The Application of Operations Research Methodologies to the Delivery of Care Model for Traumatic Spinal Cord Injury: The Access to Care and Timing Project

Vanessa K. Noonan,^{1,2} Lesley Soril,¹ Derek Atkins,³ Rachel Lewis,³ Argelio Santos,³ Michael G. Fehlings,^{1,4} Anthony S. Burns,⁵ Anoushka Singh,⁴ and Marcel F. Dvorak^{1,2}

Abstract

The long-term impact of spinal cord injury (SCI) on the health care system imposes a need for greater efficiency in the use of resources and the management of care. The Access to Care and Timing (ACT) project was developed to model the health care delivery system in Canada for patients with traumatic SCI. Techniques from Operations Research, such as simulation modeling, were used to predict the impact of best practices and policy initiatives on outcomes related to both the system and patients. These methods have been used to solve similar problems in business and engineering and may offer a unique solution to the complexities encountered in SCI care delivery. Findings from various simulated scenarios, from the patients' point of injury to community re-integration, can be used to inform decisions on optimizing practice across the care continuum. This article describes specifically the methodology and implications of producing such simulations for the care of traumatic SCI in Canada. Future publications will report on specific practices pertaining to the access to specialized services and the timing of interventions evaluated using the ACT model. Results from this type of research will provide the evidence required to support clinical decision making, inform standards of care, and provide an opportunity to engage policymakers.

Key words: computer simulation; health assessment; health care delivery; Operations Research; outcomes assessment; spinal cord injury

Introduction

SPINAL CORD INJURY (SCI) is a devastating neurological disorder that affects approximately 4200 Canadians annually, of which 1785 are due to traumatic events (Noonan et al., 2012a). Patients experience a loss of sensation, movement, and other functions such as bowel, bladder, and sexual function as a result of the injury. This in turn impacts patient functional status, participation in daily activities, and quality of life (Leduc and Lepage, 2002; Riggins et al., 2011; Wood-Dauphinee et al., 2002). While the number of new injuries is relatively small compared to other acute medical problems such as traumatic brain injury or stroke, SCI results in a substantial financial burden on both the individual and society. The costs of SCI are attributable to both the initial injury and hospitalization and the subsequent lifelong use of

health services by persons with SCI, which may include hospital readmissions for the treatment of complications or conditions secondary to SCI (Dryden et al., 2005).

Health care providers have recognized significant associations between the severity of SCI, the presence of other injuries (Injury Severity Score), the occurrence of medical adverse events, and increased costs and lengths of hospital stay (Tator et al., 1993). During the initial hospitalization for acute and rehabilitative care, complications secondary to a SCI (e.g., pressure ulcers, pulmonary and urine infections, and neuropathic pain), or secondary to treatment (e.g., post-operative hematoma and failure of implants) may dramatically increase the cost of care (New et al., 2010). Furthermore, the presence of complications in the initial hospitalization may predispose the patient to future complications. It is the likelihood of

¹Rick Hansen Institute, Vancouver, British Columbia, Canada.

²Department of Orthopaedics and ³Centre for Operations Excellence, University of British Columbia, Vancouver, British Columbia, Canada.

⁴Department of Surgery and Spinal Program, University of Toronto, Toronto, Ontario, Canada.

⁵Spinal Cord Rehabilitation Program, Toronto Rehabilitation Institute, Toronto, Ontario, Canada.

sustaining a recurrence or a new secondary complication that results in increased use of health services, particularly re-hospitalizations, emergency department admissions, physician visits, specialist visits, therapist appointments, and increased need for personal or attendant care services (Cardenas et al., 2004; Dorsett and Geraghty, 2008; Dryden et al., 2004; Jaglal et al., 2009; Johnson et al., 1998; Krause et al., 2009; Meyers et al., 1985; Middleton et al., 2004; Samsa et al., 1996).

There is emerging evidence that the systemic (administrative and clinical) processes of care can influence patient outcomes and the cost of care (Bowers and Mould, 2001; Levin et al., 2008). By minimizing the risk of developing secondary complications, there will not only be an improvement in the patient's health status, but there will also be a decrease in both the demand and cost of medical intervention, which will reduce burden on the health care system. These health care system processes are further influenced by resources, organizational structures, geography, patient demographics, and staffing levels, and directly affect time to surgery and rehabilitation intensity, which in turn affect both patient outcomes and systems outcomes (costs and hospital lengths of stay). In an effort to evaluate these influences and propose effective changes in SCI health care delivery, we have applied the science of Operations Research (OR). OR techniques have been used extensively in business and engineering to evaluate best practices and optimize complex processes.

Discrete event simulation (DES) modeling is an OR technique used to examine how an activity will perform under different conditions, and to test various hypotheses using "what if" test scenarios. Although these modeling techniques have not been applied to the entire continuum of SCI health care, previous applications of simulation modeling in health care include examining patient flow within a single phase of care, such as in emergency departments (Hoot et al., 2008, 2009; Hung et al., 2007; Khare et al., 2009), intensive care units (Kolker, 2009), and outpatient clinics (Chand et al., 2009), and has been valuable in describing the course of disease (e.g., HIV; Simpson et al., 2009).

