The Dynamics of Hospital Medication Errors: A Systems Simulator Testbed for Patient Safety Interventions

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ABSTRACT: Medication errors in hospitals are a large and increasing problem, which has traditionally been considered a result of human error. Recent attempts to reduce errors have emphasised systems approaches and improvements in information and communications technologies (ICT). As part of a multi-method evaluation project for hospital point of care clinical systems, we assembled a team of professionals from a variety of clinical, information management, health management, sociology, linguistics and engineering backgrounds. We built a systems simulation for explicitly representing the interactions among the key determinants of medication errors. These included the complex interactions of patients and staff, information, medications, work practices and the infrastructure and policies within a hospital environment.

Our team simulated hospital inpatient and staff flow, generation and interception of medication errors, and the potential impacts of ICT-enabled work practice changes. This paper describes the System Dynamics Model of long-term context that produces errors in the medication management process. Future extensions include the use of a combined agent based and SD simulation to produce a multi-method, multi-level systems simulation testbed as an integrating framework for evaluating combinations of improvement interventions.

KEYWORDS: health systems simulation, medication error, information and communications technology, multi-method evaluation

The complexity of hospital medication safety

Hospitals have been considered as the most complex organizational management challenge (1). The pharmaceutical industry now produces an ongoing stream of new potent and potentially toxic drugs for use in hospitalized patients under close supervision.

Medication errors in this complex setting are a long-standing problem, whose true scale may not be fully known (2). The harm done to patients by preventable adverse drug events can include death, long-term disability and severe pain. While there are no reliable long-term trend data available to track ward medication safety, there is evidence that many incidents are not reported. It is likely that errors may be increasing due to a multitude of interacting influences (3). A recent study in the elderly corroborates this probable increasing trend in the adverse effects of medication errors.
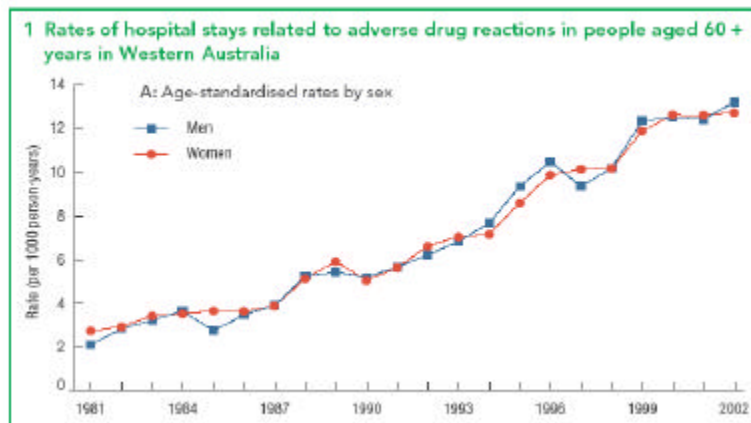
MJA 2005; 182: 267–270 Adverse drug reactions in older Australians, 1981–2002
Christel L Burgess, C D'Arcy J Holman and Anthony G Satti

Inpatient medication errors may be more frequent because sicker, more complex patients are being admitted and they receive more care during the shorter time they spend in hospital. Nurses are busier, their work constantly changes and larger teams of health professionals from many specialised disciplines are harder to organize and understand each other. Poorly introduced new medical, information and communication technologies disrupt work and add to the pressure and staff turnover. There are many more medications to choose from and to combine in complex, changing treatments. Defensive documentation and compliance reporting adds to the workload and frustration (4).

Medication errors have been represented as active failures in the medication management process of prescribing, ordering, dispensing, administering and monitoring patient medications (5). These errors occur when multiple latent system conditions interact with individual fallible human behaviors. Error prevention requires bundles of mutually reinforcing practices to discover and fix latent system conditions, foster personal mastery, and provide stronger defences to intercept the errors which will inevitably occur in complex human systems (6).

