Spine Deformity

www.spine-deformity.org

Spine Deformity 2 (2014) 248–259

Biomechanics

The Benefits of Cement Augmentation of Pedicle Screw Fixation Are Increased in Osteoporotic Bone: A Finite Element Analysis

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Received 5 November 2013; revised 3 February 2014; accepted 17 March 2014

Abstract

Study Design: Biomechanical study using a finite element model of a normal and osteoporotic lumbar vertebrae comparing resistance with axial pullout and bending forces on polymethylmethacrylate-augmented and non-augmented pedicle screws.

Objective: To compare the effect of cement augmentation of pedicle screw fixation in normal and osteoporotic bone with 2 different techniques of cement delivery.

Summary of Background Data: Various clinical and biomechanical studies have addressed the benefits of cement augmentation of pedicle screws, but none have evaluated whether this effect is similar, magnified, or attenuated in osteoporotic bone compared with normal bone. In addition, no study has compared the biomechanical strength of augmented pedicle screws using cement delivery through the pedicle screw with delivery through a pilot hole.

Methods: This study was funded by a grant from DePuy Synthes Spine. Normal and osteoporotic lumbar vertebrae with pedicle screws were simulated. The models were tested for screw pullout strength with and without cement augmentation. Two methods of cement delivery were also tested. Both methods were tested using 1 and 2.5 cm^3 volume of cement infiltrated in normal and osteoporotic bone.

Results: The increase in screw pullout force was proportionally greater in osteoporotic bone with equivalent volumes of cement delivered. The researchers found that 1 and 2.5 cm^3 of cement infiltrated bone volume resulted in an increase in pullout force by about 50% and 120% in normal bone, and by about 64% and 156% in osteoporotic bone, respectively. The delivery method had only a minimal effect on pullout force when 2.5 cm^3 of cement was injected (<4% difference).

Conclusions: Cement augmentation increases the fixation strength of pedicle screws, and this effect is proportionately greater in osteoporotic bone. Cement delivery through fenestrated screws and delivery through a pilot hole result in comparable pullout strength at higher cement volumes.

Keywords: Finite element analysis; Osteoporosis; Pedicle screw; Cement; PMMA

Author disclosures: WW (grant from DePuy Synthes Spine); GRB (grant from DePuy Synthes Spine; consultancy for DePuy Synthes Spine and Globus Medical); HG (none); RRB (grant from DePuy Synthes Spine; consultancy for DePuy Synthes Spine, Orthocom, SpineGuard, Medtronic; payment for lectures including service on speakers bureaus from DePuy Synthes Spine; royalties from DePuy Synthes Spine, Medtronic; stock/stock options from SpineGuard, MiMedx, Orthocon, Orthobond); MM (grant from DePuy Synthes Spine); PJC (grant from DePuy Synthes Spine; consultancy for DePuy Synthes Spine and Medtronic; grants from DePuy Synthes Spine; payment for lectures including service on speakers bureaus from Medtronic; payment for manuscript preparation from DePuy Synthes Spine; payment for the development of educational presentations from Medtronic).

This study was funded by a grant from DePuy Synthes Spine.

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2212-134X/$ - see front matter © 2014 Scoliosis Research Society.
http://dx.doi.org/10.1016/j.jspd.2014.03.002

Introduction

Pedicle screws are subject to higher pullout forces intraoperatively than in other areas of spine surgery owing to corrective forces imparted to correct deformity. Several studies have shown the benefit of cement augmentation of pedicle screws. Frankel and colleagues [1] reported good perioperative safety in a series of 23 patients with a variety of diagnoses including pathologic fractures, tumors, and pseudarthroses.

Biomechanical evaluation of the effects of cement augmentation of screw fixation has been undertaken. Flahiff and colleagues [2] reported increased pullout strength in cement-augmented screws over non-augmented screws in a plastic long bone model. They also reported the effect of various cement consistencies (soft, doughy, and hard) on pullout strength.

