PHOTOELASTIC SIMULATION OF A CEMENTLESS AND OF A HYDROXYAPATITE COATED TOTAL HIP PROSTHESIS

P. MAQUET[1], L. ZHANG[2], F. DE LAMOTTE

Remodelling of bone, regularly observed after the implantation of a hydroxyapatite coated Furlong hip prosthesis, stimulated the authors to analyse the stress distribution and relative magnitude in photoelastic models, of 1. the upper half of an intact femur ; 2. of a femur equipped with a prosthesis free of glue to simulate the implantation of a cementless non coated prosthesis ; and 3. of a femur in which a prosthesis was glued to simulate the implantation of a hydroxyapatite coated prosthesis. The results match precisely the remodelling thus observed in the X-rays.

Keywords : photoelastic model ; cementless ; THR.
Mots-clés : modèle photoélastique ; sans ciment ; arthroplastie de hanche.

INTRODUCTION

Remodelling of cortical and cancellous bone appears in the X-rays following implantation of a Furlong total hip prosthesis which is coated with hydroxyapatite (Maquet, 1992). This suggested an analysis of the distribution and magnitude of the stresses in photoelastic models simulating the upper femur, both intact and equipped with a prosthesis.

METHOD

The intact models were similar to those used in a previous study on fracture fixation (Maquet and Pelzer, 1980) except that their shaft was longer, to accommodate the length of the prosthesis and 5 cm beyond. The thickness was 10 mm. Models of plexiglass when loaded enabled us to see the isoclinics. The polariscope was turned by increments of 10°, showing each of the isoclinics in a variety of positions. By superimposing the isoclinics thus successively obtained, the pattern of isostatics (trajectories of the principal compressive and tensile stresses) could be drawn.

Isochromatics appeared in other models made of araldite. The loading apparatus was the same as for the previous research. An eccentric load corresponds to the force exerted by the partial body mass during gait. A tensed cable represents the abductor muscles. The resultant force acts at an inclination of 16° to the vertical, as described by Pauwels in a normal hip. Three different loads were used. Only the results with the heaviest load were retained for this analysis.

Five mm thick longitudinal sections of Furlong hip prostheses were prepared. They were sandwiched between two opposite 5 mm thick pieces of plexiglass (for the isoclinics) or araldite (for the isochromatics), after 2.5 mm deep cavities corresponding to the contour of the prosthesis had been carved out of each. These opposite sections were glued together. In a pair of models the prosthesis was sandwiched free, thus simulating the implantation of a cementless non-coated prosthesis. In another pair the prosthesis was glued in between the plexiglass or araldite pieces. Glueing of the prosthesis simulated the binding of the bone with the hydroxyapatite coating of the Furlong prosthesis as suggested by the postoperative x rays (Maquet, 1992). An overall force of 22.973 kg was acting on the models during the experiments.

To make sure that two 5 mm sheets of plexiglass or araldite glued together, provided the same pattern of isoclinics and isochromatics as one 10 mm thick sheet, preliminary experiments were carried out. A disc

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made of a 10 mm sheet of plexiglass and one made of two 5 mm thick sheets glued together were examined in the same conditions. The isoclinics were exactly the same in both experiments. The same was done with two 5 mm thick rods of araldite glued together and one 10 mm thick rod. The isochromatic patterns under load were the same for both.

RESULTS

1. The intact plexiglass model of the upper half of the femur enabled us to draw essentially the same pattern of isostatics as in a previous work on fracture fixation, with a medial bundle of trajectories of compressive stresses radiating upwards in the femoral head and laterally in the metaphysis, and a lateral bundle of tensile trajectories curving and intersecting the compressive trajectories at right angles (fig. 1a).

The isochromatics appearing in the araldite model of the intact femur show a high level of stresses in the medial (compressive) and lateral (tensile) cortices (fig. 2a). The magnitude of the compressive stresses decreases from above the lesser trochanter towards the femoral neck and head.

2. In the plexiglas model with the prosthesis free, the flow of stress is very similar to that in the intact model with, however, several singular areas laterally close to the prosthesis (1-4), which mean irregularities in the contact between the plexiglass and the metal (fig. 1b). Such irregularities do not appear medially.

