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ORIGINAL ARTICLE

Cement stress predictions after anatomic total shoulder arthroplasty are correlated with preoperative glenoid bone quality

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Hypothesis: We hypothesized that biomechanical parameters typically associated with glenoid implant failure after anatomic total shoulder arthroplasty (aTSA) would be correlated with preoperative glenoid bone quality.
Methods: We developed an objective automated method to quantify preoperative glenoid bone quality in different volumes of interest (VOIs): cortical bone, subchondral cortical plate, subchondral bone after reaming, subchondral trabecular bone, and successive layers of trabecular bone. Average computed tomography (CT) numbers (in Hounsfield units [HU]) were measured in each VOI from preoperative CT scans. In parallel, we built patient-specific finite element models of simulated aTSAs to predict cement stress, bone-cement interfacial stress, and bone strain around the glenoid implant. CT measurements and finite element predictions were obtained for 20 patients undergoing aTSA for primary glenohumeral osteoarthritis. We tested all linear correlations between preoperative patient characteristics (age, sex, height, weight, glenoid bone quality) and biomechanical predictions (cement stress, bone-cement interfacial stress, bone strain).
Results: Average CT numbers gradually decreased from cortical (717 HU) to subchondral and trabecular (362 HU) bone. Peak cement stress (4-10 MPa) was located within the keel hole, above the keel, or behind the glenoid implant backside. Cement stress, bone-cement interfacial stress, and bone strain were strongly negatively correlated with preoperative glenoid bone quality, particularly in VOIs behind the implant backside (subchondral trabecular bone) but also in deeper trabecular VOIs.
Conclusion: Our numerical study suggests that preoperative glenoid bone quality is an important parameter to consider in aTSA, which may be associated with aseptic loosening of the glenoid implant. These initial results should now be confronted with clinical and radiologic outcomes.
Level of evidence: Basic Science Study; Computer Modeling

Keywords: Anatomic total shoulder arthroplasty; glenoid bone quality; computed tomography; cement; stress; finite element

Although anatomic total shoulder arthroplasty (aTSA) is an effective treatment for end-stage glenohumeral osteoarthritis,[38] aseptic loosening of the glenoid component remains one of the most common causes of failure.[12,19] Causes of glenoid loosening are multifactorial and include glenoid

This study was approved by the institutional ethics committee (protocol 136/15), with a waiver of informed consent.

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implant positioning, humeral head subluxation, and rotator cuff muscle degeneration.[14,16,29,30]

Preoperative glenoid bone quality and the extent of subchondral bone reaming are two other factors that should be taken into consideration when assessing the risk of glenoid implant loosening.[15,49] Subchondral bone reaming should be limited as much as possible to prevent weakening of the bone support while maintaining optimal glenoid implant alignment regarding the scapular axis.[46] Excessive cement stress can indeed be caused by asymmetrical implant loading or poor bone support. For cemented polyethylene glenoid components,[20,21] peak stresses within the cement mantle are assumed to induce cement damage, inflammatory reaction, and eventually, loosening at the bone-cement interface.[3,41] Besides, the stress and damage of the cement mantle depend on the underlying bone support.[18,28,36,43,51] Preoperative glenoid bone support is thus supposed to be a key prognostic factor for aTSA failure.

To our knowledge, there is currently no accurate and reproducible method for quantifying preoperative glenoid bone quality in routine aTSA planning. A few interesting methods to measure glenoid bone support from computed tomography (CT) data have recently been reported. Knowles et al[24] showed that osteoarthritic glenoids with symmetrical erosion patterns have uniform subarticular bone density whereas asymmetrical (type B2 glenoid) erosion patterns have potentially important regional variations in bone density and porosity. In another study, Simon et al[40] evaluated the distribution of glenoid subchondral bone density from preoperative CT scans in aTSA patients but did not correlate their findings with finite element (FE) cement stress predictions around the glenoid implant. Thus, there is still no established method to quantify the quality of the preoperative glenoid bone support, as well as its influence on periprosthetic cement and bone stresses.