No previous studies in cadavers or animals have been supplemented with finite element modeling. Cadaveric models are subject to degradation of the specimen during the experiment and variations in bone density from specimen to specimen, level to level, and side to side. Slight variations in implant positioning can grossly affect outcomes with pedicle screw testing. Furthermore, testing multiple variables in human specimens becomes exponentially time-consuming and expensive with each added variable. Finite element modeling allows the problems and variability that often affect human and animal models to be eliminated and/or controlled. Most rigorous biomechanical evaluations of new spinal implants and technology use a combination of biological and finite element model testing. Thus far, to our knowledge, a study on finite element modeling of the effect of cement augmentation on pedicle screw fixation has not been performed.

The use of polymethylmethacrylate (PMMA) bone cement to enhance screw fixation in bone has been documented since 1975 [3]. Polymethylmethacrylate cement augmentation of bone increases screw axial pullout strength [4], with up to a 200% increase reported and the mode of failure in axial pullout shifted from the implant–bone interface to cortical bone failure [5]. This technique is particularly useful for fixation in osteoporotic bone [6].

Surgeons typically inject amounts of cement ranging from 1.5 cm^3 [7,8] to 2–3 cm^3 [9]. Volumes as high as 4 cm^3 have been reported [5], even though the occasional spread of cement into the spinal canal could occur with large injected cement volumes [10]. One method of reducing the risk of cement extravasation in vertebroplasty is to increase cement viscosity. However, increasing cement viscosity is accompanied by an undesirable increase in injection pressure [11]. These 2 competing demands (ie, reducing injection pressure and reducing risk of cement leakage) may best be satisfied by changing technique or by making improvements in the dispensing/injection devices. One possible alternative cement delivery method is to inject cement through cannulated, fenestrated pedicle screws.

The purpose of this study was to assess the effect of PMMA cement augmentation on resistance to failure in axial pullout and bending for pedicle screws in normal and osteoporotic bone. The researchers also compared the results of cement augmentation through 2 delivery methods: 1 through the traditional approach and another through cannulated, fenestrated screws. Finite element modeling was used to examine techniques of cement augmentation and compare them with non-augmented screws.

Materials and Methods

Model setup and boundary conditions

A finite element model of the L4 vertebra was constructed using 3-dimensional, 4-node tetrahedral elements partitioned into cancellous and cortical bone as per anatomic guidelines and published data [12,13] with changes in cortical bone thickness owing to osteoporosis, as reported by Ritzel and colleagues [14]. The angle and level of screw insertion were modeled based on pedicle morphology data from Zindrick and colleagues [4] (Fig. 1). A titanium alloy screw was modeled using 3-dimensional, 4-node elements.

When cement is introduced through the pilot hole before screw placement, radiographs suggest that the area at the tip of the screw contains the most cement (evidence gleaned from radiographs in the practice of PJC) (Fig. 2). When cannulated, fenestrated screws were used, the cement appeared to be localized to a cylindrical area surrounding the screw, rather than being primarily associated with the screw tip [7,15]. Based on that appearance, the authors modeled 2 cement infiltration patterns: 1) infiltration predominant at the tip of the screw, in a spherical shape; and 2) infiltration evenly distributed in cylindrical zone parallel to the long axis of the screw and at the tip of the screw (Fig. 3). A portion of that cement lies within the fenestrated screw, and the remainder surrounds the screw. The sizes of the cement-infiltrated zones were computed assuming a total injected cement volume of 1.0 or 2.5 cm^3.

The actual cement infiltration zone (composite) size is slightly different in normal (porosity $\approx$ 80%) and osteoporotic bone (porosity $\approx$ 90%) [16]. All of the cylindrical-shaped cement volumes are assigned the same length of 20 mm, which is approximately the distance from the most proximal fenestrated hole to the screw tip. Table 1 lists the specific calculated infiltration zone dimensions.

The residual circumferential stress after screw insertion into a slightly undersized pilot hole was modeled via a screw expansion approach. A 6-mm screw was placed into a 6-mm hole and then expanded by 0.03% in volume. The expansion coefficient was adjusted so that the resulting circumferential stress was comparable to reported levels [17].

An additional residual stress occurs as a result of cement polymerization and thermal shrinkage (cooling from the approximately 80° C peak temperature owing to