The context for medication error includes:

Organizational Management Practices (reflected in levels of trust, quality of communications, worker involvement and influence, level of centralized policy control and sanctions, and management of change and organizational learning),

W*orkforce Deployment Practices* (staffing levels, fatigue avoidance, training and skills maintenance, supervision, equipment, supplies and infrastructure support),

Work Design (the right level of production efficiency and reliability, adequate face-to-face patient surveillance, avoiding workarounds, task interruptions, excessive documentation and other low-value activities), and

Organizational Culture (management, team and individual attitudes and commitment to safety) (8).

Various interventions to reduce medication error, such as frequent checks, pharmacist review, technologies and information systems, have been introduced with mixed results. Attempts to clarify the analysis of medication error generation and interception have focussed on the nature of clinical work and the study of socio-technical systems of man-machine interaction, together with workflow and process improvement mapping (9). In the area of information and communications technology (ICT), a conceptual framework for evaluating electronic Prescribing (eRx) and clinical decision support (CDS) has been developed recently. This framework is based on a process view of the key activities of prescribing, order transmission, dispensing, and administration, with overall monitoring and evaluation of the patient and the system (10). Much more can be done to improve

clinical decision support. A complex set of eRx and CDS intervention areas have been recommended recently by the American Medical Informatics Association (11), including

• Knowledgebase – the types of rules, content, and interventions that are available in the System,

• Database – necessary data elements needed to permit targeted, patient-specific, event-specific CDS,

• Functionality and usability – aspects of the day-to-day operation of the eRx system that must be considered and implemented in order to make it acceptable, implementable, and efficient, and

• Organizational – governance, communication, policy and management structures and processes that are essential for effective, appropriate use of CDS on an ongoing basis.

In health care and other industries broader systems approaches to organizational safety have been described, including several system dynamics views of the interaction of contextual and latent human factors that allow a chain of events to result in harm, despite several levels of checks and balances (6,7). In health care, the Swiss cheese model of errors propagating through aligned holes in organizational defenses has been a popular metaphor (7,14).

The Use of Simulation

Simulation has been used to grapple with the complexity of medication error generation and interception, again using a process chain of error events and responses in prescribing, order transmission, dispensing, administration, with overall monitoring and evaluation. (15). The broader system context which leads to a chain of errors ("an accident waiting to happen") has been described for a public health water contamination disaster in system dynamics terms by Marais and Leveson (16) and organizational safety factors in mining by Cooke (17). There are other relevant system dynamics work related to hospital systems safety. Oliva (18) has covered responses to work pressure in service industries and discusses the impacts of working harder, cutting corners, lowering standards and

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expectations which delays (sometimes indefinitely) the resourcing of additional required capacity. He describes how this is particularly difficult in health care, where high professionalism and long training times make the situation worse than other industries. This results in a predominance of working harder, with resulting burnout and its consequences (19). Time pressures and the need for constant workarounds make it difficult to learn from failures in hospitals (20). Tensions between professional "tribes" can make innovations that work in one hospital fail in another (21).

The Simulation Dimension of Our Evaluation Project

This simulation work is associated with a larger, multi-year, multi-disciplinary, multi-method approach to evaluate the impact of information and communication technologies on organizational processes and outcomes. The larger project aims to comprehensively measure the impact and consequences of ICT on organizational processes and outcomes. Also, it may identify key factors that predict improvement in organizational processes and outcomes, and incorporate these factors into IT implementation and management programs. Other research questions include:

- What contributes to staff acceptance and effective use of ICT in complex organizations?
- What indicators can be used in multiple industry sectors to assess and manage the business risk of ICT implementation?
- What predicts improved decision-making and improvements in organizational processes and outcomes (e.g. error and cost reduction)?

We added simulation to the electronic prescribing component of the project to demonstrate its potential to integrate the evaluation framework. It provides a "virtual pilot" for the project to explore, test and refine hypotheses about the relevant interactions among multiple parameters of interest. It may be able to communicate the complicated story of computerized hospital prescribing more clearly. Finally we hope the "in silico" pilot can help focus the "in vivo" real evaluation efforts on the right areas and close any significant data gaps in the larger project.

