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Bone remodelling after total hip arthroplasty

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Bone remodelling of the proximal femur following total hip arthroplasty (THA) is related to stress deviation with respect to physiological condition. The clinical relevance of this process is much debated with respect to its role in THA failure. In the present study a group of 475 An.C.A. anatomic cementless stems implanted in our institution were assumed as clinical reference. Of them, 294 had a short stem and 181 had a long stem. Stress shielding was X-ray evaluated in each patient. The survivorship analysis of this study group (negative events = stress shielding) showed significantly ($p<0.05$) lower survival rates at 25 months follow-up for patients with long-stem implants. A 3-D FEM model of the proximal femur was used to analyse the load transfer mechanism for the two types of stems in fully or proximally only bonding conditions. Little difference was predicted in the proximal stress magnitudes for the different stem lengths. On the contrary, stem–bone bonding leads to a notable increase in the stress shielding.

1. Introduction

The principal role of total hip arthroplasty (THA) is to restore an adequate range of motion to the femur while transferring load from the acetabulum. The incorporation of a high stiffness femoral component in the proximal femur has the effect of sharing the joint load which was formerly carried by the bone only.

Unnatural stresses or strains can induce morphological changes and bone atrophy, possibly weakening the bone to the point of failure and creating an unfavourable basis for a revision arthroplasty. This problem has been shown to be clinically important, particularly with the use of uncemented implants [1–3].

Uncemented femoral hip prostheses, apart from being stiffer due to their greater size, also have another unfavourable attribute which can lead to serious complications; they usually do not fit very well, with the attainment of adequate initial stability of the prosthesis in the bone often depending greatly on the skill of the surgeon [4].

This phenomenon of morphological changes under unnatural loads is generally referred to as "stress-shielding". It is assumed that this induces bone atrophy, which has often been observed postoperatively [2].

The aim of this study was to use the finite element method (FEM) to investigate the effects of different stem lengths and different levels of osteointegration on the load transfer mechanism between a non-cemented stem and the surrounding bone tissue. The clinical results of the modelled stem were then compared with the biomechanical results of the FEM analysis.

2. Materials and methods

Three-dimensional finite element models of an experimental femur analogue (Pacific Research Laboratories Inc., Vashon Island, Wa, USA) were generated for both an intact femur and a femur with an implanted cementless femoral component. The experimental models were instrumented with strain gauges and the measured strains compared with the predicted values in the finite element models for a single-legged stance loading configuration. The effect on load transfer of press fitting and full bonding of the prosthesis were investigated using both the experimental model and finite element model. The validated finite element model of the fully bonded prosthesis was then used to examine the influence of implant stiffness and stem length on stress shielding in the proximal femur.

2.1. Finite element models

Three-dimensional finite element (FE) models were constructed using solid eight-noded and six-noded isoparametric elements. These elements had a linear displacement function. The model geometry was derived from CT information for the experimental model. These femur analogues consist of a glass fibre/epoxy resin composite cortex surrounding a polyurethane foam internal cavity. The meshes were constructed using an I/FEM (Intergraph, Alabama, USA) finite element system. The linear models were solved using the I/FEM solver; for the non-linear analysis, the LUSAS finite element system (FEA, Surrey, UK) was used.

The intact femur model and the model of the femur with prosthesis had 6936 and 8218 degrees of freedom, respectively (see Fig. 1). A cementless prosthesis (An. C.A. cobalt-chrome mini left stem, Cremascoli, Italy) was modelled in the treated femur. Two different stem lengths were taken into account: 16.5 cm (long) and 12.5 cm (short). The contact region between the stem and the cortical bone (glass fibre/epoxy resin cortex) was also defined using CT data from the experimental model featuring the implanted stem.

The material properties were modelled as a homogeneous linear elastic continuum exhibiting isotropic properties, following the work of others [5, 6]. Values of 14.2 GPa and 0.3 were assigned to the glass fibre/epoxy resin composite for elastic modulus and Poisson's value, respectively, in accordance with the manufacturer's data. A single-legged stance hip joint load was modelled. This featured an abducting force (G) of 1.55 body weight (BW) applied to the extremity of the greater trochanter at an angle of 40° to the main axis of the femur, and a resultant force (R) of 2.47 BW applied to the femur head at 28° of adduction. For simplicity, all the force components out of the coronal plane of the femur were omitted similarly to other investigations [7, 8]. The distal end of the diaphysis was fully constrained.

The following two contact conditions were investigated: complete osteointegration of the stem (linear solution); proximal only osteointegration of the stem, with monolateral contact in the distal part (non-linear solution). Both conditions were applied either to the long or short stems.

To investigate the accuracy of the FEM model, two intact composite material femurs were instrumented with twenty uniaxial strain gauges (HBM 6/120 LY 11, Hottinger Baldwin Messtecknik, Stuttgart, Germany) positioned on the anterior (A), lateral (L), posterior (P) and medial (M) aspects of the femurs. The level of the gauges is denoted 1 to 5 in the distal direction. The strain gauges were connected to a custom designed data acquisition unit (SA1, ADA, Bologna, Italy) and the data transmitted to a personal computer for analysis.

