J Neurosurg Spine (Suppl) 17:38–45, 2012

Predictors of pulmonary complications in blunt traumatic spinal cord injury

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Object. Pulmonary complications are the most common acute systemic adverse events following spinal cord injury (SCI), and contribute to morbidity, mortality, and increased length of hospital stay (LOS). Identification of factors associated with pulmonary complications would be of value in prevention and acute care management. Predictors of pulmonary complications after SCI and their effect on neurological recovery were prospectively studied between 2005 and 2009 at the 9 hospitals in the North American Clinical Trials Network (NACTN).

Methods. The authors sought to address 2 specific aims: 1) define and analyze the predictors of moderate and severe pulmonary complications following SCI; and 2) investigate whether pulmonary complications negatively affected the American Spinal Injury Association (ASIA) Impairment Scale conversion rate of patients with SCI. The NACTN registry of the demographic data, neurological findings, imaging studies, and acute hospitalization duration of patients with SCI was used to analyze the incidence and severity of pulmonary complications in 109 patients with early MR imaging and long-term follow-up (mean 9.5 months). Univariate and Bayesian logistic regression analyses were used to analyze the data.

Results. In this study, 86 patients were male, and the mean age was 43 years. The causes of injury were motor vehicle accidents and falls in 80 patients. The SCI segmental level was in the cervical, thoracic, and conus medullaris regions in 87, 14, and 8 patients, respectively. Sixty-four patients were neurologically motor complete at the time of admission. The authors encountered 87 complications in 51 patients: ventilator-dependent respiratory failure (26); pneumonia (25); pleural effusion (17); acute lung injury (6); lobar collapse (4); pneumothorax (4); pulmonary embolism (2); hemothorax (2), and mucus plug (1). Univariate analysis indicated associations between pulmonary complications and younger age, sports injuries, ASIA Impairment Scale grade, ascending neurological level, and lesion length on the MRI studies at admission. Bayesian logistic regression indicated a significant relationship between pulmonary complications and ASIA Impairment Scale Grades A ($p = 0.0002$) and B ($p = 0.04$) at admission. Pulmonary complications did not affect long-term conversion of ASIA Impairment Scale grades.

Conclusions. The ASIA Impairment Scale grade was the fundamental clinical entity predicting pulmonary complications. Although pulmonary complications significantly increased LOS, they did not increase mortality rates and did not adversely affect the rate of conversion to a better ASIA Impairment Scale grade in patients with SCI. Maximum canal compromise, maximum spinal cord compression, and Acute Physiology and Chronic Health Evaluation–II score had no relationship to pulmonary complications.

(http://thejns.org/doi/abs/10.3171/2012.4.AOSPINE1295)

Key Words • pulmonary complication • spinal cord • trauma • predictor • spinal cord injury

Abbreviations used in this paper: ASIA = American Spinal Injury Association; LOS = hospital length of stay; MCC = maximum canal compromise; MSCC = maximum spinal cord compression; NACTN = North American Clinical Trials Network; RR = risk ratio; SCI = spinal cord injury.

The annual worldwide incidence of SCI is 10.4–83 per 1 million people, with more than 11,000 new cases in the North American continent alone. Nearly one-half of patients with SCI have complete loss of motor and sensory function, and one-third remain

quadriplegic.[51] Acute traumatic insult to the spinal cord results in loss of balance between rostral and caudal somatic and visceral neuronal input, culminating in sudden and precipitous defects in physiological function, which negatively influences the systemic medical status of the patient, ultimately resulting in an increase in deaths, morbidity, and length of stay in the critical care unit.[10,16,17,21] Functional loss of intercostal muscles and the diaphragm result in decreased vital capacity, reduced chest wall compliance, paradoxical chest expansion, and ventilatory failure.[32–34,39,44,45,49] Ineffective cough and unopposed muscarinic neuronal impulses originating in the dorsal motor nucleus of the vagus in the medulla oblongata cause not only bronchial constriction but also inability of the victim to clear excessive secretions.[16] Atelectasis, pneumonia, and ventilatory failure contribute to an excess of oxygen cost of breathing.[10] Loss of sympathetic tone below the level of injury will result in neurogenic shock and further endangers oxygen-carrying capacity into the spinal cord, which is already suffering from an ischemic state.[21]

Pulmonary complications are the most common causes of death and morbidity following SCI. Up to 80% of inpatient deaths from cervical SCI are due to pulmonary dysfunction, and pneumonia is the cause in 50% of cases.[15,38] There is evidence that neurological level and completeness of SCI may significantly contribute to the need for artificial ventilation and pulmonary complications.[33,44,45] Furthermore, patients with complete SCI have substantially more maximum canal compromise, spinal cord compression, and longer intramedullary lesions on MR imaging studies.[36] Although judicious acute care management,[11,16,25,26,41,44] neuronal plasticity,[32,35] and significant progress in rehabilitation over time (including ventilatory support) have significantly improved our management of pulmonary complications of SCI,[10,13,44,45] knowledge of the predictors of pulmonary complications and their effect on neurological outcome further enables us to be more vigilant in applying early preventive measures such as tracheostomy and phrenic and intercostal nerve stimulator implants.[11,13,25,41]

The goals in this study were as follows. 1) Define and analyze the predictors of moderate and severe pulmonary complications following SCI. 2) Investigate whether pulmonary complications negatively affected the ASIA Impairment Scale conversion rate in patients with SCI.

