Acta orthop. scand. *54*, 29–35, 1983

PERIACETABULAR STRESS DISTRIBUTIONS AFTER JOINT REPLACEMENT WITH SUBCHONDRAL BONE RETENTION*

D. R. Carter, R. Vasu & W. H. Harris*

Design Division, Mechanical Engineering Department, Stanford University, Stanford, CA, USA and Orthopaedic Research Laboratories, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA

Two-dimensional finite element stress analyses were conducted of the acetabular region after total joint replacement. The effect of subchondral bone retention was evaluated for both conventional and metal-backed acetabular components. Stresses in the bone, cement and acetabular cup were significantly reduced when subchondral bone was retained for both component types. The results indicate that the most favorable stress conditions are created when a metal-backed acetabular component is implanted with subchondral bone retention.

Key words: acetabulum; stress distributions; subchondral bone; total hip replacement

Accepted 27.vii.82

Failures of fixation of the acetabular component in total hip replacement (THR) are found with increasing frequency as longer patient follow-ups are obtained. At 12–15 years after implantation, Charnley (1979) reported that the incidence of acetabular component migration was 11 per cent and an additional 14 per cent of cases had "severe demarcation" at the bone/cement interface; meaning the presence of a continuous radiolucent line at the interface in the frontal projection. A retrospective study of the roentgenograms of cases resulting in severe migration suggests that demarcation increases progressively following implantation. Migration is commonly delayed in onset and is usually unrecognizable during the first 5 years. Characteristically, it becomes manifest with increasing frequency in the second and third 5-year periods after insertion (Charnley 1979).

To obtain better acetabular component fixation, some have advocated that the surgeon should retain as much subchondral bone as possible during socket preparation. Eftekhar & Pawluk (1980) conducted *in vitro* studies of mechanical factors associated with subchondral bone retention under torsional cup loading. They divided cadaver acetabulum specimens to be tested into two groups. In group I (non-reamed), subchondral bone was retained. Cartilage was scraped away and multiple fixation holes were drilled into the ilium, ischium and pubis. In group II (reamed), subchondral bone was removed and the acetabulum was deepened to provide complete intrusion of the cup into the acetabulum. Cement fixation holes were drilled into cancellous bone. After socket preparation, the acetabular components were cemented in place with acrylic bone cement. All socket preparations were then subjected to torsional loading to failure with a superimposed compressive force of 2113N (475 pounds). The torque was measured with respect to angular motion of the structure during loading. Cross-correlation of the results of 48 specimens using stiffness as a function of acetabular pre-

* Supported by NIH Grants AMA30510 and AM000960 and the William H. Harris Foundation.

paration demonstrated that specimens with the subchondral bone retained, exhibited greater torsional stiffness and strength than specimens with subchondral bone removed. They argued that retention of subchondral bone provides a better distribution of stresses, offers a greater resistance to torque for small angular displacements, and may reduce interface micromotion which can lead to late acetabular loosening.

The conclusions of Eftekhar & Pawluk are not inconsistent with those of Andersson et al. (1972) who also measured the response of acetabular components to torsional loading. These researchers suggested that surgical preparation of the acetabulum should include removal of all articular cartilage and cleaning of the acetabular fossa and cautioned against the removal of subchondral bone. Contrary to Eftekhar & Pawluk, however, they found that the drilling of cement holes in the acetabulum was relatively unimportant. The torsional tests of Volz & Wilson (1977) resulted in contradictory recommendations on the removal of subchondral bone. Volz & Wilson found that the greatest torsional strength of fixation was achieved when the subchondral bone was reamed, the cup was fully intruded, and anchoring holes for cement were used.