In the araldite model with the prosthesis free, the order of magnitude of the isochromatics in the medial and lateral cortices over the length of the prosthesis is lower than in the intact model, meaning that a great deal of the stress is transmitted through the metal stem rather than through the cortices (fig. 2b). The isochromatics attain the same order of magnitude as in the intact model at a certain distance beyond the lower end of the stem.

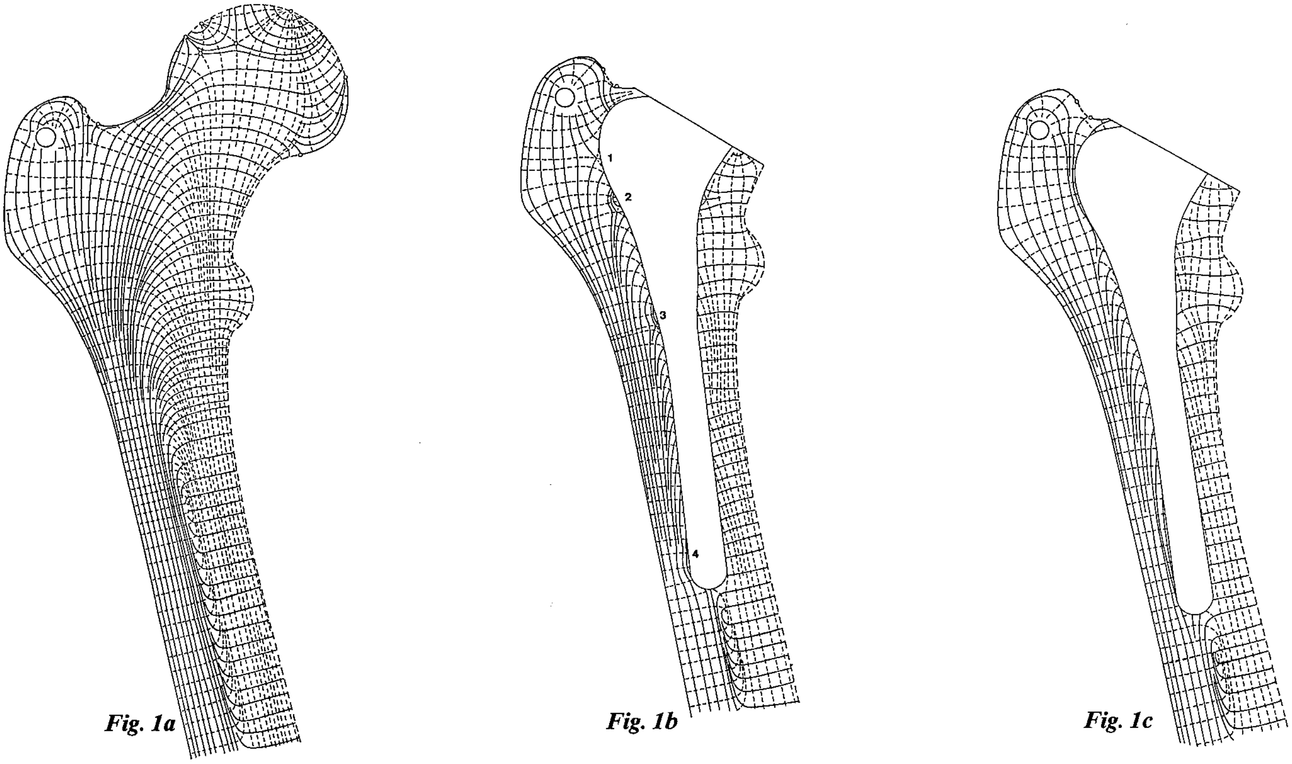

Fig. 1a *Fig. 1b* *Fig. 1c*

Fig. 1. — 1. Isostatics (trajectories of the stresses) in a model of the femur, intact (a), after implantation of a Furlong prosthesis non-glued (b), glued (c).

