Secondary Complications in SCI Across the Continuum: Using Operations Research to Predict the Impact and Optimize Management Strategies

Derek Atkins, PhD,[1] Vanessa K. Noonan, PhD, PT,[2,3] Argelio Santos, MMOR,[1] Rachel Lewis, PhD,[1] Michael Fehlings, MD, PhD,[2,4] Anthony Burns, MD, MSc,[5] and Marcel Dvorak, MD[2,3]

[1]Centre for Operations Excellence, University of British Columbia, Vancouver, BC, Canada; [2]Rick Hansen Institute, Vancouver, BC, Canada; [3]Department of Orthopaedics, University of British Columbia, Vancouver, BC, Canada; [4]Department of Neurosurgery and Spinal Program, University of Toronto, Toronto, ON, Canada; [5]Spinal Cord Rehabilitation Program, Toronto Rehabilitation Institute, Toronto, ON, Canada

Secondary complications following traumatic spinal cord injury (tSCI) have a tremendous impact on quality of life and health care costs. Although some complications result from the injury itself, many originate from the care provided; complications arising early in the tSCI journey can predispose an individual to recurrence later. To measure the total impact of secondary complications on patient outcomes and health care costs, all the stages of care, from first response to life in the community, must be spanned. Interventions to ameliorate secondary complications need to consider the effects on the whole system and not just individual phases of care; however, such an approach is not common in the literature. To measure the impact of complications as well as the effect of proposed interventions, a partnership between clinical researchers and operations research professionals was formed to develop a discrete-event simulation model of the entire continuum of tSCI care. In this article, we focus on the part of the model concerning common secondary complications (eg, pressure ulcers, pneumonia). We first describe early results from the model, discuss how the effects from the complications impact care throughout the tSCI continuum, and review assumptions of the model. The article concludes with a discussion as to the possible uses of the model, their strengths/limitations, and future directions. **Key words:** *complications, computer models, computer simulation, outcomes assessment (health care), spinal cord injury*

This article focuses on the novel concept of applying operations research methodology to examine the impact of secondary complications in persons with traumatic SCI (tSCI) starting from the time of injury, then continuing into acute care and rehabilitation and finally to reintegration into the community. Approaches predicting the impact of secondary complications are presented based on results from a computer simulation model developed to describe processes of care and outcomes in persons with tSCI.

The objectives of this article are as follows:

1. To introduce and describe operations research methodology and how it can be used to examine clinical questions spanning the continuum of care for persons with tSCI;
2. To demonstrate how management strategies for secondary complications can be targeted and optimized for the greatest benefit using the results of the computer simulation model;
3. To demonstrate the impact of secondary complications (eg, pressure ulcers, pneumonia) on system outcomes (eg, length of stay) and lifelong patient outcomes (eg, health utilities).

Overview of Operations Research in Health Care

Operations research

Operations in business is the generic term encompassing the making and delivery of any product or service, thus capturing all of manufacturing, logistics, supply chains, and the

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Table 1. Applications of the DES and HPM

Applications	Question
Basic resource questions	What if the number of beds in the rehabilitation centre was increased?
Evaluating clinical innovations	What if the incidence of urinary tract infections could be reduced?
Organizational policy questions	What is the impact of further integration of acute and rehabilitation care?
Identification of best practices, especially across Canada	What is the effect of implementing a best practice that would screen patients to prevent pressure ulcers?
Identification of gaps in knowledge	If we knew the risk of a complication following discharge into the community for persons with tSCI who initially experience that complication during acute, what would we do differently?
Forecasting system loads from changes in demographic and tSCI incidence	How will the aging population impact acute and rehabilitation care delivery in the year 2020?

Note: DES = Discrete Event Simulation; HPM = Health Progression Model: tSCI = traumatic spinal cord injury..

provision and delivery of services.[1] With this definition, most operations within health care fall into the category of "delivering a service." Operations management is likewise the generic term for managing operations, and we note that most of this is done by people who have not heard the term "operations management." For example, a program manager might be surprised to be labeled as doing operations management even though 50% of her or his time is spent doing typical operations management activities such as scheduling, staffing, managing patient flow, and ordering supplies.