The previous studies mentioned were limited to loading which was torsional in nature. It is doubtful that acetabular loosening observed clinically can be primarily attributed to torsional loads (Andersson et al. 1972, Volz et al. 1977). The primary force acting on the acetabular component during normal activities is the compressive joint reaction force exerted by the head of the femoral component (Crowninshield et al. 1978). It is difficult to devise a meaningful experimental test of the influence of subchondral bone retention which incorporates this compressive loading condition at the hip joint. In this study, we have resorted to finite element stress analyses of the acetabular region. The analyses presented are extensions of the methods used in previous papers (Vasu et al. 1982, Carter et al. 1982). These previous studies showed that in the normal acetabulum before joint replacement, much of the stress at the roof of the acetabulum is transferred via the subchondral bone to the cortical shell of the medial and lateral walls of the ilium. The insertion of a polyethylene acetabular component after removal of the subchondral bone causes a significant alteration in the distribution of stresses. During single-limb stance, the polyethylene cup is pushed between the walls of the ilium causing high stresses in the cancellous bone, cement, and medial wall of the ilium. The addition of a metal-backing to the component helped to prevent cup penetration and markedly reduced the stresses in these critical areas.

The objective of the study reported here is to determine the stress distribution for the conventional and metal-backed acetabular components when subchondral bone is retained. The results are interpreted in light of the results of our previous models.

MATERIALS AND METHODS

During THR surgery, the acetabular articular cartilage is removed. However, the removal of subchondral bone is, under some circumstances, at the discretion of the surgeon. In socket preparation, multiple holes may be drilled into the cancellous bone to provide additional

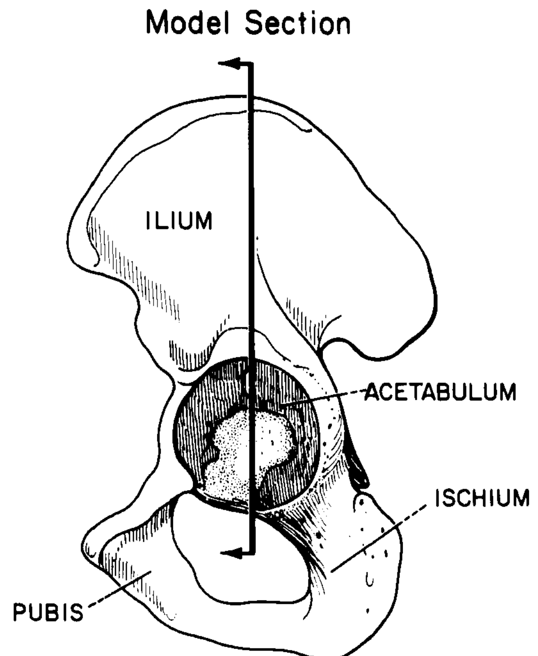

Figure 1. Illustration of the pelvis showing the orientation of the finite element model section (from Vasu et al. 1982).

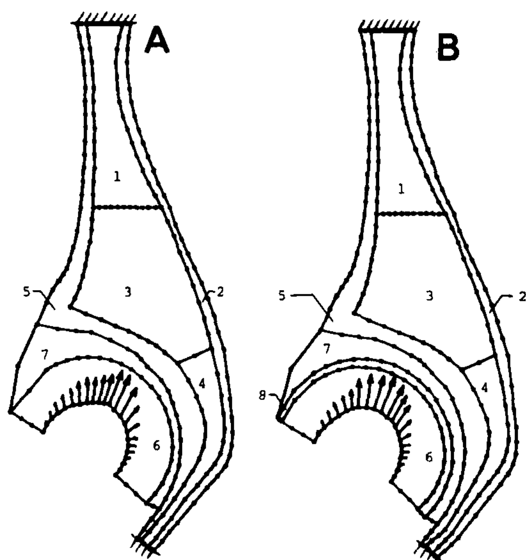

Figure 2. Diagrams of the geometry and loading conditions used in the (A) conventional, and (B) metal-backed models. The material propeties for each numbered region were as reported in Table 1.