The goals of the Access to Care and Timing (ACT) project are to model the systems of delivery; to simulate administrative, policy, and therapeutic initiatives; and to predict and measure their influence on system costs and patient outcomes. The objective of this article is to describe the application of OR methods to develop a health care delivery model for the SCI continuum of care. Specifically, this article will provide an overview of the conceptual framework, describe the methods used to document patient flow, provide an overview of the ACT model, and discuss an example of a scenario tested using the ACT model.

Methods

Overview of the conceptual framework of the ACT project

The intent of the ACT project is to create knowledge, tailor this knowledge to SCI care, and then to develop tools that will assist policymakers and the stakeholders in making informed decisions. For this project we have adopted the "Knowledge to Action" processes developed by Graham and associates (Graham et al., 2006) as part of the conceptual framework for developing the ACT project (Fig. 1).

FIG. 1. Graham's Knowledge-to-Action process (reprinted with permission from Graham et al., 2006).

The ACT project is a long-term project divided into three phases, the first of which is designated ACT/I. The goal of the ACT/I project is to develop a health care delivery model of the provision of pre-hospital, acute, and rehabilitation services for persons with traumatic SCI, in order to evaluate the timeliness and location of care delivery and how they relate to outcomes. The focus of ACT/I will be on the knowledge creation cycle component of Graham's conceptual framework (Fig. 1). This phase will provide the basis for understanding the continuum of health care delivery for SCI in Canada. Outputs from the knowledge creation cycle will produce models that can move into the action cycle component of Graham's model, whereby the evidence is applied to the local context and evaluated. Outputs will then be targeted to clinicians, health care administrators, and policymakers to facilitate evidence-based decision making.

Subsequent phases of the project will use the knowledge created to move research into action and further validate the model outputs (ACT/II). The long-term goal is to use evidence obtained from these models to identify the attributes of a SCI Program of Excellence (ACT/III).

Identification of relevant policies for traumatic SCI

Development of the methodological framework for the ACT project began with a meeting in December 2009 among clinicians, researchers, administrators, policy decision makers, and persons with SCI from across Canada who met to identify important policies related to traumatic SCI care delivery.

Thirty-five participants attended the meeting and following the breakout sessions there was general consensus that the initial focus should be on the setting (where patients with SCI receive their care), as well as the timing of when patients with SCI receive their care. It was hypothesized that patients with traumatic SCI who receive timely care in a specialized center

will have superior patient outcomes and lower short- and long-term costs compared to patients who experience delays and are treated in non-specialized centers. To manage the scope of the first three phases of ACT (ACT/I, ACT/II, and ACT/III), detailed patient flow in the community was excluded and instead a model describing the long-term costs and patient outcomes was developed. It was recommended that detailed mapping of the community phase for persons with traumatic SCI should be addressed in future phases of the ACT project.

Process mapping

Process mapping is a critical component of the project. It was used to document patient flow and resources at each site, as well as to provide the basis of the computer simulation for the ACT model. Two types of process maps were developed: level 1, which are high-level maps for all centers participating in the ACT project, and level 2, which are detailed maps for selected sites. The ACT project was specifically implemented in Canadian centers participating in a prospective longitudinal patient registry, referred to as the Rick Hansen SCI Registry (RHSCIR; Noonan et al., 2012b), which includes high-volume acute trauma facilities and specialized rehabilitation facilities in Canada. Sites for level 2 mapping were chosen to highlight differences in the organization and processes of care among facilities. The specific attributes determining site selection included: representation of Canadian provinces, grouping patients with traumatic SCI together on the same unit regardless of injury severity, acute and rehabilitation programs are located within the same SCI center, and SCI centers that provide an inpatient SCI program.

Level 1 process maps were generated for all of the Canadian regional sites participating in the project. The purposes of the level 1 process maps were threefold: (1) to document patient flow and basic processes of SCI care starting from the point of injury through to community integration at participating sites; (2) to identify and capture important differences in the delivery of care among participating sites; and (3) to identify sites that will be chosen for a detailed simulation in the future. Experts in each phase of care (pre-hospital, acute, and rehabilitation) at each site completed questionnaires and the results were validated to create the process map. The questionnaire asked for information on the structure of the facility (e.g., trauma center level and the types of units where patients are admitted), the services and processes of care (e.g., hours of operation for the MRI, if there are dedicated operating rooms for trauma or spine patients, and criteria to discharge patients to rehabilitation), and challenges with patient flow. All sites received a copy of their level 1 process map.

