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Prestresses Around the Acetabulum Generated by Screwed Cups

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Abstract: Screwed acetabular cups, applied in total hip replacements, generate stresses in the surrounding bone during implantation (prestresses). The effect of these prestresses on the endurance of the hip replacement are unknown. The prestresses in the acetabulum were examined both experimentally, using strain gauge techniques, and numerically, using the finite element method. It was found that the prestresses were of the same order of magnitude, if not larger, than the stresses due to the hip reaction force during one-legged stance. In some cases, the prestresses even approximated the ultimate tensile strength of cortical bone. The prestresses seemed to have a strong dependence on the outer shape of the cup, rather than on the flexibility of the cup or whether the cup had a self-cutting thread or not. Furthermore, it was found that the prestresses are not very susceptible to stress relaxation due to the visco-elastic behaviour of bone. This means that prestresses will remain present over long periods of time. So even when a patient has resumed normal daily activities, the prestresses will still play an important role in the overall stress distributions around the acetabulum. Due to the interaction of prestresses and stresses due to normal loading, the primary stability of a metal-backed screwed cup is better guaranteed than the primary stability of an all-polyethylene screwed cup.

INTRODUCTION

As cemented acetabular components proved to be less successful than their femoral counterparts,^{1–5} several cementless fixation techniques were developed, one of which is the screwed cup.^{6–8} Screwed acetabular cups are designed to generate stresses in the surrounding bone upon insertion to guarantee a good initial stability.⁹ Depending on the actual design of the cup, secondary stability may be realized by different principles, like the fit of the screw thread in the surrounding bone or bone ingrowth, but generating initial stresses or prestresses, as they are called, is inherent for all types of screwed cups. In stress analyses of screwed cups reported,^{10,11} these prestresses were not con-

sidered, simply because hardly anything was known about them. Yet, if the magnitudes of these prestresses are substantial, their presence may greatly influence the stress patterns during physiological loading and may even lead to fractures in the bone. The purpose of this study was to obtain more information about the magnitudes and distributions of these prestresses and to examine how they interact with the stresses due to normal loading of the hip.

The study consisted of both in vitro strain gauge experiments and finite element analyses. The types of screw cups used in this study were a solid polyethylene (PE) cup, requiring pre-tapping of the thread, and a metal-backed (MB) cup with self-cutting thread. Owing to these differences, the possible effects of the cup's flexibility and the type of thread on the prestresses could be examined as well. The cups were implanted in acetabula of

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Fig. 1. The locations of the six rosette strain gauges, projected on a left hemipelvis.

several cadaver pelvic bones and strains were recorded during insertion and subsequent loading in a materials testing machine, simulating the hip joint force. As strain gauges can only measure strains on the surface, the finite element method (FEM) was used to study the stress patterns within the bone around the acetabulum.

MATERIALS AND METHODS

Strain gauge experiments

Six embalmed hemipelves were available for the experiments. They were mounted upside down in a block of acrylic bone cement with the iliac wing submerged. Each bone was fitted with six rectangular rosette strain gauges. Three of these gauges were placed on the posterior acetabular rim, one on the anterior side of the rim and two on the medial cortex, just underneath the acetabulum. The locations of the gauges are shown in Fig. 1.

Two types of cups were used. The first one was a

pre-tapped solid polyethylene cup (Endler), the second was a self-cutting titanium-backed cup with a polyethylene liner (Zweymüller). On the outside, both cups had identical trapezoidal taper shapes. Each type of cup was implanted in three hemipelves. Before insertion, each acetabulum was prepared according to the manufacturer's guidelines (Allo Pro AG, Baar, Switzerland). For screwing the cup into the acetabulum, a torque wrench was used in order to have good control over the insertion torque. The strains in the gauges were measured at torques of 10, 20 and 30 Nm and beyond this value at every increment of 5 Nm. This continued until the cup was judged to have the right fit. From the measured strains, the principal stresses were calculated, assuming a Young's modulus of 17.0 GPa,¹² and a Poisson's ratio of 0.3 for the cortical bone. The hemipelves were left untouched after the final torque was applied and strains were measured again after 50 and 100 min to see if any stress relaxation had occurred in the bone.

