Biomechanics of experimental spinal cord trauma

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The biomechanics of the thoracic spinal cord and thorax in experimental trauma were studied in cats. Contusion of the T5–6 level of the feline spinal cord was accomplished by the weight-dropping technique; various combinations of weights and heights were used; and force, deformation/displacement, deformation velocity, and acceleration of deformation were measured. Greater force was associated with larger weights. Force was directly related to the displacement of the spinal cord and of the spinal cord/thorax. The presence of a “destruction point” on the force-displacement curve was suggested and its apparent significance discussed. Maximum deformation of the spinal cord was 1.1 mm, while the spinal cord/thorax was displaced a maximum of 4.6 mm. Deformation of the spinal cord ranged between 22% and 33% of the anteroposterior spinal cord diameter. Maximum deformation of the spinal cord was not associated necessarily with a maximum velocity of deformation; the range of velocity of spinal cord deformation was 0.12 to 0.18 m/sec. The relationship between velocity of deformation and force was a horizontal parabolic one. Greater force was required to obtain the same velocity of deformation of the spinal cord relative to that of the spinal cord/thorax unit. It was concluded that the mechanical alterations in the structures supporting the spinal cord account for a significant portion of the biomechanical measurements of the spinal cord previously reported in trauma. Since the force on the spinal cord and the thorax are the same, force may well be a most reasonable means of quantitating experimental spinal cord trauma.

KEY WORDS • biomechanics • spinal cord trauma • force • spinal cord • deformation • velocity • experimental paraplegia

Precise quantitation of the trauma actually delivered to the spinal cord is necessary if useful conclusions are to be drawn from experiments on spinal cord contusion. Description of spinal cord trauma in terms of “gm-cm” units is no longer adequate. Monitoring of the trauma stimulus itself is needed. If a better understanding of the ensuing pathophysiological alterations within the traumatized spinal cord is to be had, it is important to detail the biomechanical parameters involved in the trauma. For a more complete comprehension of the dynamics of spinal cord trauma, one must look at the biomechanical role played by those structures supporting the spinal cord as well as the mechanical properties of the spinal cord itself. Force and deformation, related to time, completely describe the deformation history of a structure. A trauma ap-
The purpose of the present study is to determine the force, deformation/displacement, velocity of deformation, and acceleration of deformation for the thoracic spinal cord in experimental trauma and to study the corresponding biomechanics of the underlying thorax.

Materials and Methods

Forty cats weighing 3 to 5 kg were anesthetized with intraperitoneal sodium pentobarbital (35 mg/kg). A catheter was introduced through the right femoral artery into the abdominal aorta for monitoring the arterial blood pressure, which was continuously recorded by a polygraph.* Muscle paralysis was achieved by an intravenous injection of 20 mg gallamine triethiodide with supplemental doses given occasionally to maintain adequate relaxation. The cats were maintained on a Harvard small animal respirator.† Through a small opening in the anesthesia tubing, a catheter was advanced into the tracheostomy tube and connected to a gas analyzer and a microcatheter sample pump‡ to constantly monitor the end-expiratory carbon dioxide pressure (pCO₂). By changing the respiratory rate and/or tidal volume, the end-expiratory pCO₂ could be maintained at 2 to 4 vol%. Temperature was monitored by a thermal probe attached to a telemeter. It was maintained between 37° and 39° C, by means of a heating pad under the animal's abdomen.

The animal was secured on the operating table in the prone position, and a laminectomy was performed. The T5-6 level of the spinal cord was exposed with the dura mater intact. The spinal cord was traumatized by the weight-dropping technique. A trauma apparatus was designed such that a weight (gm) was allowed to fall a certain distance (cm) through a vertically oriented Plexiglas tube to strike an impounder (26 gm) resting on the spinal cord. The term “spinal cord” refers to the spinal cord itself and the enveloping meninges. A displacement transducer§ was located concentrically with the impounder. The iron core of the displacement transducer formed the center of the impounder. Between this iron core and the Plexiglas impounder tip (5 mm diameter) was a force transducer|| (Fig. 1). The outputs from the displacement transducer and the force transducer were fed into a computer for analysis.