Although operations research covers any research focused on improving operations, the term is often reserved for the use of models or simplified mathematical/computer abstractions of operations that permit experimentation with alternatives, in other words, asking "what-if"questions.[2-6] Some parallels between the worlds of industry and health care are obvious. Take the case of efficiently packing a 40-foot shipping container with highly heterogeneous products that have numerous constraints about weight, shape, and stackability. A model of this would not differ much from efficiently scheduling chemotherapy patients with highly heterogeneous protocols and associated nursing/patient constraints.

A more system-wide application is modern supply chains where products flow through many "silos." The commercial innovation has not been to actually integrate these silos, but to integrate how products flow between them with minimum disruptions. It was this observation that prompted the questions, "Are there any lessons here for persons with tSCI flowing through the 'silos' of first response, acute care, rehabilitation, and life in the community? Might an operations research model of this continuum of care allow us to understand and anticipate the impact of the interventions both of a resource nature (more beds) and a clinical nature (clinical practice guideline implementation)?"

Overview of the Access to Care and Timing (ACT) project

Our response to the question of how tSCI could benefit from operations research comprises the first part (ACT/I) of a larger research project sponsored by the Rick Hansen Institute. The long-term goal of the ACT project is to make policy recommendations concerning best practices and develop accreditation standards for tSCI care across Canada. The objectives of ACT/I are to describe the current care delivery in Canada, to examine data describing the processes of care using primarily the Rick Hansen Spinal Cord Injury Registry (RHSCIR), and to develop an operations research model. The model selected combines Discrete Event Simulation (DES) and a Health Progression Model (HPM) of the entire continuum of care for tSCI (see **Figure 1**). Applications of the model are described in **Table 1**.

