Journal of Spinal Disorders
Vol. 6, No. 2, pp 175–181

Cervical Injuries Under Flexion and Compression Loading

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Summary: Cervical spine segmental tests were performed to determine the specific patterns of initial cervical injury in response to loading just beyond the point of structural failure. Well-defined combinations of flexion rotation and compression translation were applied to segments with varying degrees of disc and facet degeneration. Twelve cervical spine specimens (from human cadavers ages 52–91 years), each consisting of three vertebrae (two motion segments) from the middle (C2–C5) or lower (C5–T1) regions, were subjected to pure flexion rotation (seven specimens) or to combined flexion rotation and axial compression translation (five specimens). Specimens were sectioned and dissected to determine the patterns of structural failure. Pure flexion, and combined flexion and compression produced similar patterns of injuries. The disc was the most commonly injured structure, with annular injuries noted in 8 of the 12 specimens, and with anterior herniation of the nucleus occurring in two specimens. Wedge fractures and posterior ligament injuries were noted in both specimen groups and with both modes of loading. We conclude that similar patterns of initial anterior bony compressive failure and posterior ligamentous failure can occur with both flexion and with combined flexion–compression, without axial or lateral rotation, at low rates of loading. Anterior cervical disc herniations were produced in both middle and lower cervical segments. **Key Words:** Cervical spine—Traumatic injury—Biomechanics.

The optimal management of cervical pain syndromes and injuries requires knowledge of the extent of probable bony and ligamentous injuries. Pathologic anatomy may be assessed from bony injuries and relative displacements seen on imaging studies, and from a knowledge of the mechanism of injury. Understanding of the mechanism for specific injuries also has broad application in attempts at injury prevention.

Several authors have evaluated experimental cervical injuries under specific loading conditions through whole cadaver and spine segment testing. The importance of the initial head–neck–thorax position (8), the magnitude of the impulse (the time integral of impact force) (1), and the components of spinal loads have correlated with the patterns of injury during axial loading. In these studies, small variations in the position of the anterior to posterior point of force application and variations in the orientation of the cervical spines in flexion or extension resulted in flexion or extension failures, respectively (11,12). Although these studies provide insight into the patterns of injury possible with midsagittal plane loading of whole or multisegment cervical spine specimens, the relative magnitude of the components of loads at injured segments and the probable spectrum of injuries to specific cervical segments for specific load combinations have not been demonstrated.

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The importance of lateral flexion and axial rotation motions and loads is unclear. In cadaver impact experiments (14) and in low-velocity spine segment loading studies (16), the production of posterior ligament injuries by midsagittal loads appeared unlikely in the absence of an additional axial rotation or lateral flexion component of load. Other studies have produced posterior ligament injuries with midsagittal plane flexion and compression in human cadaver spine segments with low-velocity testing (2,11) and in porcine spine segments with high-velocity testing (18). The analysis of catastrophic football injuries by Torg (19) has suggested that axial loading of the straightened cervical spine is a common mechanism of injury.

Although most catastrophic cervical cord injuries occur with impact loading (20), other loading conditions may result in posttraumatic and occupationally related neck pain syndromes. The purpose of this study was to relate the patterns of injuries observed in cervical spine segments to the biomechanical conditions at failure, considering carefully controlled low-velocity flexion rotation alone, or in combined flexion rotation and compression translation.

MATERIALS AND METHODS

Nineteen vertebral segments, each containing three vertebrae (two functional spinal units), were harvested fresh from cadaver donors of the Harvard anatomic gifts program. Cadaver age ranged from 52 to 91 years, with a mean (±SD) age of 73 ± 11 years. Six segments were from men and seven were from women.

Spines were carefully dissected free of surrounding muscle, leaving the interconnecting ligamentous structures intact. Before mechanical testing, spines were divided immediately above or below the fifth cervical vertebra to provide two three-vertebrae segments. The resulting test specimens were therefore from the middle (C2–C5) or lower (C5–T1) cervical spine (17). Specimens were kept moist with saline throughout preparation and testing.