After inserting the cups, the hemipelves were mounted in an MTS-based loading machine (DSTS Engineering & Electronics, Zoetermeer, The Netherlands) and a force was applied to the cup, simulating the hip reaction force during the one-legged stance phase, when the hip reaction force reaches its maximal magnitude of about 3.5 to 5 times bodyweight.¹³ At each increment of 500 N up to 2500 N, the strains in the gauges were recorded and again the corresponding principal stresses were calculated.

FEM analyses

An axisymmetric finite element model was used. The mesh is shown in Fig. 2 and in Table 1 the

Fig. 2. The FE mesh (right) with the regions of the different materials (left).

Table 1. Materials and their Young's moduli, used in the FE model

Region	Material	Young's modulus (GPa)
1	cortical bone	17.0
2	cancellous bone	3.0
3	cancellous bone	1.5
4	cancellous bone	1.0
5	polyethylene	0.7
6(PE)	polyethylene	0.7
6(MB)	titanium	110.0
7(PE)	screw thread/bone	11.0
7(MB)	screw thread/bone	32.0

Young's moduli of the various materials are given. All materials were assumed to be linear elastic, homogeneous and isotropic, with the distribution of the bone elastic constants according to Pedersen and coworkers.¹⁴ The elements used in the analyses are axisymmetric with quadrilateral cross section and eight nodal points (isoparametric quadratic displacement). For the loads, an external hip contact stress distribution was directly prescribed as a distributed load over the inner cup boundary over a globular region measuring 60 degrees across. Towards the edges the magnitude of the distributed load decreased to half of its value in the centre. Because the FE model can only simulate static or quasi-static loading, the actual process of inserting the cup could not be modelled directly. Therefore, to simulate the generation of the prestresses, the elements constituting the cup were expanded by using the thermal expansion procedure of the FE code (MARC, MARC Analysis

Corporation, Palo Alto, CA, USA). The surrounding bone deformed by this increase of volume in a similar manner to if a cup was inserted and the stresses thus generated represent the prestresses. To be assured of a resulting stress pattern in the bone with a good resemblance to the actual stress patterns in the experiments, several calculations were performed for both types of cup, each time varying a group of elements involved in the expansion procedure. Then two points in the mesh were chosen; the first one corresponding to the locations of gauges 1 or 4, the second one to the locations of gauges 5 or 6. In the analysis, the ratio of the total shear strains, occurring in these points was calculated and compared to the same ratio as found in the experiments. Only the analysis which compared best to the actual ratio was considered further. For this particular analysis, scaling was applied, such that the total shear strain in the point on the lateral cortex equalled the average value of the total shear strain at the gauge locations 1 and 4 in the experiments.

RESULTS

Strain gauge experiments

Due to individual differences in bone quality of the cadaver hemipelves used in the experiments, there was a large scatter in the values of the strains and the applied torque needed to insert the cups. Yet some consistent differences between the insertion

Fig. 3. Average principal strains at the strain gauge locations, due to inserting a PE cup.

Fig. 4. Average principal strains at the strain gauge locations, due to inserting a MB cup.

of the polyethylene (PE) and the metal-backed (MB) cups could be observed. The maximal torque needed to screw the cup into the acetabulum was significantly higher for the MB cups. The mean value, averaged over the three pelvic bones, was 51.3 Nm with a standard deviation of 12.3 Nm. For the PE cups these values were 29.0 Nm and 5.9 Nm, respectively. This difference can be explained by the fact that the MB cup has a self-cutting thread and thus has to overcome much more resistance than the PE cup, for which the thread has already been cut in the preparation phase.