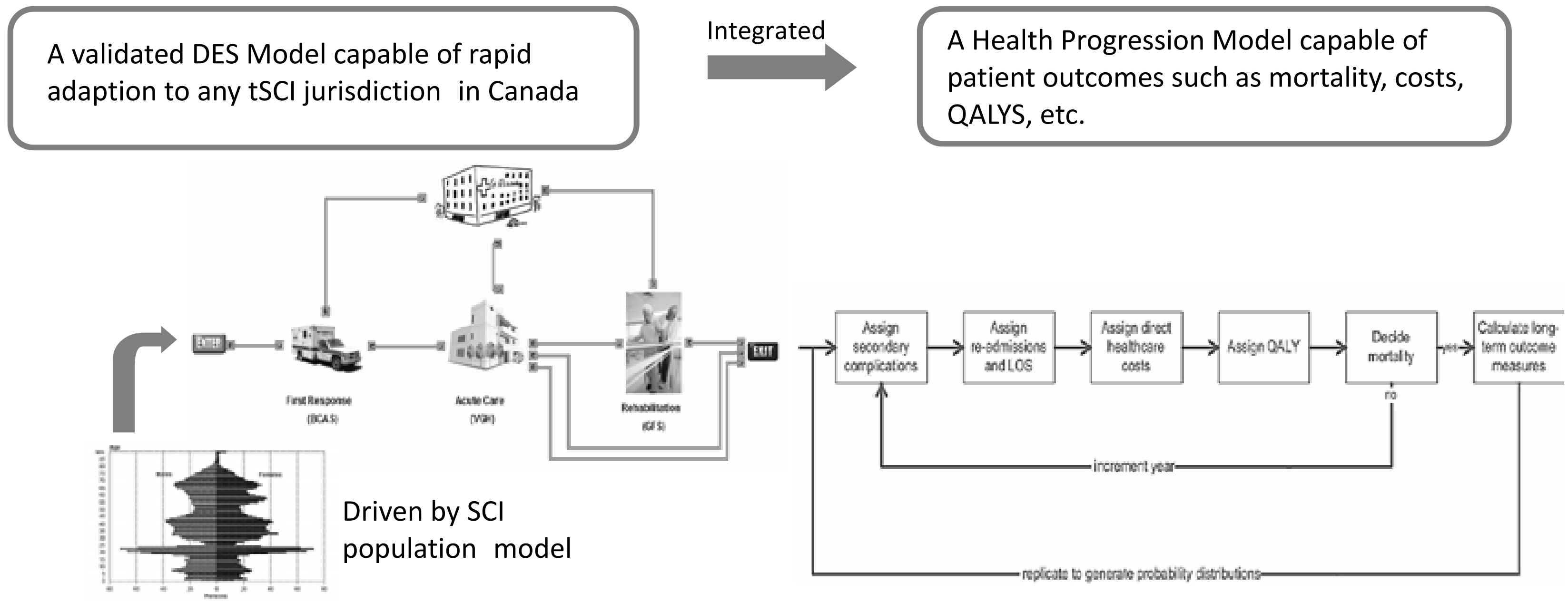

Figure 1. Overall architecture of the Discrete Event Simulation (DES) model and Health Progression Model (HPM). A traumatic spinal cord injury (tSCI) population model feeds the DES model to generate the individuals with tSCI moving through the health care system. Individuals with tSCI leaving the health care system then enter into the HPM, where long-term outcomes are calculated. LOS = length of stay: QALY = quality-adjusted life year.

