Introduction: The effectiveness of porosity reduction on the longevity of the cement mantle, and thus the lifetime of total hip arthroplasty (THA) reconstructions is subject to discussion. When studying patient cases, Ling and Lee did not find reduced survival rates for reconstructions with extreme porosity, and they concluded that porosity reduction is clinically irrelevant [1]. However, clinical studies such as the Swedish Hip Register suggest that vacuum mixing improves the overall survival rate of THA [2]. The belief that porosity reduction is beneficial is mostly based on findings of laboratory bench tests, showing that reduction of porosity distinctly increases the fatigue life of bone cement specimens [3,4]. Hence, there is a discrepancy between clinical and experimental findings. We hypothesize that these differences can be explained by differences in the stress situation created in test specimens and those found in the cement around THA implants. The stress state in a test specimen is typically homogeneous, in contrast to that around a real stem. The purpose of this study was to investigate whether the effect of porosity on failure of bone cement is dependent on the homogeneity of the local stress-state. Therefore, we analyzed the effect of porosity on the fatigue life of bone cement in a finite element (FE) model of an experimental test specimen and a model of a transverse slice of a real reconstruction with a sharp-cornered stem.

Methods: Fatigue failure of cement was simulated with an FE algorithm that simulates creep and damage accumulation [5]. It assumes that micro-cracks accumulate as a function of local stress levels and the number of loading cycles, eventually leading to rupture of the cement. The algorithm was applied to an FE model representing a specimen often used for fatigue testing of bone cement. Of this specimen, only the region of interest was modeled (Fig. 1a; width: 8 mm, thickness: 3.5 mm). Porosity was introduced into the model by setting the Young’s modulus of certain elements to virtually zero. Levels of two, four and nine volume-percent porosity were analyzed. For each level of porosity, three random pore distributions were modeled. Also a pore-free model and those found in the cement around THA implants. The stress state around femoral components has areas of relatively low stress variations alternated with areas of stress concentrations. We suggest that mechanical failure of cemented femoral components is governed by local stress intensities. Therefore, we analyzed the effect of porosity on the fatigue life of bone cement in a finite element (FE) model of an experimental test specimen and a model of a transverse slice of a real reconstruction with a sharp-cornered stem.

Results: In the fatigue test specimen model, the number of cycles to failure was clearly dependent on the level of porosity. In the pore-free model, failure did not occur until 800,000 cycles, while in the 9% porosity model the number of cycles to failure was more than four times smaller (Fig. 2a). The difference in the number of cycles to failure between the groups with different levels of porosity were all statistically significant (Student’s T-test, p<0.05). By introducing porosity into the model, the peak stresses in the cement mantle were more than 10 MPa higher than in the pore-free model, in which the peak stresses were equal to the global stress level of 15 MPa. Cracks were initiated at the pores in the models and grew from pore to pore. For the transverse slice model, the level of porosity and the pore distribution had virtually no effect on the length or direction of the crack that was formed in the cement mantle (Fig. 2b). After two million loading cycles, the crack length in all models was around 1.2 mm. Crack propagation was governed by a local stress intensity around the corners of the stem. Initial peak stresses were approximately 50 MPa. Porosity had a negligible effect on these peak stresses. No statistical differences of the final crack length could be found between the groups with different levels of porosity.

Discussion: In the current study, we investigated the effect of porosity on bone cement failure under different loading conditions. We were able to demonstrate that the effect of porosity on failure of bone cement is dependent on the local cement stress distribution. When stresses were distributed homogeneously in the cement, pores clearly acted as crack initiators, whereas under inhomogeneous stress conditions, crack formation was governed by local stress intensities. The stress situation around femoral components has areas of relatively low stress variations alternated with areas of stress concentrations. We suggest that mechanical failure of cemented femoral components is governed by the areas where stress concentrations are generated. This study shows that the effect of cement porosity reduction on the failure mechanism in these areas will be very limited and only clinically detectable in large studies such as the Scandinavian Registers. This explains why some studies suggest that cement porosity is clinically irrelevant, while experimental data show the contrary.

References: