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Biomechanics of metastatic spine cancer

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The spine is the most common site of bony metastases in the human body, with approximately 18,000 new cases diagnosed annually in North America [1–3]. At least half of all spinal metastases are from breast, lung, prostate, or renal carcinoma [3,4]. Most of these patients present to the spine surgeon with pain or weakness. The pain may be caused by destruction or collapse of the vertebral body with frank instability [5]. Weakness or paralysis may be caused by direct invasion of the spinal canal with tumor or by pathologic fracture with deformity and spinal cord compression [4].

Radiologic evidence of metastases does not become apparent on plain radiographs until approximately 30% to 50% of the bone is destroyed [3,6]. Typically, these radiographs demonstrate either uniform vertebral collapse or ventral wedge compression with ensuing kyphotic deformity [2].

With improvements in chemotherapy, hormonal manipulation, and radiotherapy, survival times of many patients with metastatic disease have improved dramatically [7]. As a result of this lengthened survival, a shift in the management strategy for treatment of spinal metastatic disease has occurred, with some authors advocating an aggressive approach, including prophylactic stabilization to prevent pathologic fractures and their associated morbidity [7]. Identification of appropriate candidates for surgical intervention, both prophylactic and symptomatic, requires a firm understanding by the spine surgeon of the biomechanical changes initiated within the spine by vertebral metastases. These biomechanical effects are often similar to trauma [8,9]. Tumor-related fractures, dislocations, and rotational injuries can occur with even slight or apparently insignificant trauma, however [8].

Biomechanics of metastases

Metastases can disrupt the normal biomechanics of the spine via bone destruction or deformity. The vertebral body is the most common site of metastatic deposition, with the dorsal elements rarely affected [10,11]. Ventrally, partial or total destruction of the vertebral body results in a decrease in its load-bearing capacity. The load-bearing capacity is determined by a number of factors, including tumor size as well as cross-sectional area of the intact body and its bone mineral density [12]. Dimar et al [6] and Windhagen et al [12] have shown that the threshold for pathologic fracture can be most accurately predicted in cadaveric models by measuring the product of the remaining intact vertebral cross-sectional area and the bone mineral density. When a critical threshold is reached (anywhere from 51%–96% of cross-sectional area depending on bone mineral density), the vertebral body becomes prone to pathologic fracture, defined as a fracture occurring under normal physiologic stress [6]. Most commonly, this results in either a compression fracture or a burst fracture, because the bulk of the force vector generated by the patient's body weight is in line with the instantaneous axis of rotation (IAR) [2]. The location of the tumor (and hence bone destruction) within the vertebral body may also play a role in the patient's risk of fracture. For

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example, if one considers the vertebral body to be a cube composed of 27 identical cube-shaped segments (Fig. 1), destruction of the middle third in the sagittal plane results in gross instability. Loss of the middle third in the coronal plane does not, however (Fig. 2). In the first case, the anterior and middle columns of Denis are completely disrupted [13]. In the second case, only one third of the anterior and middle columns of Denis have been disrupted, resulting in a relative preservation of stability. Moreover, tumor location within the sagittal plane can have varying effects on vertebral body stability, with ventrally placed tumors (anterior column) potentially having a greater destabilizing effect than dorsally located masses (middle column) in the presence of intact dorsal elements (Fig. 3) [13,14].

Although the dorsal elements are rarely affected by metastases, significant biomechanical sequelae may occur when they are present. Invasion and disruption of the facet joints may predispose patients to dislocation and translational deformity at all levels of the spine [14]. Any damage to the ligamentous structures or soft tissues supporting the spine could further disrupt the spine's ability to resist translational or shear forces [14].

Regional nuances

The thoracic spine is involved in 70% of cases of spinal metastases, whereas the cervical and lumbar spines are affected in 10% and 20% of cases, respectively [5]. The ensuing pathologic fracture types can vary greatly from region to region, however, because of the distinct anatomic differences between the cervical, thoracic, and lumbar spines.