Based on our previous system dynamics modeling in national medicines use (23), incident reporting, workforce and double loop learning, we worked with a team of professionals from a variety of clinical, information management, health management, sociology, linguistics and engineering backgrounds. Together we simulated hospital inpatient and staff flows, the generation and interception of medication errors, and the potential impacts of ICT-enabled work practice changes.

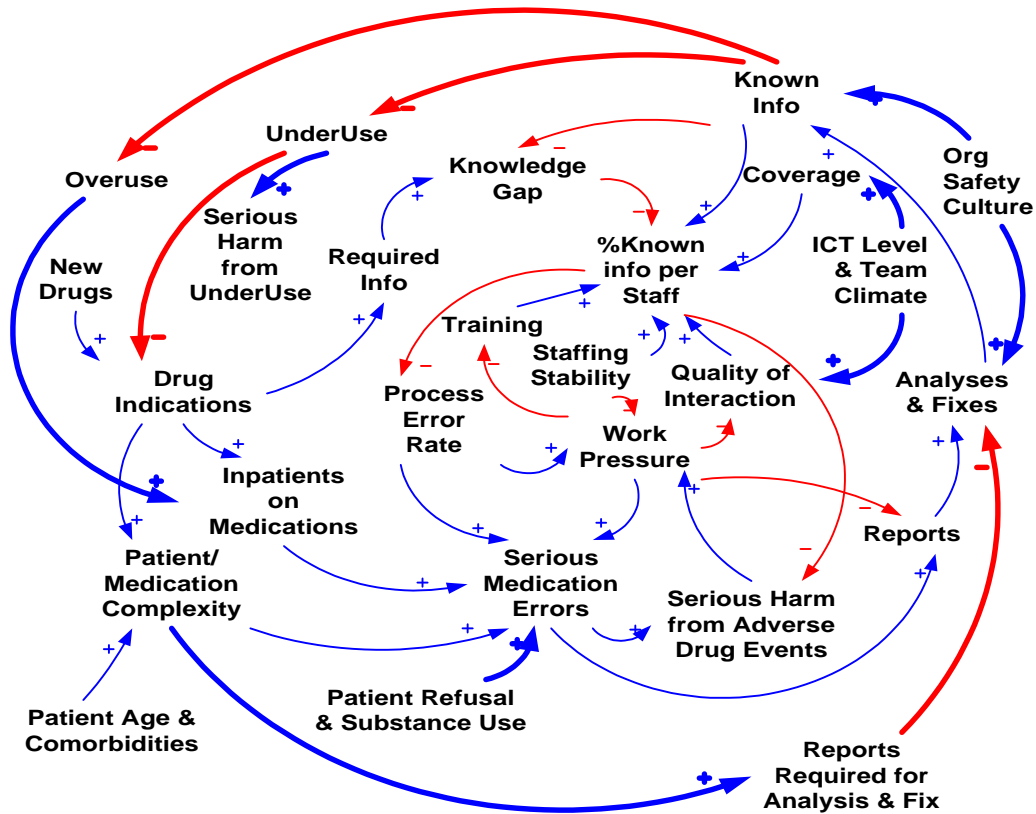**Causal Loop Diagrams Description of Long Term Medication Error Dynamics**

The dynamics of increasingly complex medication use and reporting of errors back to staff is shown in CLD A below.

New medication indications lead to increasing multiple medication use. The complexity of hospital medication use is also increased by patient complexity due to increasing age and multiple illnesses (comorbidities) in those patients ill enough to require admission. More information is required to safely use more drugs in these more complex patients, increasing the knowledge gap between the information required and the actual information acquired by staff involved in medication management processes. This actual information about a particular hospital's medication errors is acquired through error reporting, root cause analysis of reports, and developing and implementing prevention strategies that work. Reduction in process errors such as prescribing and administration and interventions to mitigate harmful effects of errors also depend on disseminating that information widely to staff.

