An evidence-based review of surgical decompression for acute spinal cord injury: rationale, indications, and timing based on experimental and clinical studies

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The authors conducted an evidence-based review of the literature to evaluate critically the rationale and indications for and the timing of decompressive surgery for the treatment of acute, nonpenetrating spinal cord injury (SCI).

The experimental and clinical literature concerning the role of, and the biological rationale for surgical decompression for acute SCI was reviewed. Clinical studies of nonoperative management of SCI were also examined for comparative purposes. Evidence from clinical trials was categorized as Class I (well-conducted randomized prospective trials), Class II (well-designed comparative clinical studies), or Class III (retrospective studies).

Studies in which animal models of SCI were used consistently demonstrated a beneficial effect of early surgical decompression, although it is difficult to apply these data directly to the clinical setting. The clinical studies provided suggestive (Class III and limited Class II) evidence that decompressive procedures improve neurological recovery after SCI. However, no clear consensus can be inferred from the literature as to the optimum timing of decompressive surgery. Many authors have advocated delayed treatment to avoid medical complications, although there is good evidence from recent Class II trials that early decompressive surgery can be performed safely without added morbidity or mortality.

There is biological evidence from experimental studies in animals that early surgical decompression may improve neurological recovery after SCI, although the relevant interventional timing in humans remains unclear. To date, the role of surgical decompression in patients with SCI is only supported by Class III and limited Class II evidence. Accordingly, decompressive surgery for SCI can only be considered a practice option. Furthermore, analysis of the literature does not allow definite conclusions to be drawn regarding appropriate timing of intervention. Hence, there is a need to conduct well-designed experimental and clinical studies of the timing and neurological results of surgical decompression for the treatment of acute SCI.

Key Words * surgical decompression * acute spinal cord injury * review

With an average incidence of 11,000 cases per year in North America, spinal cord injury (SCI) is an important cause of morbidity and mortality,[63,91] particularly among teenagers and young adults. The main
causes of acute SCI are traffic accidents, sports and recreational activities, accidents at work, falls in the home, and violence.[63,91] Because there is a lack of effective treatments for restoring neurological function below the level of the injury means the vast majority of SCI victims face many years of lost independence and continued medical expenses. Indeed, the financial cost of care for acute SCI is enormous.[97] For example, in 1975, Kraus, et al.,[63] estimated an "annual cost to the United States for support and treatment of all persons with a spinal cord injury of two billion dollars," and in 1990, Stripling[86] estimated that this figure had risen to four billion dollars annually.

The results of recent studies of pharmacotherapy, such as the use of methylprednisolone as recommended on the basis of the National Acute Spinal Cord Injury Studies (NASCIS-2 and NASCIS-3)[21-23] have shown improved recovery in patients with SCI. Unfortunately, the improved neurological recovery observed to date has been modest, with only slight improvement in the functional capability in these patients.

Recent advances in the safety and efficacy of spinal cord surgical decompressive procedures offer significant potential for repairing some of the neurological damage caused by injuries to the spine.[4,14,33,96,110] Despite the widespread use of surgery in patients with acute SCI in North America, the role of this intervention in improving neurological recovery remains controversial because of the lack of well-designed and -executed randomized controlled trials. In the present paper, we review the experimental and clinical evidence with regard to the value of surgical decompression in treating patients with acute nonpenetrating SCI and compare these data with the results of conservative, nonoperative management of SCI. This evidence-based literature analysis was conducted as part of the Surgical Trial in the Acute Spinal Cord Injury Study project, an undertaking supported by the Joint Section of Neurotrauma and Critical Care and the Joint Section of Disorders of the Spine and Peripheral Nerves of the American Association of Neurological Surgeons and the Congress of Neurological Surgeons. The goal of the Surgical Trial in Acute Spinal Cord Injury Study is ultimately to plan and conduct a randomized controlled trial to investigate the appropriate timing and clinical indications for decompressive surgery in the injured spinal cord.

**CLINICAL MATERIAL AND METHODS**

We conducted a computer-assisted Medline search of the experimental and clinical literature from 1966 to 1998 that concerned the role of decompressive surgery in the treatment of SCI. Only articles with English-language abstracts were selected for review. This computerized literature review was supplemented by a detailed examination of the reference lists from the selected articles. Fifty-nine papers (16 experimental studies in animal models and 43 clinical studies) were selected for detailed analysis (Tables 1-5). Evidence from clinical trials was classified as Class I (well-designed and -conducted randomized controlled trials), Class II (prospective cohort studies or controlled studies with well-defined comparison groups) and Class III (case series, retrospective reviews, and expert opinion).

