mu = 11.5 \pm 1.06$, Trauma B: $\mu = 4.13 \pm 1.15$).

From Fig. 3, we can see that errors make up a small percentage (26.38%) of the total deviations in the 10 Trauma cases. This is an important result from these observations as it points to the limitations of the current strategy of marking most deviations as errors in assuring compliance to a protocol. The procedural deviation were significantly higher in Trauma A when compared to Trauma B cases ($p < 0.05$). The critical condition of the patients in Trauma A cases and the individual nature of the problem cause the Trauma team to deviate often in order to manage the unique situation at hand. Our analysis also showed that most procedural deviations were reactive in nature in both Trauma A and Trauma B cases. This can be attributed to the dynamic nature of the critical care environment. Clinicians are required to react quickly to the changes to ensure efficient operation in Trauma.

4.3. Question 3 – how do these types of deviations vary with the experience (level and type) of the members of the clinical team?

Figs. 4 and 5 depict the total number of errors, innovations and procedural deviations made by core team members in the 10 Trauma cases observed.

4.3.1. Errors and innovations

In this study, the experts made no errors as defined in our analytic framework. As we consider care givers with lesser expertise (from the 3rd and 4th year resident to the 1st and 2nd year residents), we saw a decline in innovation and an exponential increase in the number of errors, as expected. This once again supports our hypothesis that experts' deviations are more often innovations than errors, while novices' deviations lead most often to errors. Trauma nurses and Technicians show little evidence of innovation. While this evidence cannot be attributed to a lack of experience, it can be hypothesized that within the confines of their roles in interacting with a patient, there is not much scope of innovation. Nurses and technicians are trained to follow a strict protocol to support the Trauma team and that training may be responsible for the observed patterns.

4.3.2. Proactive and reactive deviations

Fig. 5 provides a snapshot of distribution of procedural deviations within the Trauma team. Banner Health System, being a teaching hospital, requires all Trauma cases to be led by a senior resident (PGY3/4) under the supervision of an Attending clinician, or a junior resident (PGY1/2) under the supervision of the senior resident and the attending clinician. Trauma nurses assist in all Trauma cases. Fig. 5 shows that senior residents make the most reactive procedural deviations (as they are performing bulk of the protocol), followed by the Trauma Nurses. Junior residents who generally assist but may lead a few Trauma cases also made a significant number of procedural deviations. These observations show that leadership role and associated tasks may be connected to generating deviations to the protocol.

5. Discussion

Protocols and standards are based on observations and evidence gathered from practices. New information and novel findings from practice need to be incorporated into the guidelines and protocols. So how do such novel ideas get generated from practice? When regular or standard patterns do not fit or match the current problem, possible alternative ideas get generated. This is the process of innovation, and innovation is not possible without deviations. As practitioners gain experience in the execution of a task, their performance become increasingly smooth and efficient. While developing proficiency with attention-demanding complex tasks, some component skills become automatic, so that conscious processing can be devoted to reasoning and reflective thought with minimal interference in the overall performance. A great deal of experts' knowledge is finely tuned and highly automated enabling them to execute a set of procedures in an efficient manner. Yet they can perform such tasks in a highly adaptive manner which is sensitive to shifting contexts.

Our study provides supportive evidence for the claim that deviations do occur in critical care environments and not all deviations are errors. Deviations to the protocol can be important innovations and are tied to complex decision making and judgment calls at the point of care. The results are promising and suggest a need for the development of ontology of deviations in Trauma and other critical care environments. The recognition of deviations utilizing such ontology that classifies deviations as errors, innovations and procedural deviations can significantly alter compliance procedures and provide an overall adaptive framework to modification of existing protocols. For example, if deviations are consistently seen on a particular step in a protocol, then that step may have to be re-analyzed. Similarly if innovations are continuously seen and replicated in multiple sites, then it could be incorporated into the next version of protocol. Such an ontology could allow for a scientific framework for modification of protocols and enable protocol developers to leverage a data driven approach to modifications. Currently available tools such as checklists, protocols need to allow for note takers to mark and document deviations, errors and innovation.