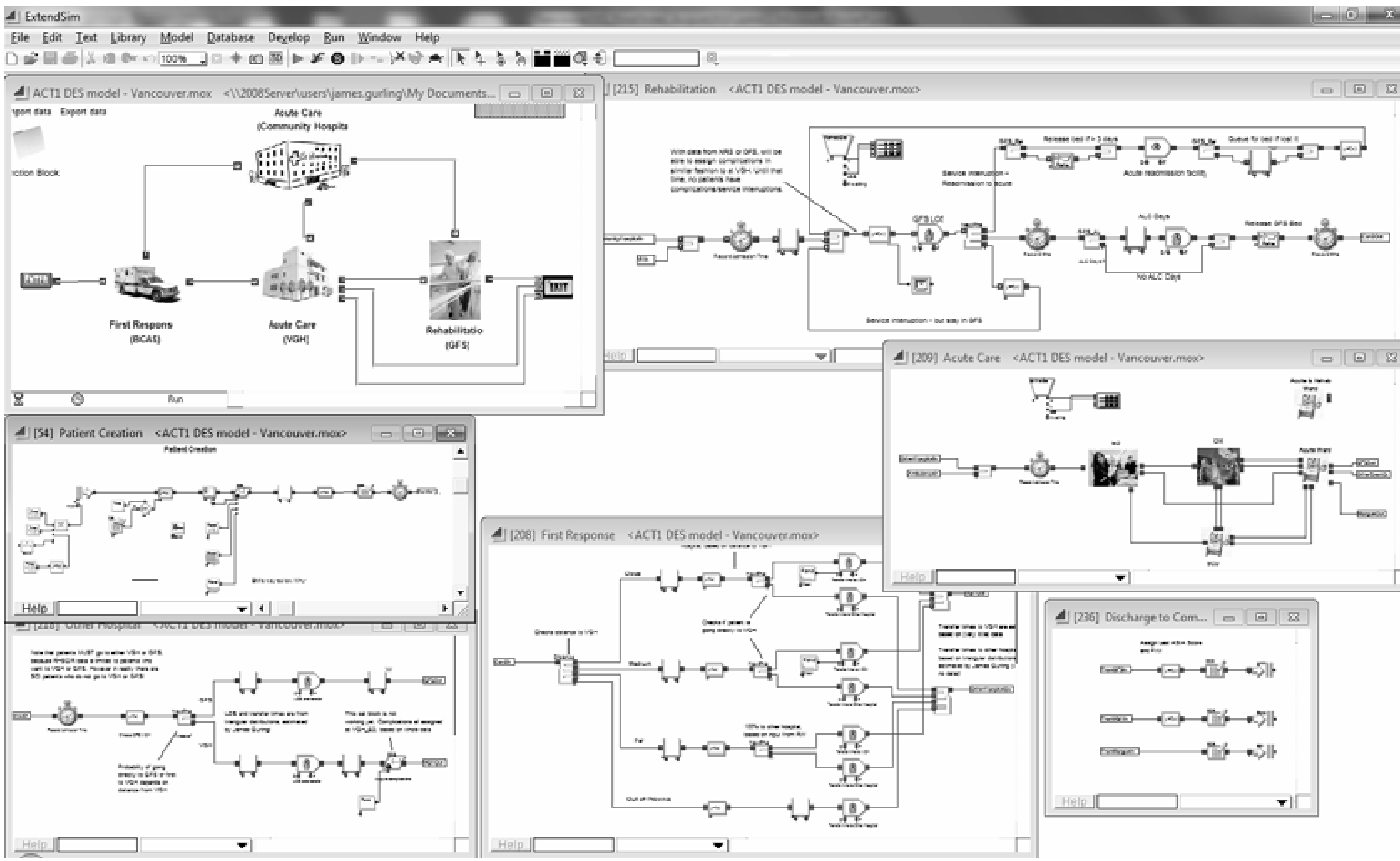

Figure 2. Detailed view of the Discrete Event Simulation (DES) model. Each window in the simulation corresponds to a stage in the health care process (eg, prehospital, acute, and rehabilitation). Within each process, the blocks refer to specific operations, such as decision points, queues, processes, delays, resources, and calculations.

Table 2. Overview of the HPM

Components of HPM assigned to or calculated for each person with tSCI				
Complications	**Hospitalizations and LOS**	**Direct health care costs**	**QALY value of year**	**Probability of death**
Current data source/methods				
Odds ratios from Hitzig et al[7]; predictors of complications: age, years postinjury, complete/incomplete, neurological level	Probability of hospitalization associated with complications and LOS based on Dryden et al[8]	Costs currently associated only with initial hospitalization	Regression uses demographic and health information to assign annual utility (SF6D algorithm on patients' SF-36 surveys.)	Cox proportional hazards model based on Krause et al[9], using Canadian life table data as baseline mortality
Planned data sources/methods				
Prospective studies on complications in acute care with follow-up of complications in the community	Provincial records on hospitalizations	Costs for prescription drug use and outpatient clinic visits	Add to RHSCIR data; revise regression model	RHSCIR data may help to establish risk factors for mortality

Note: HPM = Health Progression Model; LOS = length of stay; QALY = quality-adjusted life years; RHSCIR = Rick Hansen Spinal Cord Injury Registry; SF-36 = Short Form-36; SF6D = Short Form-36 6D; tSCI = traumatic spinal cord injury.

Briefly, the DES (see **Figure 2**) first simulates individual persons with tSCI by drawing from probability distributions constructed using data in the RHSCIR (ie, age at injury, gender, type of injury, time/date, mechanism of injury, neurological level, ASIA Impairment Scale, injury energy, and Glasgow Coma Score). Then first response protocols determine the first acute destination. Within acute care, patients go to the operating room (maybe more than once), imaging, intensive care step down unit unit(s), and hospital ward(s) until they are discharged to the community or continue their care in a rehabilitation centre or alternative facility (eg, long-term care).

At every stage, using probabilities, simulated persons with tSCI are assigned a length of stay (LOS), acquire complications, return to acute care from inpatient rehabilitation, and finally are discharged to the community. At final discharge, the simulated cohort of persons with tSCI has accumulated a set of attributes similar to a patient chart. Complications are assigned by considering patient attributes such as gender, age, and severity of injury, thus recognizing the different approaches to reporting complication incidence within the literature. The methodology employed here is planned as a stand-alone publication due to its complexity. At the time of discharge into the community, the simulated cohort of persons with tSCI leave the DES and move to the HPM, which follows them through life in the community and accumulates clinical, economic, and mortality data (**Table 2**). To compare and contrast clinical practices across Canada, both DES and HPM have been designed to be readily adaptable to different cities and provinces.