**BIOLOGICAL RATIONALE FOR EARLY TREATMENT OF PATIENTS WITH ACUTE SCI**

**Concept of Secondary Injury**

There is increasing evidence that the pathophysiology of acute SCI involves both primary and secondary injury mechanisms.[6,56,92,93,99,106,114,115] In the majority of traumatic SCIs, the mechanism of injury involves rapid cord compression due to bone displacement from a fracture-dislocation or burst fracture.[27,58,95] Acute spinal cord distraction, acceleration-deceleration with shearing, and transection from penetrating injuries are other potential mechanisms of injury.[39,63] There is considerable evidence that the primary mechanical injury initiates a cascade of secondary injury mechanisms such as: 1) vascular changes including reduction in blood flow, loss of autoregulation, neurogenic shock, hemorrhage, loss of microcirculation, vasospasm and thrombosis (see Stripling[86] and Tator[94] for reviews); 2) electrolyte...
shifts including increased intracellular calcium, increased extracellular potassium, and increased sodium permeability;[2,117] 3) neurotransmitter accumulation such as serotonin or catecholamines[77] and extracellular glutamate,[3] the latter producing excitotoxicity;[46] 4) arachidonic acid release, free radical production especially oxygen-free radicals,[37] eicosanoid production, especially prostaglandins, and lipid peroxidation;[54,56] 5) endogenous opioids;[44,45] 6) edema formation;[105] 7) inflammation;[142] and 8) loss of energy metabolism, especially decreased adenosine triphosphate production.[8] These theories of secondary injury have been the subject of several recent reviews.[7,30,43,99,116]

The improved understanding of the pathophysiology of acute SCI has led to use of novel pharmacological strategies to attenuate the effects of the secondary injury. In the NASCIS-2 study a modest beneficial effect of high-dose methylprednisolone was demonstrated if given within 8 hours postinjury in patients with complete and incomplete SCIs,[22] which emphasizes the importance of the timing of treatment. Furthermore, the NASCIS-3 study provided some evidence that treatment within 3 hours may have been superior to treatment begun between 3 and 8 hours postinjury.[23] The findings of these studies provide validity to the concept that secondary SCI mechanisms can be attenuated in the clinical setting. It is unclear, however, whether the "time window" for methylprednisolone is directly applicable to surgical decompression of the spinal cord.

There is experimental evidence that persistent compression of the spinal cord is a potentially reversible form of secondary injury. The severity of SCI in experimental models appears to vary depending on several factors, including force of compression, duration of compression, displacement, impulse and kinetic energy.[39,50,57,75,78,80,89] The evolution of these pathophysiological processes leading to progressive pathological changes during the first few hours postinjury is important with respect to the surgical and nonsurgical treatment of SCI. As we will describe in the following detail, the severity of the pathological changes and the degree of recovery are directly related to the duration of acute compression as demonstrated by experimental studies in which longer compression times produced less demonstrable clinical recovery.[21,36,39,50,76,87]

Studies of Surgical Decompression in Experimental Models

Biomechanics of spinal cord injury and classification of models. Several experimental studies of decompressive procedures performed after SCI have been conducted using these models,[16,25,29,34,36,39,50,61,62,76,87,88,90] and most have demonstrated that neurological recovery is enhanced by early decompressive surgery (Table 1).
However, to understand the rationale of spinal cord decompressive surgery in the context of acute SCI and to interpret the results of experimental studies correctly, a brief review of the biomechanics of SCI and the relevant experimental models is appropriate. The spinal cord is viscoelastic and behaves as a linear elastic material under small strains (strain = force/area).[57] Indeed, Somerson and Stokes[83] have shown in compression injuries causing less than 1.0 mm deformation of the rodent spinal cord that the cord behaves like a spring, with a linear relationship between the applied force and the resultant displacement. In contrast, at displacements greater than 1.0 mm, the spinal cord displays nonlinear characteristics. Consequently, the relationship between the degree of spinal cord displacement from a space-occupying lesion and the loss of neurological function may also be nonlinear. Nevertheless, clinical outcome and morphometric characteristics of the spinal cord lesion do appear to vary depending on a number of factors, including force, duration of compression, displacement, impulse, and kinetic energy.[39,50,57,75,78,80]

In one review we found that several experimental models have been developed that mimic human SCI.[47] Compression models can be classified as either kinetic or static according to the biomechanics of the applied forces. Kinetic compression models involve rapid compression of the cord in less than 1 second. Indeed, most kinetic models compress the cord in less than 100 milliseconds. With kinetic compression, the applied load compresses the cord with increasing velocity (acceleration > 0) to the point of maximal cord compression. In contrast, static compression models use forces that slowly compress the cord at approximately constant velocity.

**Kinetic Models of Spinal Cord Injury.** Of the many types of kinetic compression models, which most closely simulate the majority of traumatic human SCIs, the studies that relate the duration of compression to