CLD A Operational View with Drivers of Complexity and Reporting Feedback to Staff
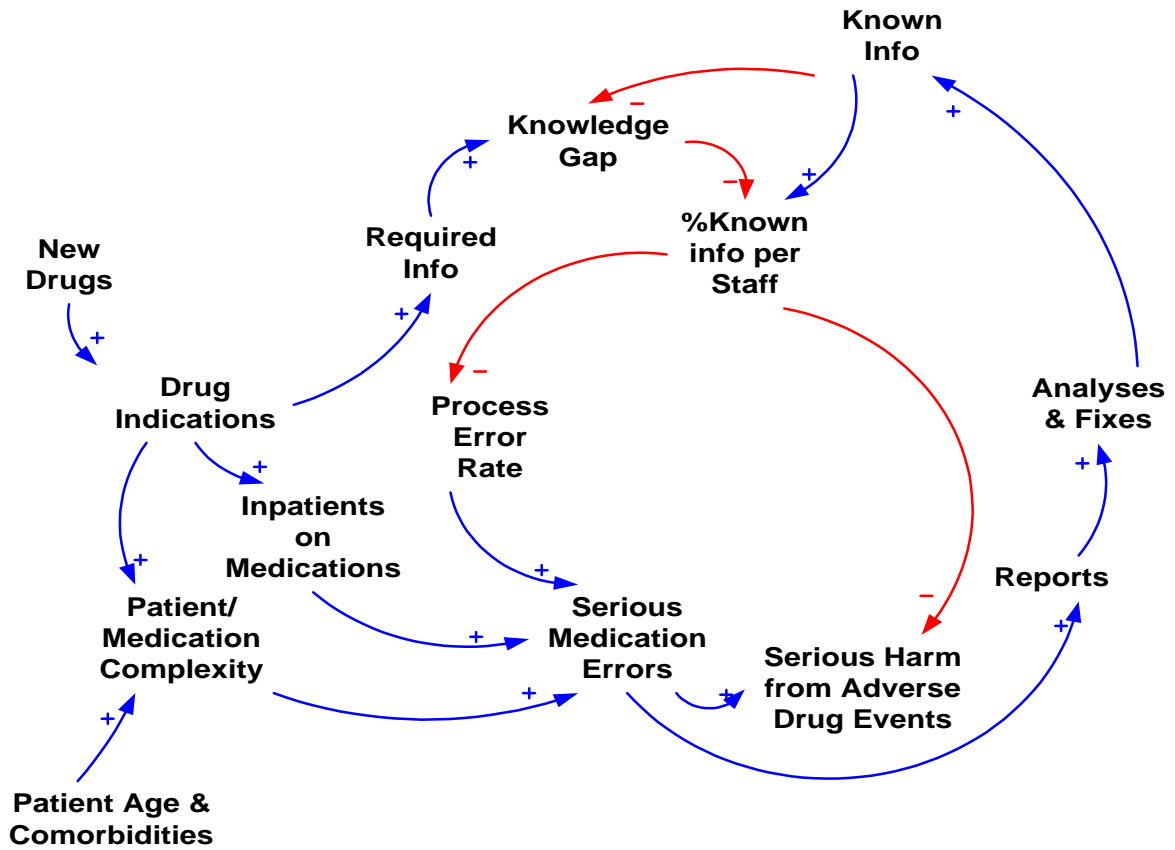
Additional interactions relating to work pressure and increasing the deployment of organizational knowledge to staff are added in CLD B below. Errors increase work pressure, which then tend to reduce the time available for training and the quality of interaction and knowledge exchange among staff. Deployment of knowledge to individuals increases with training and ability of the organization to reach every staff member. Low staff turnover also reduces work pressure and can help retain individual staff knowledge.

CLD C adds the interactions of other context issues such as organizational safety culture, team climate and level of ICT infrastructure. A good organizational safety culture is shown as increasing the quality of the hospital's knowledge repository of how things work and the amount and quality of analyzing and fixing safety problems. The levels of ICT infrastructure and team climate are shown as increasing the coverage and access to staff within the organization and the quality of interaction. The amount of known information reduces both the overuse and underuse of medicines, so reducing both the number of patients on medications and the harm due to patients being denied effective medicines.