The DES and HPM were developed using various data sources. For the DES, primary sources include the RHSCIR data, National Rehabilitation Services database at the Canadian Institute of Health Information, and other existing research data sets. All data sets were supplemented by input from subject matter experts and existing literature. The calibration of the DES (see **Figure 2**) employed more than 25 statistical regressions of various types. Models were validated by assessing the alignment and consistency of both model inputs and outputs to data obtained from RHSCIR and the Vancouver Spine Database (VerteBase). Further model validation will be conducted by using new prospective RHSCIR data.

The current version of the HPM also relies on existing literature. Complications were generated based on the odds ratios reported by Hitzig et al[7] on persons with traumatic and nontraumatic SCI living in the community in Ontario, Canada. Estimates of hospital length of stay (LOS) were obtained from a study on persons with tSCI living in Alberta, Canada.[8] Mortality was estimated based on results from a prospective study in the southern United States.[9] The intention is to supplement each of these sources with data from RHSCIR and additional sources as they become available.

Examining Secondary Complications

Secondary complications are commonly associated with tSCI. Based on data collected prospectively in acute care at Vancouver General Hospital in British Columbia, Canada, we identified the most common secondary complications. These include urinary tract infections (35.6%), pneumonia (33.0%), neuropathic pain (19.5%), delirium (18.6%), and pressure ulcers (18.6%).[10] Below are 4 examples that demonstrate how the DES and HPM can be used to understand the systemwide implications of secondary complications, predict their impact, and determine the optimal management strategies. These are hypothetical examples to demonstrate the value of using these models; it is not advised to focus on the actual results because the models are still under development and the test scenarios may not be clinically feasible. For brevity, we report only on changes to the present state.

Test Scenario 1

How might we evaluate an innovation that promises a dramatic reduction in the incidence of pneumonia during the acute phase?

A business case examining the benefits of this new innovation will typically focus on direct impacts within the acute facilities. In this example, if pneumonia could be completely eliminated in acute care, it would lead to an 11% direct decrease in acute complications (see **Figure 3**). However, the model gives a very different picture when systemwide impacts are tracked. For instance, there is a corresponding 33% decrease in acute LOS driven by (1) persons with tSCI being discharged sooner from acute, but also (2) a 10% reduction in rehab LOS, which in turn reduces rehab bed utilization, enabling persons with tSCI to transfer sooner from acute to rehabilitation. The case for investing in health innovations early following tSCI becomes more compelling when the systemwide benefits of such investments are taken into account.

Test Scenario 2

How might we evaluate an innovation that promises a dramatic reduction in the incidence of pressure ulcers during the acute phase?

An innovation, such as technology (eg, equipment) or new clinical practice guidelines that could hypothetically eliminate pressure ulcers would reduce the total number of complications in the acute phase account by 6.3% (see **Figure 4**), but its indirect effects would include a 15% reduction in acute care LOS as well as an accompanying 5.4% reduction in rehabilitation LOS.

Test Scenario 3

How might we examine the future impacts of tSCI on the health care system due to an aging population? For example, if there were a 50% increase in persons over the age of 60 with tSCI, along with a 20% increase in females over the age of 60, how would this impact care?

With an aging population, there will be an increase in the incidence of secondary complications. These impacts will be dampened by other gender and age effects (see **Figure 5**). For example, because pressure ulcers are more common in young males compared to older females, there will be a 2.5% decrease in the incidence of pressure ulcers in acute care given that the proportion of females in the test cohort has increased to 40% from 20%. Similarly, the effect of more persons with tSCI over the age of 60 years will increase the mortality in acute care by 5.4%, which in turn will actually reduce the impact of age on acute LOS and bed utilization.