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**Table 1**

**Effect of decompression in animal models of acute SCI**

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Animal Studied</th>
<th>Model of Injury</th>
<th>Duration of Compression</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarlov, 1954, Tarlov, 1957, Tarlov and Klinger, 1954</td>
<td>canine</td>
<td>extradural balloon</td>
<td>mins to days</td>
<td>decompression improved neuro-recovery</td>
</tr>
<tr>
<td>Brodkey, et al., 1972</td>
<td>cat</td>
<td>static weight</td>
<td>mins</td>
<td>early removal of weight restores axonal conduction</td>
</tr>
<tr>
<td>Croft, et al., 1972</td>
<td>cat</td>
<td>static weight</td>
<td>5–20 mins</td>
<td>early decompression at mild injuries</td>
</tr>
<tr>
<td>Thienprasit, et al., 1975</td>
<td>cat</td>
<td>extradural balloon</td>
<td>6 hrs</td>
<td>laminectomy ineffective in promoting neurorecovery</td>
</tr>
<tr>
<td>Kobrine, et al., 1978, 1979</td>
<td>monkey</td>
<td>extradural balloon</td>
<td>1–15 mins</td>
<td>early decompression promotes neurorecovery</td>
</tr>
<tr>
<td>Bohlman, et al., 1979</td>
<td>canine</td>
<td>antipiston</td>
<td>3–8 wks</td>
<td>decompression promotes neurorecovery</td>
</tr>
<tr>
<td>Dolan, Tator, et al., 1980</td>
<td>rat</td>
<td>clip</td>
<td>secs–15 mins</td>
<td>decompression promotes neurorecovery</td>
</tr>
<tr>
<td>Aki &amp; Toya, 1984</td>
<td>canine</td>
<td>static loads 6–60g</td>
<td>mins</td>
<td>vascular changes more severe with greater degrees of compression</td>
</tr>
<tr>
<td>Guha, et al., 1987</td>
<td>rat</td>
<td>clip</td>
<td>1–4 hrs</td>
<td>decompression by 2 hrs improves recovery with milder injuries</td>
</tr>
<tr>
<td>Nystrom &amp; Berglund 1988</td>
<td>rat</td>
<td>static weight</td>
<td>1–19 mins</td>
<td>early decompression promotes recovery with more severe SCI</td>
</tr>
<tr>
<td>Zhang, et al., 1993</td>
<td>rat</td>
<td>static load 35, 35, &amp; 50 g</td>
<td>5 mins</td>
<td>increased levels of lactate, inosine, hypoxanthine with SCI; reversal of metabolic changes with decompression</td>
</tr>
<tr>
<td>Delamarter, et al., 1995</td>
<td>canine</td>
<td>circumferential cable</td>
<td>1 hr–1 wk</td>
<td>decompression at 1 hr improves neurorecovery</td>
</tr>
<tr>
<td>Carlson, et al., 1997</td>
<td>canine</td>
<td>piston</td>
<td>5 mins, 1 hr, 3 hrs</td>
<td>recovery of evoked potentials in 5 mins and 1 hr group</td>
</tr>
</tbody>
</table>

*ant = anterior; com p = compression; decom p = decompression
the recovery of function have been limited to the extradural balloon compression technique in several species and the clip compression model in rodents. The advantage of the latter technique is that the force of clip closure can be calibrated precisely, and the duration of the compression can be altered over a wide range of times.

Tarlov and Klinger\cite{87,88,90} have used the extradural balloon compression technique to injure the lumbar spinal cord and cauda equina in dogs. With acute SCI, the degree of recovery varied with the size of the balloon ("medium" or "large") and with the duration of compression. For example, with a large-sized balloon, full recovery was seen with decompressive surgery after 1 minute, partial recovery was seen after 5 minutes, and no recovery was demonstrated if compression was maintained longer. With medium-sized balloons, recovery was seen if decompressive surgery was performed within 1 hour of injury. The shortcomings of this study were the variable placement of the balloon and the lack of precise quantitation of the injury force or balloon pressure.

Kobrine and colleagues\cite{61,62} conducted a series of experiments in monkeys in which spinal cord compression at the T-6 level was produced by an inflatable extradural balloon. In the slow balloon inflation group, there was return of function based on return of the spinal cord evoked potential even after periods of compression that lasted several minutes.\cite{61} However, after rapid balloon inflation and acute spinal cord compression, only the animals that underwent compression for 1 minute had return of the response by 1 hour. In contrast, animals that underwent acute compression for 3, 5, 7, or 15 minutes showed no recovery by 1 hour.\cite{62} No recordings were obtained after 1 hour, and thus it is not known if some recovery would have occurred after that timepoint. The authors concluded that recovery of spinal cord function following spinal cord compression depended on the "rapidity and length of time of compression."\cite{62} Thus, with an extradural balloon compression method in dogs and cats, the duration of compression was found to be a significant determinant of neurological recovery but only when decompression was performed after a period of minutes.

In the laboratory of one of the authors (C.H.T.), Dolan, et al.,\cite{39} used an extradural clip compression model of the T-1 cord in rats to provide a more quantitative assessment of injury force. The springs of modified aneurysm clips were machined to provide closing forces of 16, 71, or 178 g. Durations of compression times between 3 and 900 seconds were examined. We found that clinical neurological recovery, as assessed by the inclined plane technique,\cite{81} varied exponentially according to the force of injury and linearly with the duration of compression. The results of this study demonstrated that the major determinant of recovery was the initial force of injury. However, the duration of compression (and thus time to decompressive intervention) was a significant determinant of clinical recovery, even in cases of severe injury forces. The main shortcoming of this study was that the maximum duration of compression examined (900 seconds) was too short to be of clinical relevance. Subsequently, our laboratory extended the duration of compression to 4 hours in the study reported by Guha, et al.,\cite{50} with injury forces of 2.3, 16.9, or 53.0 g and durations of compression of 15, 60, 120, or 240 minutes. Again, the major determinant of recovery was the force of injury, although the time to decompression also affected clinical recovery. The beneficial effects of early decompressive surgery were most apparent in the groups receiving smaller-force injuries (2.3 and 16.9 g). For example, decompression performed at 2 hours produced significantly more recovery than when performed at 4 hours.