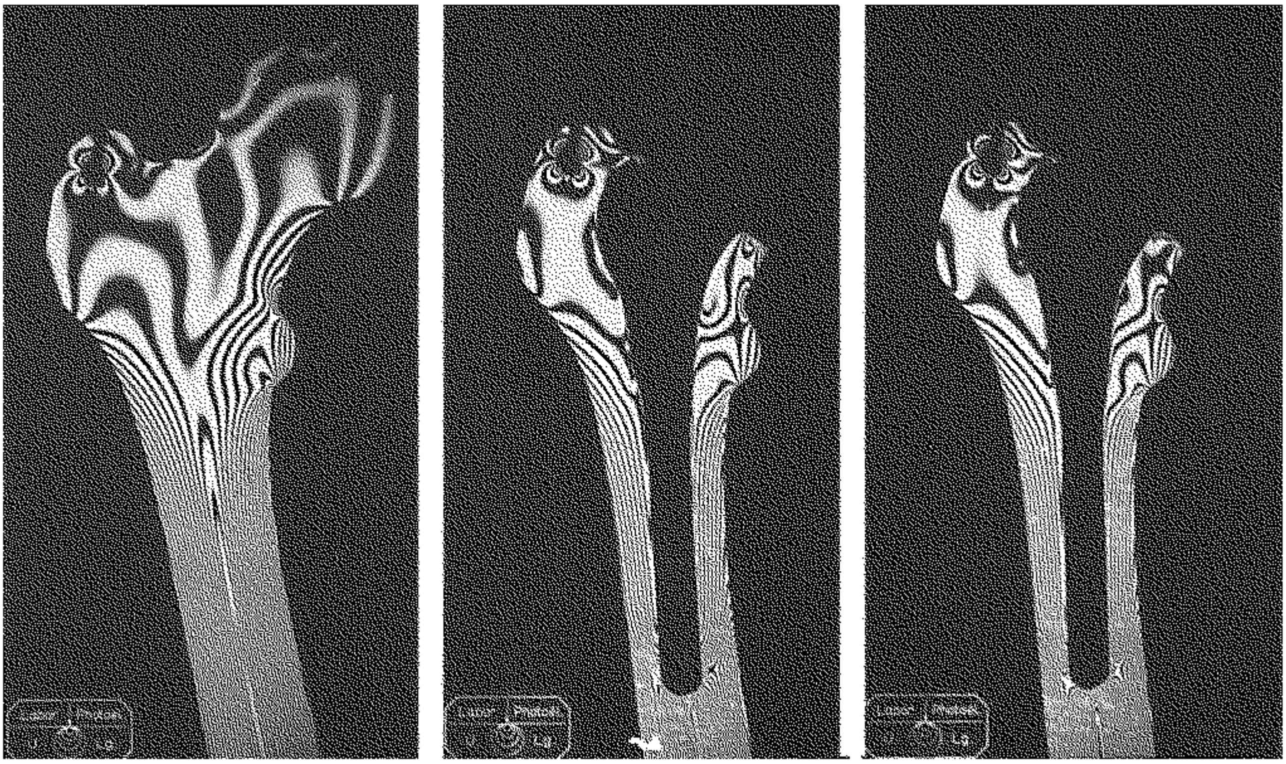

Fig. 2a *Fig. 2b* *Fig. 2c*

Fig. 2. — Isochromatics in a model of the femur, intact (a), after implantation of a Furlong prosthesis non-glued (b), glued (c).

3. In the plexiglass model with the prosthesis glued in, the trajectories of the stresses are more regular on the lateral side of the prosthesis and more similar to the intact model (fig. 1c). No singular area can be seen. The contact and transmission of the stresses are uniform.

4. Cross sections were considered at several levels in the araldite models, to analyse the quantitative distribution of the compressive and tensile stresses (fig. 3). They revealed discrepancies from normal in the araldite model with the prosthesis free and in the model with the prosthesis glued.

Cross-section E-E (fig. 4)

On the medial side the magnitude of the stresses in the model with a prosthesis free is less than 41% of that in the intact model ; 59% of the stresses are taken over by the prosthesis. The stresses are a little greater in the model with a glued prosthesis although less than 46% of those in the intact model. Glueing entails a larger involvement of the femur in the transmission of the stresses. At the lateral margin the tensile stresses are 12% higher in the model with the free prosthesis than in the intact femur. They are 25% higher with the glued prosthesis than in the intact model.