Methods

The NACTN

This study was funded by the Christopher and Dana Reeve Foundation and the Department of Defense. The NACTN is a consortium of 9 clinical centers composed of neurosurgery faculty and staff caring for patients with SCI. The NACTN was established in 2004 and is supported by a Data Management Center and a Pharmacological Center. The data registry is updated by the Data Management Center, which is in constant online communication with the coordinators and principal investigators at the 9 academic research centers.

Definition of a Complication

To grade the severity of complications, we have followed the reasoning used by the FDA, Department of Health and Human Services to classify adverse drug reactions and the severity of the reaction: "An adverse event … is considered 'serious' if, in the view of either the investigator or sponsor, it results in any of the following outcomes: Death, a life threatening event, inpatient hospitalization or prolongation of existing hospitalization, a persistent or significant incapacity or substantial disruption of the ability to conduct normal life functions…. and may require medical and surgical intervention to prevent one of the outcomes listed in this definition." (Code of Federal Regulations, Title 21, Volume 5, Sec. 312.32, IND Safety Reporting, 2011) (http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm). Following these concepts, the severity of pulmonary complications was defined in the following manner: a severe complication was defined as an event that, in the view of the investigator, required major medical and/or surgical intervention to prevent death or permanent impairment of the function or structure of an organ or system. A moderate complication was an event that required treatment and prolonged the hospitalization. A mild complication was an event that required treatment that carried little risk, had no residual effect on the patient's function, and did not prolong the patient's hospitalization. Surveillance for the occurrence of pulmonary complications was performed by physicians and research nurses dedicated to the study (http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm).[24] Surveillance consisted of daily chart reviews, screening of laboratory and imaging studies, and discussions with acute care intensivists and principal investigators. Pulmonary complications (Table 1) studied in this submission were all moderate or severe (http://www.nlm.nih.gov/medlineplus/mplusdictionary.html).

Study Design

This was a prospective observational study of moderate or severe pulmonary complications in 109 patients with SCI as registered in the NACTN cohort.[24]

The data set was extracted from the SCI data registry of the NACTN collected over 5 years (2005–2009). Nine Departments of Neurosurgery contributed to this data set.[24] Informed consent documents were signed by all the participants in the study at all the neurosurgical NACTN centers. Neurological assessment of the patients was performed by the neurosurgical staff and physical therapists of each center, who were trained in verification of International Standards for Neurological Classification of Spinal Cord Injury. The ASIA Impairment Scale and ASIA motor determinations were performed during critical care management and at discharge from the hospital and rehabilitation center. Long-term follow-up was at 6-week, 3-month, 6-month, and 12-month intervals.

Prehospital emergency management and evacuation, emergency department resuscitation, primary and secondary surveys, imaging studies, closed or open reduction, external or internal fixation, critical care management, rehabilitation, and follow-up were performed ac-

TABLE 1: Definitions of pulmonary complications seen in 109 patients with blunt SCI*

PC	Characteristics
ventilator-dependent respiratory failure	a condition in which a mechanical ventilator is required to maintain oxygenation & ventilation of the lungs because the native function is impaired or nonfunctional
pneumonia	a disease of the lungs that is characterized especially by inflammation & consolidation of lung tissue, followed by resolution; is accompanied by fever, chills, cough, & difficulty in breathing; & is caused chiefly by infection
pleural effusion	a transudation or exudation of fluid from the blood or lymph into a pleural cavity
acute lung injury	defined by the AECC as a PaO_2:FiO_2 ratio <300, w/ bilat pulmonary infiltrates seen on chest radiograph & absence of cardiogenic pulmonary edema by clinical criteria, or a PCWP <18 mm Hg in pts w/ a pulmonary artery (Swan-Ganz) catheter in place
lobar collapse	the loss of air (collapse) of a lobe of the lung
pneumothorax	a condition in which air or other gas is present in the pleural cavity, & which occurs spontaneously as a result of disease or injury of lung tissue, rupture of air-filled pulmonary cysts, or puncture of the chest wall, or is induced as a therapeutic measure to collapse the lung
pulmonary embolism	embolism of a pulmonary artery or one of its branches that is produced by foreign matter, most often a blood clot originating in a vein of the leg or pelvis, & that is marked by labored breathing, chest pain, fainting, rapid heart rate, cyanosis, shock, & sometimes death
hemothorax	blood in the pleural cavity
mucus plug	airway secretions composed of water, carbohydrates, proteins, & lipids, which become dry, thick, & tenacious, forming a plug that may block airways if not removed

* AECC = American European Consensus Conference; FiO_2 = fraction of inspired oxygen; PC = pulmonary complication; PCWP = pulmonary capillary wedge pressure; pts = patients.

cording to the guidelines recommended by the AANS/CNS and American College of Surgeons Committees on Trauma.[3,4,7] Calculation of maximum canal compromise, maximum spinal cord compression, and the length of the intramedullary lesion was performed according to the methodology of Fehlings and colleagues.[18,19,22,23,36]

Statistical Analysis

Pulmonary complications were modeled using negative binomial regression, with covariates that included age and ASIA Impairment Scale scores. The negative binomial regression model is appropriate for assessing the influence of covariates to the presence of pulmonary complications. The Bayesian methodology selects samples from simulation algorithms. The samples produce maximum likelihood estimates of terms that relate covariates to the incidence of pulmonary complications. Bayesian analysis involves 3 steps. The first step consists of deciding prior negative binomial probability estimates of parameters. The second step involves fitting the negative binomial model to the data. In the third step, a posterior probability model is produced using information from the first step and the estimates of repeated samples of Monte Carlo simulations. The GENMOD procedure of SAS (version 9.2; SAS Institute, Inc.) was used to perform Bayesian analysis and obtain estimates of the negative binomial probability model.

Results

Patient Characteristics and Pulmonary Complications

One hundred nine patients with SCI were included. Seventy-nine percent were male, and the mean age was 42.7 years (Table 2). Approximately 73% of the patients were involved in either motor vehicle accidents or were victims of falls. Almost 60% of the patients were motor complete (ASIA Impairment Scale Grades A and B), and the admission ASIA motor score in the entire cohort was 40. The mean Acute Physiology and Chronic Health Evaluation–II score was 8. The single neurological level was C2–T1 in close to 80% of the patients. Mathematical calculations[19] of imaging studies indicating the degree of injury severity showed that the mean canal compromise was 32.4%, the degree of spinal cord compression was 11.2%, and the length of the intramedullary lesion on T2-weighted MRI studies was 35 mm.[1,2] The LOS for acute care management was 26 days, and patients were followed after discharge for a mean of 9.5 months. Patients had a mean improvement of their ASIA motor score of 20 points (from 40 to 60); however, one-third of the patients maintained a complete physiological transection of the spinal cord.

Eighty-seven pulmonary complications occurred in 51 patients. Twenty-six patients had ventilatory failure, 25 had pneumonia, 17 had pleural effusion, 6 had acute lung injury, 4 had pneumothorax, and 4 had lobar collapse. Pulmonary embolus and hemothorax were each encountered in 2 patients, and 1 patient had a mucus plug.

Univariate Analysis

Demographic and Clinical Characteristics and Pulmonary Complications. Univariate analysis indicated that patients with sports injuries and those between the ages of 26 and 35 years were particularly prone to pul-

TABLE 2: Characteristics of the study population in 109 patients with SCI*

Variable	No. (%) or Mean ± SD
demographic data	
male sex	86 (78.9)
mean age, in yrs	42.7 ± 16.7
injury mechanism	
MVA	47 (43.1)
fall	33 (30.3)
sports	21 (19.3)
other	8 (7.3)
mean APACHE-II score	8 ± 8
neurological level	
C2–4	47 (43.1)
C5–T1	40 (36.7)
T2–12	14 (12.8)
L1–S1	8 (7.3)
mean ASIA motor score at adm	40 ± 30
ASIA Impairment Scale Grade at adm	
A	48 (44.0)
B	16 (14.7)
C	13 (11.9)
D	32 (29.4)
complete vs incomplete SCI	48 (44)
mean % MCC	32.4 ± 17.8
mean % MSCC	11.2 ± 21
mean LIL, in mm	35.2 ± 20.7
mean LOS, in days	25.9 ± 38.5
mean FU, in mos	9.5 ± 4.8
mean FU ASIA motor score	60.3 ± 33.9
FU ASIA Impairment Scale Grade	
A	34 (31.2)
B	10 (9.2)
C	15 (13.8)
D	35 (32.1)
E	15 (13.8)

* Adm = admission; APACHE-II = Acute Physiology and Chronic Health Evaluation–II; FU = follow-up; LIL = length of intramedullary lesion; MVA = motor vehicle accident.

monary complications and had an RR of 1.65 and 1.73, respectively ($p = 0.04$, Table 3). Individuals with ASIA motor scores less than 25 were almost 9 times more at risk of pulmonary complications than those with an ASIA motor score more than 50 (RR 8.7, $p < 0.0001$). Similarly, patients with ASIA Impairment Scale Grade A scores had more pulmonary complications (RR 8.2, $p < 0.0001$). Patients with complete SCI were 3 times more prone to pulmonary complications than patients with incomplete injuries (RR 3.36, $p < 0.0001$). As the single neurological level of injury ascended from S-1 to C-2, the rate of pulmonary complications increased concordantly. A patient with a single neurological level of C2–4 had 2.3 times more chances of developing pulmonary complications than a similar patient with a lumbosacral neurological level of injury; however, the difference was only marginally significant ($p = 0.09$).

Imaging Characteristics as Risk Factors for Pulmonary Complications. The degree of MCC in the spinal canal and MSCC did not influence the occurrence of pulmonary complications (Table 3). However, as the length of intramedullary lesion on T2-weighted MRI studies exceeded 40 mm, the risk of pulmonary complications also increased by a factor of 2 ($p = 0.004$).

Hospital Length of Stay, Duration of Follow-Up, and Mortality Rate. Patients with pulmonary complications had significantly longer LOSs (40.7 vs 12.8 days, $p = 0.05$). Each patient was followed for a mean of 9.5 months. Three of 109 patients died in this series, 2 with and 1 without pulmonary complications.

Effect of Pulmonary Complications on the ASIA Impairment Scale Grade Rate of Conversion. Overall, 34% of 109 patients converted to a better ASIA Impairment Scale grade during their follow-up: 35.4% of 48 patients in the Grade A group; 62.5% of 16 patients with Grade B; 77% of 13 patients in the Grade C group; and 37.5% of 32 patients in the Grade D group. The overall rate of conversion in patients with moderate or severe pulmonary complications was 37.2%, compared with 31% in patients without moderate or severe pulmonary complications (Table 4), and the difference was not significant. In the entire cohort, 3 patients regressed to a lower ASIA Impairment Scale grade; 2 in the Grade B group (1 with and 1 without moderate or severe pulmonary complications) and 1 in the Grade C group (without moderate or severe pulmonary complications).

Bayesian Multivariate Regression Analysis

We had 3 covariates that were inherently interrelated and had an association with moderate or severe pulmonary complications in the univariate analysis, as follows: 1) complete versus incomplete SCI injury; 2) ASIA motor score at the time of admission; and 3) ASIA Impairment Scale grade at the time of admission. For the regression analysis we took the ASIA Impairment Scale grade as the most comprehensive, conceptual, and functionally relevant covariate. We therefore designed a Bayesian multivariate regression model composed of 5 independent variables. Controlling for age, mechanism of injury, neurological level, and length of intramedullary lesion, only the admission ASIA Impairment Scale grade predicted moderate or severe pulmonary complications; patients with increasing severity of ASIA Impairment Scale grade had a markedly increased risk. Patients with Grade A were nearly 10 times as likely, those with Grade B were 2.6 times as likely, and those with Grade C were 1.7 times as likely to have a moderate or severe pulmonary complication compared with those with Grade D (Table 5).

Discussion

Although age, spinal level, and completeness of SCI

TABLE 3: Risks and unadjusted RRs and 95% CIs for moderate to severe pulmonary complications in 109 patients with SCI, based on potential risk factors

Potential Risk Factor	No. of Pts	No. w/ PCs	Risk (%)	Unadjusted	
				RR	95% CI (p value)*
demographic data					
sex					
female	23	10	43.5	referent	
male	86	41	47.7	1.1	0.65–1.84 (0.4323)
age, in yrs					
16–25	24	10	41.7	referent	
26–35	18	13	72.2	1.73	1.00–3.01 (0.0480)
36–45	16	6	37.5	0.90	0.41–1.98 (0.5280)
46–55	20	8	40.0	0.96	0.47–1.96 (0.5780)
56–65	23	9	39.1	0.93	0.47–1.88 (0.5479)
>65	8	5	62.5	1.50	0.73–3.07 (0.2699)
mechanism					
MVA	47	19	40.4	referent	
fall	33	14	42.4	1.04	0.62–1.78 (0.5197)
sports	21	14	66.7	1.65	1.04–2.61 (0.0407)
other	8	5	62.5	1.54	0.82–2.93 (0.2177)
neurological level					
L1–S1	8	2	25.0	referent	
T2–12	14	5	35.7	1.43	0.36–5.74 (0.4897)
C5–T1	40	17	42.5	1.66	0.47–5.81 (0.3239)
C2–C4	47	27	57.4	2.30	0.67–7.82 (0.0937)
severity					
adm ASIA motor score					
51–100	33	3	9.1	referent	
25–50	33	14	42.4	4.67	1.48–14.7 (0.0049)
<25	43	34	79.1	8.70	2.92–25.9 (<0.0001)
adm ASIA Impairment Scale grade					
D	32	3	9.4	referent	
C	13	4	30.8	3.28	0.85–12.7 (0.0935)
B	16	7	43.8	4.67	1.39–15.7 (0.0097)
A	48	37	77.1	8.22	2.77–24.4 (<0.0001)
SCI					
incomplete	61	14	23.0	referent	
complete	48	37	77.1	3.36	2.07–5.45 (<0.0001)
% MCC					
0–20	25	13	52.0	referent	
21–40	48	20	41.7	0.80	0.48–1.33 (0.2759)
41–67	36	18	50.0	0.96	0.58–1.58 (0.5425)
% MSCC					
<0	29	13	44.8	referent	
0–19	31	13	41.9	0.94	0.52–1.67 (0.5137)
20–57	49	25	51.0	1.14	0.70–1.85 (0.6447)
LIL, in mm					
<21	31	10	32.2	referent	
21–40	37	14	37.8	1.17	0.61–2.26 (0.4121)
>40	41	27	65.9	2.04	1.17–3.56 (0.0046)