Level 2 process maps described the detailed patient flow through the health care system, considering clinical protocols and therapeutic decision making, as well as resource capabilities that may affect patient flow. The level 1 process maps served as the basic templates for the detailed level 2 maps. The study team conducted on-site visits to observe processes first hand, and to interview key personnel required for the level 2 mapping data. Site visits were conducted by two team members, representing SCI care delivery and OR. Each site visit began with a presentation describing the ACT project and was followed by a tour of the facility. At each site, experts involved with first response, patient triage, acute care

(admissions, emergency room, radiology, operating room, intensive care units, patient wards, and discharge planning), and rehabilitation (admissions, patient wards, inpatient and outpatient programs, and discharge planning) were interviewed. Standardized case scenarios were used to obtain information on processes of care, and site staff were asked to describe cases where the patient flow was problematic. Follow-up interviews with site personnel were conducted to ensure face validity of the process maps. The type of data collected included as part of the level 2 mapping were similar to the level 1 data (details on structure and processes of care), but additional details were obtained, and copies of protocols and data sources describing care were identified and requested. The level 2 process maps served as the template for the simulation model of the site's specific processes. To assist with translating the knowledge obtained regarding the SCI continuum of care at each site, a toolkit was provided to each site, which included a descriptive summary of the patient population based on available databases, copies of the level 2 process maps, and an accompanying document outlining each phase of care (pre-hospital, acute care, and rehabilitation), and the challenges experienced.

Model development

An overview of the DES model, which assesses the pre-hospital, acute, and rehabilitation phases of care, and the health progression model (HPM), which assesses the long-term patient outcomes, and costs are described in Figure 2. Together the DES and HPM are collectively referred to as the ACT model. The detailed statistical methods used to develop these models will be included in future publications.

The process of developing a simulation model for any given site began by identifying the input variables, as well as the input data files that drove the simulation. The end users at each site were involved as early as possible in the development of the simulation to ensure that it met the users' needs (Lehane and Hlupic, 1995), and to identify possible errors in assumptions and flow. The general procedure for the development of a DES model was to start with a "black box" for each phase of care in the system, and to continue to add detail until a useful representation of the real process had been reached.

The simulation model requires detailed input data. Data from the published literature were used to help determine demographics; SCI incidence; incidence of secondary complications; timing of interventions and therapies; dependence of length of stay on injury type, complications, and comorbidities; effects of rehabilitation on patient function; and economic data such as direct health care costs. The RHSCIR was the most appropriate data source for developing the simulation model, as it currently captures the majority of the above data elements from 31 different health care facilities across Canada from the time of injury, through to 1, 2, and every 5 years post-injury, until death or a participant's voluntary withdrawal from the study (Noonan et al., 2012b). Since the RHSCIR was only recently implemented in some sites, other hospital and national databases were also used to develop the models. In instances where data were not available, literature searches were conducted and relevant information was obtained from subject matter experts (e.g., the impact of a specific complication such as a delirium on acute length of stay). The DES

FIG. 2. Overall architecture of the DES model and HPM, which collectively are referred to as the ACT model. Information on the incidence of SCI feeds the DES model to identify individuals with traumatic SCI moving through the health care system. Those with traumatic SCI leaving the health care system then enter into the HPM, where long-term outcomes are calculated (DES, discrete event simulation; HPM, health progression model; LOS, length of stay; QALY, quality-adjusted life year; tSCI, traumatic spinal cord injury)

model was validated using two approaches: (1) site personnel verified that the process maps reflected current patient flow; and (2) outputs from the DES model were compared with results from the RHSCIR for a given site.

Since persons with SCI experience lifelong alterations to their activities and physical function, and also have a propensity to develop further or recurrent secondary complications (e.g., chronic pain, pressure ulcers, and pulmonary and urinary tract infections), it is important to model these post-injury influences on health. Not only does SCI and the possibility of secondary complications impact patient quality of life, but it also affects life expectancy and the need for further interventions. The HPM tracks specific events, such as the occurrence of a complication or the presence of pain following SCI (Fig. 2).

In addition to measuring condition-specific health-related outcomes, it is possible to derive quality-adjusted life years (QALYs) to track the overall lifetime impact of SCI. A statistical model has been developed from RHSCIR data and the SF-6D algorithm (Brazier et al., 2002), to deduce associations between a patient's reported health state (e.g., incidence of complications, injury characteristics, and physical function) and the utility of their health state as evaluated by a sample of the general U.K. population. This annual utility is then added up over all remaining years of life to calculate the QALYs lived by that individual after injury. As well as calculating health-related quantities, the HPM can also calculate economic quantities using the available Canadian literature on costs directly attributable to SCI to calculate direct health care costs (Dryden et al., 2005).

The HPM for SCI calculates the quantities described above by tracking a hypothetical person's health state after leaving the health care system as simulated using the DES, and cycling them through individual years of life until death, as predicted by the literature on the lifespan of individuals with varying severities of SCI. Several inputs are used, including the initial state of the person following SCI, which is specified in terms of age, sex, level and severity of SCI, and their

history of complications and functional status. Various data sources are used to determine their annual transitional probabilities to future states (e.g., incidence of complications and change in functional status), their annual utilities associated with health status, the costs, and finally their risk for mortality.

Results

The four phases of the ACT/I project have been completed (selection of the conceptual framework, identification of relevant policies, process mapping, and development of the ACT model). Graham's model, referred to as Knowledge to Action, served as the conceptual framework for this project. The focus on evaluating the effect of "access to specialized care" and "the need for timely care" was identified by multiple stakeholders working in the field of SCI. A summary of the data obtained from the level 1 and level 2 mapping is described below, and a sample scenario is provided to demonstrate the outputs that can be obtained from the ACT model.