Cross-section A-A (fig. 5)

The same phenomenon is observed medially and laterally, as it is medially in cross section E-E. The diminution of stresses in the femur, however, is less considerable medially in the prosthetic models in relation to the intact model than it is in cross section E-E. The compressive stresses at the medial margin of the model, with the prosthesis free, are 56% of those in the intact model in the

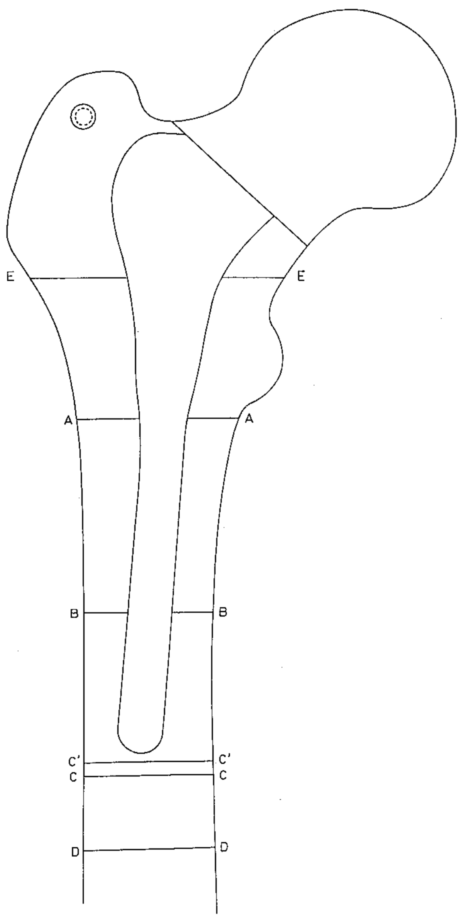

Fig. 3. — Cross-sections of the models considered.

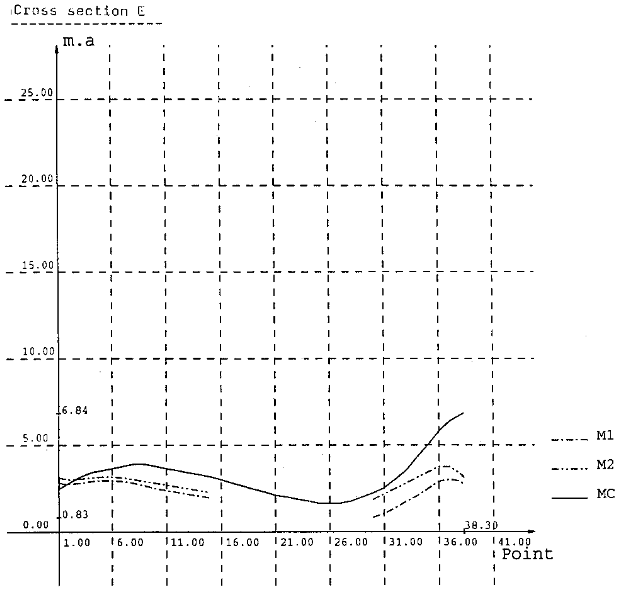

Fig. 4. — Cross-section E-E.

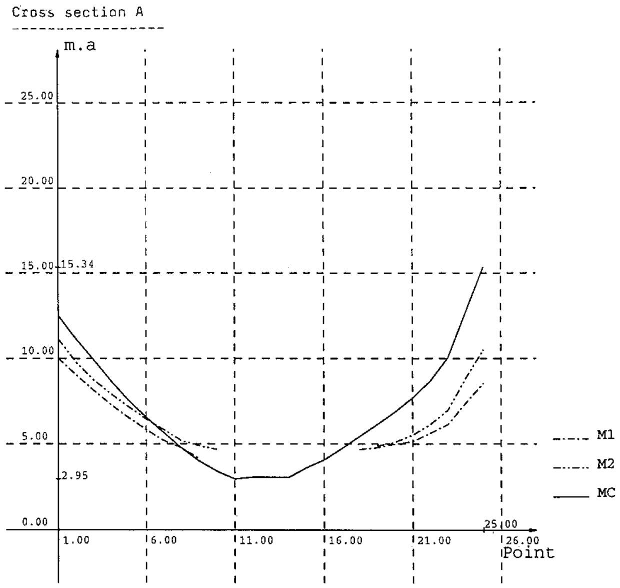

Fig. 5. — Cross-section A-A.