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*Polygraph manufactured by Grass Instrument Co., 101 Old Colony Road, Quincy, Massachusetts.
†Respirator manufactured by Harvard Apparatus, 150 Dover Road, Millis, Massachusetts.
‡Gas analyzer and microcatheter sample pump made by Beckman Instruments, Inc., 3900 River Road, Schiller Park, Illinois.
§Displacement transducer manufactured by Schaevitz, P.O. Box 505, Camden, New Jersey.
||Force transducer manufactured by P.C.B. Piezotronics, Inc., P.O. Box 33, Buffalo, New York.
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to a 4-channel digitizing and recording computer. A displacement-time curve and a force-time curve were displayed on an oscilloscope and photographed. A detailed description of this trauma apparatus and the method and calculations of monitoring of the trauma stimulus has been published. Additional displacement caused by movements of the rib cage and vertebral column was accounted for by traumatizing the spinal cord, then excising it and traumatizing the underlying vertebral body. Subtracting the displacement of the latter from that of the former produced data relating to the spinal cord only, referred to as "spinal cord" or "spinal cord only." Without this subtracting procedure, the data obtained represent the displacement of the spinal cord and thorax with respect to the operating table and, therefore, are referred to as "spinal cord and thorax" or simply as "spinal cord/thorax." Velocity and acceleration measurements are obtained from the displacement-time curve by the computer; the first derivative gives velocity and the second derivative gives acceleration. No such subtracting procedure is thought to be necessary for the force measurement. This is because the force as measured by the force transducer is the precise force applied to the spinal cord. In the graphs, the force, displacement/deformation, velocity, and acceleration for each of the trauma groups are expressed as the mean.

A "400 gm-cm" injury was delivered to the spinal cord of 37 cats. The animals were apportioned in the following trauma groups: 5 gm × 80 cm (four cats); 10 gm × 40 cm (five cats); 20 gm × 20 cm (five cats); 40 gm × 10 cm (eight cats); 60 gm × 6.6 cm (five cats); 80 gm × 5 cm (five cats); and 100 gm × 4 cm (five cats). In the three control animals the impounder of the trauma device was allowed to rest on the spinal cord for 1 minute but the weight was not dropped.

Results

Control Group

In all three cats in the control group it was noted that the impounder was passively set in rhythmical vertical motion by the breathing of the animal. No alterations of the blood pressure or pulse were noted. No motor activity of the lower extremities was present during this period. There was no subarachnoid hemorrhage (SAH) in the region of the spinal cord where the tip of the impounder had been resting.

Experimental Group

At the time of the trauma, deformation of the spinal cord and downward movement of the thorax were noted and appeared to increase relative to the mass of the falling weight. Considerable motor outflow to the lower extremities was seen at impact.

Within 2 to 6 seconds after contusion, the characteristic pressor response occurred as systolic levels above 300 mm Hg were observed. In general, the response reflected an increase of about 90 to 130 mm Hg above pretrauma systolic levels. A period of hypotension approximately 60% to 70% of pretrauma levels immediately followed the hypertensive phase and persisted for 15 to 30 minutes. Pressure then began a gradual climb toward pretrauma levels over the next hour.

Immediately after trauma, the impounder was removed and SAH was seen. The degree of hemorrhage increased somewhat relative to the increasing mass of the falling weight.

In this study, "deformation" is used to describe the motion of one surface of a structure relative to another surface of the structure; "displacement" is a more general term referring to motion of one surface of the structure with respect to a space coordinate system. The deformation of the spinal cord alone was far less than for the spinal cord and thorax; however, it increased with the weight (Figs. 2 and 3). Maximum deformation of the spinal cord was 1.1 mm while the spinal cord/thorax was displaced a maximum of 4.6 mm. Transverse strain of the spinal cord (the percentage ratio of the spinal cord deformation to the anteroposterior diameter of the spinal cord) increased very little with the larger weights (Fig. 3). This strain varied from 22% in the 5 gm × 80 cm trauma group to 33% in the 60 gm × 6.6 cm trauma group (Fig. 3). A peak velocity of deformation was noted in the 40 gm × 10 cm group of both spinal cord only (0.18 m/sec, Fig. 4) and the spinal cord and thorax considered as one unit (0.67 m/sec). Velocities of deformation were less with the former. The velocity of spinal cord deformation was approximately the same in the 5 gm × 80 cm group as in those animals that sustained a 100 gm × 4 cm injury. The acceleration of deformation varied much as
FIG. 2. Graph showing height vs deformation. For the same weight dropped from the same height there is greater displacement of the spinal cord/thorax unit than deformation of the spinal cord itself. Most of the displacement of the spinal cord/thorax is due to the movement of the thorax, thereby illustrating the importance of monitoring the mechanical properties of the thorax as well as the spinal cord in experiments on spinal cord trauma.