The multiplier effect of increasing complexity of use requiring more reports to understand and prevent what is happening, together with the complicating effect of patient refusal of effective medicines and surreptitious use of alternative therapies, is also shown below.

ithink Model Description

An ithink model of the overall long-term dynamics of hospital medication use is supplied in the supplementary material. It consists of the listing and removal of drugs on the hospital formulary and the impact of number of drugs in use and the rate of new indications on the stock of required information.

The influences on the stock of actual known information are also represented, including staff turnover. The difference between the information levels of new employees and those staff that quit is also explicitly represented. Also the positive feedback effect of increasing level of adverse events on turnover is included.

The effects of these context variables on the flow of patients with prescribing (Rx) and administration errors and the points where errors can be intercepted and mitigated before causing serious harm are shown in the model segment below.

Other sections represent reporting and analysis and overall ICT impacts.

Patient Medication Error Flow Chain of ithink model
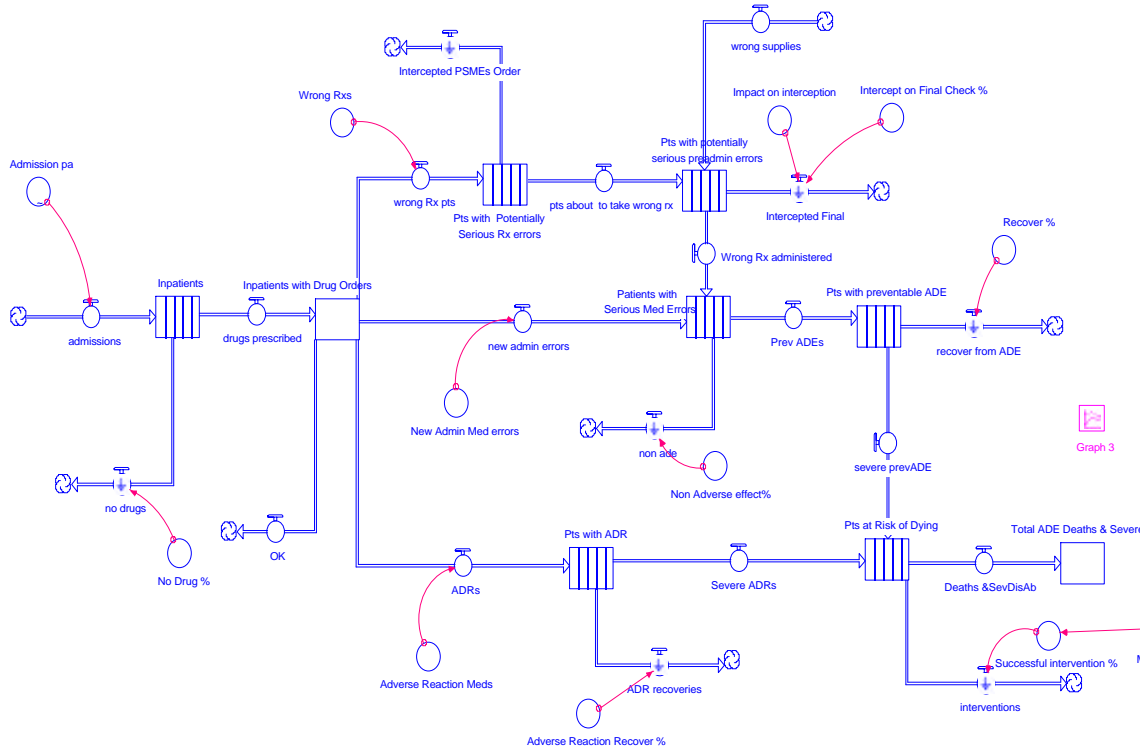
Model Output for the "as-is" Base Case

Behavior over time (20 years) for average required information per drug, average staff information, the overall impact on error generation, the total number of adverse drug events (ADEs) and the number of reported incidents are shown below (for agreed indicative values). The number of adverse drug events continues to rise over time. Average information per staff decreases due to staff turnover, then increases later due to progressive improvements in ICT infrastructure.