The distal condyles of the femur were potted with methylmethacrylate and a vertical load corresponding to body weight was applied in accordance with the work of others [9]. An epoxy resin cylinder was potted on the greater trochanter in order to allow the simulation of the abductor muscles, and an imprint of the femoral head was used to apply the load to the head. This was connected to a cantilever beam which was in turn connected to the actuator of an Instron 8502 material testing machine (Instron, UK). In this way, the abducting force and the hip force were generated simultaneously at the desired angles and in the prescribed ratio by adjusting the lever arms. A reproducible computer controlled load ramp was used to apply the load. The loading conditions were identical to those described for the FE models above and the orientation of the femur in all planes was identical for both the experimental and FE models.

One of the femurs was then prepared for implantation with an uncemented An.C.A. short stem by an experienced surgeon using a standard surgical technique. The stem was inserted using the actuator of the materials testing machine to achieve a constant insertion load. The implanted femur was then tested again using the same loading protocol as employed for the intact femur, with the stem being extracted and reinserted and the load repeated for a total of five iterations. Finally, the stem was glued in one of the femurs using two-component epoxy glue and tested once more under identical loading conditions.

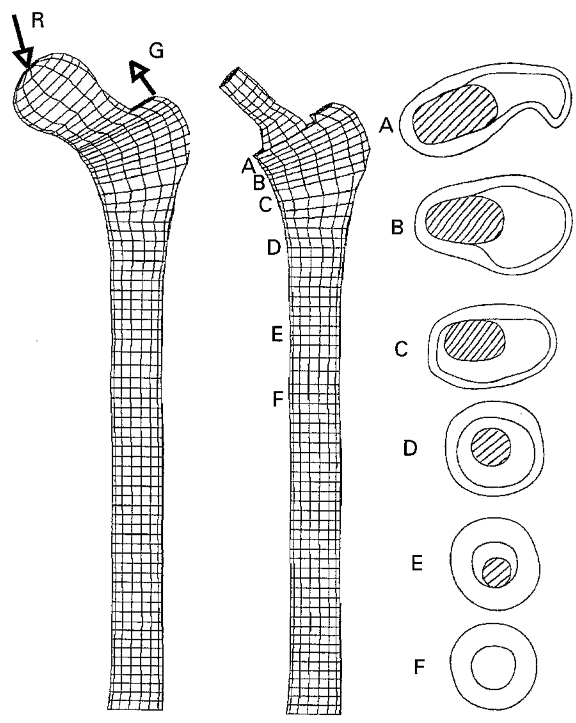

Figure 1 Finite element meshes (3-D) of the intact and treated femur together with an illustration of the implant–bone contact pattern. The applied loading condition is shown on the intact femur.

2.2. Clinical study

The An.C.A. total hip replacement has been employed in Rizzoli Orthopaedic Institute since 1985. A group of 475 stable implants was selected to form a homogeneous radiological follow-up group. In this group, 181 patients were treated with the long stem and 294 received the short stem. All the patients had regular follow-up. At each follow-up examination, mineralization of the proximal operated femur was determined using the X-ray based protocol proposed by Gruen [10]. Stress shielding was assumed to take place when, in the X-ray control, at least the four proximal-most regions of interest (ROI) of the six defined by Gruen showed demineralization. Details on the protocol employed can be found in [11]. From this evaluation the two patient groups were compared using survivorship analysis.

3. Results

3.1. FEM analysis

Excellent correlation was achieved between the experimental results and the FE results. The FE model

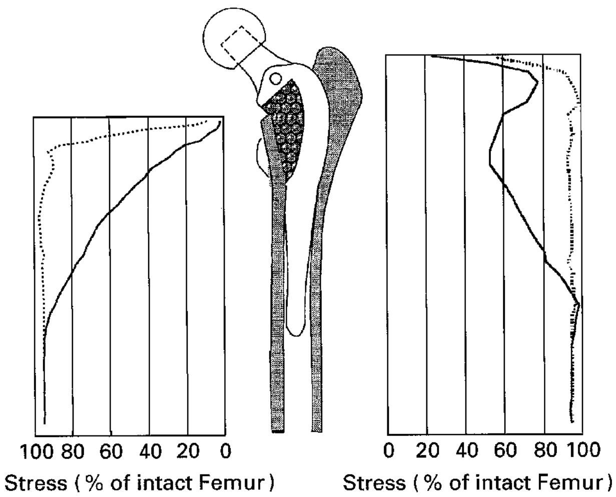

Figure 2 The stress shielding (axial surface stress) produced in the proximal femur as predicted by the FE model for the two bonding conditions analysed: —— full bonding; ---- proximal bonding.

has been validated by comparison of the predicted FE strains with experimentally measured values for the same femur–prosthesis system for a fully bonded situation. The correlation coefficient for the experimental and FE predicted strains for the fully bonded system was 0.986, taking the FE result to be the independent variable.