All specimens were tested on a three-degree-of-freedom material testing apparatus capable of simultaneous application of axial compression or distraction, anterior to posterior shear translation, and flexion or extension rotation (17). For mechanical testing, the upper and lower vertebrae of each segment were first embedded in a polymethyl-methacrylate resin in aluminum mounting cups. Lateral and anteroposterior radiographs of the specimen were taken to determine specimen orientation and position in the fixtures. The lower embedded vertebra was mounted on the moveable test stage and the upper embedded vertebra was attached to the load cell. The lower vertebra was displaced, while the loads induced in the specimen were measured by the load cell attached to the upper vertebra. Based on specimen geometry obtained from radiographs, it was possible to program the system to translate and rotate the specimens with respect to the geometric center of the middle vertebral body (17). Electromechanical transducers were attached to the middle vertebra, and the motion of this vertebra relative to the adjacent fixed vertebra was measured. This motion was described by three translations and three Euler rotations (17).

To ensure standard initial conditions for each specimen, the specimens underwent small anteroposterior shear translations (±5 mm), compression–tension translations (±2 mm), and flexion–extension rotations (±3°). After analysis of the resulting load versus displacement curves, the test stage was then positioned so that there were no forces or moments on the specimen. From this initial unloaded position, the specimen was rotated in flexion with the center of rotation at the geometric center of the middle vertebral body. Flexion rotation was applied to seven specimens, at 2–5°/s, until failure, which was defined as an abrupt change in the slope of the load-displacement curve. An additional five specimens were rotated in flexion to a maximum of 30°, and then compressed to failure, at 3–5 mm/s, along the cephalocaudal axis (Fig. 1). The specimen was rotated in flexion about the center of the middle vertebral body and then compressed to failure along the cephalocaudal axis (Z) as shown. These loading rates simulate a 20-mm/s compression across the complete cervical spine (occiput to T1, T8 disc levels). This controlled testing to failure avoids extreme damage, which would obscure initial patterns of failure near the threshold of tissue damage. After testing, the specimens were again radiographed, refrozen, and subsequently dissected.

The resulting patterns of injury were assessed through detailed dissection of the spine segments. The refrozen specimens were cut midsagittally with a band saw and then thawed. The half specimens were manually redisplaced to the displaced position observed at failure, and the ligamentous and bony injuries were recorded. A small amount of additional dissection was needed posteriorly at the facet capsules and in the spinal canal to evaluate the integrity of these struc-

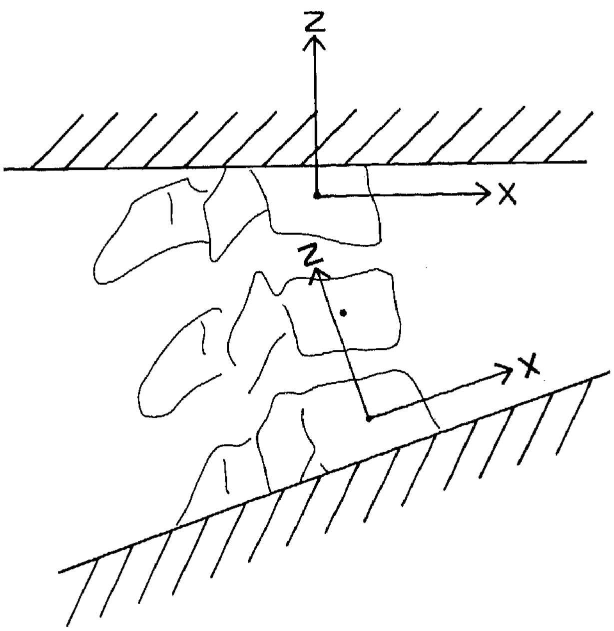


FIG. 1. The specimen was rotated in flexion about the center of the middle vertebral body, and then compressed to failure along the cephalocaudal axis (Z) as shown. Motions were chosen to reproduce physiologic compression and flexion motion across the three-vertebrae segment.

tures. The degree of disc and facet degeneration was assessed by inspection of the radiographs and from the dissected specimens. The degeneration was graded on a scale from 0 to 3 for discs (7,13), with a similar grading scheme used for facets (9), with 0 being the normal end of the scale. The sectioned specimens were photographed in their neutral and displaced positions.

RESULTS

On dissection of the specimens, three specimens were found with spontaneous fusion of one of the two motion segments, and four specimens loosened in the embedding media. These seven were excluded from further analysis.