Test Scenario 4

How might we test a "what if" question regarding triaging persons with tSCI to acute care? For example, suppose it was possible to implement a policy that would direct these individuals to a specialized SCI trauma center (within range of helicopter service) rather than initially taking them to community

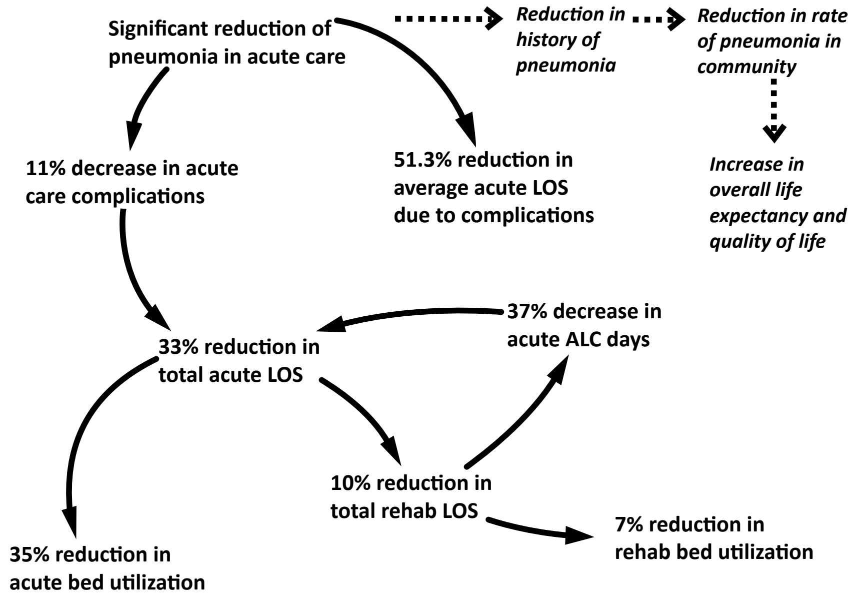

Figure 3. Test Scenario 1: The effect of significantly reducing the incidence of pneumonia in acute care. The direct effects of reducing the incidence of pneumonia in acute care are a reduction in acute care complications (11%) and the average length of stay (LOS) in acute care due to complications (51.3%). However there are other indirect effects throughout the system such as a reduction of acute LOS (33%), reduction of rehabilitation LOS (10%), reduction of bed utilization in acute (35%), and reduction in rehabilitation bed utilization (7%). ALC = alternative level of care (ie, ready for rehabilitation).