Such ontology could also enable the development of simulators driven by real-world data that provide training to maximize innovation and minimize error occurrence. Such an educational tool will be critical in developing decision making skills of residents and care givers. It would allow for a comprehensive evaluation of the skills of the caregivers as well as a means to train teams for not only adherence to a protocol but enabling recognition of circumstances where innovation is needed.

One limitation of this study is the number of Trauma cases studied. With our current methods, it is a challenging task to study more cases, primarily because Trauma is an unpredictable environment and it is hard to anticipate occurrence of events, and a great deal of data have to be collected for analysis. We have recently developed a system for capturing events automatically using *radio-frequency identification* (RFID) systems [20]. Clinicians in a Trauma team wear electronic RFID tags that automatically track their movement and activities. We will leverage this system to gather data from Trauma centers in an automated manner. In addition to tracking events, the system allows for playing back events in the virtual world. This can enable more efficient data annotation and collection.

6. Conclusion

Clinicians deviate from protocols when managing patients. Our study shows that clinical teams in critical care environments make significant number of deviations per case and not all deviations are errors. The study of these deviations can provide new insight into how teams operate in complex environments and what distinguishes experts from novices. The results are in coherence with existing literature on exploring cognitive basis of clinical expertise. We can hypothesize that existence of retrieval structures in experts and top down information processing allows for time critical thinking that supports innovation in experts. This is supplemented by the information filtering that the retrieval structures support. On the other hand, novices are driven by bottom up reasoning mechanisms and without retrieval structures and filtering are overwhelmed by the data and often make errors. While only further experimentation can investigate this hypothesis, our observations clearly point to the plausibility of such mechanisms.

An analysis of deviations can enable building models of expertise and workflow that can be then used to design the next generation of effective interventions. Interventions could be standardized communication tools, to information technology that supports innovations by effective presentation of information and cognitive decision support to educational efforts such as simulations. Simulations offer an exciting means of teaching clinical care givers to learn how to effectively innovate in complex environments. Accreditation Council of Graduate Medical Education recognizes simulation as an effective means of promoting critical thinking, professionalism and clinical knowledge [21]. It is generally seen only as an effective means of promoting standardization and adherence to a protocol [19]. This study however, shows that simulation should be used for teaching clinical care givers the nuances of errors and innovations. Simulation offers a safe environment to achieve such goals. We hope to develop such simulations that are not just a means of achieving standardization but also help develop certain knowledge structure fairly quickly through practice that would make any deviations safer. The data presented in this paper suggests that there is a strong link between innovations, errors and expertise. Expert care givers deviate from the protocol almost as often as novices but make significantly more innovations. This seems to suggest that expert have a strong mental model of how and when to innovate and can employ their knowledge and application abilities to innovate on the fly. Such innovations and recognizing them should be an important part of clinical practice as it helps is redesigning protocols and procedures.

Future studies will explore in detail the underlying mechanisms of expertise and innovations in Trauma. The methodologies described by Arocha et al. [22] will be employed for these studies. Specifically, we will focus on semantic analysis as a means of studying the innovations process in experts and novices. We expect that semantic analysis will yield important insights into how information is assimilated and processed by clinical care givers. This would be crucial in understanding how to develop novel protocols and standards. For example, given the seriality of information as it passes from working memory to long term memory [23], one may include markers within the case description that may invoke the correct knowledge structures in the long term memory that support creativity. Continuation of this research will enable us to test such interventions (including simulations mentioned above) and evaluate them.

We also plan to apply the same methodologies to study team creativity, innovations in Trauma environments. An important element of clinical care today is teamwork and often bas teamwork can overshadow individual innovations. Teamwork involves professionalism, communication and situation awareness and innovations need to be catalyzed by a supportive infrastructure within teams. We intend to investigate mechanisms of creativity and innovations in complex Trauma environments at a team level to facilitate development of standards, protocols and communication tools.