Seven mid- and lower cervical specimens completed testing with pure flexion rotation (Table 1). These specimens failed at a mean flexion angle of 25 ± 7° (SD) and a mean flexion moment of 8.6 ± 3.9 N-m. The mean compressive force and maximum posterior shear force generated during flexion rotation were 215 and 125 N, respectively. Three of the midcervical specimens (C2–C4) sustained posterior ligamentous injury, with damage to the supraspinous and interspinous ligaments, the ligamenta flava, and the facet capsules. One of these segments (H342) also sustained a disc injury with avulsion of a flake of the posterior corner of the vertebral body above, attached to the posterior annulus fibrosus. Another specimen (H233) exhibited no evidence of bony or posterior ligamentous failure, but showed herniation of the nucleus pulposus anteriorly beneath the longus colli musculature.

Three of the specimens tested in flexion exhibited predominantly bony injuries. One midcervical specimen (H527) sustained minimal anterior compression failure of the vertebral body, which was evident only on reproduction of the applied flexion rotation (Fig. 2). Both lower cervical specimens sustained fractures. One specimen (H228) exhibited a wedge fracture with compression of the upper endplate, and anterior inferior body adjacent to the same disc, with injury of the intervening disc. The second specimen (H124) exhibited avulsion fracture of the middle vertebra posteriorly and a small anterior fracture of the lower vertebra.

Five cervical segments underwent combined flexion rotation and compression translation (Table 2). These specimens failed at a mean compressive displacement of 4.2 ± 1.3 mm, mean compressive force of 1,948 ± 985 N, and a flexion moment and angle of 7 ± 5 N-m and 25 ± 3°, respectively. The posterior shear force generated during flexion–compression loading was a maximum of 115 N. The middle cervical specimen (H106) exhibited injury only to the disc at the upper of the two motion segments. On reproduction of the flexion rotation and compression translation, this specimen exhibited shear translation of the upper motion segment with widening of a cleavage plane through the disc extending to the peripheral portion of the annulus.

Of the four lower cervical specimens tested to failure with combined flexion rotation and compression translation, all sustained disc injuries. Two demonstrated posterior ligament damage including supraspinous and interspinous ligament and facet capsular injury, one of which also sustained mild wedge fractures. One specimen in this group exhibited an anterior disc herniation (Fig. 3).

Disc injuries were frequently noted in specimens displaced to failure in both flexion and flexion–compression. The disc injuries occurred in association with both ligamentous injuries and with wedge fractures or avulsion fractures. On posttest examination of the undisplaced specimens, the preexisting degenerative changes were commonly noted. In one of these specimens, it was difficult to differentiate acute injury

TABLE 1. *Cervical spine injuries: flexion loading*

Structure injured	Specimen						
	H000	H342	H233	H277	H527	H124	H228
Segment level	C2–C4	C2–C4	C3–C5	C2–C4	C2–C4	C6–T1	C5–C7
Supraspin. l.	x	x		x			
Interspin. l.	x	x		x			
Lig. flav.	x	x		x			
Facet caps.	x	x		x			
Disc		x					x
Ant. disc hern.			x				
Vert. body Fxs					x		x
Other vert. Fxs		x				x	x
Grading							
Disc above	1	1	0	1	0	0	3
Disc below	1	1	2	1	0	0	3
Facet above (R-L)	0–0	3–2	0–0	2–2	1–1	1–1	1–1
Facet below (R-L)	0–0	3–3	2–2	2–2	1–1	1–1	1–2
At failure							
Flexion moment (N-m)	4.4	4.2	5.2	11.6	10.3	12.0	12.8
Flexion angle (deg.)	30	36	21	25	22	15	27
Compression force (N)	230	300	215	0	140	480	140
Compressive translation (mm)	0	0	0	0	0	0	0

from degenerative changes. However, abnormal translation was noted on reproduction of the failure configuration, with extension of the disc cleavage planes to the peripheral annulus. Therefore, this was regarded as a disc injury.

Although there was marked variation in the motion-segment injuries in the same region and under identical displacement conditions, consistent trends in the results were observed. Among both mid- and lower-cervical segments, similar patterns of injuries were noted in specimens damaged by flexion rotation alone and in specimens damaged by axial compression of the flexed specimen. These injuries were generally either mild compression fractures of the anterior vertebral body or posterior ligamentous injury. Anterior longitudinal ligament and posterior longitudinal ligament injuries were not seen in any of these specimens. Posterior ligament injuries occurring in these specimens consisted of disruption of the interspinous ligaments and stretching or tearing of facet capsular ligaments, at times in an asymmetric pattern, although only midsagittal plane displacements were applied.