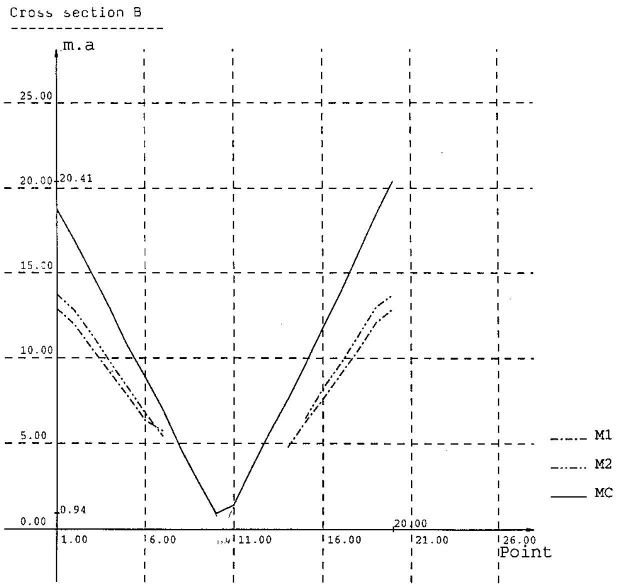

Fig. 6. — Cross-section B-B.

femur. They are 69% in the model with the glued prosthesis. On the lateral side the percentages of the normal value are respectively 80% and 89%.

Cross-section B-B (fig. 6)

The results are similar to cross section A-A. However, the gradient of the stresses is higher. The stresses at the medial margin are 63% of normal in the model with the prosthesis free and 67% of normal with the prosthesis glued. At the lateral margin, these percentages are respectively 69% and 74%.

Cross-section C-C (fig. 7)

At the tip of the stem of the non-glued model the compressive stresses are 11% more at the medial edge than in the intact model. They are 16% more in the glued model than in the intact model. At the lateral edge the tensile stresses are respectively 13% and 19% more than in the intact model.

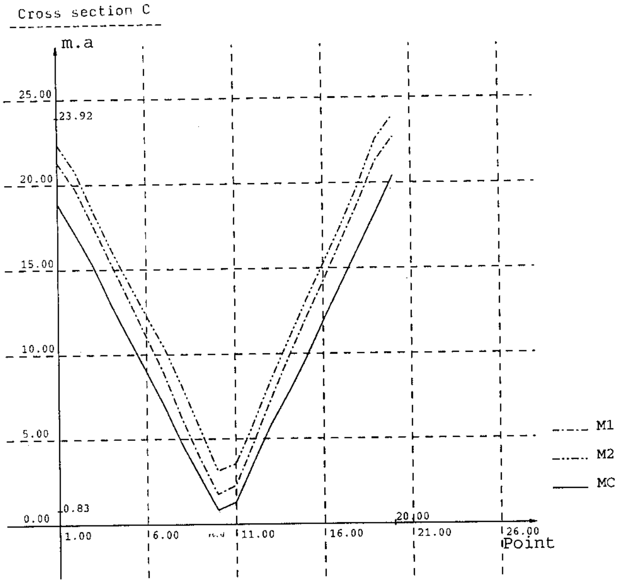

Fig. 7. — Cross-section C-C.

Cross-section C'-C' (fig. 8)

The situation is about the same as for cross section C-C. The lateral tensile stresses at the edge are 11% more in the model with a non-glued prosthesis and 13% more in the model with a glued prosthesis than in the intact model. On the medial side the compressive stresses are respectively 8% and 16% more than in the intact model.

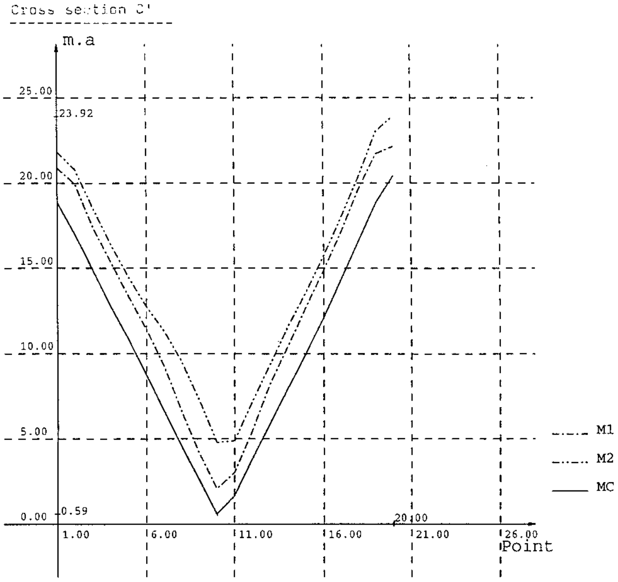

Fig. 8. — Cross-section C'-C'.