However the increasing number and uses of medications on increasingly complex patients increase both the knowledge required for drug use and the number of reports needed to analyze and fix problems.
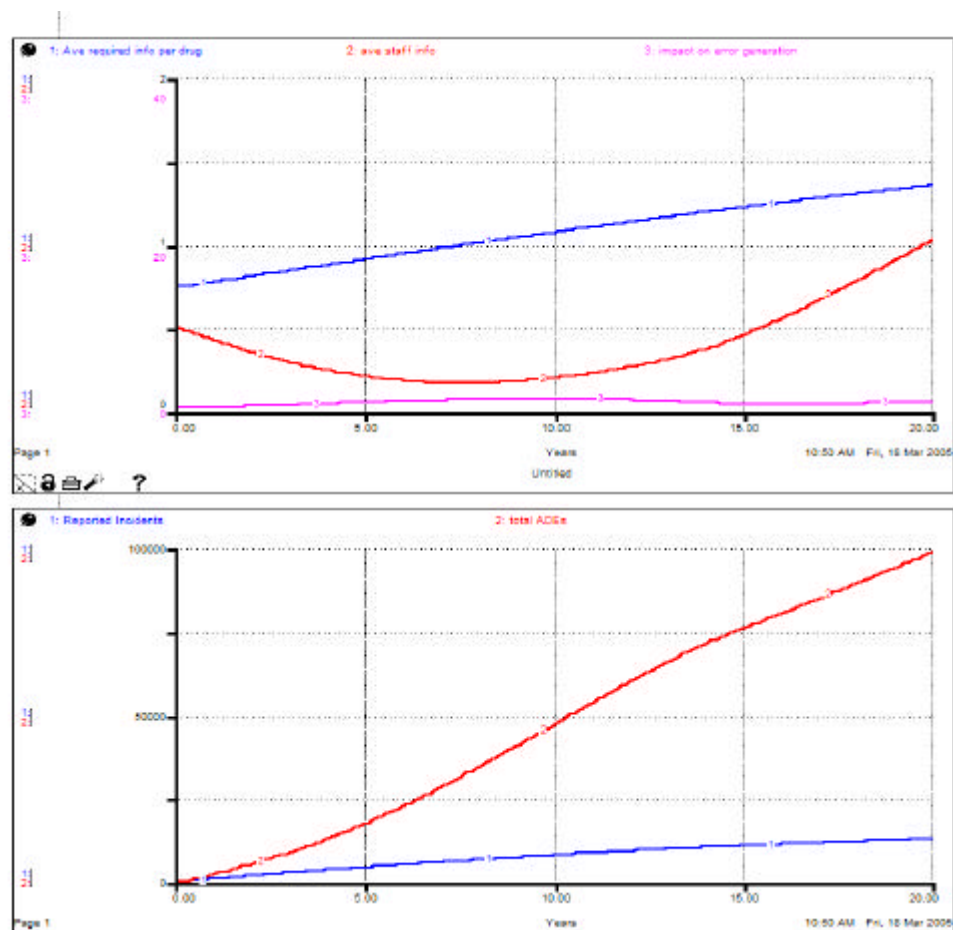
Note the shape of the total Adverse Drug Events is similar to the reference mode behavior in the first figure.

Combining Long Term System Dynamics with Agent Based Simulation

Clinical work has been described as "messy" and not well suited to routine automation (24,9), due to the variation and complexity of the mix of individual and collective non-routine work required to get the job done in hospitals. Individuals often switch tasks and can simultaneously undertake a mix of physical, cognitive and communications activities (25). Agent based (AB) simulation is well suited to simulating this type of complex behavior (26,27); we are completing a combined SD and AB systems simulation using AnyLogic software which is suited to multi-level and multi-method simulation (28). The graphical interface of this software can also produce a compelling and engaging animation, which can tell a complex story clearly and accurately. A prototype version of