A positive correlation was found between the magnitude of the torque applied and the values of the strains measured in each case. The torque-strain relationships showed considerable variations, even in the same series of implants, probably due to interspecimen variations. However, the strain values

at maximal torque were qualitatively very similar, regardless of the type of implant inserted. In Figs 3 and 4, the principal strains, averaged over the three bones, are graphically displayed. For this purpose, the magnitudes and the directions of these principal strains have been averaged separately to ensure that the average maximal and average minimal principal strains remain perpendicular to one another.

In Table 2, the accompanying values for the principal and the Von Mises stresses at the individual gauge locations are given for each type of cup, averaged over the three pelvis. The Von Mises stresses can be seen as a measure for the stress intensity. Despite large standard deviations, it is evident that for both types of cup, the gauges 1 and 4 are the most highly strained and gauges 3 and 5 the least. Furthermore, it was observed that

Table 2. Average values and the standard deviations (in brackets) of the principal stresses and the Von Mises stresses (in MPa) at the individual gauges for both PE and MB cups for maximal applied torque

Gauge	$\sigma_{max} PE$	$\sigma_{min} PE$	$\sigma_{Mss} PE$	$\sigma_{max} MB$	$\sigma_{min} MB$	$\sigma_{Mss} MB$
1	14.9 (10.9)	-63.9 (24.4)	73.6 (16.8)	33.4 (29.3)	-20.4 (16.3)	51.3 (21.1)
2	16.5 (10.1)	-22.1 (5.3)	34.2 (7.1)	6.1 (9.8)	-43.5 (31.9)	48.1 (30.4)
3	5.8 (2.5)	-6.2 (2.7)	10.6 (2.5)	22.0 (27.3)	2.8 (20.7)	27.0 (18.1)
4	35.8 (28.1)	-44.5 (26.4)	74.0 (15.7)	14.4 (28.2)	-41.6 (10.5)	54.7 (14.7)
5	4.2 (3.1)	-10.9 (10.1)	14.3 (7.8)	2.5 (0.5)	-21.5 (8.8)	22.9 (8.5)
6	43.7 (11.4)	14.9 (10.0)	39.0 (8.8)	36.3 (7.9)	5.3 (14.2)	35.9 (5.9)

Table 3. Average values and standard deviations (in brackets) of the principal stresses and the Von Mises stresses (in MPa) at the individual gauges for both PE and MB cups for a load of 2500 N

Gauge	σ_{max} PE	σ_{min} PE	σ_{Mss} PE	σ_{max} MB	σ_{min} MB	σ_{Mss} MB
1	14.8 (0.9)	-27.3 (2.6)	37.0 (1.8)	12.4 (9.9)	-10.4 (12.0)	22.6 (5.7)
2	11.0 (6.9)	-23.5 (7.9)	31.4 (2.3)	4.7 (5.4)	-7.7 (7.3)	12.6 (2.7)
3	15.0 (10.3)	-16.9 (15.7)	30.5 (4.7)	22.1 (5.6)	-10.0 (19.4)	31.7 (12.9)
4	5.8 (6.2)	-12.0 (1.0)	16.5 (3.3)	27.3 (9.4)	4.0 (6.0)	25.9 (8.3)
5	61.3 (37.9)	7.5 (7.7)	58.0 (34.5)	22.8 (14.7)	3.1 (5.4)	21.7 (12.7)
6	0.7 (19.8)	-44.2 (15.7)	47.8 (5.2)	3.5 (1.5)	-20.4 (10.4)	22.5 (10.0)

for the gauges on the acetabular rim, tension occurred circumferential to the rim and compression perpendicular to it. On the medial cortex tension occurred more or less in the direction of the foramen obturatum and again compression perpendicular to it. This deformation mode shows that the cups are acting as wedges, trying to force the acetabulum open by hinging it around an axis from the ilium to the incisura acetabuli.