* Calculated using the Fisher exact test.

TABLE 4: The ASIA Impairment Scale conversion rate in 109 patients with SCI admitted to 9 neurosurgical centers of the NACTN*

ASIA Impairment Scale Grade	ASIA Impairment Scale Grade						
	A	B	C	D	E	Total	% CR
all pts							
A	31	6	7	4	0	48	35.4
B	2	4	6	3	1	16	62.5
C	1	0	2	8	2	13	77.0
D	0	0	0	20	12	32	37.5
total	34	10	15	35	15	109	34.0
pts w/o PCs during acute care management							
A	7	0	2	2	0	11	36.4
B	1	2	2	3	1	9	66.7
C	0	0	1	6	2	9	88.9
D	0	0	0	19	10	29	34.5
total	8	2	5	30	13	58	31.0
pts w/ PCs during acute care management							
A	24	6	5	2	0	37	35.1
B	1	2	4	0	0	7	57.1
C	1	0	1	2	0	4	50.0
D	0	0	0	1	2	3	66.7
total	26	8	10	5	2	51	37.2

* CR = conversion rate.

as predictors of pulmonary complications have been studied before,[6,9,14,20,27,32,40,43] we found no studies clearly investigating predictive values of clinical (ASIA motor score, ASIA Impairment Scale grade) and imaging evidence of injury severity (MCC, MSCC, and length of intramedullary lesion) in the English literature.

Pulmonary complications in patients with SCI significantly contribute to increased LOS,[50] deaths,[8,10,15,38] and morbidity[6,10,43] during acute as well as rehabilitation care. Defects in the neuroanatomical[20,28] and physiological[6,14,16,27,42,43,46] infrastructure of the pulmonary apparatus result in ineffective use of breathing mechanisms and in a significant burden on activities of daily living.[6,10,42] Pulmonary function tests clearly indicate declines in forced vital capacity and forced expiratory volume in 1 second, resulting in atelectasis and pneumonia.[32–35,37,39,45,46,49] Neuronal plasticity, earlier tracheostomy, intermittent positive pressure breathing, newer ventilator settings, and neuromuscular and spinal cord stimulators all have improved our management of pulmonary complications following SCI.[10,13,16,25,32,35,41,44] Nevertheless, knowledge of predictors of pulmonary complications can prepare us to better use preventive and modern therapeutic measures.[11,13,16,17,25,26,41,44]

TABLE 5: Adjusted RRs and 95% CIs for moderate to severe pulmonary complications in 109 patients with SCIs*

Variable	aRR	95% CI	p Value
age	1.00	0.97–1.02	0.674
ASIA Impairment Scale grade†			
C	1.72	0.73–4.05	0.002‡
B	2.60	0.84–8.06	
A	9.80	2.74–35.7	

* aRR = adjusted RR.
† The reference standard was ASIA Impairment Scale Grade D.
‡ Test for trend.

In this study, complete (Grade A) SCIs were more prone to pulmonary dysfunction than incomplete SCIs (77.1% vs 23%, $p < 0.0001$). Other investigators have also confirmed this reality. Body weight, wheeze, and cigarette smoking seem to be added risk factors for pulmonary complications, in addition to the level and completeness of SCI.[28,45,49] Lower ASIA motor scores at admission were significant predictors of pulmonary complications ($p = 0.0001$). Similarly, patients classified in Grades C, D, and E were almost 10 times less susceptible to pulmonary complications. Reviewing the results of pulmonary function tests obtained in 123 patients at the time of admission, Reines and Harris[40] recorded a forced vital capacity of 1127 cm^3 in patients with pulmonary complications, compared with a forced vital capacity of 1865 cm^3 in patients without pulmonary complications. In this study, the PaO_2 in patients with pulmonary complications was 67 mm Hg, compared with a PaO_2 of 90 mm Hg in patients without pulmonary complications. Age, wheeze, obesity, and smoking, which contribute to physiological derangements, have been reported to be significant predictors of pulmonary complications.[26,28,30,34,46,49] The degree of physiological derangement (according to the Acute Physiology and Chronic Health Evaluation–II score) at the time of admission was not a predictor of pulmonary complications in our study.