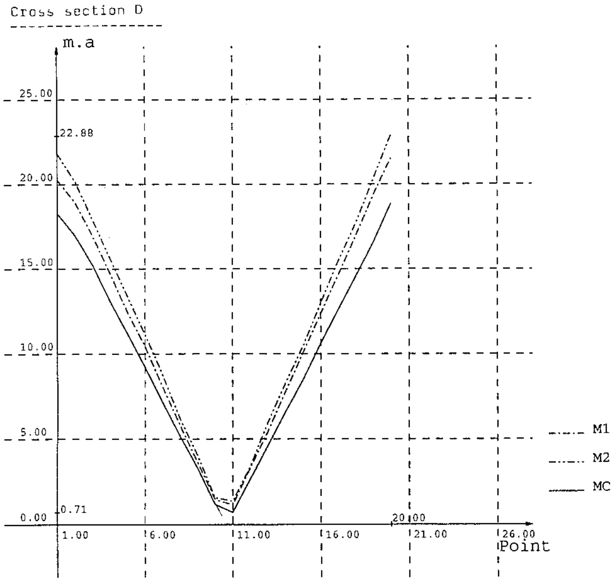

Fig. 9. — Cross-section D-D.

Cross-section D-D (fig. 9)

The same phenomenon appears as in cross section C'-C'. At the lateral edge the tensile stresses are 11% more in the model with the non-glued prosthesis and 20% more in the model with the glued prosthesis than in the intact model. On the medial edge the compressive stresses are respectively 14% and 22% more than in the intact prosthesis.

There is thus a decrease of the stresses medially at the upper extremity (calcar) of the femur equipped with a prosthesis : there is stress shielding. This stress shielding is less pronounced with a glued prosthesis than with a free prosthesis. On the contrary, at the tip of the stem and a little below, stresses are higher in the models with a prosthesis than in the intact model, more so when the prosthesis is glued.

DISCUSSION

Bidimensional photoelastic models have been used to illustrate the distribution of stresses in bones of the same configuration (Pauwels, 1980 ; Maquet, 1984). The similarity of the stress trajectories in the model and the architecture of the cancellous bone, and that of the quantitative distribution of the stresses in the model and the quantity of bone tissue as appearing in the X-rays, suggest a good correlation.

The isostatics illustrate the trajectories of the stresses. In the present analysis they are disturbed after the implantation of a non-glued prosthesis. This is due to the irregularities of the contact between the model and the prosthesis. When the prosthesis is glued the stress trajectories appear very similar to those in the model of an intact femur. In the metaphyseal area they arch upwards and towards the cone and upper part of the stem of the prosthesis medially and laterally.

During the first months following the implantation of a Furlong prosthesis in a living femur, the diminution of the stresses in the metaphyseal area provokes some resorption of bone with spongialization of part of the cortex (Kummer). The cancellous bone thus formed then remodels along the stress trajectories (fig. 10) as could be foreseen according to the work of Pauwels. Trabeculae arch medially and laterally from the cortices upwards towards the cone of the prosthesis, into which they seem to adhere firmly. This may occur by pure contact on the medial side where the trabeculae are stressed in compression. On the lateral side, according to the analysis, the trabeculae are stressed in tension. But this is possible only if they are anchored firmly into the prosthesis, i.e. into the hydroxyapatite coating. Without such a firm anchorage tension would not be possible.