Fig. 2 presents the bone stress-shielding due to the short implant as predicted in the FE model for the two bonding conditions. The axial stresses on the periosteal bone surfaces for the treated femur are presented as percentages of the values recorded on the intact femur, which were assumed to be the reference (physiological) values. Stress-shielding was seen to occur along the entire length of the implant on the medial surface with the fully bonded stem. Severe stress shielding is predicted only in the most proximal region for the partially coated stem. Similar trends are observed for both the medial and lateral cortices, although the stress-shielding phenomenon is much more pronounced on the medial cortex. The upper part of the calcar is almost completely shielded from stress.

Analysis for the long and short stems showed little difference in terms of stress shielding under the hypothesis of full bonding (see Fig. 3). When only the proximal part was assumed bonded, virtually no difference was observed in the stress pattern with different stem lengths. Thus, stem length has little effect on the stress shielding induced in the calcar region. In the case of complete osteointegration of the stem, however, the length over which load transfer occurs depends on stem length, with the load being transferred over the complete stem length and thus producing greater stress shielding distally for the longer stem. Furthermore, the relative motion between the short stem and bone at the region of the stem tip was predicted to be 0.8 mm in the case of the partially coated stem. This indicates that the stem tends to toggle, being bonded proximally and free to move distally. The same analysis made with the long stem showed an increase of the relative motion up to 1.6 mm.

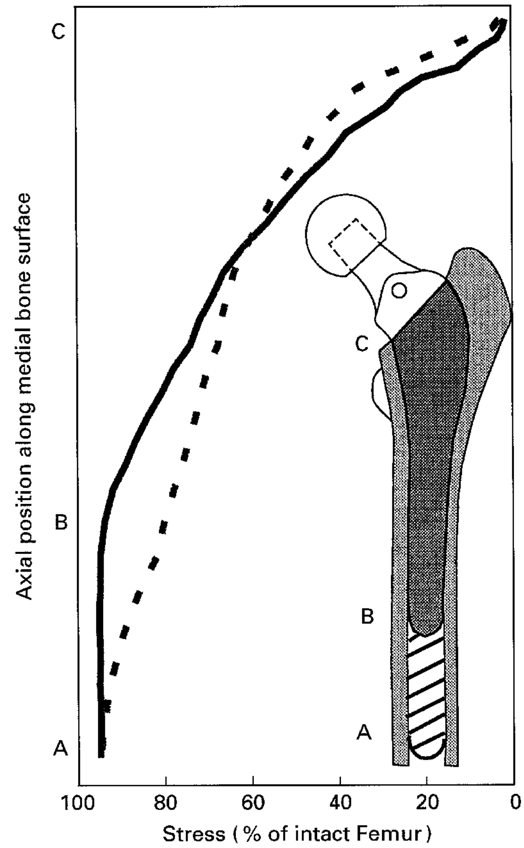

Figure 3 The stress shielding (axial surface stress) produced in the medial aspect as predicted by the FE model for the two stem lengths under the hypothesis of full bonding: —— short; ---- long.

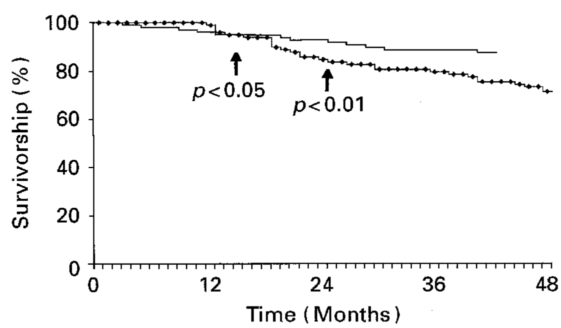

Figure 4 Survivorship curve for two different stem lengths of the An.C.A. cementless prosthesis (negative event = stress shielding): —— short; —◆— long.

3.2. Clinical study

In Fig. 4 the results of the survivorship analysis are summarized in a survivorship curve (negative event = stress shielding, as defined in the materials and methods). Noticeably, the short stems performed sensibly better than the long ones. Around 20 months the percentage of survivorship for the short stem became significantly higher ($p < 0.05$) than that of the long stem.

4. Discussion

The high correlation between the measured and predicted strains in the experimental and FE model indicates that a valid FE model was realized. This high correlation provides us with a valid model for application in the study of the femur's structural behaviour and provides a tool for use in the analysis of prosthesis design. The bonding conditions considered in the present study are probably two extremes between which most patients will fall. The An.C.A stem has a porous structure for bone ingrowth in the proximal posterior–medial anterior part; the whole stem is coated with a plasma-sprayed bioactive ceramic. Thus it is reasonable to assume that, depending on the patient, the bone can bond over the whole stem or, in other cases, only grow into the porous structure. Since it is impossible to assess this condition *in vivo*, the load transfer mechanism must be assumed to lie somewhere between the two extremes.

The FEM analysis predicted little difference between the two stem lengths despite the wide differences observed in the clinical trial if similar bonding conditions are considered.

The analysis suggests that a degree of initial tip stem motion is to be expected post-operatively. Progressive bone ingrowth would lead to a secondary stability, with a notable increase in the stress shielding induced in the proximal femur, thus presenting competitive objectives.

A possible speculation induced by clinical results could support a different bonding behaviour of short and long stems.

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