Finite Element Analysis of the Deformation Behavior and Fixation Stability of Newly Monolithic Ceramic Cups

Christian Schulze, Rainer Bader.
Orthopaedic Biomechanics Laboratory, Rostock, Germany.

Disclosures: C. Schulze: None. R. Bader: None.

Introduction: In the last decades press-fit fixation has become a common cementless fixation method for acetabular cups in total hip arthroplasty (THR) [1-3]. The usage of monolithic thin-walled acetabular components implicates several advantages owing to the surgical technique. One of the major benefits is the potential of conserving the acetabular bone stock while prosthetic heads with large diameters (> 32 mm) can be used. However, thin-walled acetabular cups tend to deform during insertion into the bone stock. Excessive cup deformation may increase micromotions at the bone-implant interface and compromise clearance and lubrication at the articulating surface [4]. Micromotions with an amount greater than 100 µm between the implant surface and the surrounding bone negatively affect bony ingrowth [5]. The missing of lubricant film between articulating surfaces results in increased wear. Cup deformation in combination with the occurring hip forces during gait cycle also increases frictional torques at the articulating surfaces [6]. Hence, the aim of the present numerical study is to characterize the deformation behavior of newly monolithic thin-walled ceramic acetabular cups during impaction into artificial bone cavities (cancellous bone model) and how implant deformation affects the radial clearance. Furthermore, primary stability of two different monolithic cup designs after press-fit fixation was numerically determined.

Methods: In present study the deformation behavior of newly monolithic press fit cups made of composite ceramics (ceramys®, ATZ-ceramic, Mathys Orthopädie GmbH, Mörsdorf, Germany) during the implantation process as well as the influence of the acetabular cavity on their press-fit fixation were investigated in static finite element analyses. Therefore, the intraoperative insertion (push-in) of two cup sizes (48/40 and 46/36) into cancellous bone substitute blocks and the fixation stability (push-out) was numerically simulated using the finite element software ABAQUUS/CAE (ABAQUUS, v6.12, Dassault Systèmes, Simulia, Providence, RI, USA). Two different cavity forms, i.e. hemispherical (HS) and hemispherical with cylindrical entry region (HCE), were modeled and three values of interference press fit (1.5 mm, 1.0 mm and 0.5 mm) were assumed for the generated cavities to consider intraoperative deviations of the reamed acetabular cavity. The load displacement behavior of the closed cell polyurethane foam blocks was modeled by combining linear elasticity (Young’s modulus = 0.284 GPa, Poisson ratio = 0.3 and Density p = 20 pcf) and crushable foam plasticity material model. For the ATZ-ceramic cups elasticity material model (Young’s modulus = 242.36 GPa and Poisson ratio = 0.25) was assumed and a porous titanium-coating on the outer cup surface was geometrically modeled as a solid layer with thickness of 0.3 mm. Contact behavior between cups and bone substitute cavities were described by normal and tangential contact formulation including penalty friction model (µ = 0.4). Displacement in x-direction of the polyurethane foam block was fixed at the bottom (BC1) (Figure 1a). The laterally fixation of the block (BC3) was realized on the basis of the experimental test setup and prevents displacement in z-direction. At four corner points at the bottom of the bone block
displacement boundary conditions (BC2) were applied to prevent displacements in y-direction (Figure 1). Only displacements in axial direction of the cup were approved (BC4). Rotation of the acetabular cup was prevented. The cup geometries were discretized by about 9,300 quadratic hexahedral elements whereas bone substitute blocks were discretized by about 9,000 quadratic hexahedral elements. Convergence analysis for the models was carried out. First static push-in simulation was performed whereby the acetabular cups were displacement-controlled pushed into the bone blocks until the cup overhang ascertained by the validation experiments which were conducted previously was reached. Thereby, radial displacements (deformations) and the push-in force (Fin) were recorded. Experimental validation of the model was performed by push-in tests of the ceramic cups. Simultaneously strain measurements were conducted. Four strain gauges (Type 1-LY17-3/120A, Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) were tangentially arranged every 90° about 4.75 mm under cup entry plane (MP1 to MP4) (Figure 1b). In all numerical static models displacements and strains were analyzed at four measuring points based on the experimentally arranged strain gauges. The strain values were compared to the experimentally measured strains for model validation. In the second simulation step the acetabular cups were displacement-controlled pushed out of the block geometries and the push-out force (Fout) was computed at the reference point of the monolithic ceramic cup to quantify primary fixation stability.

**Results:** The calculated data for deformation and strain at opposite measuring points were averaged and given as mean values with standard deviation for MP1+3 and MP2+4. Cup size 48/40 in combination with the HCE cavity form showed the highest radial cup deformations (2.47µm ±1.5E-05µm) in laterally fixed direction (MP2+4) at an interference press-fit of 1.5mm (Figure 2). The highest radial cup deflections (1.92µm ±1.5E-05µm) for cup size 44/36 were calculated at HCE cavity form at a press-fit of 1.5mm (Figure 2). Experimental validation showed deviation of approximately 211% between the measured and computed strains. However, the strains showed accordance by tendency. In general, the cavities with cylindrical entry region (HCE) showed higher push-out forces compared to the hemispherical (HS) cavities. The maximum push-out forces (1150N for 44/36 and 1027N for 48/40) were found for a cavity with cylindrical entry region and a press-fit of 1.5mm (Figure 2). A decrease in interference resulted in a decreasing push-out force.

**Discussion:** In comparison to the radial clearance of the articulating partners of about 50µm the calculated radial cup deflections can be considered as slightly and may not affect the lubrication of the articulating surfaces negatively. In contrast to the findings of Curtis et al. [8] press-fit interference between 1.5 mm and 1.0 mm seems to be appropriate to ensure a sufficient primary stability of the monolithic thin-walled ceramic cups while the radial cup deflections can be limited. The HCE cavity form allows improved primary fixation stability whereas required insertion force decreases. In contrast to the two point-clamping model showed by Jin et al. [4] the acetabular bone substitute was modeled as a uniform block. In further numerical simulations the dynamic impaction of the ceramic cups will be performed to increase the accordance between experimental test and numerical simulation.

**Significance:** The present numerical study provides relevant data for the deformation behavior of newly monolithic thin-walled ceramic acetabular cups during impaction into artificial bone cavity and their primary fixation stability. Hence, the impact of precise bone resection and implant alignment has to be considered during implantation of thin-walled ceramic cups.
Figure 1: a) Meshed cup block model with applied displacement boundary conditions. Boundary condition BC2 was applied to all corner points at the bottom of the block. At the upper rim of the acetabular cup boundary condition BC4 was applied to all the four depicted nodal points. b) MP1 to MP4 represent the position of the tangentially arranged strain gauges in the experimental validation set up.
Figure 2: Comparison of radial cup deformation after numerical simulation of cup push-in into hemispherical cavity with cylindrical entry (HCE) at three press fit values for cup size 44/36 and 48/40. The secondary axis shows the computed push-out forces for the HCE cavity form of both the cup sizes.