The upper cervical spine is especially prone to injury because of its unique anatomy and the degree of spinal movement allowed [8]. In this region, the orientation of the force vector applied, in combination with the location of the lesion, determines the type of injury observed. For example, an axially directed force applied to upper cervical spine could result in a C1 burst fracture, a C2 burst-pedicle fracture, or a subaxial cervical burst fracture. The relative strengths of the C1, C2, and subaxial vertebral bodies dictate the type of fracture, with the weakest of the three (ie, the one with the tumor) fracturing first and dissipating the load [8]. In most cases, the energy imparted to the upper cervical spine travels through the odontoid process via the arch of C1 or the transverse ligament of C1 [8]. The location of the tumor, along with the direction of the force vector, can cause any of the following fracture types: judicial hangman's fracture, hangman's fracture, dorsal C2 body fracture (vertical or horizontal), C1 burst fracture, or C1 arch fracture (see Fig. 2). Moreover, soft tissue damage from metastatic infiltration may make these patients more prone to dislocation or rotatory subluxation because of the degree of mobility inherent to the upper cervical spine.

The anatomy of the subaxial spine is relatively monotonous compared with the upper cervical spine. As such, the types of pathologic fractures are less variable [8]. In the subaxial spine, the fracture pattern of a particular segment is determined by the position of the point of force application in relation to the IAR [8]. When the

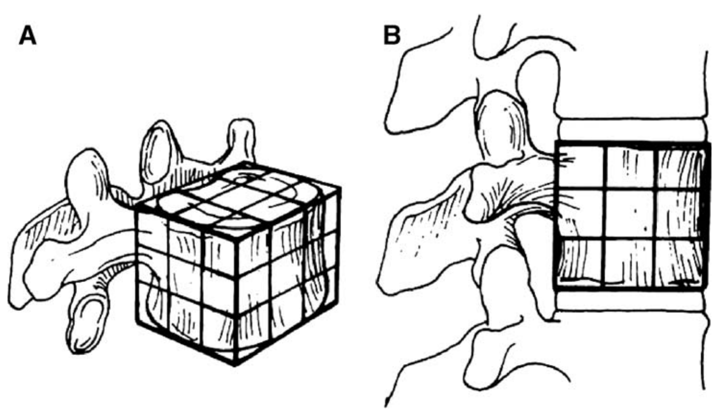

Fig. 1. Vertebral body depicted as a cube composed of 27 smaller cubes for theoretic purposes. Oblique (*A*) and lateral (*B*) views.

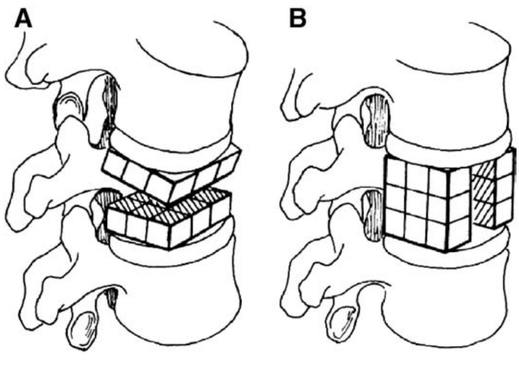

Fig. 2. Destruction of portions of the cube depicted in Fig. 1. Destruction of the middle third in the axial plane (*A*) and in the sagittal plane (*B*). Although the magnitude of bony destruction is identical, the portion in the sagittal plane is not significantly destabilized.