Due to the visco-elastic behaviour of bone, the strains and stresses, caused by inserting a cup, will reduce after a while. To estimate the order of magnitude of this relaxation, the Von Mises stresses were considered just after insertion, and 50 and 100 min later. The maximal decrease in value that occurred was 6.5% after 50 min and 8.0% after 100 min. If an exponential function is assumed to describe this relaxation process in time, it can be calculated that the Von Mises stresses will never drop below 91.5% of their original values. This means that the major parts of the prestresses remain, even after an infinitely long period of time, assuming of course that no biological relaxation effect, like bone remodelling, takes place.

After inserting the cups, the pelvic bones were placed in a testing machine to simulate the hip reaction force. As should be expected, linear relations between the stresses and the load magnitude were observed, but due to the intraspecimen variations the magnitudes of the stresses again varied from case to case.

In Table 3, the principal and the Von Mises stress values at the individual gauge locations are given at the maximal load value, averaged over the three pelvis. Compared to the values during insertion (Table 2), the standard deviations were smaller,

suggesting a more uniform response of the bone to this kind of loading. It was observed for the gauges on the acetabular rim that the average direction of tension had shifted about 90 degrees relative to the one during insertion of the cup. So now compression occurred more or less circumferential to the rim, except for the gauges 2 and 4 in the case of a PE cup, where tension remained circumferential. This shift of 90 degrees causes the tensile stresses due to inserting the cup to be somewhat neutralized by the compressive stresses due to loading and vice versa, when the two loading situations are superimposed. The direction of the principal stresses in the medial cortex is less clear. For the PE cups, the direction of tension was pointing towards the ischial bone and for the MB cups the direction of tension was pointing towards the foramen obturatum at gauge 6 and perpendicular to this at gauge 5.

The results of superpositioning the two loading cases (Tables 2 and 3), are summarized in Table 4. Comparing the ranges of the principal stresses during insertion (Table 2) to those after insertion with a physiological load (Table 4), it appears that for the MB cups the combined range is for the greater part based on the prestresses and only slightly enlarged by the stresses due to loading. For the PE cups, the high tensile stresses due to loading are tempered by the prestresses, while for compression the stress peaks of inserting and loading seem to add up.

FEM analyses

As already shown in Figs 3 and 4, a prominent component of the prestresses around the acetabulum are the hoop stresses, which, because of the

Table 4. Average values and standard deviations (in brackets) of the principal stresses and the Von Mises stresses (in MPa) at the individual gauges for both PE and MB cups in the combined load case

Gauge	σ_{max} PE	σ_{min} PE	σ_{Mss} PE	σ_{max} MB	σ_{min} MB	σ_{Mss} MB
1	5.9 (4.7)	-67.5 (34.2)	71.0 (31.3)	33.5 (26.6)	-17.8 (9.7)	45.9 (29.8)
2	-0.7 (0.2)	-13.9 (0.8)	13.6 (0.7)	9.5 (3.8)	-48.5 (37.1)	54.3 (35.7)
3	16.4 (12.3)	-21.2 (10.2)	34.6 (0.9)	42.5 (32.9)	-7.0 (40.2)	56.6 (21.0)
4	9.0 (16.5)	-51.7 (32.9)	59.8 (21.4)	38.9 (23.5)	-35.6 (6.6)	65.7 (20.2)
5	49.3 (25.2)	7.9 (6.9)	46.0 (22.3)	12.6 (9.3)	-5.4 (11.8)	18.3 (8.5)
6	24.9 (15.8)	-9.5 (1.5)	31.0 (16.1)	26.0 (12.1)	-1.3 (9.0)	27.5 (13.8)

stretching of the acetabular rim, are tensile by nature. Figure 5 shows the values of this stress component in the bone for both types of cup from the FE analyses simulating the insertion of the cup. Because of symmetry, only half of the meshes are shown. In accordance with the experimental findings, the distributions of this stress component are very similar for both types of cup. In the acetabular rim and at the medial cortex, right underneath the cups' domes, the highest values occur and these stresses are indeed tensile. In fact, all along the cup/bone interface, hoop stresses are tensile. In Fig. 6, the hoop stresses and the other stress components are combined in the Von Mises stress. Like the hoop stresses, the Von Mises stress distributions are also very similar for both types of cups. High stresses occur particularly in the bone directly around the cups and in the cortical shells.

