A Conceptual Framework for Applying the Anticipatory Theory of Complex Systems to Improve Safety and Quality in Healthcare

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Abstract Effective anticipation is a fundamental characteristic of highly reliable organizations. In Rosen's anticipatory theory of complex systems, all living systems and virtually all other complex systems require anticipatory models to maintain an organized state. This paper provides an overview of Rosen's anticipatory theory of complex systems and presents a conceptual framework for applying this framework to improve safety and quality in healthcare. Organizational interventions based on this theory could include education of clinicians, patients, and families on how anticipatory complex systems function and improve safety in clinical environments, and systems interventions to promote optimal concordance between a team's model of a clinical situation and the actual clinical situation. Enhanced general understandings of anticipatory complex systems and of their failure modes could help reduce communications failures that are a common cause of serious adverse events.

Keywords Anticipation · Complexity · Safety · Quality · Medicine · Situational awareness · Communication

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1 Introduction

Clinical Scenario: *A mother brings her 1-year-old son to an emergency department for evaluation of his respiratory symptoms. Following an evaluation the treating physicians advise her that it is safe for the child to be discharged. The nurses caring for the child express concerns and say they don't think the child should go home. While driving home from the emergency department, the child exhibits increased respiratory distress. The mother returns to the emergency department. The child is admitted, spends several days in the intensive care unit, and makes a satisfactory recovery.*

Substantial efforts are needed to further improve the quality and safety of healthcare [1]. Communication failures are recognized to be an extremely common contributing factor for adverse events [2]. Concepts from safety science are increasingly being employed in efforts to create high reliability systems in healthcare [1]. Some are applying theories from systems and complexity sciences to further improve healthcare systems and processes [3]. Applying complexity principles in healthcare can be challenging in the absence of a generally agreed upon definition of complexity and without a shared understanding of optimal approaches for applying these principles to improve outcomes [4].

A capacity for effective anticipation is recognized as a fundamental characteristic of highly reliable organizations [5]. Theoretical biologist Robert Rosen made the first description of an anticipatory system [6]. Mihai Nadin, another seminal contributor to understanding anticipation [7, 8] has documented a substantial current body of theoretical and applied research in anticipation. In Rosen's anticipatory theory of complex systems, all living systems and virtually all other complex systems require anticipatory models to maintain an organized, far from equilibrium state [9]. This paper provides an overview of Rosen's anticipatory theory of complex systems and presents a conceptual framework and implementation options for applying this framework for improving safety and quality in healthcare.

2 Anticipatory Systems

In *Anticipatory Systems: Philosophic, Mathematic, and Methodological Foundations*, Rosen defined an anticipatory system as containing "a predictive model of itself and/or its environment, which allows it to change state at an instant in accord with the model's prediction pertaining to a later instant," [6]. Nadin's definition: "An anticipatory system is a system whose current state is influenced not only by a past sate, but [especially] by possible future states," [9] connects to the space of possibilities [10]. An anticipatory system cannot produce perfect models of its future internal or external environments since the future is always somewhat uncertain. In an anticipatory system, the system's imperfect models of the future influence how the system changes. Changes occurring in an anticipatory system can range from increased activation of regulatory enzymes to changes in individual or group behavior based on anticipated future conditions.

Anticipatory systems differ fundamentally from recursive (simple/reactive) systems, in which change is entirely due to the influence of forces occurring in the past acting on the present state of the system. Recursive change in physical systems was one of Newton's key discoveries [11]. Recursion in Newtonian mechanics means that what is occurring at a given instant in time (i.e., the positions, velocities, and forces acting on a set of particles) determines what occurs at the next instant in time. As Rosen wrote, "the heart of recursion is the conversion of the present to the future, or the entailment of the future by the present." In describing the Newtonian paradigm and its impact on scientific thought, Rosen said:

> The essential feature of that paradigm is the employment of a mathematical language with a built-in duality which we may express as the distinction between internal states and dynamical laws. In Newtonian mechanics the internal states are represented by points in some appropriate manifold of phases, and the dynamical laws represent the internal or impressed forces. The resulting mathematical image is what is now called a dynamical system […] Through the work of people like Poincare, Birkhoff, Lotka, and many others over the years, however, this dynamical systems paradigm or its numerous variants, has come to be regarded as the universal vehicle for representation of systems which could not be technically described mathematically: systems of interacting chemicals, organisms, ecosystems, and may others. Even the most radical changes occurring within physics itself, like relativity and quantum mechanics manifest this framework […] This, then, is our inherited mechanical paradigm, which in its many technical variants or interpretations has been regarded as a universal paradigm for systems and what they do. These variants take many forms: automata theory, control theory, and the like, but they all conform to the same basic framework first exhibited in the Principia [11, p. 78].