In conclusion, the results of these studies confirm the efficacy of surgical decompressive procedures in attenuating the deleterious effects of acute SCI. However, it is difficult to extrapolate the results of these studies to clinical practice. Intuitively, it appears likely that the time window in humans is much longer than in the species studied experimentally.
Static Models of Spinal Cord Injury. Static models, which involve a gradual compression of the spinal cord, are useful to model the effect of spinal cord displacement, as well as strain and duration of compression. However, because the load is applied slowly to the cord, these models do not accurately simulate the biomechanical aspects of the majority of human SCI. Nystrom and Berglund[76] have used a static model of SCI in rats to examine the role of injury force and duration of compression on clinical neurological recovery. Weights of 20, 35, or 50 g were applied to the midthoracic cord of rats for periods of 1, 5, or 19 minutes, and clinical neurological recovery was assessed by using the inclined plane technique.[81] In the 20-g injury group, the duration of compression was not a significant determinant of neurological recovery. However, when the 35- and 50-g weights were applied, neurological recovery varied directly according to the duration of the compression period. Unfortunately, the durations of compression studied were too brief to be clinically meaningful, although the results suggest that the timing of decompressive intervention may play a significant role in outcome after acute SCI. Tarlov[88] also examined the role of decompressive surgery in a model of gradual extradural balloon inflation. Functional recovery varied both as a function of injury “force” (determined by the size of the balloon) and duration of compression. For example, if the extradural balloon was inflated over 75 minutes to the point of paralysis, excellent neurological recovery was attained if deflation was performed within 9 hours. In contrast, if the period of balloon inflation was extended to 48 hours, full neurological recovery was seen if decompression was performed within 7 days.

CLINICAL STUDIES

Role of Conservative Management in Acute Spinal Cord Injury

To evaluate the possible role of surgery in the management of SCI, it is important, for comparative purposes, to examine the results of conservative, nonoperative treatment (Table 2).

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>No. of Patients [level treated]</th>
<th>Study Design</th>
<th>Class of Evidence</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guttman, 1963</td>
<td>396 (all levels) nonop</td>
<td>retro case</td>
<td>III</td>
<td>30 died; 3 neurologically worse; 120 improved &gt; 1 grade</td>
</tr>
<tr>
<td>Frankel, et al., 1969</td>
<td>612 (all levels) nonop</td>
<td>retro case series</td>
<td>III</td>
<td>only 4,612 developed delayed instability; 29% of Frankel A pts impro ved &gt; 1 grade</td>
</tr>
<tr>
<td>Maynard, et al., 1979</td>
<td>123 (cervical), 57 nonop</td>
<td>retro case series</td>
<td>III</td>
<td>nonop showed similar results to surgical treatment</td>
</tr>
<tr>
<td>Harris, et al., 1980</td>
<td>145 (cervical), 48 op, 97 nonop</td>
<td>retro case series</td>
<td>III</td>
<td>neither surgery nor realignment of spinal column improved neuro outcome</td>
</tr>
<tr>
<td>Bedbrook, et al., 1979</td>
<td>253 (all levels) nonop in all but 171</td>
<td>retro case series</td>
<td>III</td>
<td>13% of Frankel A pts recovered spontaneously</td>
</tr>
<tr>
<td>Donovan, et al., 1987</td>
<td>61 (cervical) 43 nonop</td>
<td>retro case series</td>
<td>III</td>
<td>3143 conservatively treated pts impro ved ≥ 1 Frankel</td>
</tr>
<tr>
<td>Duh, et al., 1994</td>
<td>487 (all levels) 189 nonop</td>
<td>pro series w/ controls; nonran</td>
<td>II</td>
<td>mean change score of 13.2 in nonop pts &lt; group undergoing surgery w/in 25 hrs (mean change score 17.8)</td>
</tr>
<tr>
<td>Katoh, et al., 1996</td>
<td>63 (incomplete cervical SCI)</td>
<td>retro case series</td>
<td>III</td>
<td>neuro deterioration in 6.63; neuro improvement in 44 pts</td>
</tr>
</tbody>
</table>

* neuro = neurological; nonran = nonrandomized; pro = prospective; retro = retrospective.

This approach has been advocated by those who adhere to the tenets of Sir Ludwig Guttmann, founder of the...
Stoke-Mandeville Hospital in England. Guttmann used postural techniques combined with bedrest to achieve reduction and spontaneous fusion of the spine. Operative approaches were rarely performed because of a higher incidence of neurological complications and impaired recovery after laminectomy procedures.\[11,12,31,51,52\] For example, Frankel, et al.,\[48\] reported on a cohort of 612 patients who suffered "closed spinal injuries" and who were treated by these techniques. Only four of these patients developed delayed instability and required operative fusion. However, detailed descriptions of the fractures and the criteria for determining spinal cord instability or failure of nonoperative management were not provided. Importantly, 29% of Frankel A patients (with complete motor and sensory paralysis below the level of the injury) improved at least one grade during the course of their hospital stay.

In patients undergoing conservative therapy, the spontaneous improvement in neurological status has been replicated in several subsequent studies.\[8,31,38,98,111,113\] Accordingly, the comparative beneficial results of surgical treatment need to be weighed against the limited spontaneous recovery that occurs after SCI. Indeed, some authors have reported that neither spinal cord surgery or anatomical realignment of the spinal column improved neurological outcome in patients with acute SCI with the possible exception of those patients with bilateral locked facets.\[35,55,70\] To date, studies of nonoperative management are limited to noncontrolled, retrospective analyses of clinical databases and, accordingly, provide Class III evidence. Furthermore, it is now well recognized that laminectomy as the sole surgical technique is contraindicated in most cases of acute SCI because it usually fails to produce adequate decompression of the spinal cord and often causes spinal instability that itself can lead to neurological deterioration.