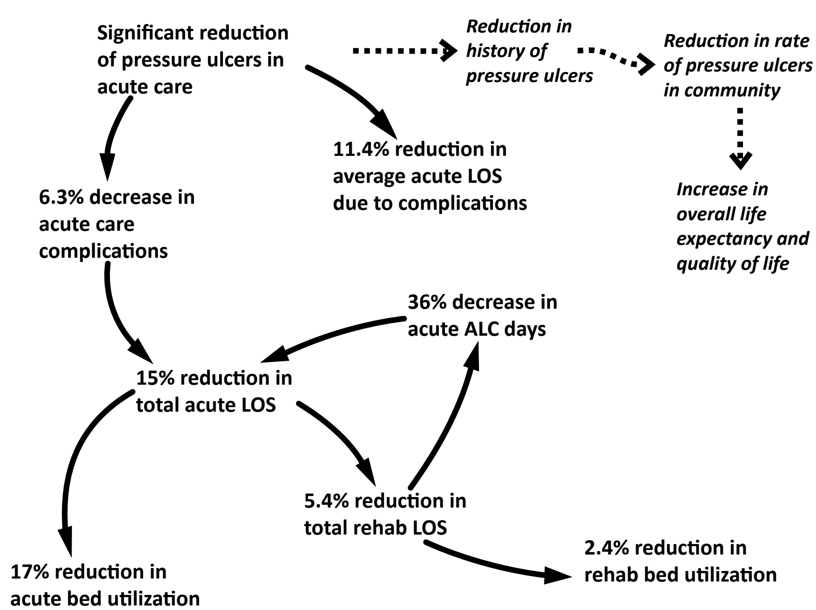

Figure 4. Test Scenario 2: The effect of significantly reducing the incidence of pressure ulcers in acute care. The direct effects of reducing the incidence of pressure ulcers in acute care are a reduction in acute care complications (6.3%) and the average length of stay (LOS) in acute care due to complications (11.4%). However there are other indirect effects throughout the system such as a reduction of acute LOS (15%), reduction of rehabilitation LOS (5.4%), reduction of bed utilization in acute (17%), and reduction in rehabilitation bed utilization (2.4%). ALC = alternative level of care (ie, ready for rehabilitation).

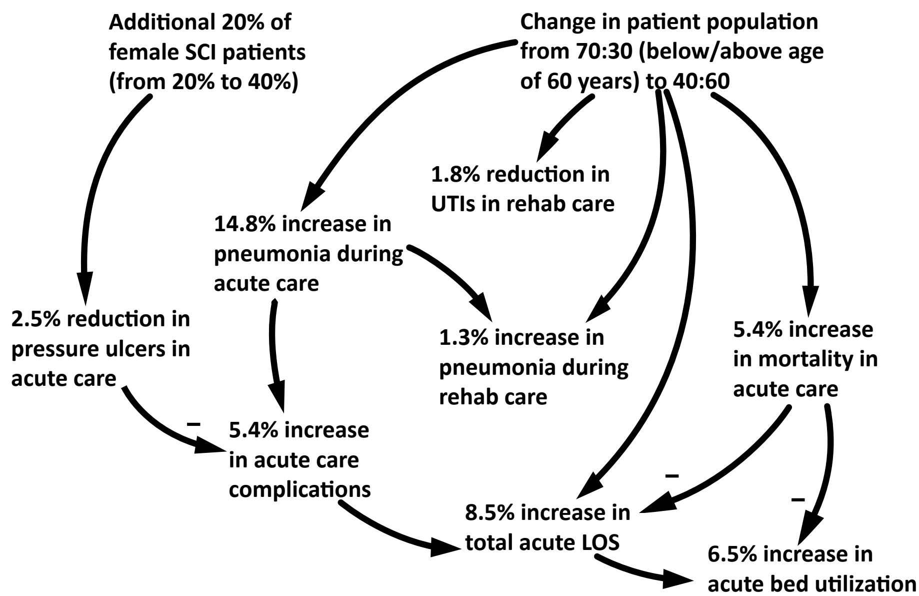

Figure 5. Test Scenario 3: The effect of an aging population in persons with traumatic spinal cord injury (tSCI) on future health care delivery. The direct effects of an aging population in persons with tSCI on future health care delivery are an increase in acute and rehabilitation pneumonia (14.8% and 1.3%), reduction in urinary tract infections (UTIs) in rehab (1.8%), increase in mortality in acute care (5.4%), and a reduction in pressure ulcers in acute care (2.5%, due to an increase in the female proportion of tSCI). The indirect effects are an increase in the overall complications in acute (5.4%), increase in acute total LOS (8.5%), and an increase in acute bed utilization (6.5%).

hospital? If persons with tSCI admitted directly to a specialized SCI trauma center were half as likely to experience a pressure ulcer, what would the impact be?

If implementation of such a policy led to a 40% increase in the number of persons with tSCI admitted directly to a specialized SCI trauma center (see **Figure 6**), the result would be a 5.8-hour reduction from time of injury to admission and a subsequent 6.2-hour reduction in the time to surgery for patients who are inured within range of helicopter service. The reduction in the incidence of pressure ulcers in this group would result in a 5% decrease.

Discussion and Conclusions

The purpose of this course was to provide examples of how operations research can assist in answering questions pertaining to the continuum of care for persons with tSCI. Although the DES and HPM are still in the early stages of development, the benefits are already being realized. The test scenarios highlight the importance of understanding the entire continuum of care within a tightly coupled system where interventions as well as events outside our control will impact phases of care both upstream and downstream. Furthermore, the indirect effects from a given decision are likely to be more compelling compared to direct effects alone.