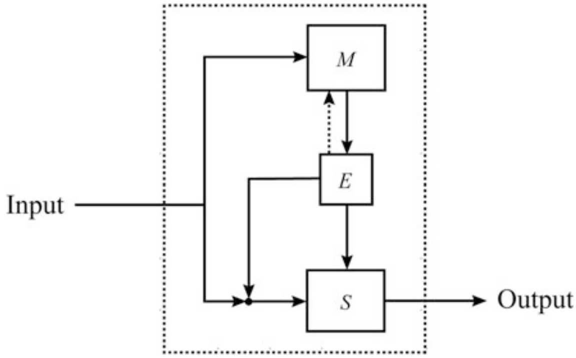
Louie, in "Robert Rosen's anticipatory systems" stated:

> Note, in contrast, that a reactive system can only react, in the present, to changes that have already occurred in the causal chain, while an anticipatory system's present behavior involves aspects of past, present, and future. The presence of a predictive model serves precisely to pull the future into the present; a system with a "good" model thus behaves in many ways as if it can anticipate the future. Model-based behavior requires an entirely new paradigm, an "anticipatory paradigm", to accommodate it. This paradigm extends—but does not replace—the "reactive paradigm" which has hitherto dominated the study of natural systems. The "anticipatory paradigm" allows us a glimpse of new and important aspects of system behavior [12].

Figure 1 depicts an anticipatory system. The system enclosed in the dotted box could represent an organism, an organization, or a social system. S, M, and E are components of the system depicted. M is a predictive model of S. Time variables in M run faster than real time. As a result, any observable of M serves as a predictor of a corresponding observable of S at a later instant. In addition, the "system M is equipped with a set E of effectors that operate either on S itself or on the environmental inputs to S" [12]. Louie describes how this system functions as follows:

> We shall now allow M and S to be coupled; i.e., allow them to interact in specific ways. For the simplest model, we may simply allow the output of an observable on M to be an input to the system S. This then creates a situation in which a future state of S is controlling the

Fig. 1 Anticipatory system (Modified from Louie [12])



present state transition in S. But this is precisely what we have characterized above as anticipatory behavior. It is clear that the above construction does not violate causality; indeed, we have invoked causality in an essential way in the concept of a predictive model, and hence in the characterization of the system M. Although the composite system (M + S) is completely causal, it nevertheless will behave in an anticipatory fashion [12].

2.1 Feedforward and Feedback

The concept of feedforward is closely linked to anticipatory systems. Feedforward in biochemistry has been defined as: *the anticipatory effect that one intermediate in a metabolic or endocrine control system exerts on another intermediate further along in the pathway; such effect may be positive or negative* [13].

Descriptions of feedforward regulation include this example from glycolysis:

> Control of a metabolic pathway by a metabolite of the pathway that acts in the same direction as the metabolic flux, i.e., downstream or "later" in the pathway, e.g., the activation of pyruvate kinase by fructose 1,6-bisphosphate [14].

If the anticipatory features of glycolysis are represented in Fig. 1, E = pyruvate kinase, M = Fructose 1.6 pyrophosphate, S = phosphoenolpyruvate (a substrate catalyzed by pyruvate kinase). The level of Fructose 1.6 pyrophosphate serves as predictor of subsequent levels of phosphoenolpyruvate. Increased Fructose 1.6 pyrophosphate levels upregulate the effector, pyruvate kinase. Pyruvate kinase then catalyzes the transfer of a phosphate group from phosphoenolpyruvate to adenosine diphosphate (ADP).

Louie has described the role of feedforward in anticipatory systems as follows:

> Anticipatory behavior involves the concept of feedforward, rather than feedback. The distinction between feedforward and feedback is important, and is as follows. The essence of feedback control is that it is error-actuated; in other words, the stimulus to corrective action is the discrepancy between the system's actual present state and the state the system should be in. Stated otherwise, a feedback control system must already be departing from its nominal behavior before control begins to be exercised.

> In a feedforward system, on the other hand, system behavior is preset, according to some model relating present inputs to their predicted outcomes. The essence of a feedforward system, then, is that the present change of state is determined by an anticipated future state, derived in accordance with some internal model of the world.
>
> We know from introspection that many, if not most, of our own conscious activities are generated in a feedforward fashion. We typically decide what to do now in terms of what we perceive will be the consequences of our action at some later time. The vehicle by which we anticipate is in fact a model, which enables us to pull the future into the present. We change our present course of action in accordance with our model's prediction. The stimulus for our action is not simply the present percepts; it is the prediction under these conditions. I emphasize again that "prediction" is not prescience, but simply "output of an anticipatory model". Stated otherwise, our present behavior is not just reactive; it is also anticipatory [12].