There seems to be a progressive deterioration of respiratory function as the SCI severity approaches the craniocervical junction. In the present investigation, patients with high (C2–4) cervical injuries were 2.3 times more prone to have pulmonary complications ($p = 0.09$).[20,27,32] Evidence indicates that patients with paraplegia at high thoracic levels (T2–6) have greater chances of pulmonary complications than those with paraplegia at lower levels (T7–12).[6,9,14,20,43] We investigated validated measures of skeletal and SCI severity, including the degree of encroachment on the spinal canal (the MCC), the degree of spinal cord compression (the MSCC), and the length of the intramedullary lesion on MRI studies.[18,19,23,36] Validated reports have indicated that quadriplegic patients have more significant MCC, MSCC, and length of intramedullary lesion. Although MCC and MSCC were not significant risk factors, univariate analysis indicated that the longer the intramedullary lesion on the T2-weighted MRI studies of patients with SCI, the higher their chances of respiratory complications ($p = 0.004$). Preclinical studies indicate that ischemia is one the contributing factors in secondary insult to the spinal cord following primary injury.[5,12,29,31,47,48] Pulmonary complications and secondary hypoxemia may be detrimental factors for natural physiological repair and regeneration. We compared the rate of conversion in patients with no pulmonary complications and those who suffered pulmonary complications and found no difference in neurological recovery of function.

Conclusions

One of the fundamental principles of SCI management is prevention of pulmonary complications, which occur in more than half of these patients. Prevention of pulmonary complications, including pneumonia and atelectasis, might mitigate the adverse effects of ischemic insults to the injured spinal cord. Therapeutic trials such as cell-based trials of SCI management may need medications that might suppress immunity; therefore, extreme vigilance is needed to prevent superimposed pulmonary and systemic infections. Knowledge of the demographic characteristics, the injury level, and the ASIA Impairment Scale grade of SCI, in addition to the admission ASIA motor score and the length of intramedullary lesion on admission T2-weighted MRI studies, can help effectively prevent and better manage pulmonary complications. These factors may help reduce the ischemic insults to the vulnerable spinal cord and diminish deaths, morbidity, and LOS.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. Dr. Harrop is a consultant for DePuy Spine. Dr. Shaffrey is a consultant for Medtronic, DePuy, Biomet, Globus, and NuVasive; a patent holder with Medtronic and Biomet; and receives royalties from Medtronic, fellowship support from AO North America and Neurosurgery Research and Education Foundation, and grant support from the NIH, Department of Defense, and NACTN.

Author contributions to the study and manuscript preparation include the following. Conception and design: Aarabi. Acquisition of data: Aarabi, Grossman, Mirvis, Shanmuganathan, Zacherl, Burau, Frankowski, Toups, Habashi, Andrews. Analysis and interpretation of data: Aarabi, Alexander, Dettori, Zacherl, Frankowski. Drafting the article: Aarabi. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Aarabi. Statistical analysis: Alexander, Dettori. Administrative/technical/material support: Aarabi. Study supervision: Aarabi.