When subject only to external loading, the major part of the load is transferred straight through the

dome of the cup onto the medial cortex for both MB and PE cups. Due to the stiff backing, however, the MB cup is able to direct a small part of the load to the lateral cortex, while for the PE cup, the lateral cortex is hardly loaded at all. The Von Mises stress patterns resulting from the hip joint force only, without prestresses, are shown in Fig. 7. Unlike in the experiments, the stresses due to hip joint loading are now much smaller than the prestresses. Because of this, the prestress patterns seem hardly affected by the hip reaction force when both loading modes are combined. The resulting Von Mises stress distributions are shown in Fig. 8. For both cups, a slight attenuation in the medial cortex is observed, but the high prestresses around the implant remain fully present. The combination of prestresses and stresses due to loading resulted in a decrease of the (tensile) hoop stresses and an increase in the (compressive) parallel stresses in the acetabular rim for

Fig. 5. Tensile hoop stress distributions, due to inserting the cup, for both MB and PE cups (white areas denote compressive hoop stresses).

Fig. 6. Von Mises stress distributions, due to inserting the cup, for both MB and PE cups.

Fig. 7. Von Mises stress distributions, due to the hip reaction force, for both MB and PE cups.

Fig. 8. Von Mises stress distributions in the combined case for both MB and PE cups.

both types of cup. The decrease in the hoop stress for the PE cup, however, was somewhat larger than for the MB cup.

DISCUSSION

Screwed acetabular cups obtain a press-fitted primary fixation by generating prestresses in the surrounding bone upon insertion. Hardly any quantitative data on these prestresses were available. The present study was performed to provide quantitative information about prestresses and to analyse the interaction of these prestresses with the stresses due to normal loading. For this purpose two different types of acetabular cup were selected in order to study the effects of the cup flexibility characteristics and the type of screw thread on the prestresses, as well.

Strain measurements during insertion of both the metal-backed (MB) and the solid polyethylene (PE) cups in cadaver pelvic bones revealed peak values of about 5000 μ strain (both tensile and compressive). The values of the corresponding stresses were about the same for both cups (Table 2), suggesting that the prestresses are not so much dependent on either the cup's flexibility or the method of implantation (pre-tapped or self-cutting thread). In some cases, these prestresses were even of the same order of magnitude as the ultimate tensile strength of human compact bone.¹⁵ This means that cracks in the acetabular rim might easily occur, so it requires both care and experience on behalf of the orthopaedic surgeon to decide whether he can tighten the cup a bit more or not. He should also pay attention to the bone quality around the acetabulum, for we found in our experiments a large intraspecimen variation, which will surely also show up in the reality of an operating room. This variety in bone quality has a great influence on the magnitude of the prestresses and thus makes them somewhat unpredictable. Despite these variations, however, the MB and PE cups showed the same trend in the prestress patterns they generated in the surrounding bone. At the strain gauge locations 1–4, tensile stresses occurred circumferentially and compressive stresses were found perpendicular to this. The compressive stresses tended to be somewhat larger in magnitude than the tensile stresses. These locations were also shown to have the highest stresses in an absolute sense. In the bone underneath the acetabulum (locations 5 and 6), tensile stresses occurred in the

direction of the foramen obturatum and the pubic bone with compressive stresses perpendicular to this. These stresses suggest a deformation mode in which the acetabulum is 'hinged open' along a line perpendicular to the foramen obturatum. This is caused by a structural weakening of the acetabular wall by the incisura acetabuli.