Summary of the results from the level 1 and 2 mapping

Level 1 process maps were developed for 12 Canadian sites, comprising 24 acute and rehabilitation facilities, and covering 7 provinces (Fig. 3). There was wide diversity in how care is provided among the SCI centers. Three SCI centers have the acute and rehabilitation program located in the same center (Table 1), and there were 12 free-standing acute centers and 9 free-standing rehabilitation centers. Centers providing acute and rehabilitation care in one hospital were described separately, resulting in data from 15 acute and 12 rehabilitation centers. An example of the process map developed for each SCI center is shown in Figure 4.

Level 2 process maps were then developed for a subset of the level 1 sites, specifically 5 Canadian regional sites comprising 8 facilities in 4 Canadian provinces. In all, 101 subject matter experts were interviewed from all level 2 sites (Table 2), and a list of the types of clinical roles is included in Table 3.

FIG. 3. Locations of the facilities participating in the ACT project in Canada.

An example of a detailed process map is provided in Figure 5. The detailed process mapping conducted as part of the level 2 mapping was an effective communication tool. It allowed subject matter experts to view their own contribution to SCI health care delivery as a part of an integrated system, as opposed to only considering their own role on the team. Developing the process maps at the sites promoted discussion among subject matter experts and other stakeholders (e.g., administrators) about the barriers to patient flow in the system. It also demonstrated the dependencies among the phases

of care, particularly between acute care and rehabilitation. While patient flow through the system is multi-factorial, involving many different units and services, often the “back end” (discharge) is considered the greatest impediment to efficient patient flow. Another important benefit of conducting the process mapping was to provide anecdotal information related to clinical decision making based on real-life scenarios, which facilitated discussions about how protocols and clinical practice often differ. Examples of challenges in patient flow from each of the pre-hospital, acute care, and rehabilitation phases of care are described in Table 2.

TABLE 1. DATA FROM LEVEL 1 PROCESS MAPPING

Type of information		
<i>Geography</i>		
Number of provinces participating in the ACT project for level 1 mapping	7 of 10 Canadian provinces	
<i>Structure</i>		
SCI center is a Level 1 trauma center	14/15 acute centers	
Group patients with SCI on the same unit regardless of injury severity	7/15 acute centers 9/12 rehabilitation centers	
Acute and rehabilitation programs are within the same SCI center	3/15 acute centers 3/12 rehabilitation centers	
<i>Service</i>		
Acute and rehabilitation centers provide an inpatient SCI program	7/15 acute centers 10/12 rehabilitation centers	

ACT, Access to Care and Timing; SCI, spinal cord injury.

An example of how the ACT simulation model (DES and HPM) can be used in practice

The ACT model, comprising the DES and the HPM, has been developed and can now be used in future phases of the ACT project (ACT/II and ACT/III) to identify the attributes of an SCI Program of Excellence. The model is tailored to each SCI site (acute and rehabilitation facility) using site-specific parameters (e.g., resource levels such as number of beds). Using the site model, “what if” scenarios can be run to examine hypothetical changes or interventions to either the administrative or clinical processes. Results from the model will assist the site by providing evidence for proposed clinical innovations or interventions. For example, hypotheses related to the implementation of clinical practices (e.g., timing of interventions), or barriers to patient flow, can be examined for specific phases of care (acute or rehabilitation). The potential outcome from one particular simulated scenario is illustrated in Figure 6 which demonstrates the direct and indirect effects of triaging patients who sustain a traumatic SCI directly to a specialized acute care facility, rather than initially transferring

FIG. 4. Level 1 (high-level) process map. This figure provides an example of a basic level 1 process map. This high-level process map contains the main blocks used to describe the different centers and facilities; however, the main characteristic of this map is that it does not contain any data describing facility performance, patient characteristics, patient outcomes, or any other detailed information about the process of care (ED, emergency department; ICU, intensive care unit; OR, operating room; PAR, post-anesthetic recovery; CT, computed tomography; MRI, magnetic resonance imaging; SCI, spinal cord injury).

TABLE 2. DATA FROM LEVEL 2 MAPPING

Type of information	
<i>Geography</i>	
Number of provinces participating in the ACT project for level 2 mapping	4 of 10 Canadian provinces
<i>Structure and location of acute and rehabilitation centers</i>	
Acute centers	4
Rehabilitation centers	2
Acute and rehabilitation programs are within the same SCI center	2
<i>Subject matter experts interviewed</i>	
Total number	101
<i>Challenges identified in patient flow</i>	
Pre-hospital phase	Variations in pre-hospital structure/jurisdiction can lead to difficulties in standardization of protocols (and differences within provinces): some sites have provincially-run programs, other sites have many different EMS (road) service companies within a region/province, while in other sites road EMS can be serviced provincially and air ambulance is run privately Inexperience with traumatic SCI (and related protocols) can lead to inaccurate diagnosis and delays in routing to designated SCI centers (trauma)
Acute care phase	Challenge balancing care with decreases length of stay with the “no refusal policy” (increase admission), limited inpatient resources (e.g., staff and beds), and no change in discharge policies Discharge criteria from acute and admission criteria to rehabilitation do not often correlate, waiting for beds in rehab can be an impediment to patient flow
Rehabilitation phase	Delays to final discharge destination (or even placing them in a discharge destination in the community) can be one of the greatest challenges to flow, most often due to delays for equipment and home modifications Some rehabilitation centers are not properly equipped to deal with acute care issues, or are not integrated with acute centers, so they must send patients on service interruption (back to the acute site) to deal with secondary complications

