Computer visualisation of patient safety in primary care: a systems approach adapted from management science and engineering

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ABSTRACT

Patient safety and medical errors in ambulatory primary care are receiving increasing attention from policy makers, accreditation bodies and researchers, as well as by practising family physicians and their patients. While a great deal of progress has been made in understanding errors in hospital settings, it is important to recognise that ambulatory settings pose a very large and different set of challenges and that the types of hazards that exist and the strategies required to reduce them are very different.

What is needed is a logical theoretical model for understanding the causes of errors in primary care, the role of healthcare systems in contributing to errors, the propagation of errors through complex systems and, importantly, for understanding ambulatory primary care in the context of the larger healthcare system. The authors have developed such a model using a formal ‘systems engineering’ approach borrowed from the management sciences and engineering. This approach has not previously been formally described in the medical literature.

This paper outlines the formal systems approach, presents our visual model of the system, and describes some experiences with and potential applications of the model for monitoring and improving safety. Applications include providing a framework to help focus research efforts, creation of new (visual) error reporting and taxonomy systems, furnishing a common and unambiguous vision for the healthcare team, and facilitating retrospective and prospective analyses of errors and adverse events. It is aimed at system redesign for safety improvement through a computer-based patient-centred safety enhancement and monitoring instrument (SEMI-P). This model can be integrated with electronic medical records (EMRs).

Keywords: EMR, medical errors, modelling, patient safety, quality, systems, visualisation
Introduction

The problem of errors in health care

As a result of the well-known reports on safety and quality from the Institute of Medicine (IOM) and other influential publications, patient safety is receiving increasing attention from all parties that are involved in health care including doctors, nurses, other healthcare workers, clinics, hospitals, third-party payers, accreditation bodies (most notably in the United States [US], the Joint Commission on Accreditation of Healthcare Organizations [JCAHO]) and, importantly, the patients themselves. This concern and attention has begun to result in some significant advances.

However, progress is slow and far short of expectations. The healthcare industry has continued to lag behind the major safety developments that have taken place in other high-risk industries such as aviation, defence, nuclear and chemical industries. Fragmentation, decentralisation and the lack of a safety culture in health care are among the major causes of this lag. In addition, healthcare systems are highly complex, involving multiple diverse entities with sophisticated and unpredictable interactions that make them much more difficult to study.

Errors in primary care

While much information exists about hospital-based errors, the IOM acknowledges the dearth of data from office-based settings. Much of what is known so far comes from the American Academy of Family Physicians (AAFP) Policy Center’s Studies. From their US studies of errors reported by family physicians, nearly 66% of errors are caused by process and charting problems (such as missed lab results, failure to schedule follow-ups), 15% by non-compliance, 13% by medication errors and 3% each are caused by clinical judgement and interdisciplinary communication problems. Half the errors did not appear to affect patients, but one in ten led to worsening illness, one in five to delayed care, one in four to patient upset and one in 20 led to hospitalisation. Other important studies in primary care have examined errors reported by physicians and staff, errors perceived by patients, adverse drug events, and missing information. Much remains to be done.

Importance of the ‘system’

A common and important thread that runs through all of the most influential work on patient safety is the importance of seeing safety as a ‘systems’ property. Most notably, the IOM reports describe the current US healthcare system as a fragmented and decentralised ‘non-system’ and identify this ‘non-system’ as a major source of medical errors. The challenge is to understand the current systems as the context in which errors occur so that we can begin to take steps towards redesigning the systems for safer care. In this process, it is hoped that healthcare organisations, accreditation bodies, and the legal system will gradually shift from the prevailing culture of blame to a culture of safety in which individuals are held accountable for their actions but are not blamed or punished for the majority of errors that are due to system problems.

Many organisations are trying to adopt such an approach that focuses on the system and some are using analytical methods such as root cause analysis for retrospective analysis of adverse events and failure mode and events analysis for prospective anticipation of errors. Although they represent progress, these and other efforts to focus on the system are hampered by the sheer complexity of the processes of healthcare delivery, the involvement of multiple personnel, the lack of standardisation, and the fragmentation and decentralisation of the healthcare system as a whole. In addition, success of these efforts will require that the information and understanding gained be conveyed in an easily understood fashion so that it can be widely disseminated to all relevant parties within an organisation.