Although meticulous, conservative care remains the cornerstone of SCI management, modern surgical techniques have evolved considerably since the era of Guttmann. Furthermore, there are major limitations to using an exclusive policy of nonoperative management to treat patients with SCI. For example, there is evidence that neurological deterioration can occur in up to 10% of patients with incomplete cervical SCI who undergo an exclusively conservative management protocol.\[59\]

**Role of Decompressive Surgery in the Management of Acute SCI**

The evidence regarding the role of decompressive procedures in the management of SCI is summarized in Tables 3, 4, and 5.

### TABLE 3

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>No. of Patients (level treated)</th>
<th>Timing of Surgery</th>
<th>Study Design</th>
<th>Class of Evidence</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larson, et al., 1976</td>
<td>44 (thoracic &amp; lumbar): &lt; 1 wk; 8 pts; &gt; 1 wk; 8 pts</td>
<td>early &lt; 1 wk; late &gt; 1 wk</td>
<td>retro case</td>
<td>III</td>
<td>no difference in neurological recovery between &quot;early&quot; &amp; &quot;late&quot; groups; preferable to wait</td>
</tr>
<tr>
<td>Maynard, et al., 1979</td>
<td>123 (cervical); 51 early; 10 late; 62 nonop</td>
<td>early &lt; 4 wk; late &gt; 4 wk</td>
<td>retro case</td>
<td>III</td>
<td>surgery w/ 4 wks not associated w/ improved neurorecovery</td>
</tr>
<tr>
<td>Wagner &amp; Chehrazi, 1982</td>
<td>44 (cervical); 24 op; 20 nonop</td>
<td>early &lt; 8 hrs; late 9-48 hrs</td>
<td>retro case</td>
<td>III</td>
<td>decom w/ 8 hrs not better than 9-48 hrs; surgery does not improve recovery</td>
</tr>
<tr>
<td>Bohmian, et al., 1985</td>
<td>218 (T1-10)</td>
<td>most delayed (&gt;1 week post-SCI)</td>
<td>retro case</td>
<td>III</td>
<td>pt w/ complete injury recovered w/ surgery; ant decom best for neurorecovery in incomplete injuries</td>
</tr>
<tr>
<td>Aebi, et al., 1986</td>
<td>100 (cervical): all surgical</td>
<td>75% reduced w/ 6 hrs</td>
<td>retro case</td>
<td>III</td>
<td>early reduc &amp; surgery im proved 31/100 cases</td>
</tr>
<tr>
<td>Benzol &amp; Larson, 1986</td>
<td>105 (thoracic &amp; lumbar)</td>
<td>all delayed surgery (19-48 days)</td>
<td>retro case</td>
<td>III</td>
<td>ant decom &amp; stabil resulted in superior neurorecovery to a nonop approach or only stabil</td>
</tr>
<tr>
<td>Benzol &amp; Larson, 1986</td>
<td>35 cervical all</td>
<td>1-4 wks</td>
<td>retro case</td>
<td>III</td>
<td>ant decom improves nerve root</td>
</tr>
</tbody>
</table>
Most studies, with a few notable exceptions, are retrospective case series with historical controls (Class III evidence). From these studies, there is no clear consensus as to the appropriate timing of surgical intervention, nor is there compelling evidence that surgical decompression influences patient neurological outcome after SCI. For example, Aebi et al.,[1] Wiberg and Hauge,[109] Hadley, et al.,[53] and Wolf, et al.,[112] have advocated early spinal cord reduction procedures (4-10 hours) and operative fixation of spinal fractures associated with SCI. Suggestive evidence is presented in these studies that early decompressive surgery in selected patients may enhance neurological recovery. However, these studies were uncontrolled, and the beneficial effects need to be considered in the context of spontaneous recovery, which can occur in nonoperatively managed patients with SCI.[48,59]

The benefits of early surgical reduction procedures to treat spinal dislocations by either open or closed techniques are difficult to evaluate in the absence of randomization (Table 4).[1,26,32,49,107] Accounts of