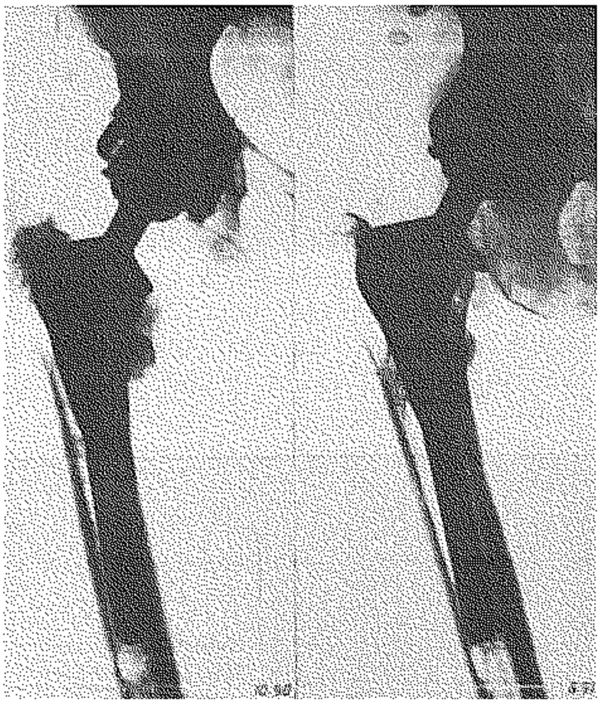

Fig. 10. — 59 year-old patient immediately after the implantation of a Furlong hydroxyapatite coated prosthesis (a) and 8 months later.

This remodelling is observed regularly. The resulting structure of the cancellous bone is very similar to the stress trajectories in the corresponding model (fig. 1c). The cancellous trabeculae form a kind of cradle which supports the prosthesis more elastically than stiffer cortical bone would do. Interposed between the stiff prosthesis and the stiff bone, they must have an action of shock absorption thanks to their higher flexibility.

The isochromatics indicate the relative magnitude of the stresses in the cross-sections of the models. In the present instance, bending adds to compression (Pauwels, 1980). Therefore, the compressive stresses on the medial side are always greater than the tensile stresses on the lateral side. The presence of the prosthesis decreases proximally, more so when the prosthesis is not-glued. This makes sense since, when non glued, the prosthesis, less elastic than the araldite or bone, takes over more of the stresses than when glued. When glued, the model is forcefully more involved in the transmission of the stresses. Stress shielding thus seems to be less, when the prosthesis is firmly fixed through its hydroxyapatite coating than just by press fit. The stresses in the upper extremity of the femur are, however, less after the replacement than in the normal femur (fig. 11).

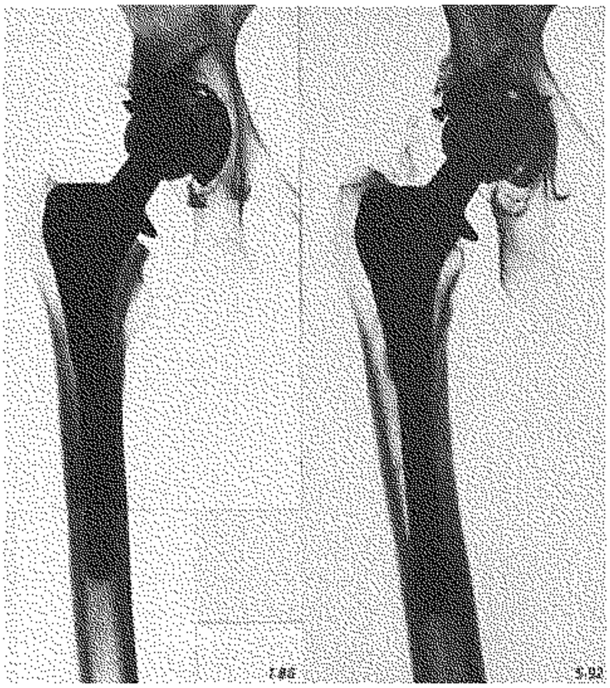

Fig. 11. — Stress shielding in the calcar area. Immediately after a replacement (a) and 6 years later (b).