TABLE 3. EXAMPLES OF THE CLINICAL ROLES INVOLVED IN THE LEVEL 2 MAPPING

<i>Phase of care</i>	<i>Clinical role</i>
Pre-hospital	Paramedics
	Emergency physicians
	Researchers
	Program directors
Acute	Spine surgeons
	Intensivists
	Program directors
	Nurse specialists/managers
	Nurses (patient units, emergency, operating, recovery rooms)
	Program/unit managers (patient units, operating rooms)
	Clinical coordinators
	Physical therapists
	Occupational therapists
	MRI/CT technicians
Rehabilitation	Researchers
	Physiatrists
	General practitioners
	Physical therapists
	Occupational therapists
	Social workers
	Nurse specialists
	Nurses
	Clinical coordinators
	Researchers

CT, computed tomography; MRI, magnetic resonance imaging.

them to community hospitals, in order to reduce the time to surgery. The figure illustrates how it is important to consider both the direct effects (transferring all patients within a 20 min drive and 350 km helicopter range), and the indirect effects (e.g., impact on length of stay). Often the indirect effects provide a stronger business case for the intervention compared to only reporting the direct effects, and they also provide insight into the impact on other outcomes within the continuum of care. Furthermore, a decision maker could compare how the effect of triaging patients directly to an SCI center compare with other options, such as changing the number of operating rooms, to see which has a greater impact on reducing the time to surgery.

Discussion

While translational research studies in SCI have often involved the investigation of moving potential therapies generated in pre-clinical settings (e.g., animal-based laboratories) to the clinical realm, the basic principle underlying translational research is the application of techniques and lessons cultivated in one discipline or realm for use in another. The ACT project is unprecedented in that it involves an innovative partnership between leading experts in the fields of Operations Research, health administration, clinical research, medicine, surgery, and rehabilitation, and is a prime example of translational research.

The general model developed in the ACT project can help predict the impact of innovations and interventions before they are implemented. This type of tool assists in the translation of research into practice by providing an opportunity to

test which ones are the most effective, and then to identify the circumstances that would either support or detract from the initiative. For example, a policy initiative that would result in patients arriving earlier to an acute care facility would provide earlier access to surgery (Fig. 6). However, our experience using the DES model highlights the indirect impacts that the policy change might have downstream in rehabilitation and the community. Such indirect impacts might significantly change the cost/benefit calculations for these competing innovations. In this way the DES and HPM methodology of the ACT project serve as a testing framework to facilitate the translation of research into practice.

Another contribution from the ACT project is that it provides one a view from the patient's perspective. Many of the stakeholders in the continuum of care are exposed to, funded by, and evaluated by the particular phase of care in which they operate. However, from the patient's perspective, this can result in inefficiencies and potentially poorer outcomes. Systems that provide health care can be fragmented in their geographic locations, resourcing, organizational structures, and therapeutic approaches. Similarly, policy decisions often are made with little knowledge or regard for the upstream or downstream influences that exist beyond the health care facility. By modeling all phases of SCI health care delivery (pre-hospital, acute care, and rehabilitation) as one comprehensive and integrated system, the effects of implementing a change in policy or practice at one end of the continuum can be quantitatively estimated for all the facilities that comprise that system.

After discharge from the health care facility, the person with traumatic SCI continues to live with a chronic health condition and may experience new or recurrent medical complications; the probability of future complications can be affected, for better or worse, by the type of initial treatment offered. Including the HPM in this model allows the user to evaluate the lifelong consequences of the injury and its initial treatment. For example, the presence of a complication such as a pressure ulcer in the early phases of acute hospitalization will lead to the possibility of either new or recurrent complications. This is a unique feature that is precisely modeled not only during the patient's hospitalization, but is linked to the rest-of-life modeling of the HPM. The importance of this long-term causal link is highlighted by the fact that within the first year post-injury, rehospitalization rates due to secondary complications have been reported to be 27.5% in Canada (Jaglal et al., 2009), and between 39% and 50% in the United States (Cardenas et al., 2004; Davidoff et al., 1990; Eastwood et al., 1999; Samsa et al., 1996). These increasing rehospitalization rates are associated with substantial costs to society and poor patient health status.