Acknowledgments

This work was support in part by Grant from the James S. McDonnell Foundation (JSMF 220020152). We would like to thank the Trauma team at Banner Good Samaritan for their support and cooperation in this research study.

References

[1] Plsek PE, Greenhalgh T. Complexity science: the challenge of complexity in health care. BMJ 2001;323:625–8.
[2] Gilmour D, Woodwards S. The surgical safety checklist: legacy and next step. J Preoperat Pract 2010;20:78.
[3] Duane T, Brown H, Borchers C, Wolfe L, Malhotra A, Aboutanos M, et al. A central venous line protocol decreases bloodstream infections and length of stay in a trauma intensive care unit population. Ann Surg 2009;75:1166–70.
[4] Semel ME, Resch S, Haynes AB, Funk LM, Bader A, Berry WR, et al. Health Affairs 2010;29:1593–9.
[5] The American Board of Surgery (ABS). ABS to require ACLS, ATLS and FLS for general surgery certification; 2008.
[6] Mayo Clinic Awarded Major Health Information Technology Grant. <http://www.mayoclinic.org/news2010-rst/5728.html>.
[7] Donchin Y, Gopher D, Olin M, Badihi Y, Biesky M, Sprung CL, et al. A look into the nature and causes of human errors in the intensive care unit. Qual Saf Health Care 2003;12:143–7.
[8] Weingart SN, Wilson RM, Gibberd RW, Harrison B. Epidemiology of medical error. BMJ 2000;320:774–7.
[9] Rothschild JM, Landrigan CP, Cronin JW, Kaushal R, Lockley SW, Burdick E, et al. The critical care safety study: the incidence and nature of adverse events and serious medical errors in intensive care*. Crit Care Med 2005;33:1694–700.
[10] Langewiesche W. Fly by wire: the geese, the glide, the miracle on the hudson. New York: Farrar, Straus and Giroux; 2009.
[11] Patel VL, Groen GJ, Arocha JF. Medical expertise as a function of task difficulty. Mem Cogn 1990;18:394–406.
[12] Groen G, Patel V. Medical problem-solving: some questionable assumptions. Med Educ 1985;19:95–100.
[13] Patel V, Arocha J, Kaufman D. Diagnostic reasoning and medical expertise. Psychol Learn Motiv 1994;31:187–252.
[14] Ericsson K, Patel V, Kintsch W. How experts' adaptations to representative task demands account for the expertise effect in memory recall: comment on Vicente and Wang (1998). Psychol Rev 2000;1:578–92.
[15] Joseph G, Patel V. Domain knowledge and hypothesis generation in diagnostic reasoning. Med Decis Mak 1990;10:31–46.
[16] Finke R, Ward T, Smith S. Creative cognition: theory, research and applications. Cambridge, MA: MIT Press; 1996.
[17] American College of Surgeons. Advanced trauma life support for doctors. 7th ed. Chicago, IL: American College of Surgeons; 2004.
[18] Collicott PE, Hughes I. Training in advanced trauma life support. JAMA 1980;243:1156–9.
[19] Kahol K, Leyba MJ, Deka M, Deka V, Mayes S, Smith M, et al. Effect of fatigue on psychomotor and cognitive skills. Am J Surg 2008;195:195–204.
[20] Vankipuram M, Kahol K, Cohen T, Patel V. Toward automated workflow analysis and visualization in clinical environments. J Biomed Informatics; 2011;44:432–40.
[21] ACGME. ACGME competencies: suggested best methods for evaluation [document on the Internet]. ACGME; September 2000. <http://www.acgme.org/Outcome/assess/ToolTable.pdf> [cited 12.12.07]
[22] Arocha JF, Wang D, Patel VL. Identifying reasoning strategies in medical decision making: a methodological guide. J Biomed Informatics 2005;38:154–71.
[23] Groen G, Patel V. The relationship between comprehension and reasoning in medical expertise. In: Chi M, Glaser R, Farr M, editors. The nature of expertise. Hillsdale, NJ: Erlbaum; 1988. p. 287–310.