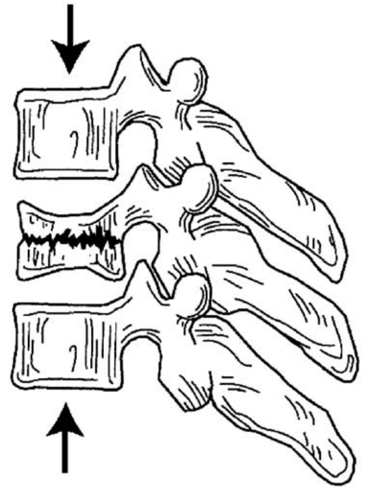

Fig. 4. Burst fracture resulting from a true axial force.

point of force application is in line with the IAR, it creates a pure axial load, resulting in a burst fracture (Fig. 4). If the load is eccentrically placed ventral to the IAR, the ensuing bending moment creates a ventral wedge compression fracture (Fig. 5). The thoracic and thoracolumbar regions of the spine are particularly prone to this type of injury because of their normal kyphosis. In this region, the length of the moment arm is increased by the kyphotic posture, thereby increasing the magnitude of the bending moment created by an eccentrically place axial load

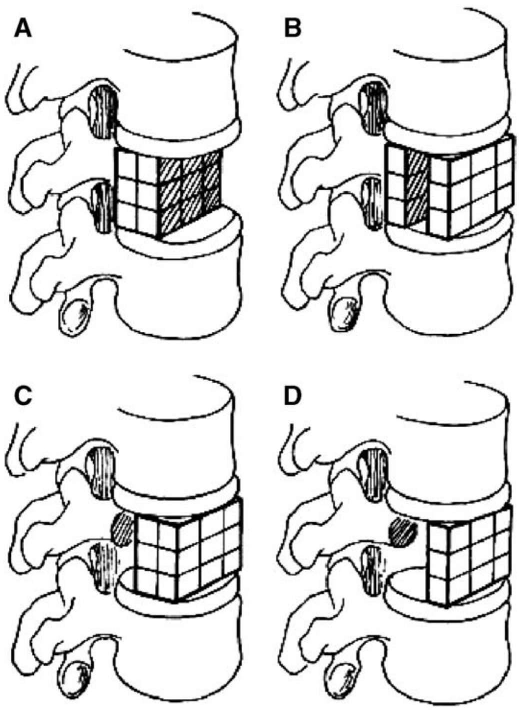

Fig. 3. Destruction of portions of the cube depicted in Fig. 1. A lesion in the ventral portion of the vertebral body in the coronal plane (*A*) affects stability more than lesions in the middle (*B*) or dorsal (*C, D*) portions.

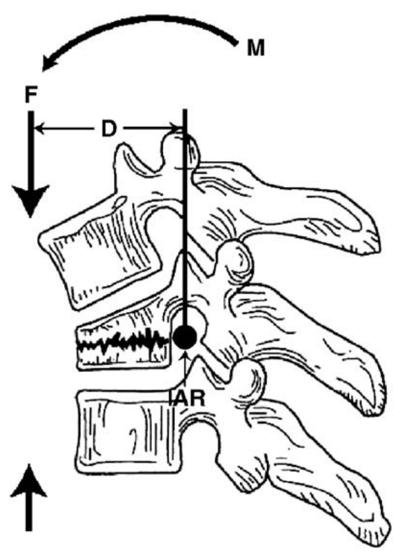

Fig. 5. Ventral wedge compression fracture resulting from an applied force vector (F) ventral to the instantaneous axis of rotation (IAR), resulting in a bending moment (M). The length of the moment arm is depicted by (D).

(Fig. 6). The intrinsic lordosis of the lower cervical and lumbar spines results in a situation in which most forces are applied in line with the IAR. This situation results in burst type fracture patterns rather than compression, as seen in the thoracic spine. If the force vector encountered is lateral to the IAR, a lateral wedge compression fracture may occur. This may occur in isolation or concomitantly with a ventral wedge compression fracture.

Dorsal element metastatic involvement, although rare, can predispose the patient to translational and rotational deformity in the subaxial spine. Infiltration of the facet joints can result in their compromise, mimicking traumatic facet fractures and yielding rotational or translational hypermobility at the affected segment. The cervical spine is especially prone to this type of injury because of the coronal orientation of the facet joints, which allows for rotation and flexion [15,16]. By contrast, the rib cage limits the degree of rotation and flexion in the thoracic spine. In the lumbar spine, rotation is limited by the sagittal orientation of the facet joints. Facet disruption in the lumbar spine has been associated with glacial instability, however, which may become an issue in long-term survivors [17].