FIG. 3. Graphs showing height vs transverse strain (left) and deformation (right). The transverse strain ranged from 22% with the smallest weight to 33% with the larger weights. The maximum deformation of the spinal cord was 1.1 mm.
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**Fig. 4.** Graph showing height vs velocity of deformation in the spinal cord only. Generally, the larger the weight and the smaller the height, the smaller will be the velocity of spinal cord deformation.

**Fig. 5.** Graph showing height vs acceleration of deformation in the spinal cord only. Maximum deformation acceleration is noted in the 20 gm \( \times \) 20 cm trauma group. The variation between groups is similar to that for deformation velocity.

...did the velocity of deformation (Fig. 5), ranging from 35 m/sec\(^2\) (meters per second per second) to 51 m/sec\(^2\) for the spinal cord and from 86 m/sec\(^2\) to 180 m/sec\(^2\) for the spinal cord/thorax unit. Peak deformation acceleration was seen in the trauma groups with a middle range of weight and height.

Force (N) was greater with larger weights regardless of the distances they fell, ranging from 5.1 N for the 5-gm weight falling 80 cm to 16 N for the 100-gm weight falling 4 cm (Fig. 6). Force, by definition, was the same for the spinal cord as that determined for the spinal cord and thorax.

Force was directly related to the deformation of the spinal cord (Fig. 7), and the slope of the force-displacement curve for the spinal cord was greater than that for the spinal cord...
and thorax. The relationship of force to velocity of deformation of both the spinal cord and the spinal cord and thorax appeared to be a horizontal parabolic one; greater force was required to obtain the same velocity of deformation of the spinal cord relative to that of the spinal cord/thorax (Figs. 8 and 9). The same velocity of deformation was associated with forces of two different magnitudes. For example, in Fig. 8 a deformation velocity of 0.12 m/sec could be produced by applying 5 N of force by a weight-height combination of 5 gm × 80 cm or 15 N of force by 80 gm × 5 cm. Force was related to deformation acceleration in a similar manner as that for deformation velocity (Fig. 10).

Spinal cord and spinal cord/thorax deformation also appeared to be related to the velocity of the deformation in a horizontal
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**FIG. 10.** Graph showing force vs acceleration of deformation in the spinal cord only. It can be seen that the relationship between force and acceleration of spinal cord deformation is similar to that for force and velocity of spinal cord deformation (Fig. 8).

parabolic manner (Figs. 11 and 12). Maximum deformation of the spinal cord (1.1 mm) was not associated with maximum velocity of deformation (0.18 m/sec). A direct relationship between velocity and acceleration existed; both were greater for each of the trauma groups in regard to the spinal cord/thorax than to the spinal cord alone. In general, the greatest deformation velocities correlated with the greatest accelerations of deformation for all weight-height combinations.

**Discussion**

Only after attempts had been made to standardize and quantify experimental trauma did advances occur in the understanding of the pathophysiology of the spinal cord after contusion. Quantitation of experimental spinal cord trauma has been in terms of "gm-cm" units since the initial description of this method of quantitation by Allen in 1911. Allen employed a weight-dropping apparatus to injure the spinal cord. A weight was allowed to fall a certain distance to strike the spinal cord, which had been exposed by laminectomy. The degree of trauma was expressed as the product of the weight (gm) and the height (cm) from which it fell. Variations in this method for producing experimental trauma have been used, but Allen's concept of the "gm-cm" unit as a means for quantitating the trauma has remained. As various combinations of weights and heights can give the same gm-cm value, it is clear that a more accurate means of quantification of the trauma sustained by the spinal cord is necessary. Attention has been focused on this problem and a more accurate biomechanical quantification of experimental spinal cord trauma has been sought.