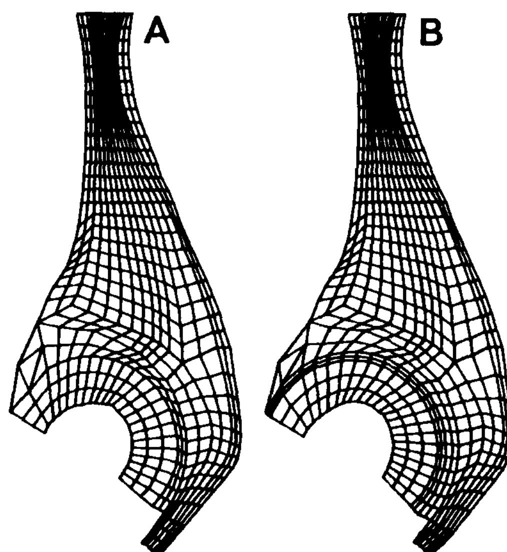

Figure 3. The element meshes used in (A) conventional, and (B) metal-backed models.

cement fixation. To generate our two-dimensional finite element models, we selected a plane of high loading by cutting a thin slice from a pelvis through the center of the dome of the acetabulum normal to the acetabular surface (Figure 1). To account for the bone material property distribution, the slice (with only cartilage removed) was divided into five discrete bony regions. In the model, a layer of acrylic bone cement was introduced and the acetabular components to be analyzed were then added (Figures 2A–B). A detailed description of the specimen preparation and techniques for estimating material properties in each bone region is provided by Vasu et al. (1982). The material properties used for each of the regions shown are documented in Table 1.

The two-dimensional plane strain finite element models that were analyzed consisted of the basic model slice with a layer of cement approximately 3 mm thick and the acetabular component, with or without a metal backing (Figures 2,3). No fixation holes were included since their representation in a two-dimensional model cannot adequately reflect their mechanical function. The analyses were conducted using a total hip resultant force of 89.9 N directed superior-medial at an angle of 21° from the vertical. The magnitude of this two-dimensional force resultant was selected to be consistent with the three-dimensional joint reaction pressure distribution created during the single-limb stance phase of gait (Vasu et al. 1982). The distribution of the hip force resultant in terms of nodal point loads is illustrated in

Table 1. Distribution of material properties

Region	Volume fraction V_f	Apparent density g/cm³	Yield stress S MPa	Modulus E MPa	Poisson's ratio
1-Bone	0.126	0.252	2.86	40	0.18
2-Bone	0.676	1.352	82.20	6188	0.326
3-Bone	0.260	0.52	12.17	352	0.22
4-Bone	0.3725	0.743	24.82	1025	0.247
5-Bone	0.676	1.352	82.2	6188	0.326
6-Polyethylene			22	500	0.4
7-Polymethylmethacrylate			25	2000	0.4
8-Chrome-cobalt alloy			690	2 000 000	0.29

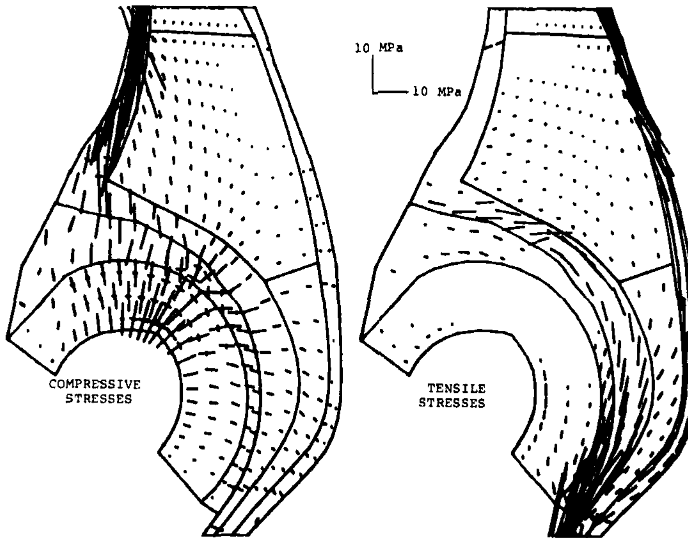

Figure 4. Principal stress distributions after conventional total hip replacement with subchondral bone retained.