Measurements show that some degree of relaxation of the prestresses occurs during the first few hours after implantation, due to visco-elastic effects. However, they remain at about 90% of their initial value over a long period of time. These measurements were performed using embalmed bone material, so it may well be that for fresh bone the results would be different. Adaptive bone remodelling will certainly also affect these stresses *in vivo*. As the prestresses constitute an unphysiological loading, the affected bone will remodel in such a way that these stresses are reduced. This effect, however, was not further evaluated in this study.

During loading of the pelvic bones in the testing machine, the stresses in the bones implanted with PE cups were almost twice as high as the stresses in the bones implanted with MB cups. This is caused by the deformation restraints which the metal backing imposes on the underlying bone. The stresses were of the same order of magnitude as the prestresses, suggesting that the prestresses are quite substantial in relation to the stresses due to normal activities. However, the presence of prestresses does not necessarily mean that the bone will be stressed additionally; theoretically, both stress states can level each other out. This all depends on the direction and magnitude of the principal stresses. When there is no or only a minor shift in the directions of the maximal principal stresses as a result of the insertion and due to physiological loading, the stresses will amplify each other. However, if that shift is about 90 degrees, then compressive and tensile stresses will be neutralized. In our experiments, a decrease in the overall stress level in the acetabular rim was observed in the case of a PE cup, while with a MB cup the stresses increased around the acetabulum.

Because the strain gauge experiments can give only information about the strains and stresses on the outside of the bone, numerical simulations (FEM) of these experiments were made to obtain data on the stresses within the bone. FE analyses of the pelvic bone have been reported by several authors. For modelling the acetabular region, there are three basic possibilities: two-dimensional (2-D) models,^{16–18} semi 3-D axisymmetric models,^{10, 11, 14, 19}

and 3-D models.²⁰⁻²² Unlike finite element models of the femoral reconstruction,²³ however, the similarity between 2-D, axisymmetric and 3-D pelvic models of acetabular reconstruction is not very good. Obviously, a 3-D model has the best potential to produce the most realistic results. A 2-D model tends to underestimate the real acetabular stiffness, because it takes no account of the out-of-plane part of the acetabular wall. Therefore, stresses calculated from a 2-D pelvic model are usually too high. Conversely, an axisymmetric model tends to overestimate the real stiffness. This means that 2-D and axisymmetric pelvic models should, therefore, rather be interpreted in a qualitative sense.

The same trends in the experimental findings were also found in the FE analyses. As far as the prestresses are concerned, both types of cup generated similar stress patterns. The stresses due to the hip joint force showed a difference in the load transfer characteristics between a metal-backed and a non-backed cup. The metal backing seems to take over the mechanically important role of the subchondral bone,^{2,24} and spreads the load transfer from cup to bone more evenly along the interface. In 3-D FE analyses, however, it appears that this results in a concentrated load transfer along the acetabular rim.²² The present FE analyses confirmed the experimental finding that the interaction of prestresses and stresses due to normal loading leads to a decrease of the stresses in the acetabular wall when PE cups are used. In particular, the tensile hoop stress, which is the 'containing' component for the cup, decreases. This suggests that the primary stability of all-polyethylene screwed cups may suffer more relative to metal-backed screwed cups once normal loading is resumed. At the end of the eighties use of the all-polyethylene Endler cup led to a high number of loosening, in fact so many that further production of the cup was stopped.²⁵ Apparently, the cups had suffered badly from micromotions, because upon revision the polyethylene which had been in contact with bone showed much wear. Load transfer predominantly takes place in the first and last screwthread,¹⁰ resulting in high stress concentrations locally at the interface between cup and bone. Gross migrations, following from disruption of this interface, are not an unfamiliar problem for fully-threaded cups.²⁶ Early loss of initial stability, as this study has demonstrated, may have accelerated the process of loosening, leading to the dramatic performance of the Endler cup.

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