Perhaps the most powerful outcome of the ACT project will be the ability to examine both system- and patient-level outcomes using "what if" scenarios related to clinical practices and administrative policy scenarios. Example scenarios include: "what would be the results for persons with SCI if we transferred every SCI patient by helicopter to the nearest specialized spine facility?" and "what if we integrated acute and rehabilitation SCI programs?" Recently reported clinical research studies have identified a possible neurological benefit to early surgical decompression in patients with SCI (Fehlings et al., 2012). If this is true, then the timely provision of surgical care will influence patient outcomes by improving

FIG. 5. Level 2 (detailed) process map. This figure provides an example of a detailed or level 2 process map. With similarities to the larger blocks seen in the level 1 process map, the major distinguishing feature of the level 2 map is the increasingly detailed information that is featured within each phase of care. The blocks in this figure correspond to each center/facility, which are further described (inner blocks), and outline required system data, such as available resources, incidence rates, service times, waiting times, decision points, and decision criteria (ISNCSCI, International Standards for the Neurological Classification of Spinal Cord Injury; SCI, spinal cord injury).

neurological recovery. The effect of advancing age at the time of injury can also be quantified by examining its effect on costs and health care resources, allowing administrators and policymakers to appropriately plan for the aging of the Canadian

population. Future enhancements to the ACT model will include replacing the national incidence rate for traumatic SCI with incidence rates for each of the Canadian provinces, along with low-, medium-, and high-growth population projections.

FIG. 6. Illustrated here is an example of a policy that can be assessed using the DES model. This figure shows the direct impact of directly transferring all patients injured within a 20-min drive from an acute SCI center and within helicopter range (up to 350 km) to the hospital, which results in a 45% increase (from 24% to 69%) in the number of patients admitted directly to an acute SCI center. The indirect impacts are a reduction of 3.8 h in the average time to admission, and a reduction of 3.5 h in the average time to surgery, thus increasing the number of patients getting surgery within 24 h by 6%, and decreasing the number of patients getting surgery later than 48 h post-injury by 3.4%. These results are for the specific group of patients who are not sent directly to the acute SCI center. On the negative side, admission of more patients directly to the acute SCI center creates an increase of 3.2% in the number of patients experiencing delays waiting for transfer to inpatient rehabilitation (referred to as alternative level of care [ALC] days), thus increasing the average total length of stay by 2.4 days for all patients, not just the group of patients admitted directly to the acute SCI center (DES, discrete event simulation; SCI, spinal cord injury).

This detailed information will enable the ACT model to be tailored specifically for each province, and allow more refined projections of the health care resources required for future SCI care delivery.

The final unique aspect of our methodology is the potential use of the findings of this model to identify the characteristics of a SCI Program of Excellence. By encouraging the accreditation of these SCI Programs of Excellence in Canada, the results from this study would be more likely to be translated from knowledge into action.

There are a number of recommendations to share with other groups developing similar models based on our experiences to date. First, the potential policy changes or initiatives of interest must be clearly defined. These policy questions determine the data required, the outcomes selected, and the structure of the DES model, and ensure that answers can be obtained. Second, process mapping requires a considerable amount of time from clinical experts, so it is important to set appropriate timelines to ensure that the project is feasible and all stakeholders are included. Third, the process maps developed in our first pilot site served as a template for the other sites. Starting at one site enabled the project to be piloted, and enhanced feasibility and collaboration when involving other sites. Finally, consideration must be given to the type of model used. A DES was selected for this project since it is an intuitive extension of the process map. Animating the patient flow according to feedback from the stakeholders allows a more accurate interpretation of the actual processes and ensures the

validity of the content. It is also well suited for handling complex systems involving multiple and highly articulated stages. An alternate methodology such as queuing theory, the mathematical study of waiting lines or queues, has many rigid assumptions, is less flexible, is not transparent to the user (more like a “black box”), and is suitable only for simple problems. Markov models, which have been demonstrated to be good for disease progression modeling (Palmer et al., 2004), are also not suitable for this project, again because of the complexity of the situation. The amount of data related to the history of the patient during their journey through the health care system (technically called the “state space”) is so large as to be computationally intractable.

As with any project there are limitations. The development and validation of the simulation model was only possible due to the availability of input data to populate the model, and the results can only be as accurate as the data. The data collected as part of the Canadian RHSCIR (Noonan et al., 2012b) were selected with the intent of developing a detailed and comprehensive data set that spans the pre-hospital, acute care, rehabilitation, and community phases of traumatic SCI. The ACT project used approximately 80% of the data elements collected by the RHSCIR. Future revisions to the RHSCIR data set, for example replacing the Functional Independence Measure (Granger et al., 1993) with the Spinal Cord Independence Measure III (Catz et al., 2007), will further enhance the validity of the models. The process maps were also able to identify gaps in existing data and literature that

RHSCIR should capture in the future to further develop these models. Alternatively, if generalized data or evidence (e.g., results reported in peer-reviewed publications rather than measured data at the sites) are used, the relevance and specificity of the model's predictions may subsequently be reduced. In the future, additional sites that participated in the level 1 mapping will undergo level 2 process mapping, and this will add to the external validity of the ACT model for describing SCI care in Canada.

Conclusions

The ACT project has the potential to affect multiple SCI stakeholders across Canada, and its results demonstrate a unique and novel use of a large-scale observational dataset like the RHSCIR. It is anticipated that the methodology utilized in this study will prove to be robust, with the potential to be adopted for other similar conditions and injury states with similar access and patient flow issues, such as acute stroke, brain injury, and the trauma care system. However, the ACT project is part of a broader vision to create a methodological framework to evaluate clinical practices, and in particular to develop an accreditation process for SCI Programs of Excellence.