The ligamentum flavum was avulsed from the inferior edge of the superior lamina of the motion segment in three of the seven flexion specimens (Table

A,B

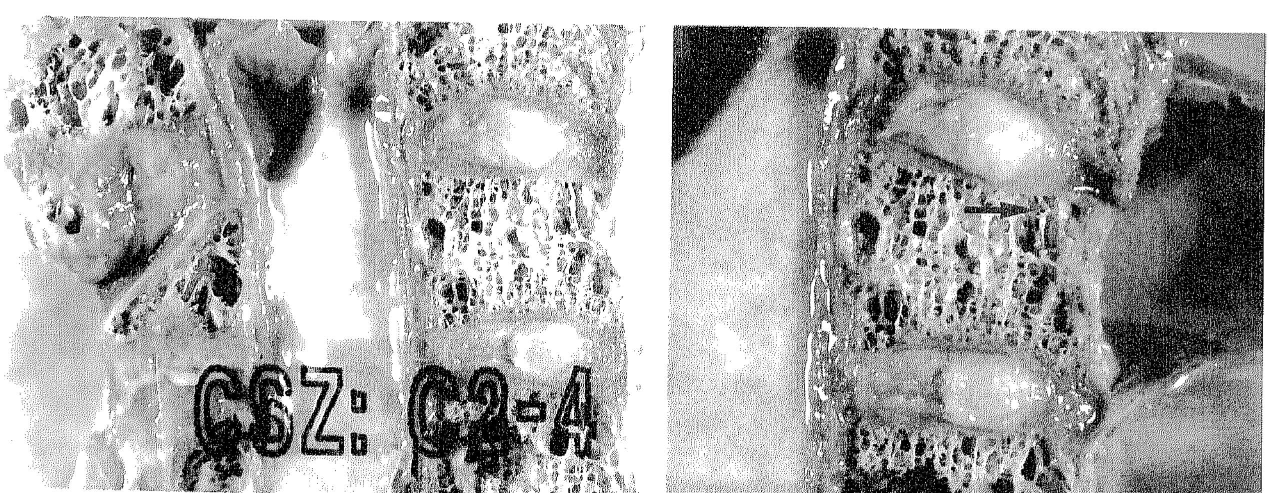


FIG. 2. Wedge compression fracture after flexion loading. **A:** The injury is not apparent in neutral position. **B:** When the specimen is flexed to the previously displaced position, mild wedging of the vertebral body occurs, and buckling of anterior trabeculae is seen (arrow).