In the clinical scenario given above, the treating physicians and nurses had different anticipatory models of the likely clinical course of the patient being evaluated. These models strongly influenced their actions. A better-shared anticipatory model by the clinical team would have led to a better outcome.

3 Simple and Complex Systems

While complex systems are described in a variety of ways, it is generally accepted that the components (parts with a function) of a complex system are interrelated and that fragmentation or decomposition of these components causes a loss of information regarding the system [4, 15]. In *Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life*, Rosen defined complex systems in similar, albeit more precise, terms [11]. Rosen defined a simple system as one in which all of the information can be captured in a single formal model and complex systems as those in which all of the information cannot be represented by any single formal model or any finite sets of formal models. More details about Rosen's extensive work on modeling relationships can be found in Louie's brief summary "Robert Rosen's anticipatory systems" [12], or in Rosen's *Fundamentals of Measurement and Representation of Natural Systems* [16].

A brief summary of Rosen's conceptual approach to simple and complex systems is as follows:

1. Simple systems:
   a. Are non-living
   b. All of the information about the system can be captured in a single model of the system
   c. The system can be fractionated (broken into parts) and reassembled without loss of information about the system
   d. A system may be complicated and composed of many parts (i.e., an aircraft carrier) and still be "simple"
   e. All change is recursive

2. Complex systems:
    a. All living systems are complex systems
    b. No finite set of models can capture all of the information about the system
    c. A complex system can't be fractionated without destroying information about the relationship of the components of the system
    d. A primary characteristic of complex living systems is a capacity to adapt to a changing environment
    e. Complex living systems are anticipatory, meaning they have a capacity for change based on inputs from their anticipatory models

3.1 Stability of Anticipatory Complex Systems

There are important differences governing the stability of simple and anticipatory complex systems. To paraphrase Rosen, in a simple system every global failure results from local failures in the component subsystems; however in a complex system, a global failure is not necessarily associated with a local subsystem failure [17]. Anticipatory complex systems may malfunction when a component in the system fails. What distinguishes an anticipatory complex system from a simple system is that its stability is also dependent upon the accuracy of its models or representations of its present environment and of its anticipatory models of its future environment. While a complex system cannot, by definition, have a perfectly accurate and comprehensive model of its internal and external environments, the more accurate an anticipatory complex system's models are of the states of its present and future environments, the greater the likelihood of the ongoing stability of the system. Conversely, the greater the divergence between the models or representations of an anticipatory complex system and the actual present and future environments, the less adaptive will be the system's responses to the present and future environments, and the greater the likelihood of the system malfunctioning.

4 Application to Improving Safety and Quality in Healthcare

If Rosen's theory of anticipatory complex systems is correct, the following actions would be appropriate approaches for improving the safety and quality of healthcare [18]:

4.1 Education for Clinical Teams

Members of clinical teams, including physicians, advanced practice providers, nurses, pharmacists, social workers, and ancillary care providers, should be educated about the characteristics of anticipatory complex systems in clinical environments. Key concepts would include the following:

a. All patient care encounters involve interactions between complex systems (people).
b. A clinician or clinical team's model/representation of a patient (complex system) can never be absolutely accurate.
c. It is impossible for a team of clinicians, or a team of clinicians, patient, and families to ever have a fully congruent shared mental model of a patient's complex clinical situation.
d. Clinicians, clinical teams, patients, and families are continuously generating anticipatory models representing possible future events and risks [19]. Inputs from the anticipatory models of clinical team members, patients, and families may be useful for identification of and real time mitigation of some clinical situations in which there is an increased risk of a future serious adverse outcome.
e. Clinical experience is likely to contribute to a capacity for generating more accurate anticipatory models. For example, nurses with more than 1 year of experience were significantly more accurate in identifying patients at risk for physiologic deterioration than those with less than 1 year of experience. (72 % vs. 53 %, $p < 0.05$) [20].
f. Clinicians, clinical team members, patients, or family members who believe, even if based only on a "gut sense" or intuition that the diagnosis or plan for a patient is wrong or that a patient is at high risk for an adverse outcome, should be encouraged to speak up.
g. Greater concordance between the models of the current situation and anticipatory models of future states among clinical team members, and among the clinical team, patient, and family increases the likelihood of attaining preferred outcomes.
h. Better concordance between a team's model of a clinical situation and the actual clinical situation will occur if there is an opportunity for meaningful input and for the expression of discrepant views from all team members and from patients and families. A team environment that encourages the expression of divergent input is likely to arrive at a better understanding of the current clinical situation and to have an improved capacity to more reliably anticipate future events.
i. Significantly discrepant present-state or anticipatory mental models between clinical team members or between team and patients/families may indicate an increased risk for an adverse outcome. Recognizing and reevaluating when such divergent opinions exist may provide opportunities to mitigate future risks.
j. Situational Awareness education could be enhanced by including the fact that people (and other complex systems) are continually generating anticipatory predictions of future outcomes and that these predictions can be useful for guiding present decision making. This could help augment and strengthen the approach promoted in situational awareness to "thinking ahead" based on an extrapolation of information known about the current situation [21].