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this combined model is available (running as a java applet in a web browser) at

http://www.healthsims.com.au/Public.htm

Combined Simulation Overview
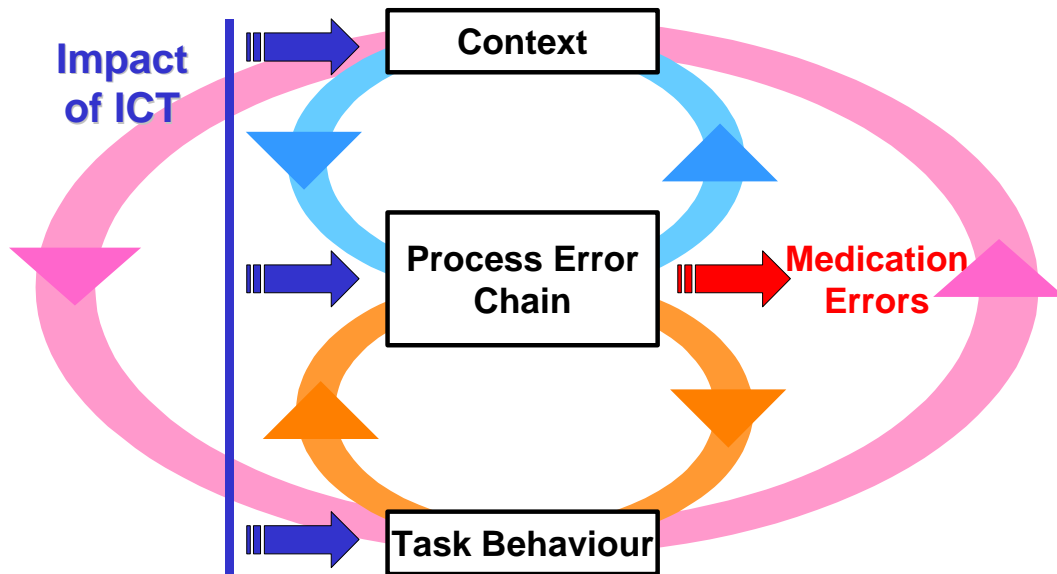
The interaction between context and process error has been represented in the SD model and we have migrated this into a multi-method simulation tool. This has been combined with a proof of concept agent based simulation.

Next Steps

We are refining the model calibration using variables collected in organizational and work sampling field studies from several individual hospitals participating in detailed multi-method evaluations of ICT interventions.

We are also pinpointing the actual impacts of the various components of specific hospital information and decision support technologies and specifying and calibrating their mechanism of impact on medication error detection and generation.

After completing these two studies, we will be able to discuss the feedback interactions and individual behaviors more confidently. Policy design experiments will then be able

to clarify the effects of context and variability on the best combination and timing of ICT and supporting interventions for a particular hospital. On completion of the evaluations, we plan to use the simulation to assist the rollout of hospital ICT interventions across many hospitals. The simulation will be used as a tool for ongoing profiling, implementation planning and evaluation for future hospital point of care clinical information systems projects.

Conclusion

This paper describes the initial long-term system dynamics context of hospital medication errors. Work is progressing on combining these long-term dynamics with an agent-based simulation of the everyday clinical work interactions among patients and staff that deliver medications safely. This simulation is being used to plan, implement and evaluate the impacts of information and decision support technologies on medication error generation and interception, a significant aspect of improving hospital patient safety.

References

1. Henry Mintzberg. Toward Healthier Hospitals Health Care Mgt Review 1997,22(4),9-18
2. Institute of Medicine. *To Err is Human* Washington, DC: National Academy Press, 2000
3. Timothy S Lesar; Ben M Lomaestro; Henry Pohl. Medication-prescribing errors in a teaching hospital: a 9 year experience. Archives of Internal Medicine; Jul 28, 1997; 157, 14; 569-1576
4. Institute of Medicine. *Crossing the quality chasm*: a new health system for the 21st century. Washington, DC: National Academy Press, 2001
5. Bates DW, Cohen M, Leape LL, Overhage JM, Shabot MM, Sheridan T. Reducing the frequency of errors in medicine using information technology. J Am Med Inform Assoc 2001;8:299–308
6. Charles Perrow. *Normal Accidents* Princeton University Press, 1999
7. James T Reason *Managing the Risks of Organizational Accidents* 1997 Ashgate ISBN 1 84014 105 0
8. Timothy Hoff, Lottie Jameson, Edward Hannan, Ellen Flink. Organisational Dynamics Simulation and Error: A Review of the Literature Examining Linkages between Organizational Factors, Medical Errors, and Patient Safety Medical Care Research and Review, Vol. 61 No. 1, (March 2004) 3-37
9. Robert L. Wears, Marc Berg. Computer Technology and Clinical Work: Still Waiting for Godot JAMA, March 9, 2005—Vol 293, No. 10 1261-3

10. Bell DS, Cretin S, Marken RS, et. al. A conceptual framework for evaluating outpatient electronic prescribing systems based on their functional capabilities. J Am Med Inform Assoc, 2004. 11(1): p. 60-70.