Figures 2A and 2B. The model boundary conditions consisted of rigid support provided superiorly and inferiorly on the bone slice. Four-noded, isoparametric quadralateral and three-noded triangular elements were used exclusively. The model with the conventional acetabular component consisted of 938 nodes with 557 elements (Fig. 3A). The model with the metal-backed acetabular component consisted of 1012 nodes with 601 elements (Figure 3B).

RESULTS

The distribution of principal stresses calculated after insertion of the conventional and metal-backed component are shown in Figures 4 and 5 respectively. The mechanics of deformation were qualitatively similar for hip replacement with either component. The high stresses borne by the components and cement were transmitted primarily to the subchondral bone and the walls of the ilium. The stresses in the cancellous bone were relatively low regardless of the component being modelled. Superiorly, the ilium was exposed to a bending action such that the lateral wall was in compression and the medial wall was in tension.

The primary difference in the stress fields calculated for the two models relates to the greater efficiency of the metal backed component in transmitting stresses to the walls of the ilium while maintaining relatively low stresses in the cement and subchondral bone. In the conventional component model, biaxial tensile-compressive stresses are created in both the bone cement and subchondral bone (Figure 4). The tensile stresses are of particular concern due to the lower strength of bone cement and dense bone under tensile loading. The addition of a metal-backing to the component was effective in reducing the principal tensile stress in the subchondral bone and eliminating tensile stress in the superior and lateral areas of the bone cement layer (Figure 5).

In interpreting the distribution of stresses in Figures 4 and 5, one must be aware of the differences in strength in each of the materials being modelled. A strong material such as a Cr–Co alloy can withstand much higher streses than a weak material like cancellous bone. A critical parameter in assessing the severity of the local stress state is therefore the ratio of the local stress to the yield stress of the material being examined. To allow a preliminary look at the stress magnitudes relative to the yield stress in each material, we calculated the von Mises's effective stress at each element. The percent of yield stress based on these values and the assumed yield stress of each region (Table 1) were calculated using the von Mises's yield criterion (Vasu et al. 1982). The yield percentages are presented as contour plots in Figure 6. These plots dem-

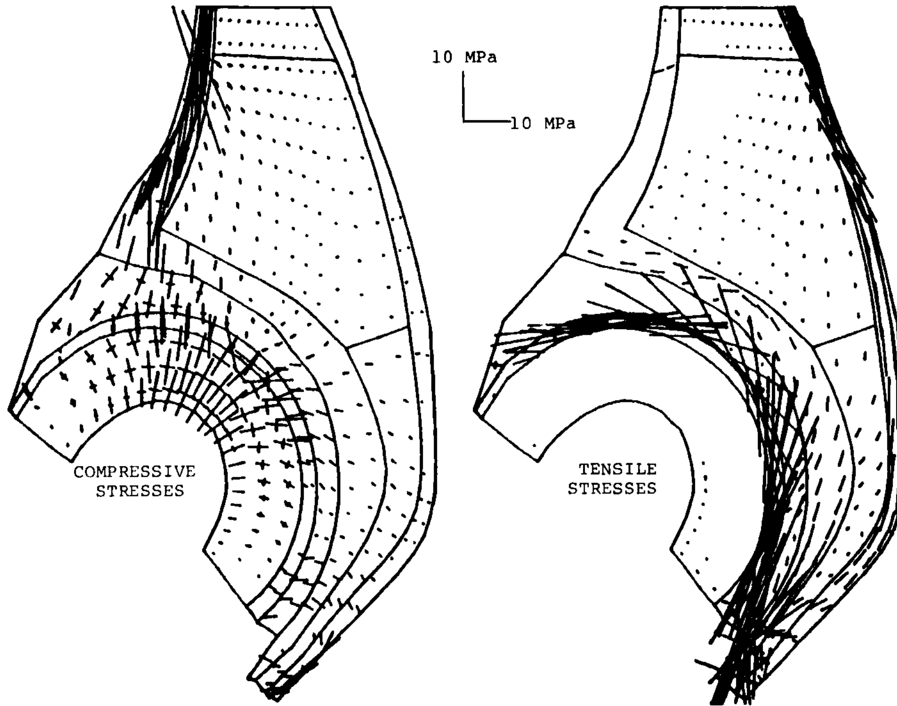

Figure 5. Principal stress distributions after total hip replacement using a metal-backed acetabular component with subchondral bone retained.

onstrate that for both models relatively low stresses are created in the subchondral and trabecular bone. The addition of the metal-backing, however, reduces these stresses further and also reduces the stress in the bone cement at the superior pole of the component.