What is needed to complement and stimulate these system-based efforts is an approach that is able to capture the complexity of the system and facilitate analyses, development of system-based solutions and dissemination of results. Such an approach exists; it is known formally in the engineering and management fields as ‘the systems approach’, or ‘systems engineering’. In health care the term ‘systems approach’ is widely used to convey a general focus on system issues as described above. However, the approach that we are presenting here is a specific one borrowed from management science and engineering. For clarity we shall refer to it as the systems engineering approach. This approach has been widely used in other industries with considerable success and has been advocated by the IOM. Despite the widespread acknowledgement of the importance of systems and the IOM’s endorsement of systems engineering, the approach has not previously been formally described in the medical literature. We will now give a brief overview of this approach and describe how we have used it to develop a visual model of the healthcare system that has helped us to understand safety and errors in primary care and enhance safety education, at undergraduate and postgraduate levels, as well as to improve safety practices.
Systems engineering: a very brief overview of the established philosophy

The systems engineering approach has been widely used in engineering, nuclear power and other safety-critical industries with a great deal of success.\textsuperscript{27–32} There is a very large number of professional societies, associations, institutes and academic departments that propagate systems thinking and practice. Most masters’ programmes in business administration incorporate this discipline and some of its techniques in their curricula. While it is important to acknowledge that health care is not the same as these other industries, it would be unwise to ignore the lessons that have been learned in these other contexts. In fact, the systems engineering approach has been used in many diverse contexts and its widespread success is testament to its generalisability.

The origins of the systems engineering approach can best be seen in the philosophy of holism. Holism is defined as: \textit{the tendency in nature to form wholes that are greater and better than the sum of the parts, by creative evolution.}

This approach centres on acknowledging the existence of wholes (systems) that are greater and better than the sum of their parts (components) due to multiple interactions and synergism between these components. It therefore mandates the study of these interactions and synergies (or lack thereof) and their effects on the whole system. Any study or evaluation that is limited to individual components and fails to acknowledge their interactions is flawed and inadequate. By studying and understanding not only the individual components of a system but also the way in which these components interact and work together as a whole, the systems engineering approach provides for meaningful evaluation and effective intervention to improve the functioning of any system. It has been applied in a vast variety of human endeavours ranging from political campaigns to space exploration. The approach can be qualitative and/or quantitative. The terms \textit{management science} and \textit{operations research} (OR) are frequently used to refer to the quantitative aspects. The beginnings of OR can be traced to World War II, when the United States and Britain employed many of their best mathematicians and physicists to analyse and optimise military operations.

Subsequent development of new techniques that could be applied to a host of decision-making problems, combined with the availability of powerful computers, allowed these techniques to be enhanced and applied rapidly to large-scale optimisation problems, taking into account constraints on resources. These techniques can be broadly classified as deterministic (relying on single estimates of input data) and probabilistic (acknowledging uncertainty in the input data). The latter are particularly relevant to risk and reliability problems in equipment, human behaviour and their interaction. Healthcare systems can derive great benefits from the use of the various OR techniques, including multi-objective and multi-resource optimisation algorithms. Recent developments, for example in artificial neural networks, expert systems and relational databases, are best seen in the context of the systems engineering approach.

Systems engineering is a comprehensive approach that calls for and encourages ‘transdisciplinary’ teams to attack decision-making problems. This approach is made up of two essential steps, known as ‘analysis’ and ‘synthesis’. The first is to ‘analyse’ the problem through clear identification of all the \textit{entities} and \textit{processes} involved. The second is to ‘synthesise’ or model by clearly establishing the interactions or desired interactions between these \textit{entities} and \textit{processes}. We will illustrate this approach by describing how it was used to develop our visual model.

Implementation of the systems engineering approach to modelling of the healthcare system: analysis and synthesis

The two key steps in the systems approach, namely analysis and synthesis, are achieved as follows.

Analysis

This is achieved through clear identification of all the \textit{processes} and \textit{entities} involved in the healthcare system, and the \textit{domains} in which they exist. The processes are the activities or steps that take place. For our analysis we identified the five basic processes of care listed in Box 1(a). Once the processes have been identified, the next step is to acknowledge all the various entities that are involved in these processes. These will include people as well as equipment and other items that are involved, as shown in Box 1(b). Finally, it is important to define the domains in which the processes and entities exist. In our model for primary care patient safety we needed to capture all the domains with which the patient might interact, that is, the entire healthcare system. The list of domains is given in Box 1(c).

The analysis, that is, identification of these processes, entities and domains, should be as detailed as possible, within the time/resource constraints under...
which one is working. The next step is to construct the model, that is, synthesis.

**Synthesis**

This requires that for each domain there is clear identification of all the interactions or desired interactions between processes and entities. These are then expressed in a systems mode. The resulting model is greater and better than the sum of the individual parts. By modelling the healthcare system using the systems engineering approach, healthcare professionals and policy makers can start to address many of the problems of fragmentation and decentralisation, that plague the current healthcare 'non-system', particularly that of the US. In the approach presented here, synthesis is achieved by a visual portrayal of all the processes, entities, interactions and the temporal relationships involved in each domain. Such a visualised model can permit a common language so that all parties can focus their energies together toward achieving safer health care.