Therefore, the primary objective of this work was to look for correlations between biomechanical parameters typically associated with glenoid implant failure after aTSA and preoperative glenoid bone quality. To test our hypothesis, we first developed an objective automated method to quantify glenoid bone quality from preoperative CT scans. To identify the relative importance of various glenoid regions, we defined several volumes of interest (VOIs) within the glenoid bone. We then correlated these quantitative CT measurements with patient-specific FE predictions of cement stress, bone-cement interfacial stress, and bone strain.

Materials and methods

Patients

Twenty patients (mean age, 71 years; range, 54-88 years) examined between June 2002 and July 2014 with shoulder CT scan as part of planning before aTSA were randomly selected from the institutional shoulder arthroplasty database. There were 13 women (mean age, 71 years; age range, 54-82 years; mean height, 162 cm; mean weight, 74 kg) and 7 men (mean age, 72 years; age range, 63-88 years; mean height, 176 cm; mean weight, 81 kg) matched for age ($P = .917$), weight ($P = .106$), and body mass index (BMI) ($P = .276$). Men were significantly taller than women ($P < .0001$). The inclusion criteria were primary glenohumeral osteoarthritis treated with aTSA and availability of preoperative nonarthrographic shoulder CT scans. The exclusion criteria were Walch type B2 and C glenoids. The following patient-specific quantitative morphologic parameters were obtained according to methods detailed elsewhere: Glenoid version and scapulohumeral subluxation were measured in 3 dimensions.[45,46] The average 3-dimensional (3D) amplitude of glenoid version was 9° (range, 1°-14°), whereas the average 3D amplitude of subluxation was 23% (range, 4%-50%). The 3D version and subluxation were both mainly posterosuperiorly oriented. Projected in a plane perpendicular to the scapular plane, the average 2-dimensional glenoid version was 2° of retroversion, ranging from 13° of retroversion to 11° of anteversion. The average glenoid radius was 33 mm (range, 21-44 mm). The degeneration ratio of rotator cuff muscles was quantitatively measured on a standardized sagittal-oblique CT slice.[44] The average degeneration ratio was 38%, with a maximum of 59% in the supraspinatus.

CT imaging protocol

All CT scans were performed using 8– or 64–detector row CT scanners (LightSpeed Ultra, LightSpeed VCT, and Discovery CT750 HD; GE Healthcare, Milwaukee, WI, USA) with the following standardized acquisition parameters: tube voltage, 120 kV (peak); tube current, 180-340 mA; and gantry rotation time, 0.5-0.8 seconds. The image reconstruction parameters were as follows: field of view, 16×16-26×26 cm (yielding in-plane voxel size of 0.31×0.31-0.51×0.51 mm); slice thickness, 0.6-1.3 mm; slice interval, 0.3-1 mm; and both smooth (standard) and sharp (bone) convolution kernels.

Total shoulder arthroplasty simulation

An aTSA was simulated in all cases. First, the scapula was segmented from CT images using a lower threshold value of 300 Hounsfield units (HU).[2,13] Subsequent removal of the humerus and clavicle, as well as glenoid osteophytes, was performed manually. These semi-automated segmentations were then verified by a musculoskeletal radiologist and a shoulder surgeon (with 7 years and 21 years of experience, respectively) in consensus and corrected if necessary. A 3D geometric model was subsequently built from each segmentation, and a glenoid implant (Aequalis PerFORM; Tornier, Bloomington, MN, USA) was virtually inserted into the model. This implant had a spherical backside and a keel. For each case, the size, backside radius, and positioning of the implant were evaluated and adjusted by the same shoulder surgeon, according to the manufacturer's recommendations. The glenoid implant was aligned within 5° of the mediolateral scapular axis, and minimum bone reaming was performed.[46] The head size of the humeral implant was chosen to best fit patient anatomy and respect the optimal radial mismatch recommended by the manufacturer. These virtual arthroplasties were carried out by use of computer-aided design software (SolidWorks; Dassault Systèmes, Vélizy-Villacoublay, France) and validated by the shoulder surgeon.