References

1. Aarabi B, Alexander M, Mirvis SE, Shanmuganathan K, Chesler D, Maulucci C, et al: Predictors of outcome in acute traumatic central cord syndrome due to spinal stenosis. Clinical article. **J Neurosurg Spine 14:**122–130, 2011
2. Aarabi B, Koltz M, Ibrahimi D: Hyperextension cervical spine injuries and traumatic central cord syndrome. **Neurosurg Focus 25(5):**E9, 2008
3. Alexander RH, Proctor HJ, American College of Surgeons Committee on Trauma: **Advanced Trauma Life Support Program for Physicians: ATLS, ed 5.** Chicago: American College of Surgeons, 1993
4. American College of Surgeons: **Advanced Trauma Life Support Program for Doctors: ATLS, ed 7.** Chicago: American College of Surgeons, 2004
5. Anderson DK, Means ED, Waters TR, Spears CJ: Spinal cord energy metabolism following compression trauma to the feline spinal cord. **J Neurosurg 53:**375–380, 1980
6. Ayas NT, Garshick E, Lieberman SL, Wien MF, Tun C, Brown R: Breathlessness in spinal cord injury depends on injury level. **J Spinal Cord Med 22:**97–101, 1999
7. Badjatia N, Carney N, Crocco TJ, Fallat ME, Hennes HMA, Jagoda AS, et al: Guidelines for prehospital management of traumatic brain injury, ed 2. **Prehosp Emerg Care 12 (Suppl):**S1–S52, 2007
8. Berlly M, Shem K: Respiratory management during the first five days after spinal cord injury. **J Spinal Cord Med 30:** 309–318, 2007
9. Boakye M, Patil CG, Santarelli J, Ho C, Tian W, Lad SP: Laminectomy and fusion after spinal cord injury: national inpatient complications and outcomes. **J Neurotrauma 25:**173–183, 2008
10. Brown R, DiMarco AF, Hoit JD, Garshick E: Respiratory dysfunction and management in spinal cord injury. **Respir Care 51:**853–870, 2006
11. Call MS, Kutcher ME, Izenberg RA, Singh T, Cohen MJ: Spinal cord injury: outcomes of ventilatory weaning and extubation. **J Trauma 71:**1673–1679, 2011
12. Carlson GD, Gorden CD, Oliff HS, Pillai JJ, LaManna JC: Sustained spinal cord compression: part I: time-dependent effect on long-term pathophysiology. **J Bone Joint Surg Am 85-A:**86–94, 2003
13. Cheng PT, Chen CL, Wang CM, Chung CY: Effect of neuromuscular electrical stimulation on cough capacity and pulmonary function in patients with acute cervical cord injury. **J Rehabil Med 38:**32–36, 2006
14. Cotton BA, Pryor JP, Chinwalla I, Wiebe DJ, Reilly PM, Schwab CW: Respiratory complications and mortality risk associated with thoracic spine injury. **J Trauma 59:**1400–1409, 2005
15. DeVivo MJ, Black KJ, Stover SL: Causes of death during the first 12 years after spinal cord injury. **Arch Phys Med Rehabil 74:**248–254, 1993
16. Dicpinigaitis PV, Spungen AM, Bauman WA, Absgarten A, Almenoff PL: Bronchial hyperresponsiveness after cervical spinal cord injury. **Chest 105:**1073–1076, 1994
17. Estenne M, De Troyer A: Cough in tetraplegic subjects: an active process. **Ann Intern Med 112:**22–28, 1990
18. Fehlings MG, Furlan JC, Massicotte EM, Arnold P, Aarabi B, Harrop J, et al: Interobserver and intraobserver reliability of maximum canal compromise and spinal cord compression for evaluation of acute traumatic cervical spinal cord injury. **Spine 31:**1719–1725, 2006
19. Fehlings MG, Rao SC, Tator CH, Skaf G, Arnold P, Benzel E, et al: The optimal radiologic method for assessing spinal canal compromise and cord compression in patients with cervical spinal cord injury. Part II: Results of a multicenter study. **Spine 24:**605–613, 1999
20. Fishburn MJ, Marino RJ, Ditunno JFJ Jr: Atelectasis and pneumonia in acute spinal cord injury. **Arch Phys Med Rehabil 71:**197–200, 1990
21. Furlan JC, Fehlings MG: Cardiovascular complications after acute spinal cord injury: pathophysiology, diagnosis, and management. **Neurosurg Focus 25(5):**E13, 2008
22. Furlan JC, Fehlings MG, Massicotte EM, Aarabi B, Vaccaro AR, Bono CM, et al: A quantitative and reproducible method to assess cord compression and canal stenosis after cervical spine trauma: a study of interrater and intrarater reliability. **Spine 32:**2083–2091, 2007
23. Furlan JC, Kailaya-Vasan A, Aarabi B, Fehlings MG: A novel approach to quantitatively assess posttraumatic cervical spinal canal compromise and spinal cord compression: a multicenter responsiveness study. **Spine (Phila Pa 1976) 36:**784–793, 2011
24. Grossman RG, Frankowski RF, Burau KD, Toups EG, Crommett JW, Johnson MM, et al: Incidence and severity of acute complications after spinal cord injury. **J Neurosurg Spine 17 Suppl:**77–86, 2012
25. Habashi NM: Other approaches to open-lung ventilation: airway pressure release ventilation. **Crit Care Med 33 (3 Suppl):** S228–S240, 2005
26. Harrop JS, Sharan AD, Scheid EH Jr, Vaccaro AR, Przybylski GJ: Tracheostomy placement in patients with complete cervical spinal cord injuries: American Spinal Injury Association Grade A. **J Neurosurg 100 (1 Suppl Spine):**20–23, 2004