The first step in this synthesis is to formulate an overall model of the macro-system, as shown in Figure 1. This is a high-level view of the healthcare system. The processes listed above are represented by the radials. The processes of health care are recognised to occur in a cyclical fashion as shown by the clockwise progression around the circle from Assessment to Plan to Implementation, Feedback, Review and back to Assessment again.

These processes in the cycle of care take place in various **domains** (as identified above) that are depicted by concentric circles. The increasing sizes of the circles depict the enlarging involvement of the system, starting from the patient level (circle no. 0) at the centre to the international health authority level (circle no. n) on the outside. The innermost circle represents the patient in his/her own domain (that is, home/community) and recognises that this is the place where most health care actually occurs. International authorities, depicted by the outer circles, play an important role in devising public health policies that can impact everyday management of patients in primary care.

Office-based care, the focus of primary care, is represented by circle no. 1. Depending on the system under study, circle no. 2 might represent the emergency room and no. 3 might represent the hospital inpatient setting, and so on.

The intersections between the circles and the radials represent the various micro-systems within the overall macro-system. Alphanumeric codes are used to identify each micro-system unambiguously. For example, 1A represents assessment of the patient in the office setting (circle 1).

The next level in synthesising the model is to construct the micro-system diagrams that show how

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**Box 1 Processes, entities and domains of care modelled**

(a) **Processes of care**
- Assessment (of the patient)
- Plan (formulation of a plan of management)
- Implementation (of the plan)
- Feedback (from the patient and other parts of the system, regarding the patient’s progress, results of investigations and interventions, and so on)
- Review and learn (evolution of the system)

(b) **Entities involved in these processes** (these are numerous but can be classified broadly)
- Patients, families and communities
- Health system workers
- Leadership and teams
- Non-human entities such as equipment, supplies, charts, EMR and so on

(c) **Domains in which care processes takes place**
- Home/community
- Ambulatory primary care
- Ambulatory specialty care
- Nursing home/long-term care
- Emergency room
- Inpatient
- Regulatory authorities (local/national/international) – these are included because of their ability to influence care in the other domains
the entities listed earlier interact at each point in the cycle. Depending on the purpose for which the model will be employed, the synthesis could be more or less detailed and could focus on specific areas of interest.

Each of the micro-systems is represented by two diagrams – an ‘influence’ diagram and a precedence diagram. The influence diagram depicts the entities, their interactions and the processes that take place. The precedence diagram shows these relationships in terms of chronology.

Figure 2(a) is a simplified example of the ‘influence’ diagram for micro-systems 1A and 1P. In general, a separate diagram is used to depict each micro-system. However, in this presentation we have chosen to combine the Assessment and Plan processes since they occur in close proximity to one another and involve many of the same entities and interactions. The diagram depicts the entities involved (doctor, patient, nurse, medical record, and so on) and the interactions that take place between them. Each interaction is shown as an arrow. Errors or safety problems can originate at any point in the system.

Figure 2(b) is the corresponding simplified ‘precedence’ diagram. This depicts the chronology of the interactions/steps that must take place. This helps in understanding the time-dependence of the interactions/steps and in identifying problems such as waiting time, fatigue, and delays and ambiguities in communication and hand-offs.

The macro-system and micro-system diagrams are computerised and contain hyperlinks that facilitate hierarchical links and dynamic data links with various databases and reporting templates. For example, any point on the influence diagram can be linked electronically to a table containing relevant data about errors that are known to occur at that point in the system with details of frequency and consequences of these errors as well as corrective action.

Discussion

It is well known that visual portrayal of a system is an efficient representation strategy, one that enhances both learning and memory. Specifically, a visual model can enhance the user’s identification of the problem, its understanding, solution and communication with minimum ambiguity. Advantage of this has been taken
in numerous other domains including the military, aviation industry, construction and manufacturing.

The model we have presented and used is adaptable, upgradable, easily transferable, can be integrated into electronic medical records/electronic health records (EMRs/EHRs) and can provide the following functions:

- **Research**: The visual model provides a common ‘road map’ for researchers by helping to break down the patient safety problem into its component parts, and helping scholars to understand the relationships between the parts. This approach can help researchers to identify the entities, domains and processes that require study, and to see their research in the context of the whole system; in other words, to see their own and others’ work as part of the ‘whole picture’.