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Group</th>
<th>Duration</th>
<th>Type</th>
<th>Study Design</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzel &amp; Larson, 1987</td>
<td>10 post</td>
<td>retro case series</td>
<td>17-52 days</td>
<td>III</td>
<td>surgery improved neurofunction in incomplete SCI; no relationship between time to decom &amp; neuro-recovery</td>
<td></td>
</tr>
<tr>
<td>Donovan, et al., 1987</td>
<td>43 nonop</td>
<td>retro case series</td>
<td>8 pts w/ 24 hrs; 2, 1-7 days; 20, &gt; 7 days</td>
<td>III</td>
<td>no difference in outcome between op &amp; nonop cases</td>
<td></td>
</tr>
<tr>
<td>Tator, et al., 1987</td>
<td>208 (all levels): 75 decom or reduced; 41 fusion; 92 nonop</td>
<td>retro case series</td>
<td>8 pts w/ 24 hrs; 2, 1-7 days; 20, &gt; 7 days</td>
<td>III</td>
<td>surgery did not improve neuro-recovery or length of stay</td>
<td></td>
</tr>
<tr>
<td>Wiberg &amp; Hauge, 1988</td>
<td>30 (thoracic &amp; lumbar)</td>
<td>retro case series</td>
<td>2 pts w/ complete SCI op w/10 hrs showed recovery</td>
<td>III</td>
<td>early surgery reduced LOH &amp; promoted earlier rehab</td>
<td></td>
</tr>
<tr>
<td>Murphy, et al., 1990</td>
<td>102 (cervical): 58 op; 44 nonop</td>
<td>retro case series</td>
<td>6 hrs-60 days (av 13 days)</td>
<td>III</td>
<td>decom improved neurorecovery in motor complete cervical SCI</td>
<td></td>
</tr>
<tr>
<td>Weinsdel, et al., 1990</td>
<td>90 (cervical ASIA A &amp; B)</td>
<td>retro case series</td>
<td>40 pts reduced &lt; 4 hrs by traction; 23 op &lt; 24 hrs</td>
<td>III</td>
<td>early reduc of bilat locked facets resulted in neurorecovery in complete &amp; incomplete SCI</td>
<td></td>
</tr>
<tr>
<td>Wolf, et al., 1991</td>
<td>52 (cervical; bilat locked facets)</td>
<td>retro case series</td>
<td>8 pts w/ 24 hrs; 2, 1-7 days; 20, &gt; 7 days</td>
<td>III</td>
<td>no difference in outcome between op &amp; nonop cases</td>
<td></td>
</tr>
<tr>
<td>Levi, et al., 1991</td>
<td>103 (cervical): early 45; late 58</td>
<td>retro case series</td>
<td>12 pts &lt; 24hrs; 1 pt 36 hrs; 1 pt 5 days</td>
<td>III</td>
<td>early surgery may benefit overall management but not associated w/ improved neurorecovery</td>
<td></td>
</tr>
<tr>
<td>Krengel, et al., 1993</td>
<td>14 (T2-11 incomplete)</td>
<td>retro case series</td>
<td>12 pts &lt; 24hrs; 1 pt 36 hrs; 1 pt 5 days</td>
<td>III</td>
<td>early surgical reduc &amp; decom is safe &amp; improves neuro function; superior to historical controls</td>
<td></td>
</tr>
<tr>
<td>Duh, et al., 1994</td>
<td>487 (all levels): 303 op; early 38 late 105</td>
<td>pro, nonran</td>
<td>early &lt; 25 hrs; late &gt; 200 hrs</td>
<td>II</td>
<td>surgical decom &lt; 25 hrs or &gt;200 hrs may be associated w/better recovery</td>
<td></td>
</tr>
<tr>
<td>Petitjean, et al., 1995</td>
<td>49 (thoracic): 65% associated w/ head injury</td>
<td>average 12 hrs; average 9 days</td>
<td>retro case series</td>
<td>III</td>
<td>spinal decom has no benefit in complete thoracic paraplegia</td>
<td></td>
</tr>
<tr>
<td>Waters, et al., 1996</td>
<td>269 (all levels): 142 nonop; 127 op</td>
<td>pro, nonran</td>
<td>a &gt; 14 days</td>
<td>II</td>
<td>no benefit to surgery, however, all pts underwent delayed treatment</td>
<td></td>
</tr>
<tr>
<td>Botel, et al., 1997</td>
<td>255 (all levels): 178 op; 51.4% early; 10.5% late</td>
<td>retro case series</td>
<td>early &lt; 2 hrs; late &gt; 2 hrs</td>
<td>III</td>
<td>no neurorecovery in complete SCI; no clear relationship of neurorecovery to timing</td>
<td></td>
</tr>
<tr>
<td>Vaccaro, et al., 1997</td>
<td>62 (cervical): early 34; late 28</td>
<td>pro ran; 20 pts lost to FU</td>
<td>early &lt; 72 hrs; late &gt; 5 days</td>
<td>II</td>
<td>no difference in neurological outcome</td>
<td></td>
</tr>
<tr>
<td>Vale, et al., 1997</td>
<td>77 (all levels): 58 op</td>
<td>pro, nonran</td>
<td>11 pts &lt; 24 hrs; 13 24-72 hrs; 34 &gt; 72 hrs</td>
<td>II</td>
<td>no clear relationship between neuro outcome &amp; timing of surgery</td>
<td></td>
</tr>
</tbody>
</table>

* ant = anterior; ASIA = American Spinal Injury Association; av = average; FU = follow up; LOH = length of hospitalization; pos = posterior; reduc = reduction; rehab = rehabilitation; stabil = stabilization.
impressive neurological recovery in some patients who underwent early cervical decompression by traction must be considered anecdotal[26] (Table 4).