27. Jackson AB, Groomes TE: Incidence of respiratory complications following spinal cord injury. **Arch Phys Med Rehabil 75:**270–275, 1994
28. Jain NB, Brown R, Tun CG, Gagnon D, Garshick E: Determinants of forced expiratory volume in 1 second (FEV1), forced vital capacity (FVC), and FEV1/FVC in chronic spinal cord injury. **Arch Phys Med Rehabil 87:**1327–1333, 2006
29. Kobrine AI, Evans DE, Rizzoli HV: Experimental acute balloon compression of the spinal cord. Factors affecting disappearance and return of the spinal evoked response. **J Neurosurg 51:**841–845, 1979
30. Krassioukov AV, Furlan JC, Fehlings MG: Medical co-morbidities, secondary complications, and mortality in elderly with acute spinal cord injury. **J Neurotrauma 20:**391–399, 2003
31. Kwon BK, Okon EB, Plunet W, Baptiste D, Fouad K, Hillyer J, et al: A systematic review of directly applied biologic therapies for acute spinal cord injury. **J Neurotrauma 28:**1589–1610, 2011
32. Ledsome JR, Sharp JM: Pulmonary function in acute cervical cord injury. **Am Rev Respir Dis 124:**41–44, 1981
33. Linn WS, Adkins RH, Gong H Jr, Waters RL: Pulmonary function in chronic spinal cord injury: a cross-sectional survey of 222 southern California adult outpatients. **Arch Phys Med Rehabil 81:**757–763, 2000
34. Linn WS, Spungen AM, Gong H Jr, Bauman WA, Adkins RH, Waters RL: Smoking and obstructive lung dysfunction in persons with chronic spinal cord injury. **J Spinal Cord Med 26:**28–35, 2003
35. McMichan JC, Michel L, Westbrook PR: Pulmonary dysfunction following traumatic quadriplegia. Recognition, prevention, and treatment. **JAMA 243:**528–531, 1980
36. Miyanji F, Furlan JC, Aarabi B, Arnold PM, Fehlings MG: Acute cervical traumatic spinal cord injury: MR imaging findings correlated with neurologic outcome—prospective study with 100 consecutive patients. **Radiology 243:**820–827, 2007
37. Mueller G, de Groot S, van der Woude L, Hopman MT: Time-courses of lung function and respiratory muscle pressure generating capacity after spinal cord injury: a prospective cohort study. **J Rehabil Med 40:**269–276, 2008
38. Myllynen P, Kivioja A, Rokkanen P, Wilppula E: Cervical spinal cord injury: the correlations of initial clinical features and blood gas analyses with early prognosis. **Paraplegia 27:**19–26, 1989
39. Postma K, Bussmann JB, Haisma JA, van der Woude LH, Bergen MP, Stam HJ: Predicting respiratory infection one year after inpatient rehabilitation with pulmonary function measured at discharge in persons with spinal cord injury. **J Rehabil Med 41:**729–733, 2009
40. Reines HD, Harris RC: Pulmonary complications of acute spinal cord injuries. **Neurosurgery 21:**193–196, 1987
41. Romero J, Vari A, Gambarrutta C, Oliviero A: Tracheostomy timing in traumatic spinal cord injury. **Eur Spine J 18:**1452–1457, 2009
42. Spungen AM, Grimm DR, Lesser M, Bauman WA, Almenoff PL: Self-reported prevalence of pulmonary symptoms in subjects with spinal cord injury. **Spinal Cord 35:**652–657, 1997
43. Spungen AM, Grimm DR, Schilero G, Lenner R, Oei E, Bauman WA, et al: Relationship of respiratory symptoms with smoking status and pulmonary function in chronic spinal cord injury. **J Spinal Cord Med 25:**23–27, 2002
44. Stiller K, Simionato R, Rice K, Hall B: The effect of intermittent positive pressure breathing on lung volumes in acute quadriparesis. **Paraplegia 30:**121–126, 1992
45. Stolzmann KL, Gagnon DR, Brown R, Tun CG, Garshick E: Longitudinal change in FEV1 and FVC in chronic spinal cord injury. **Am J Respir Crit Care Med 177:**781–786, 2008
46. Stolzmann KL, Gagnon DR, Brown R, Tun CG, Garshick E: Risk factors for chest illness in chronic spinal cord injury: a prospective study. **Am J Phys Med Rehabil 89:**576–583, 2010
47. Tator CH: Ischemia as a secondary neural injury, in Salzman SK, Faden AI (eds): **Neurobiology of Central Nervous System Trauma.** New York: Oxford University Press, 1994, pp 209–215
48. Tator CH, Fehlings MG: Review of the secondary injury theory of acute spinal cord trauma with emphasis on vascular mechanisms. **J Neurosurg 75:**15–26, 1991
49. Waddimba AC, Jain NB, Stolzmann K, Gagnon DR, Burgess JF Jr, Kazis LE, et al: Predictors of cardiopulmonary hospitalization in chronic spinal cord injury. **Arch Phys Med Rehabil 90:**193–200, 2009
50. Winslow C, Bode RK, Felton D, Chen D, Meyer PR Jr: Impact of respiratory complications on length of stay and hospital costs in acute cervical spine injury. **Chest 121:**1548–1554, 2002
51. Wyndaele M, Wyndaele JJ: Incidence, prevalence and epidemiology of spinal cord injury: what learns a worldwide literature survey? **Spinal Cord 44:**523–529, 2006

Manuscript submitted January 26, 2012.
Accepted April 6, 2012.
Please include this information when citing this paper: DOI: 10.3171/2012.4.AOSPINE1295.

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