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Superior cortical screw in osteoporotic lumbar vertebrae: A biomechanics and microstructure-based study

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ABSTRACT

Background: Osteoporosis reduces the bone-screw purchase, potentially reducing pullout strength and other biomechanical properties. However, the existing pedicle screw approach may not compensate for the detrimental effects of decreased vertebral bone mineral density.

Methods: Two methods of screw insertion were performed in thirteen cadaveric osteoporotic lumbar vertebrae: Magerl's method in the left pedicle, and superior cortical screw method in the right (its entry point located vertically 3 mm above Magerl's point). Before screw fixations, the pedicle and its corresponding vertebral body were divided into six equal layers from cranial to caudal by performing micro-CT and tested for microstructure properties, such as bone mineral density, trabecular bone volume fraction, trabecular thickness, trabecular separation and trabecular number. Further, pedicle was horizontally divided into three regions and tested. After screw fixations, microstructure properties of the bone surrounding the screws were analyzed. Finally, the screw pullout strength was tested biomechanically.

Findings: The bone structure is denser in the upper third of the pedicle and its corresponding vertebral body. A similar microstructure is seen within the pedicle. This study reveals that the pullout strength is significantly correlated to the bone mineral density, trabecular bone volume fraction and trabecular thickness. Biomechanical test showed pullout strength in the superior cortical screw group with mean 613.3 N (SD 200.4) was 22.4% higher than that in the Magerl group with mean 501.2 N (SD 256.6).

Interpretation: The superior cortical screw method can be a reliable alternative, to provide better pullout strength for posterior lumbar instrumentation, especially in osteoporotic patients.

1. Introduction

Osteoporosis is a pathological state, generally defined as a decrease in bone density and associated deformation in the structure of bone tissue, leading to reduction in bone strength. Consequently, osteoporosis has a significant impact on the quality of life at different ages, especially in postmenopausal women and aged populations (Khadilkar and Mandlik, 2015). The incidents of fractures and bone degeneration increase remarkably and the lumbar vertebrae may be the most common sites that often need surgical intervention. Further, osteoporosis has a great impact on spinal surgery because the fragile characteristics of the bone may lead to micromotions between the bone and internal fixation device (Hu, 1997). As a result, fusion devices used for osteoporotic patients require a specific design, including a deep screw thread, an optimized pilot hole size for non-self-tapping screws, modification of the implant's trajectory, and bone cement augmentation (Shea et al., 2014).

A previous study on the cancellous bone of the human lumbar vertebral body by stereo-binocular microscope revealed that the central region of the vertebrae might be the weakest part, whereas the upper and lower zones were relatively tough, especially in osteoporotic samples (Jayasinghe et al., 1994). In recent years, the use of high-resolution micro-CT imaging to assess trabecular and cortical bone morphology in spinal specimen has grown immensely as lumbar vertebral microstructure measurements are presented with more details (Bouxsein et al., 2010).

As described above, the upper and lower zones of the lumbar vertebra may have microstructures that are more robust. The present study is based on the hypothesis that this morphological feature of the lumbar vertebrae can be used to enhance the mechanical strength between the vertebrae and the implantation. Therefore, the study was designed to compare superior cortical screw (SCS), a new trajectory (its entry point located vertically 3 mm above Magerl's point) for posterior lumbar pedicle screws for osteoporotic patients, with traditional pedicle screw. The pullout strength was tested and vertebrae microstructures were measured, to assess the link between the mechanical performance and

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Table 1
Patient demographics and parameters. Lumbar segments varied from the first lumbar to the fourth lumbar segment. The values of BMD were measured using dual energy X-ray absorptiometry (DXA). T value ≤ −2.5 meets the standard of osteoporosis among Asians. Three specimens with T value > −2.5 were excluded.

Patient	Sex	Age (y/o)	Lumbar segment	BMD (g/cm^2)	*t* value
Patient 1	Male	68	Lumbar 1	0.688	−2.7
			Lumbar 3	0.761	−2.9
			Lumbar 4	0.742	−2.9
Patient 2	Male	78	Lumbar 1	0.65	−3
			Lumbar 2	0.71	−3.1
			Lumbar 3	0.783	−2.7
			Lumbar 4	0.682	−3.4
Patient 3	Male	80	Lumbar 2	0.745	−2.8
			Lumbar 3	0.744	−3
			Lumbar 4	0.773	−2.7
Patient 4	Male	82	Lumbar 1	0.698	−2.6
			Lumbar 2	0.788	−2.5
			Lumbar 4	0.78	−2.6

morphological status of the vertebrae.

2. Methods

2.1. Specimen preparation

Four formalin treated cadaveric lumbar spines (containing L1–L4 segments) were obtained from the Department of Anatomy at the Medical College of Zhejiang University. All specimens were inspected visually, using fluoroscopic imaging and computed tomography scanning to exclude the presence of a pre-existing fracture or compromised osseous integrity. Any samples with congenital spinal disorders, pars defects, or spinal tumors were excluded from the study. Bone mineral density (BMD) of the spines was measured using dual energy X-ray absorptiometry (DXA). Three spinal segments were excluded for failing to meet the standards of osteoporosis among Asians (Table 1). The soft-tissue was dissected from the specimens and the lumbar segments were separated from each other by transection through the intervertebral disc and facet joints. The remaining soft tissues, especially those around the pars and the pedicles, were then removed carefully (Fig. 1). All specimens were stored at −20 °C until further testing. Before micro-CT scan, screw placement, or biomechanical testing, the specimens were thawed for 4 h at room temperature. The screws of the TSRH (Texas Scottish Rite Hospital Instrumentation) system (Canwell, Zhejiang, China) were made of titanium alloy and were 5.5/6.0/6.5 mm in diameter and 45 mm in length.

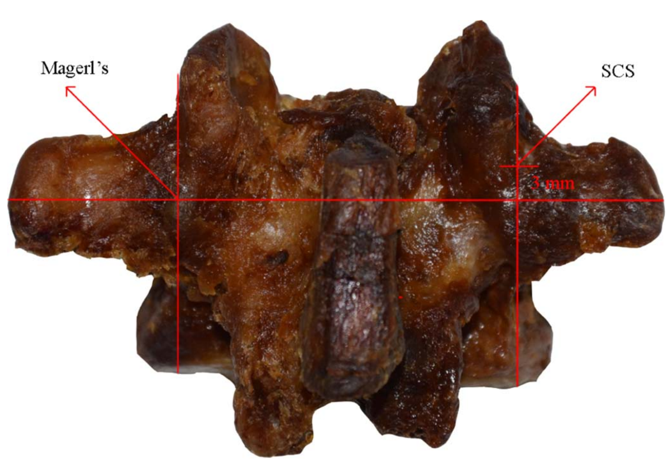

Fig. 1. The cadaveric spine specimen with bone landmarks visible in an anterior-posterior view (left for the Magerl method and right for the SCS).

2.2. Image acquisition

Thirteen vertebrae described above were scanned using micro-CT (microCT-100, Scnco Medical AG, Brüttisellen, Switzerland) before and after screw placement. During scanning, the vertebral body was fixed on a carbon bed, soaked in saline, with the specimen axis aligned with the rotation axis of the system. Scan settings: source voltage 90 kVp, current 200 μA, rotation step 0.5°, full rotation over 180°. The isotropic pixel size was 49.2 μm, and exposure time 0.30 s. Each vertebra was scanned in a consecutive, automated process, producing a series of projection images, with an inter-slice distance of one pixel (49.2 μm). Each projection was 1834 × 1834 pixels in size, and was saved as an 8 bit tiff file (420 KB each) (Fig. 2). The scans before the process of screw placement were performed in transverse sections (Fig. 2-A), covering the entire vertebral body. After the process of screw placement, each vertebra was scanned in coronal planes (Fig. 2-B, C), with screws included.

The cross-sectional images were reconstructed by VMS system (Xming and PuTTY_V0.63, Simon Tatham, Cambridge, UK) and saved as 32-bit TIFF files (476 KB each). Before screw placement, the region of interest (RoI) included both the pedicle and its corresponding vertebral body (only trabecular bone included). The trabecular bone of interest was contoured manually a few pixels inside the endocortical surface. The volume of interest (VoI) was constructed from a stack of RoIs. The VoI was then divided into 6 transverse layers from cranial to caudal, and recorded as the 1st layer (L1), the 2nd layer (L2), the 3rd layer (L3), the 4th layer (L4), the 5th layer (L5) and the 6th layer (L6), each approximately 2 mm in thickness (Fig. 3-A, B, C). Further, the pedicle volume of left or right part in a vertebra was calculated separately and then divided into 3 equal parts, namely the upper layer, the middle layer, and the lower layer (Fig. 3-D, E, and F). After the process of screw placement, the VoI was selected as the trabecular bone of 2 mm thickness encompassing the screw (Fig. 3-G, H).

2.3. Morphometric analysis

Before the screw placement, bone mineral density (BMD, HA/ccm), trabecular bone volume fraction (BV/TV, %), trabecular thickness (Tb.Th, μm), trabecular separation (Tb.Sp, μm) and trabecular number (Tb.N, 1/mm) of each layer were calculated, as described in detail by the guidelines for assessment of bone microstructure (Bouxsein et al., 2010).

After the process of screw placement, each vertebra in the Magerl and SCS groups were analyzed for BMD, BV/TV, Tb.Th, Tb.Sp, and Tb.N.

2.4. Screw technique

In thirteen cadaveric lumbar vertebrae, screws on the left side were inserted from Magerl's point, which is where the lateral border of the superior facet intersects with the mid portion of the transverse process. The entry point of screws on the right side was 3 mm vertically above the Magerl's point, namely superior cortical screw. Adequate screw size was determined by pre-surgery CT results. The screw sizes were identical on both sides of the same vertebra. All the screw placements were performed by a single experienced spinal surgeon with the help of intraoperative fluoroscopy.

Before screw insertion, the cortical bone overlying the entry point was removed with a rongeur to expose the underlying cancellous bone. Walls and floor of the hole were detected with a ball tip probe to determine the appropriate position of the drill. Anteroposterior and lateral fluoroscopy were performed when necessary. The pathway was parallel to the superior endplate of the vertebrae in the sagittal plane, and angled convergently from lateral to medial in the axial plane. Finally, pedicle screws were drilled into the vertebrae at the same depth, approximately 80% of the vertebrae body length. Fluoroscopy was used to