As with any model, a number of assumptions and simplifications have been made. The DES might appear detailed, but it still does not capture all the complexities associated with clinical care. The important test is whether clinicians and administrative decision makers are comfortable enough with the approximations to use them as the basis for decisions regarding the allocation of resources or provision of clinical care. The DES and HPM are still evolving, and it is critical that potential users of these models are continually consulted to ensure that their needs are met.

One of the benefits of our model was that it met the need to view the continuum of care as an interrelated system and to carefully identify the

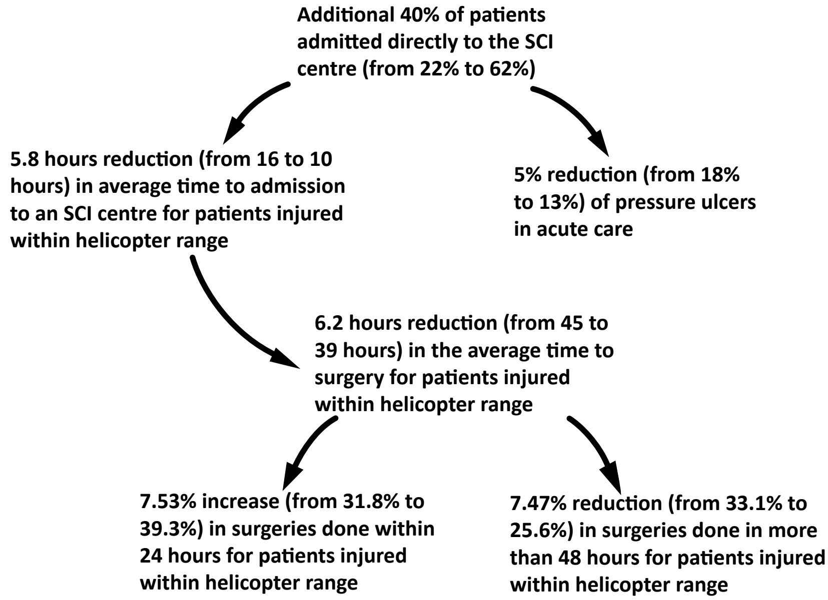

Figure 6. Test Scenario 4: The effect of implementing a policy to increase the number of persons with traumatic spinal cord injury (tSCI) directly admitted to a specialized SCI center (within range of helicoper service), which results in a significant reduction in pressure ulcers. The direct effect of implementing a policy to increase the number of persons with tSCI directly admitted to a specialized SCI center is an increase in direct admissions from 22% to 62%. The indirect effects are a reduction in the average time to admission (5.8 hours), reduction in the average time to surgery (6.2 hours), increase in the number of surgeries within 24 hours after injury (7.53%), and a reduction in the number of surgeries taking place after 48 hours of injury (7.47%).

components. A second benefit was that intensive use of the data sources forced us to clean the data and further enhance the standardization of data collection for RHSCIR in the future. Both the DES and HPM are largely calibrated from the worldwide literature; this has led to the third benefit of being able to draw many of these disparate sources together and highlight major gaps in what we know. A significant value of this work is the ability to prioritize the value of which specific knowledge gaps are most critical to fill. As an example, additional information is needed regarding how early secondary complications predispose the incidence of complications later in the continuum following tSCI.

The 2 main developments currently underway are completing the HPM (as the full value of the DES will not be realized until it is completed) and ensuring the DES can be applied to other health care facilities providing care to persons with tSCI in Canada. The goal is to use the model to assess the impact of administrative or clinical interventions. Examples include evaluating the full downstream impact of faster times to surgery or, more generally, identifying best practices. The next series of questions will consider the role of organizational structures, for example, examining the degree of integration of acute and rehabilitation care. We anticipate that results from the model will help to identify attributes of a tSCI Program of Excellence and form the basis for accreditation.

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