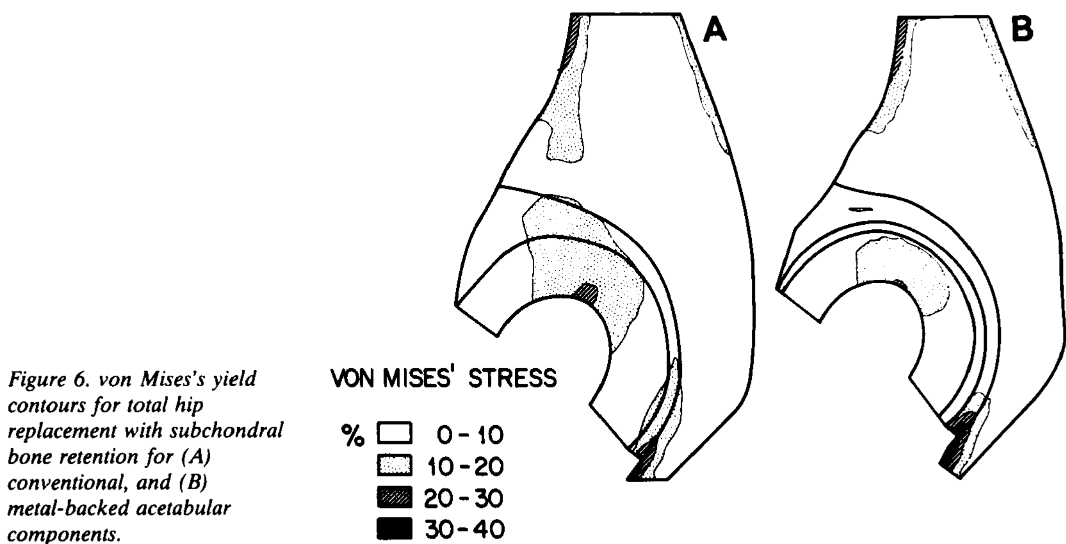

Figure 6. von Mises's yield contours for total hip replacement with subchondral bone retention for (A) conventional, and (B) metal-backed acetabular components.

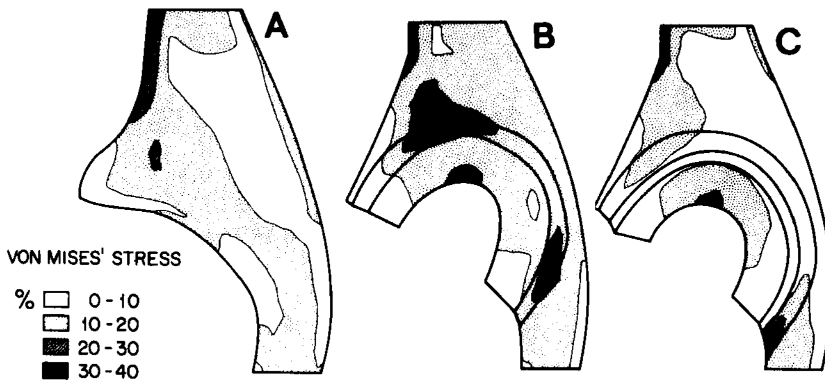

Figure 7. von Mises's yield contours for the (A) normal acetabulum (Vasu et al. 1982), (B) total hip replacement with a conventional component and subchondral bone removed (Vasu et al. 1982) and (C) total hip replacement with a metal-backed component and subchondral bone removed (Carter et al. 1982).