TABLE 2. *Cervical spine injuries: flexion–compression loading*

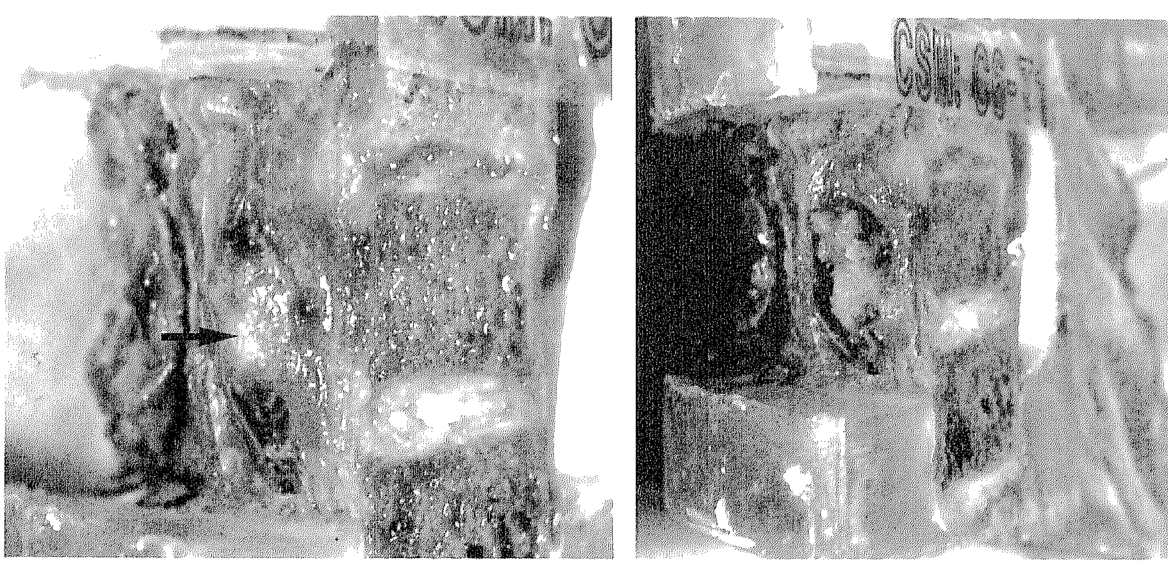
	Specimen				
Structure injured	H106	H433	H772	H342	H966
Segment level	C2–C4	C6–T1	C5–C7	C5–C7	C5–C7
Supraspin. l.			x		x
Interspin. l.			x		x
Lig. flav.					
Facet caps.			x		x
Disc	x	x	x	x	x
Ant. disc hern.		x			
Vert. body Fxs					x
Other vert. Fxs					
Grading					
Disc above	0	2	0	2	2
Disc below	0	1	2	2	1
Facet above (R-L)	1–1	2–2	1–1	2–2	2–1
Facet below (R-L)	2–1	1–1	1–2	2–2	2–1
At failure					
Flexion moment (N-m)	7.3	15.8	7.3	3.1	2.2
Flexion angle (deg.)	25	21	30	25	25
Compression force (N)	1,800	3,250	1,640	2,450	600
Compressive translation (mm)	3.7	5.6	4.6	4.8	2.2

1). Interspinous ligament disruptions generally consisted of elongation and attenuation of the thin ligament at the involved interspace.

Compression fractures occurred as anterior wedging of the vertebral body, which was often not apparent until the applied displacement was reproduced (Fig. 2). Avulsion fractures were produced by avulsion of a corner of the endplate attached to the peripheral annulus.

Anterior disc herniations were seen in two specimens—one that underwent flexion rotation alone and the other that underwent combined flexion rotation and compression translation. These herniations presented as a pocket of nuclear material beneath a focal bulge under the longus colli muscles, lateral to the anterior longitudinal ligament, and inferior to the annulus. This extruded nucleus was loose and easily separable from the adjacent tissue. There was no surrounding fibrous tissue and the continuity with the disc space could be easily demonstrated (Fig. 2).

Twenty-four discs and 48 facets were graded in 12 specimens. Of these 24 discs, 8 were grade 0, 8 were



A,B

FIG. 3. Anterior disc herniation after flexion–compression loading. **A:** Localized bulge of soft tissue is present over the anterior vertebral body (arrow). **B:** Minimal dissection reveals loose nuclear material in continuity with the intervertebral disc.

grade 1, 6 were grade 2, and 2 were grade 3. Of the 48 facets, 6 were grade 0, 21 were grade 1, 18 were grade 2, and 3 were grade 3. There was no apparent association between the degree of facet or disc degeneration and the type of ligament or bony injury. Likewise there was no relationship between the degree of degeneration and the magnitude of load, moment, displacement, or rotation at failure.

DISCUSSION

Previous studies of the cervical spine have provided mixed findings regarding the relative contribution of sagittal motions (flexion–extension rotation and compression) to observed patterns of injury. The relationship between external impacts and other externally applied loads, and the forces and moments that result at each of the motion segments of the cervical spine have not been well defined. Consequently, external loading of whole cadaver cervical spines and spine segments has resulted in a wide variety of injury patterns.

Roaf (16), Nusholtz et al. (14), and others have suggested that ligamentous injury is unlikely with flexion–extension motions alone. Roaf was unable to produce ligamentous damage with flexion rotation of cadaver spine segments without prior axial rotation of the specimens (16). Nusholtz et al. (14) demonstrated an increased frequency of posterior ligamentous injuries in cadavers positioned to produce axial rotation and lateral flexion with external impacts. However, posterior cervical ligament injuries were seen in impact studies of porcine cervical spine segments, when subjected to flexion–compression trauma (18).

Bauze and Ardran were also able to consistently produce complete posterior ligamentous disruption and dislocation with axial compression and flexion of cadaver cervical spines under midsagittal loading, when the spine below the level of injury was stiffened by insertion of a metal rod into the spinal canal (2).

The present study examined injury patterns and the mechanical conditions that produce flexion rotation injuries or combined flexion–compression injuries. The findings show that injury of the posterior ligaments is possible in the absence of lateral flexion or axial rotation, for sagittal rotations and translations applied to the threshold of injury. In axial compression, bony failure and soft-tissue lesions occurred at conditions only a few millimeters beyond the initial point of injury as detected by the load-displacement curves. Had these displacements been carried much farther, more severe injuries, including posterior longitudinal ligament injuries, may have been observed under midsagittal loading conditions.

Neck pain syndromes may originate after a variety of less traumatic loading conditions, and without apparent "injury" but with clear mechanical risk factors. In a study of neck pain patients, less than half (76 of 205) had been involved in motor vehicle accidents and 84 of 205 did not report a neck injury (6). In an epidemiological study by Kelsey et al. (10), those engaged in heavy lifting (lifting >25 lb) were at increased risk of acute cervical disc prolapse. Anterior disc herniations resulting in extrinsic esophageal compression have been described (3,4), but may occur without history of known trauma. Such a history might be expected for lesions produced by muscular exertion or other low-velocity load application just beyond the initiation of structural damage. Thus, the translation and rotations producing these lesions in our study may account for the clinically observed lesions.

Our results demonstrate a variation in the pattern of injuries even for well-controlled displacements at specific motion segments. We found earlier that posterior ligamentous injury is more likely when axial rotation is applied in combination with flexion (17). Specimens that were flexed to a mean angle of 24° (8.6 ± 3.9 N-m flexion moment, 215 ± 150 N compression force) and specimens that were placed in a flexed position (mean 25°) and then compressed (7.1 ± 5.4 N-m flexion moment, 1,950 ± 985 N compression force) exhibited similar injuries. For both displacement modes, the range of injuries included anterior compressive bony failure and posterior ligamentous tensile failure. The occurrence of disc injuries here was consistent with the large number of disc lesions seen in pathologic examinations after clinical cervical trauma (5,15). However, a relationship between a specific combination of displacements and a particular anatomic injury could not be established.

The clinical application of these conclusions may be limited by the variation of loading and the injury mechanism involved. Patterns of injury are affected by the rate of loading, particularly for higher rates of loading and greater displacement magnitudes. In a study by Yoganandan et al., which examined the influence of the rate of distraction on the response of the human cervical ligamenta flava and anterior longitudinal ligaments, the ultimate failure tensile load stiffness and the energy-absorbing capacity did increase with increasing loading rate (21). The stiffness and the energy-absorbing capacity did increase with increasing loading rate (21). The importance of impact biomechanics research in the evaluation of such injuries has been previously emphasized by Viano et al. (20). Many catastrophic spinal cord injuries involve impact loading conditions that were not produced in this study. A further limitation of our study was the age range of specimens used (52–91 years). This age range is greater than that reported for neck pain patients who were of mean age 43 ± 12 (1 SD) years (6). In addition, in an epidemiologic study of cervical disc prolapse patients, only 24% of patients were >50 years of age (10). Expanding these experiments to include specimens of a younger age range would offer useful insights into age-related differences in injury patterns.

We conclude that similar patterns of anterior bony compressive failure and posterior ligamentous failure can occur with both flexion and flexion–compression loading, without axial rotation or lateral flexion at low rates of loading. Most of the wedge compression fractures and ligament injuries in our study were not apparent on radiographs of the neutrally positioned spine segment, but were evident only on reproduction of the applied translation and rotation for some specimens. This emphasizes the importance of dynamic radiography and close radiographic follow-up of neck injuries. The study demonstrates that knowledge of injuries resulting from a variety of conditions, including those just beyond the initiation of failure, is important in understanding the full spectrum of neck pain syndromes from mechanical causes.

Acknowledgment: This study was supported by General Motors Research Laboratories (W.T.E.), the Maurice E. Mueller Professorship in Biomechanics at Harvard Medical School (W.C.H.), the Daniel E. Hogan Spine Fellowship Program (R.R.C.), and the Beth Israel Orthopaedic and Research Fund.

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