### Table 4

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>No. of Patients</th>
<th>Intervention</th>
<th>Study Design</th>
<th>Class of Evidence</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burke &amp; Berryman, 1971</td>
<td>75</td>
<td>CR; 50% admitted w/ 8 hrs timing of reduc</td>
<td>retro case series</td>
<td>III</td>
<td>early CR improved neuro outcome in incomplete SCI</td>
</tr>
<tr>
<td>Dall, 1972</td>
<td>75</td>
<td>NS</td>
<td>retro case series</td>
<td>III</td>
<td>anatomical reduc of fracture-dislocations did not improve neurorecovery</td>
</tr>
<tr>
<td>Harris, et al., 1980</td>
<td>145</td>
<td>protocol for traction NS</td>
<td>retro case series</td>
<td>III</td>
<td>reduc of cervical dislocations did not improve neurooutcome</td>
</tr>
<tr>
<td>Sonntag, 1981</td>
<td>15</td>
<td>CR in 11; open in 4</td>
<td>retro case series</td>
<td>III</td>
<td>transient root palsy in 1; root recovery in 2</td>
</tr>
<tr>
<td>Aebi, et al., 1986</td>
<td>100</td>
<td>75% reduced w/ 6 hrs</td>
<td>retro case series</td>
<td>III</td>
<td>early reduc resulted in neuroimprovement in 31/100</td>
</tr>
<tr>
<td>Brunette &amp; Rockswold, 1987</td>
<td>1</td>
<td>C3–4 reduced by 90 mins</td>
<td>case report</td>
<td>III</td>
<td>improvement from ASIA A to ASIA E by rapid reduc of C3–4 dislocation</td>
</tr>
<tr>
<td>Star, et al., 1990</td>
<td>53</td>
<td>39/53 required &gt; 50 lbs</td>
<td>retro case series</td>
<td>III</td>
<td>68% of pts improved neurologically; no deterioration</td>
</tr>
<tr>
<td>Hadley, et al., 1992</td>
<td>54</td>
<td>10 reduced w/ 8 hrs</td>
<td>retro case series</td>
<td>III</td>
<td>reduc w/ 8 hrs in 10 cases resulted in neuro improvement</td>
</tr>
<tr>
<td>Lee, et al., 1994</td>
<td>210</td>
<td>rapid traction up to 150 lbs</td>
<td>retro case series</td>
<td>III</td>
<td>rapid realignment improves neuro outcome</td>
</tr>
</tbody>
</table>

* CR = closed reduction; NS = not specified.

Moreover, the authors of several studies have found no neurological benefit associated with reduction procedures,[35,55,107] with the possible exception of patients with bilateral facet dislocation.[10] Burke and Berryman[28] have described 76 patients in whom unilateral or bilateral dislocations of the cervical spine were treated by performing closed reduction after induction of general anesthesia, often with manipulation; 50% of the patients were admitted to their center within 8 hours of injury. These authors concluded that early surgical reduction procedures improved the neurological recovery of patients with incomplete SCI.

Aebi, et al.,[1] have examined the records retrospectively of 100 patients with cervical spine injuries and attempted to relate neurological recovery to the timing of the reduction procedure by closed manual traction or open surgical reduction. A manual or surgical reduction procedure was performed within the first 6 hours postinjury in only 25% of the cases and within the first 24 hours in 57%. Overall, 31% of the 100 patients recovered, and 75% of the recoveries were in patients in whom reduction was performed manually or surgically within the first 6 hours (Table 94). Cotler's group[32,73] studied the safety and effectiveness of early reduction procedures, and performed a prospective study of early reduction by traction in 24 patients. They found no neurological deterioration in any of the patients, most of whom underwent successful reduction procedures within 24 hours of injury, although the exact interval in hours between injury and intervention was not provided. All of the patients were awake during the procedure, although a muscle relaxant was administered to some patients.

In contrast to the aforementioned studies in which decompressive procedures were performed in the early stage after injury, Larson and coworkers[65] have advocated the surgery be performed a week or more after SCI to allow medical and neurological stabilization of the injured patient (Table 3). This remains the practice in many institutions, particularly in light of early reports, the results of which suggest an increased rate of medical complications when surgery is performed to early after injury (< 5 days after SCI).[71] Interestingly,
a number of authors (summarized in Table 5) have documented recovery of neurological function after performing delayed decompressive surgery in the spinal cord (months to years) postinjury.[9,15,17,19,24,65,101]

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>No. of Patients (level treated)</th>
<th>Timing of Surgery</th>
<th>Study Design</th>
<th>Class of Evidence</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larson, et al., 1976</td>
<td>25 (all levels)</td>
<td>all &gt; 4 wks; 15 &gt; 6 mos</td>
<td>retro case series</td>
<td>III</td>
<td>improved neurorecovery with surgery in complete and incomplete SCI</td>
</tr>
<tr>
<td>Bohlman &amp; Freehafer, 1979</td>
<td>36 (2 cervical, 4 thoracolumbar)</td>
<td>av 22 mos</td>
<td>retro case series</td>
<td>III</td>
<td>8.27 pts w/incomplete SCI had motor recovery, 29.66 had nerve root recovery</td>
</tr>
<tr>
<td>Brodkey, et al., 1980</td>
<td>83 wks-4 yrs</td>
<td>retro case series</td>
<td>III</td>
<td>improved neurorecovery in incomplete SCI</td>
<td></td>
</tr>
<tr>
<td>Mainn, et al., 1984</td>
<td>20 (thoracolumbar)</td>
<td>1 mo-5 yrs</td>
<td>retro case series</td>
<td>III</td>
<td>17.20 pts made neurorecovery</td>
</tr>
<tr>
<td>Transfeldt, et al., 1990</td>
<td>49 (thoracolumbar)</td>
<td>&gt; 3 mos</td>
<td>retro case series</td>
<td>III</td>
<td>46.5% of incomplete SCI improved neurologically</td>
</tr>
<tr>
<td>Anderson &amp; Bohlman, 1992</td>
<td>51 (cervical: motor complete)</td>
<td>1 mo-8 yrs (av 15 mos)</td>
<td>retro case series</td>
<td>III</td>
<td>improved neurorecovery in incomplete SCI</td>
</tr>
<tr>
<td>Bohlman, Anderson, 1992</td>
<td>58 (cervical: motor incomplete)</td>
<td>1 mo-9 yrs (av 13 mos)</td>
<td>retro case series</td>
<td>III</td>
<td>46 incomplete SCI pts</td>
</tr>
<tr>
<td>Bohlman, et al., 1994</td>
<td>25 (thoracolumbar)</td>
<td>av 4.5 yrs</td>
<td>retro case series</td>
<td>III</td>
<td>21.25 patients improved neurologically; proportion incomplete unclear</td>
</tr>
</tbody>
</table>