DISCUSSION

To appreciate the role of subchondral bone in the distribution of stresses after total hip replacement, one must compare the results of this study to those of our previous studies. Using similar finite element models we have previously shown that when a conventional component is inserted after removal of subchondral bone, the stresses in the superior pole cancellous bone and in the medial wall of the ilium are increased (Figure 7A, B). Significant tensile stresses are also created in the bone cement at the superior pole. The addition of a metal-backing significantly reduced the stress in these areas (Figure 7C).

If one compares the yield stress contours of the conventional component with and without the subchondral bone retained (Figures 6A, 7B), the advantages of subchondral bone retention are obvious. The bone, cement, and cup stresses are markedly reduced by retaining subchondral bone. When a metal-backed component is used (Figures 6B, 7C) it is also advantageous to retain the subchondral bone. However, subchondral bone retention does not appear to be as important with a metal-backed cup as with a conventional cup. In all of our joint replacement models it should be noted that there is a concentration of stress at the inferior lip of the component. We believe that this concentration is an artifact of our model since a two-dimensional model cannot adequately represent the out-of-plane stiffness and support provided by the pubis and ischium (Vasu et al. 1982).

Holm (1982) conducted photoelastic investigations of the stress fields in the os coxae under various loading conditions. The correlations between the principal stress trajectories and the cancellous bone orientation were noted. Holm argued that it would be desirable to have stress fields after prosthetic replacement to be similar to those prior to surgery. Our results indicate that by retaining subchondral bone, the principal stresses are essentially unchanged in orientation but slightly reduced in magnitude.

These studies have indicated that subchondral bone is important in transmitting stresses to the walls of the ilium and protecting the cancellous bone and bone cement from elevated stresses after total joint replacement. This finding is consistent with that of Pederson et al. (1981) and Van Syckle & Walker (1980) although their finite element models were considerably different from ours. The use of a metal-backed cup results in improved stress distributions. If it is necessary to remove the subchondral bone to obtain adequate seating of the component, the use of a metal-backed component is strongly advised. The metal-backing provides a greatly increased component stiffness and effectively acts as a surrogate subchondral plate in protecting the bone cement and cancellous bone from elevated stresses.

REFERENCES

Andersson, G. B. J., Freeman, M. A. R. & Swanson, S. A. V. (1972) Loosening of the cemented acetabular cup in total hip replacement. *J. Bone Joint Surg.* **54-B,** 590.

Carter, D. R., Vasu, R. & Harris, W. H. (1982) Stress distributions in the acetabular region. II. Effects of cement thickness and metal-backing of the total hip replacement. *J. Biomech.* **15**, 165–170.

Charnley, J. (1979) *Low Friction Arthroplasty of the Hip.* Springer, New York.

Crowninshield, R. D., Johnston, R. C., Andrews, J. G. & Brand, R. A. (1978) A biomechanical investigation of the human hip. *J. Biomech.* **11**, 75–85.

Eftekhar, N. S. & Pawluk, R. J. (1980) Role of surgical preparation in acetabular cup fixation. In: *The Hip, Proceedings of the Eighth Open Scientific Meeting of the Hip Society.* pp. 308–328. C. V. Mosby, New York.

Holm, N. J. (1980) The development of a two-dimensional stress-optical model of the os coxae. *Acta Orthop. Scand.* **52**, 135–143.

Pedersen, D. R., Crowninshield, R. D. & Brand, R. A. (1981) An analysis of acetabular component design. *Trans. Orthop. Res. Soc.* **6**, 71.

Van Syckle, P. B. & Walker, P. S. (1980) Parametric analysis of design criteria for acetabular components of surface replacement hip devices. *Trans. Orthop. Res. Soc.* **5**, 292.

Vasu, R., Carter, D. R. & Harris, W. H. (1982) Stress distributions in the acetabular region. I. Before and after total joint replacement. *J. Biomech.* **15**, 155–164.

Volz, R. G. & Wilson, R. J. (1977) Factors affecting the mechanical stability of the cemented acetabular component in total hip replacement. *J. Bone Joint Surg.* **59-A,** 501–504.

Correspondence to: Dennis R. Carter, Ph.D., Design Division, Mechanical Engineering Departement, Stanford University, Stanford, CA 94305, USA.