**FIG. 12.** Graph of displacement vs velocity in the spinal cord and thorax. A horizontal parabolic relationship was noted between displacement of the spinal cord/thorax and the velocity with which the displacement occurred.
The pressor response after spinal cord trauma has been described and often is referred to as the "Cushing reflex." The primary event in the hypertensive phase is thought to be the activation of sympathetic preganglionic cells in the spinal cord by mechanical deformation rather than by adrenal catecholamine release, anoxia, or activation of specific spinal canal baroreceptors. The hypotensive phase that follows the initial hypertension was thought to be related to a subsequent absence of sympathetic vascular tone. The alteration in systemic blood pressure in both components of this response may be significant in the ensuing post-traumatic dysfunction of the spinal cord, as it has been demonstrated that there are changes in the autoregulation of blood flow in the traumatized spinal cord.

With the trauma device described here, a complete definition of the mechanical alteration of the spinal cord during trauma has been accomplished, in that determinations of force and deformation were made relative to time. As the thoracic spinal cord lies in the spinal canal above the rib cage, a posterior force applied to it also affects those structures lying beneath the spinal cord. In other published experiments on spinal cord trauma, the displacement of the spinal cord itself was not separated from that of the thorax. In the present experiment, the spinal cord was first traumatized, then excised, and finally the vertebral body over which the spinal cord had been lying was traumatized. The differences between the former and the latter measurements gave the biomechanical effect on the spinal cord. Therefore, it was possible to study biomechanical alterations of the thorax as well as that of the spinal cord above. Diagrammatic representations of the spinal cord, vertebral bodies, and rib cage, as well as a representative mathematical model are shown in Fig. 13.

In experiments on the biomechanics of spinal cord trauma, the biomechanics of the vertebral column and/or rib cage have not been studied. Spinal cord deformations of up to 4 mm or even 10 mm have been reported in animals in which the entire anteroposterior diameter of the spinal cord is less than those displacement values. In other words, the corresponding transverse strain would be greater than 100%. The spinal cord cannot be deformed more than its own diameter. In this experiment, the maximum displacement of the spinal cord/thorax was 4.6 mm (100 gm × 4 cm trauma group); however, the feline spinal cord at the level studied seldom had a diameter greater than 4 mm and the mean anteroposterior diameter was approximately 3 mm. Accounting for the displacement of the thorax in the above instance, the actual deformation of the spinal cord was 1.1 mm (Fig. 2).

Measurements of force are the same for the spinal cord/thorax as for the spinal cord because these were both recorded directly from the force transducer; force on the spinal cord is essentially the same as that on the underlying supporting structures. The force-deformation curve for the spinal cord (Fig. 7) resembles the stress-strain curve of other biological materials. In such curves, a point at which the curve becomes vertical may be identified. This point for the spinal cord appears to correspond to the 40 gm × 10 cm trauma group (approximately 12 N), as shown in Fig. 7. Beyond this point much disruption of the nervous tissue probably occurs. For these reasons, force may well be a good biomechanical parameter for quantitation of experimental spinal cord trauma.

No direct relationship existed between force and velocity of deformation. The larger weights had lower velocities of deformation; therefore, velocity of deformation does not appear to be a good biomechanical parameter to use for quantitation.

It is interesting to note that in this study of experimental spinal cord trauma, the
velocities of deformation of spinal cord and spinal cord/thorax are very low (Figs. 8 and 9). The maximum velocity of deformation of the spinal cord is only 0.4 mph and that of the spinal cord and thorax is 1.4 mph.

In a previous study of biomechanical parameters in experimental spinal cord trauma, a mathematical model of the relationship between the height of the falling weight and the theoretical impounder velocities with varying impounder masses was constructed; the interrelationships postulated by the authors have been noted in the present study (Fig. 4). A direct correlation between impulse and lesion volume in experimental spinal cord trauma has been reported; however, force is definitely easier to monitor.

The utility of the trauma apparatus in the present study has been confirmed. The "trauma stimulus" is monitored at all times, and the amount of trauma actually delivered to the spinal cord is quantitated. With the force transducer, it is no longer necessary to calculate the force by integration of the acceleration-time curve. The direct method of measurement of force is more accurate.

Future studies comparing biomechanical parameters such as force and deformation to histological alterations within the spinal cord are necessary to test whether these parameters are useful in predicting the amount of actual tissue damage in the traumatized spinal cord. Chronic animal studies should be undertaken and the trauma groups should be classified, probably on the basis of force, and their neurological function observed over time. This should give a more standardized and readily reproducible injury and, therefore, the efficacy of various methods of treating the traumatized spinal cord could be more correctly assessed.

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References


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