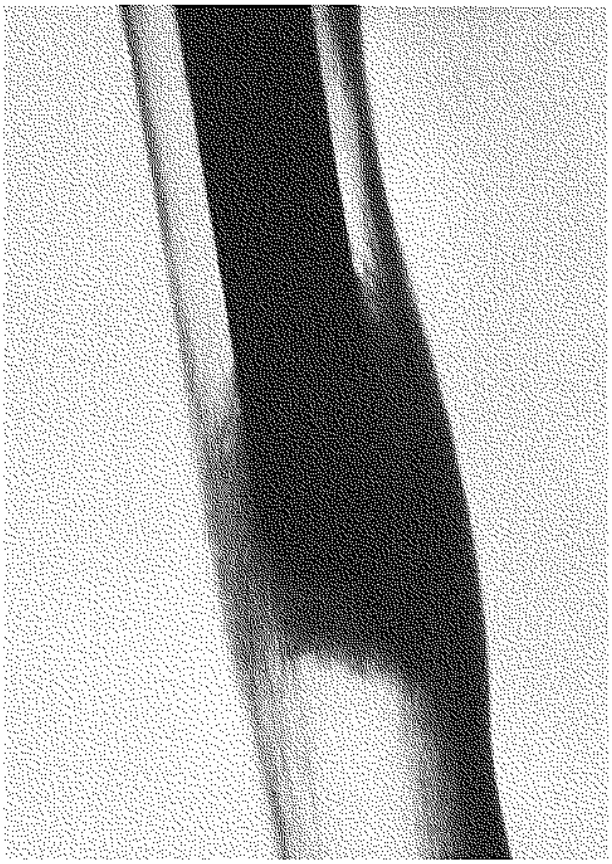

Fig. 12. — Apposition of bone in the vicinity of the tip of the stem. Four years after a replacement.

Near the tip of the prosthesis and beyond, the stresses are higher in the model with a free prosthesis than in that of an intact femur, and even higher in the model with a glued prosthesis. Increase of stresses at the boundary of a composite material is well known by the engineers. The model and the prosthesis form such a composite material so that the increase of stresses in the boundary area close to homogeneous material, araldite alone, is not surprising. Bone and prosthesis also constitute a composite material. Increase of stresses in the area of the tip of the stem of the prosthesis may have accounted for the few fractures which have been reported after a fall in the days following implantation and which always occurred in this area. The femoral model was 21% and 22% more fragile than the intact femur after implantation respectively of the free prosthesis and of the glued prosthesis. As far as fragility is concerned, the increase of tensile (lateral) stresses is important since bone is by far less resistant to tension than to compression (Pauwels, 1980).

Increase in the stresses stimulates bone formation (Pauwels, 1980). This is what is observed regularly in this area during the months following the implantation of a Furlong prosthesis. In some instances the apposition of bone is very considerable (fig. 12). The risk of fracture at this level is thereby reduced to normal.

CONCLUSION

Analysis of the photo-elastic models concurs with and explains to a large extent the changes observed in the X-rays after hip replacement with the Furlong hydroxyapatite coated prosthesis.

Acknowledgements

The longitudinal slices of Furlong prostheses were kindly provided by Joint Replacement Instrumentation, 104-112, Marylebone Lane, London W1M 5FU, and the experimental work was subsidized by the Furlong Research Foundation, Lister House, 11-12 Wimpole street, London W1M 7AB.

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SAMENVATTING

P. MAQUET, L. ZHANG, F. DE LAMOTTE. Foto-elastische simulatie van een cementloze heupprothese en van een met hydroxyapatite bedekte prothese.

De botremodellering die geregeld gezien wordt na inplantatie van de heupprothese, type Furlong, bedekt met hydroxyapatite, was de aanleiding tot een studie van de verdeling en de grootheid van de verschillende stresselementen bij foto-elastische modellen :

1. t.h.v. de proximale helft van het gaaf femur
2. t.h.v. een femur met een niet gelijmde prothese, dus de simulatie van een cementloze prothese
3. van een femur met een gelijmde prothese, simulatie van een prothese, bedekt met hydroxyapatite, na fusie met het bot.

De resultaten zijn in overeenstemming met wat er in vivo gezien wordt ; hierdoor wordt een uitleg gegeven voor de vastgestelde transformaties.

RÉSUMÉ

P. MAQUET, L. ZHANG, F. DE LAMOTTE. Modèles photoélastiques simulant l'implantation d'une prothèse de hanche sans ciment et d'une prothèse couverte d'hydroxyapatite.

Le remodelage osseux régulièrement observé après implantation de la prothèse de hanche de Furlong couverte d'hydroxyapatite a incité les auteurs à analyser la distribution et la grandeur relative des contraintes dans des modèles photoélastiques :

1. de la moitié proximale du fémur intact ;
2. d'un fémur équipé d'une prothèse non collée simulant une prothèse sans ciment ;
3. d'un fémur équipé d'une prothèse collée simulant une prothèse couverte d'hydroxyapatite après son union avec l'os.

Les résultats correspondent aux transformations observées dans l'os vivant et permettent d'expliquer ces transformations.