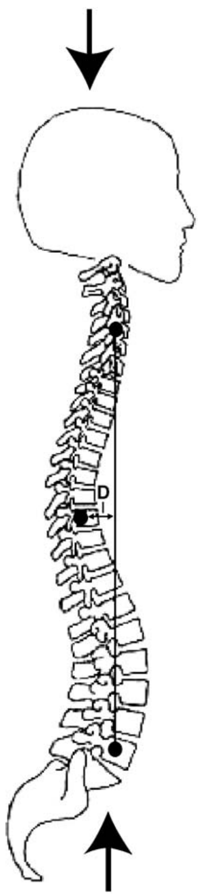

Fig. 6. Kyphosis increases the length of the moment arm (D), thereby increasing the magnitude of the bending moment resulting from an axial load (*arrows*) eccentric to the axis of rotation (*dots*) in the thoracic spine.

Clinical application

One of the goals for surgery in patients with spinal metastases is restoring spinal stability [18]. In the case of an existing pathologic fracture, Denis' three-column classification for thoracolumbar fractures may be applicable to the subaxial spine [13,19]. More recently, Weinstein [20] described a four-zone classification specifically for use in tumors. In the four zone-model, zone I comprises the laminae, spinous process, pars, and inferior facet. The upper half of the pars, superior facet, and transverse processes comprise zone II. Zone III includes the ventral three quarters of the vertebral body. Zone IV consists of the dorsal quarter of the vertebral body. The letter A, B, or C is then applied to each zone to describe intraosseous, extraosseous, or distant tumor spread, respectively. The approach used for tumor resection and for spinal stabilization is dictated by which zones (and columns) have been affected [19]. For example, a patient with a metastatic lesion (breast adenocarcinoma) in the ventral aspect of the C6 vertebral body (zone III) with a subsequent pathologic compression fracture, as seen in Fig. 7, would require reconstruction of the ventral column for appropriate stabilization. In this specific case, the patient also had dorsal element involvement (zone I) at C6 and thus required dorsal stabilization as well. Because of the adjacent affected vertebral levels at the cervicothoracic junction, a long construct (C4–T5) was used to achieve adequate ventral fixation. Of note, although the patient also had a metastatic lesion in the T1 vertebral body, no ventral stabilization was needed at this level because of its small size and its location in the dorsal aspect of the body (see Fig. 3 C,D). Moreover, the long construct was, in part, used to compensate for anticipated growth of the cervicothoracic lesion.