4.2 Education for Patients and Families

Patients and families should be advised that: (1) Care maps represent what we anticipate happening; (2) if they don't agree with the clinical teams' plans that they should alert any care provider; (3) if things don't seem to be going the way the patient/family thought they should (either by a gut sense or something different from the care maps) the patient/family should let any care provider know, because the patient and family know the patient better than any of the clinical team and may notice changes earlier than will members of the clinical team.

4.3 To Do List for Healthcare Institutions

a. Support systems for capturing the clinical team's anticipatory predictions of risk of deterioration or events and to encourage planning based on these predictions. The I-PASS handoff tool, which encourages identification of patients requiring additional monitoring and contingency planning, is an example of this approach [22].
b. Encourage clinical team members to voice concerns about the understanding of the current clinical situation and/or of the risk of future adverse events.
c. Promote a culture in which hierarchy and power gradients do not inhibit clinical team members from sharing anticipatory predictions.
d. Reward clinical team members who express anticipatory predictions.
e. Provide Institutional support for structured clinical rounding, including patients and family members, to create opportunities for information sharing and for raising of questions, concerns, or identification of situations in which divergent models may indicate an increased risk to patient outcomes and safety.
f. Encourage team briefs/huddles as team strategies for creating plan for the day.
g. Support increased availability of clinical decision making tools (e.g., dashboards/reports/summaries to use during rounding that would incorporate real-time results of risk stratification models).

4.4 Measurement Possibilities

An agreement tool, such as one developed to assess a patient's degree of agreement with the clinical team about diagnosis, diagnostic plan, and treatment plan could be administered to patients or patients and families and in one or more of the following ways [23]:

i. Tracking incidence of significant disagreement on an ICU or inpatient unit, providing an alert to clinical team members and assessing the frequency in which identification of significant disagreement resulted in a clinically important change in management.

ii. To determine if a correlation exists between care coordination sensitive outcomes (LOS, patient satisfaction, show rates at follow-up appointments) and clinical teams with higher agreement scores.
iii. If a correlation between better agreement and care-coordination sensitive clinical outcomes exists, feedback to teams about aggregated patient/family agreement scores could be provided to determine if this resulted in improved agreement scores and in improved care-coordination sensitive clinical outcomes.
iv. A modified agreement instrument (do you agree with the team's diagnosis, diagnostic plan, and treatment plan) could be administered to interdisciplinary clinical team members to determine if a correlation exists between teams with higher agreement scores and improved care coordination sensitive outcomes (LOS, patient satisfaction, show rate a follow-up appointments).
v. An agreement instrument could be employed in an outpatient setting to determine if better agreement is associated with outcomes such as intention to adhere to treatment, patient satisfaction, or symptom resolution. (In a pilot study of 39 patients with new or worsening problems higher agreement scores were correlated with both better patient satisfaction ($p = 0.029$), and intent to adhere to treatment ($p = 0.011$) [24].

5 Conclusions

Healthcare organizations are complex adaptive systems in which improving safety is an ongoing challenge and imperative. If Rosen's and Nadin's anticipatory systems hypotheses are correct, an enhanced understanding of the characteristics and failure modes of anticipatory systems could supplement existing safety practices and help an organization further reduce the risk of certain serious adverse events. Organizational interventions based on an anticipatory theory of complexity could include: (1) education of clinicians, patients, and families on how anticipatory complex systems function and contribute to improving safety in clinical environments; (2) systems interventions to promote optimal concordance between a team's model of a clinical situation and the actual clinical situation; and (3) development of measurement instruments to provide feedback to help improve performance in these areas. An enhanced general understanding of anticipatory complex systems and of their failure modes could help reduce communications failures that are the most common root cause of serious adverse event.

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