- **Creation of an intuitive visual error taxonomy and reporting system**: Error taxonomies have an important role to play in classification and communication of error data. Most taxonomies suffer from problems of ambiguity and accessibility due to their high complexity. Using a visual format is one way of making taxonomies more manageable from the user’s perspective. For example, to facilitate error reporting, the visual model would be incorporated into a computer database and the reporter could simply click on the relevant part of the macro-system model on their computer screen to identify the domain and process in which the error occurred. They would then be presented with the relevant micro-system model and they would click on the appropriate point to identify the entity or interaction where the error took place. They would then have the opportunity to enter detailed information regarding the circumstances, causes and consequences of the error. Collecting data in this fashion gives rise to a ‘visual database’ that can be accessed by the same ‘point and click’ approach. Such a database could be used for research, or quality improvement purposes or even be integrated into an EMR (incorporating inductive and deductive decision support systems) to provide real-time error information to healthcare workers at the point of care.

- **Analysis**: Various analytical methods are used by safety experts to examine the causes of adverse events (such as root cause analysis), as well as to look prospectively and anticipate errors and evaluate their potential consequences (for instance, failure
modes and effects analysis). Woolf et al have reported the use of cascade analysis to delineate the causal chain of events for primary care errors. While the details of these analyses are beyond the scope of this paper, it is worth noting that the computer-based visual modelling approach that we have proposed can be very helpful as a tool to enhance/augment these methods of analysis.

- **Team-building**: The model provides a common and shared vision for formation of healthcare teams, including the patient in the team. This visual portrayal can help each individual to understand their role within the system and their relationship to the larger system.

- **Training**: Interdisciplinary education of healthcare providers, including students, nurses, physicians, as advocated by the Department of Health and Human Services. The model can help identify educational needs and also be used as an educational tool.

- **Patient education**: Helping patients to understand their role within the larger system and thus empowering them to advocate for themselves and potentially leading to reductions in patient- attributable errors.

- **Patient tracking**: Providing a means to track a patient’s encounters with the healthcare system over time, recording their interactions across the various parts of the system (for example, office, emergency department, inpatient setting). This can help improve continuity of care and reduce the risk of ‘hand-off’ errors that occur at transitions, such as from inpatient to office.

- **Dissemination of information**: The model facilitates visual portrayal of complex information that can be tailored for each stakeholder, ranging from the individual patient, to the safety committee of the organisation, to a national accreditation body. The computerised visual database format described earlier could provide a user-friendly interface.

The authors have used these macro- and micro-systems models in various ways with success, including development of an error survey tool termed ‘safety enhancement and monitoring instrument’ (SEMI-P). This tool identifies multiple errors at each point in the system and elicits staff perceptions of frequency and severity of each. It has been used to help form teams to identify priorities for quality improvement, and also to estimate the effects of implementation of an EMR on perceived safety hazards within a practice. Figure 3 shows an example of the SEMI-P. The models have also been successfully used as the basis of patient
Figure 3  Hyperlinks between macro-system, micro-system and errors instrument (part of safety enhancement and monitoring instrument (SEMI-P))
safety training programmes for medical students and residents. Further, the authors are currently collaborating with leading national and international primary care error taxonomy developers to use the visual system models as an interactive interface, with the aim of creating an unambiguous and intuitive visual error database of the kind described above. Our experience to date suggests that a variety of healthcare workers are able to relate to the visual models and find them helpful in understanding their roles within the system as well as opportunities for errors and ways of preventing them.

The extent to which healthcare workers will relate intuitively to this visual systems approach is uncertain and will likely vary with the type of training received and the nature of the healthcare systems in a particular country. Advances in healthcare training incorporating team perspectives and informatics will likely facilitate acceptance of this kind of approach.

To be maximally relevant and useful, models such as the ones presented need to be adapted to the user’s specific circumstances and needs. This can be labour-intensive and requires training.

Conclusions

Safety is increasingly being recognised as a system property. The challenge faced by today’s healthcare leaders (in the US at least) is to understand the current fragmented and decentralised systems as the context in which errors occur so that we can begin to take steps towards redesigning the systems to prevent errors and reduce the potential for harm to our patients.

A comprehensive and transdisciplinaries systems approach has been applied to identify and analyse the processes, entities and domains of health care as well as to synthesise the interactions between them in the form of a computer-based interactive visual model. The model is comprised of macro- and micro-system diagrams that are linked hierarchically to one another and dynamically to databases to capture the complexity of healthcare systems.

There is a tremendous need for further research to understand the causes and consequences of errors in primary care. It is hoped that the proposed visual model based on a formal ‘systems engineering approach’ can serve as a framework to guide and shape some of these efforts.

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CONFLICTS OF INTEREST

None.

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Accepted March 2005