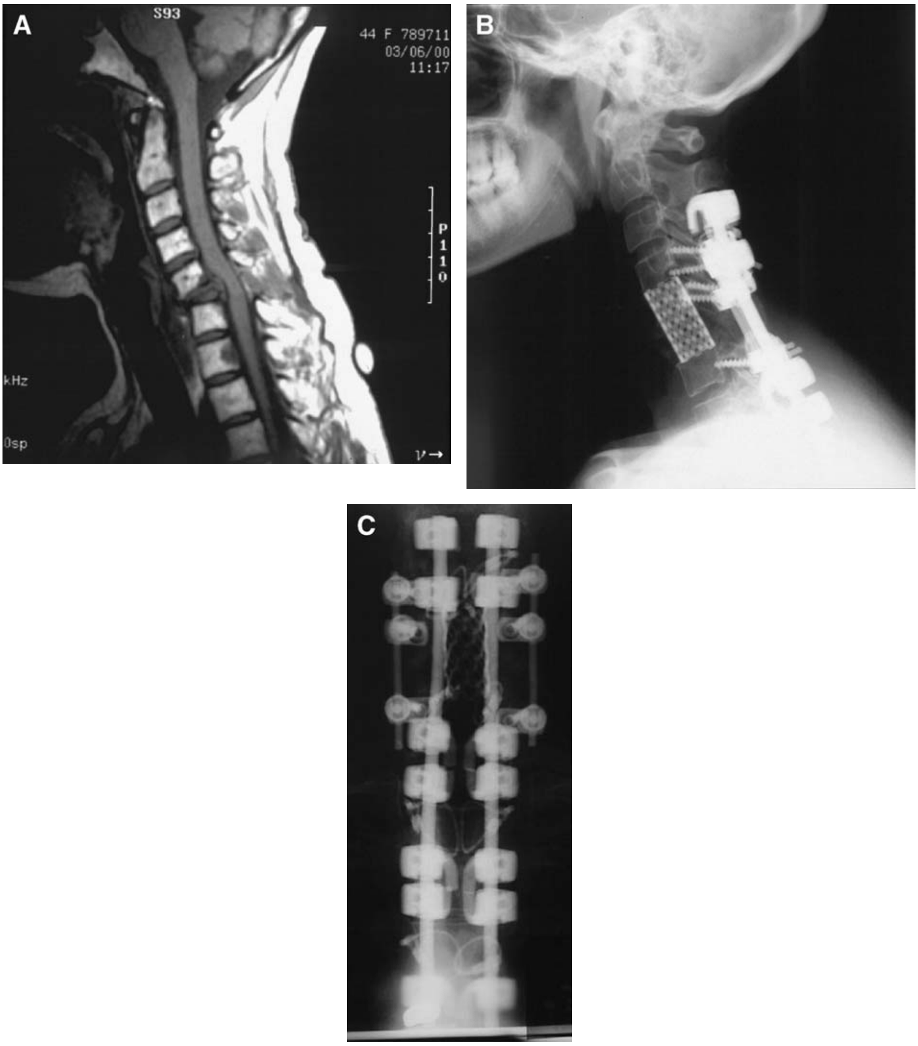

Fig. 7. Sagittal cervical spine MRI of a 44-year-old woman with known breast adenocarcinoma with multiple metastatic lesions and a C6 pathologic compression fracture. Anteroposterior (*A*) and lateral (*B*) postoperative radiographs showing C6 to C7 corpectomies with ventral reconstruction and fusion with a titanium cage and autologous bone graft and C4 to T5 dorsal fixation and fusion with C4 to C7 lateral mass screws and C4 to T5 laminar hook and rod construct.

Although Weinstein's and Denis' classification systems are helpful in assessing the biomechanical stability of a patient's spine, neither is useful in predicting a patient's risk of pathologic fracture when asymptomatic metastasis is discovered. If this risk could be determined, only patients at high risk could be selected for prophylactic resection and stabilization. It has been shown that the product of the intact cross-sectional area of the vertebral body and the bone mineral density is linearly related to the strength of the vertebral body under axial load [6,12]. All these studies have been performed on cadaveric spines, however, and may not be directly applicable to the in situ living spine.

Taneichi, et al attempted to address this issue by studying 53 patients with osteolytic metastatic tumors to the thoracic or lumbar spine. They found, as predicted by biomechanical studies, that risk of vertebral body collapse was related to tumor size. In their study, impending collapse was predicted by 50–60% involvement of the vertebral body in the thoracic spine and 35–40% involvement in the thoracolumbar/lumbar spine. Interestingly, they also noted that destruction of the costovertebral joint in the thoracic spine and the dorsal elements in the lumbar spine seemed to lower the threshold for vertebral collapse. No attempt, however, was made to analyze the effects of bone mineral density on the risk of collapse [21]. When selecting a patient for prophylactic treatment, therefore, the vertebral level, the extent of metastatic vertebral involvement, the location of the lesion within the vertebral body, and the extent of any underlying osteoperosis/osteopenia should be considered in determining the optimum timing and method of treatment.

Summary

The spine is the most common site of skeletal metastases. Most of these occur within the vertebral body, thereby predisposing patients to pathologic fracture. The risk of fracture is related to the extent of bony destruction, location of the lesion, and inherent bone quality. The regional variation in spine anatomy exposes the cervical, thoracic, and lumbar spines to different forces, resulting in varying fracture types.

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