Acknowledgment

We would like to acknowledge the Rick Hansen Institute, Health Canada, and the provinces of British Columbia and Ontario for funding this project. In addition, we would like to thank all of the members of the Access to Care and Timing team who provided input related to this project, and the site leads at each of our Canadian facilities, who have supported the ACT project. We wish to thank Lesley Soril for her assistance in managing the Access to Care and Timing project, and Sophia Park and Antoinette Cheung for their assistance in preparing this manuscript. The work detailed here was made possible through a financial contribution from Health Canada. The views expressed herein represent the views of the Rick Hansen Institute. Provincial financial contributions for the RHSCIR have been received from British Columbia and Ontario.

Author Disclosure Statement

Vanessa K. Noonan and Lesley Soril are employees of the RHI. Drs. Marcel F. Dvorak and Michael G. Fehlings consult for the RHI.

References

- Bowers, J., and Mould, G. (2001). Organisational implications of concentration orthopaedic services. *Health Bull. (Edinb.)* 59, 381–387.
- Brazier, J., Roberts, J., and Deverill, M. (2002). The estimation of a preference-based measure of health from the SF-36. *J. Health Econ.* 21, 271–292.
- Cardenas, D.D., Hoffman, J.M., Kirshblum, S., and McKinley, W. (2004). Etiology and incidence of rehospitalization after traumatic spinal cord injury: a multicenter analysis. *Arch. Phys. Med. Rehabil.* 85, 1757–1763.
- Catz, A., Itzkovich, M., Tesio, L., Biering-Sorensen, F., Weeks, C., Laramie, M.T., Craven, B.C., Tonack, M., Hitzig, S.L., Glaser, E., Zeilig, G., Aito, S., Scivoletto, G., Mecci, M., Chadwick, R.J., El Masry, W.S., Osman, A., Glass, C.A., Silva, P., Soni, B.M., Gardner, B.P., Savic, G., Bergstrom, E.M., Bluvshstein, V., and Ronen, J. (2007). A multicenter international study on the Spinal Cord Independence Measure, version III: Rasch psychometric validation. *Spinal Cord* 45, 275–291.
- Chand, S., Moskowitz, H., Norris, J.B., Shade, S., and Willis, D.R. (2009). Improving patient flow at an outpatient clinic: study of sources of variability and improvement factors. *Health Care Manag. Sci.* 12, 325–340.
- Davidoff, G., Schultz, J.S., Lieb, T., Andrews, K., Wardner, J., Hayes, C., Ward, M., Karunas, R., and Maynard, F. (1990). Rehospitalization after initial rehabilitation for acute spinal cord injury: incidence and risk factors. *Arch. Phys. Med. Rehabil.* 71, 121–124.
- Dorsett, P., and Geraghty, T. (2008). Health-related outcomes of people with spinal cord injury—a 10 year longitudinal study. *Spinal Cord* 46, 386–391.
- Dryden, D.M., Saunders, L.D., Jacobs, P., Schopflocher, D.P., Rowe, B.H., May, L.A., Yiannakoulis, N., Svenson, L.W., and Voaklander, D.C. (2005). Direct health care costs after traumatic spinal cord injury. *J. Trauma* 59, 443–449.
- Dryden, D.M., Saunders, L.D., Rowe, B.H., May, L.A., Yiannakoulis, N., Svenson, L.W., Schopflocher, D.P., and Voaklander, D.C. (2004). Utilization of health services following spinal cord injury: a 6-year follow-up study. *Spinal Cord* 42, 513–525.
- Eastwood, E.A., Hagglund, K.J., Ragnarsson, K.T., Gordon, W.A., and Marino, R.J. (1999). Medical rehabilitation length of stay and outcomes for persons with traumatic spinal cord injury—1990–1997. *Arch. Phys. Med. Rehabil.* 80, 1457–1463.
- Fehlings, M.G., Vaccaro, A., Wilson J.R., Singh, A., Cadotte D., Harrop, J.S., Aarabi, B., Shaffrey, C., Dvorak, M., Fisher, C., Arnold, P., Massicotte, E.M., Lewis, S., Rampersaud, R. (2012). Early versus delayed decompression for traumatic cervical spinal cord injury: results of the Surgical Timing in Acute Spinal Cord Injury Study (STASCIS). *PLoS One* 7, e32037.
- Graham, I.D., Logan, J., Harrison, M.B., Straus, S.E., Tetroe, J., Caswell, W., and Robinson, N. (2006). Lost in knowledge translation: time for a map? *J. Contin. Educ. Health Prof.* 26, 13–24.
- Granger, C.V., Hamilton, B.B., Linacre, J.M., Heinemann, A.W., and Wright, B.D. (1993). Performance profiles of the functional independence measure. *Am. J. Phys. Med. Rehabil.* 72, 84–89.
- Hoot, N.R., LeBlanc, L.J., Jones, I., Levin, S.R., Zhou, C., Gadd, C.S., and Aronsky, D. (2008). Forecasting emergency department crowding: a discrete event simulation. *Ann. Emerg. Med.* 52, 116–125.
- Hoot, N.R., LeBlanc, L.J., Jones, I., Levin, S.R., Zhou, C., Gadd, C.S., and Aronsky, D. (2009). Forecasting emergency department crowding: a prospective, real-time evaluation. *J. Am. Med. Inform. Assoc.* 16, 338–345.
- Hung, G.R., Whitehouse, S.R., O'Neill, C., Gray, A.P., and Kisson, N. (2007). Computer modeling of patient flow in a pediatric emergency department using discrete event simulation. *Pediatr. Emerg. Care* 23, 5–10.
- Jaglal, S.B., Munce, S.E., Guilcher, S.J., Couris, C.M., Fung, K., Craven, B.C., and Verrier, M. (2009). Health system factors associated with rehospitalizations after traumatic spinal cord injury: a population-based study. *Spinal Cord* 47, 604–609.
- Johnson, R.L., Gerhart, K.A., McCray, J., Menconi, J.C., and Whiteneck, G.G. (1998). Secondary conditions following spinal cord injury in a population-based sample. *Spinal Cord* 36, 45–50.