*Late decompressive surgery was defined as > 4 weeks postinjury.

Although these studies were retrospective in design, the improvement in neurological function after delayed decompressive surgery in patients with cervical or thoracolumbar SCI whose recovery has plateaued is noteworthy; it suggests that compression of the cord is an important contributing cause of neurological dysfunction.

In our literature review we found five prospective, controlled studies of surgical decompression in acute spinal cord injury (Table 3).[1,12,13,18,20,40,41,64,65,68,72,74,79,96,102-104,107-109,112] In a prospective, nonrandomized case control study of 208 patients with acute spinal cord or cauda equina injury, Tator and colleagues[96] compared the results of surgery (56% of patients) with nonoperative management (44% of patients). Operative management was associated with a lower overall mortality rate (6.1%) than nonoperative treatment (15.2%) despite a higher rate of thromboembolic complications in the surgical group. Overall, there was no difference between surgically and nonsurgically treated patients in length of stay or neurological recovery.

In an analysis of the NASCIS-2 database (Class II evidence), Duh, et al.[41] reported that patients who underwent acute surgery (< 25 hours after injury) achieved statistically insignificant improvement (mean neurological change score of 17.8) when compared with a control cohort of patients who were treated nonoperatively (mean change score of 13.2). Interestingly, results of surgery were similar in the early (< 25 hours postinjury) and delayed (> 200 hours postinjury) groups. In contrast, in a series of prospective studies Vale, et al.[103] Vaccaro, et al.[102] and Waters, et al.[107] could not document a beneficial effect of decompressive surgery. It is noteworthy, however, that all patients underwent delayed operative management in the study by Waters, et al. Moreover, although the study by Vaccaro, et al., was a prospective randomized
trial, 20 of the 62 patients were lost to follow up, and "early" surgery was defined as that performed within 72 hours after SCI. In view of the large number of patients lost to follow-up review, we have considered the study by Vaccaro, et al., to provide Class II evidence.

THE EFFECT OF SURGERY ON THE COMPLICATION RATE AND THE LENGTH OF STAY AFTER SCI

There has been controversy about whether surgery, especially early surgery, increases the rate of complications in patients with SCI. Many SCI patients with high cervical complete injuries or significant associated injuries to the limbs or viscera suffer critical illness due to either hemodynamic or respiratory difficulties. Early investigators such as Guttmann[51,52] and Bedbrook and Sekae[11] and, more recently, Wilmot and Hall[111] and Marshall, et al.,[71] have warned against surgery, (especially early surgery) in these critically ill patients. However, modern methods of respiratory and hemodynamic resuscitation[60,67,82,103] have allowed these patients to undergo surgery with minimal differences in complication rates between operative and nonoperative cases.[96,111] Indeed, Wilberger's recent study[110] showed that those patients in whom operations were performed within the first 24 hours had a lower rate of complications than those who underwent surgery at later times. In a previously mentioned study from our center,[96] the only difference in morbidity rates between the surgical and nonsurgical cases was a slight increase in the incidence of deep venous thrombosis in the surgically treated group. The length of stay in the two groups did not differ.[96] In the randomized trial in which Vaccaro, et al.,[102] examined the timing of the surgery, there was no significant difference in length of acute postoperative intensive care stay or length of inpatient rehabilitation between the early and late groups. Thus, with respect to complications, there is no compelling evidence that early surgery increases the rate of complications.

CONCLUSIONS

There is strong experimental evidence from animal models to indicate that decompressive surgery in the spinal cord improves recovery after SCI. However, it is difficult to determine a time window for the effective application of surgical decompressive intervention in the clinical setting from these animal models. Results of these studies on secondary injury mechanisms including ischemia, free radical-mediated lipid peroxidation, and calcium-mediated cytotoxicity suggest that early intervention within hours after SCI is critical to attain a neuroprotective effect. Whether the same time window applies to surgical treatment is as yet unclear. To date, the clinical studies that have examined the role of decompressive surgery in the treatment of SCI are limited to Class II and Class III evidence, except for one study in which the timing of decompression was examined. Surgery remains a valid practice option, although there is no conclusive data showing a benefit over conservative management approaches. There is limited Class II evidence suggesting that either early (< 25 hours) or delayed (> 200 hours) surgical intervention is safe and equally effective. Clearly, to define better the role of surgery in the management of acute SCI, randomized controlled prospective trials are required.

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