11. AMIA Clinical Decision Support in Electronic Prescribing: Recommendations and an Action Plan Report of the Joint Clinical Decision Support Workgroup March, 2005 http://www.amia.org/pubs/whitepapers/index.html

12. Ash JS, Berg M, et al. (2004). Some unintended consequences of information technology in health care: the nature of patient care information system-related errors. J Am Med Inform Assoc 11(2): 104-12

13. Koppel R, Metlay JP, Cohen A, et al. Role of computerized physician order entry systems in facilitating medication errors. JAMA. 2005;293:1197-1203.

14. Charles Vincent, Sally Taylor-Adams, and Nicola Stanhope Framework for analysing risk and safety in clinical medicine BMJ, Apr 1998; 316: 1154 - 1157.

15. Anderson JG, Jay SJ, Anderson M, Hunt TJ. Evaluating the capability of information technology to prevent adverse drug events: A computer simulation. J Am Med Inform Assoc 2002 ;9:2479–490.

16. Nancy Leveson, Mirna Daouk, Nicolas Dulac, Karen Marais A Systems Theoretic Approach to Safety Engineering Aeronautics and Astronautics Dept. Massachusetts Institute of Technology 2003 http://sunnyday.mit.edu

17. David L Cooke. Learning from Incidents ISD Conference 2003 NYC

18. Rogelio Oliva Tradeoffs in Responses to Work Pressure in the Service Industry California Mgt Review 2001 43(4) 26-43

19. Jack Homer. Worker Burnout: a dynamic model with implications for prevention and control System Dynamics Review 1 (1) 42-62

20. Anita Tucker Amy C. Edmondson Why hospitals don't learn from Failures: Organizational and Psychological Dynamics that inhibit system change Calif Mgt Review winter 2003 45, 1-18

21. Laura J. Black, Paul R Carlile, Nelson P Repenning. Formalizing Theoretical Insights from Ethnographic Evidence: Revisiting Barley's Study of CT-Scanning http://web.mit.edu/nelsonr/www/Barley.html

23. G McDonnell, M Heffernan and A Faulkner. National Medicines Use Dynamics: Influencing Health Policy with System Dynamics http://www.systemdynamics.org/conf2004/indexpapers.htm

24. Nemeth CP, Cook RI, Woods DD. The messy details: insights from the study of technical work in health care. IEEE Trans Syst Man Cybern Part A. 2004;34:689-692.

25. Anne-Sophie Nyssen Integrating Cognitive and Collective Aspects of Work in Evaluating Technology IEEE Trans Syst Man Cybern Part A. 2004;34:743-8.

26. Alessandro Lomi and Erik R Larsen. Ed. *Dynamics of organizations: computational modeling and organization theories.* AAAI/MIT Press 2001

27. Carol HsenFae Cheng Cain REPRESENTING AND REASONING ABOUT CONTEXTUALLY CHANGING ORGANIZATIONAL BEHAVIOR USING SIMULATION MODELS OF MEDICAL WORK Stanford PhD   SMI-2004-0977 http://smi-web.stanford.edu/pubs/SMI_Abstracts/SMI-2004-0977.html

28. Andrei Borshchev & Alexei Filippov. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools ISDC Oxford2004 www.xjtek.com/download/papers

Screenshot of Combined SD and AB Prototype available at www.healthsims.com.au
Generation and interception of prescribing and administration drug errors are dynamically animated in the colored rectangles. The left hand column allows the base error rates of doctors, nurses and pharmacists to be varied. The right hand column reproduces the output of the SD context model.