- Khare, R.K., Powell, E.S., Reinhardt, G., and Lucenti, M. (2009). Adding more beds to the emergency department or reducing admitted patient boarding times: which has a more significant influence on emergency department congestion? *Ann. Emerg. Med.* 53, 575–585.
- Kolker, A. (2009). Process modeling of ICU patient flow: effect of daily load leveling of elective surgeries on ICU diversion. *J. Med. Syst.* 33, 27–40.
- Krause, J.S., and Saunders, L.L. (2009). Risk of hospitalizations after spinal cord injury: relationship with biographical, injury, educational, and behavioral factors. *Spinal Cord* 47, 692–697.
- Leduc, B.E., and Lepage, Y. (2002). Health-related quality of life after spinal cord injury. *Disabil. Rehabil.* 24, 196–202.
- Lehaney, B., and Hlupic, V. (1995). Simulation modelling for resource allocation and planning in the health sector. *J. R. Soc. Health* 115, 382–385.
- Levin, S.R., Dittus, R., Aronsky, D., Weinger, M.B., Han, J., Boord, J., and France, D. (2008). Optimizing cardiology capacity to reduce emergency department boarding: a systems engineering approach. *Am. Heart J.* 156, 1202–1209.
- Middleton, J.W., Lim, K., Taylor, L., Soden, R., and Rutkowski, S. (2004). Patterns of morbidity and rehospitalisation following spinal cord injury. *Spinal Cord* 42, 359–367.
- New, P.W., and Jackson, T. (2010). The costs and adverse events associated with hospitalization of patients with spinal cord injury in Victoria, Australia. *Spine* 35, 796–802.
- Noonan, V.K., Fingas, M., Farry, A., Baxter, D., Singh, A., Fehling, M., and Dvorak, M. (2012a). The incidence and prevalence of spinal cord injury in Canada: A national perspective. *Neuroepidemiology* 38, 219–226.
- Noonan, V.K., Kwon, B.K., Soril, L., Fehlings, M.G., Hurlbert, R.J., Townson, A., Johnson, M., and Dvorak, M.F. (2012b). The Rick Hansen Spinal Cord Injury Registry (RHSCIR): a national patient-registry. *Spinal Cord* 50, 22–27.
- Palmer, A.J., Roze, S., Valentine, W.J., Minshall, M.E., Foos, V., Lurati, F.M., Lammert, M., and Spinas, G.A. (2004). The CORE Diabetes Model: Projecting long-term clinical outcomes, costs and cost-effectiveness of interventions in diabetes mellitus (types 1 and 2) to support clinical and reimbursement decision-making. *Curr. Med. Res. Opin.* 20 Suppl. 1, S5–S26.
- Riggins, M.S., Kankipati, P., Oyster, M.L., Cooper, R.A., and Boninger, M.L. (2011). The relationship between quality of life and change in mobility 1 year postinjury in individuals with spinal cord injury. *Arch. Phys. Med. Rehabil.* 92, 1027–1033.
- Samsa, G.P., Landsman, P.B., and Hamilton, B. (1996). Inpatient hospital utilization among veterans with traumatic spinal cord injury. *Arch. Phys. Med. Rehabil.* 77, 1037–1043.
- Simpson, K.N., Strassburger, A., Jones, W.J., Dietz, B., and Rajagopalan, R. (2009). Comparison of Markov model and discrete-event simulation techniques for HIV. *Pharmacoeconomics* 27, 159–165.
- Tator, C.H., Duncan, E.G., Edmonds, V.E., Lapczak, L.I., and Andrews, D.F. (1993). Complications and costs of management of acute spinal cord injury. *Paraplegia* 31, 700–714.
- Wood-Dauphinee, S., Exner, G., Bostanci, B., Exner, G., Glass, C., Jochheim, K.A., Kluger, P., Koller, M., Krishnan, K.R., Post, M.W., Ragnarsson, K.T., Rommel, T., Zitnay, G., and SCI Consensus Group. (2002). Quality of life in patients with spinal cord injury—basic issues, assessment, and recommendations. *Restor. Neurol. Neurosci.* 20, 135–149.

Address correspondence to:

Marcel F. Dvorak, M.D.

6th Floor Blusson Spinal Cord Centre

818 West 10th Avenue

Vancouver, British Columbia, Canada V5Z 1M9

E-mail: marcel.dvorak@vch.ca