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Periprosthetic Bone Remodelling in Total Knee Arthroplasty

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ABSTRACT

Introduction: *The clinical studies have shown that the displacement of the prosthesis components, especially of the tibial one is higher during the first year, after which it reaches an equilibrum position compatible with a good long term functioning. This displacement takes place due to bone remodelling close to the implant secondary to different loading concentrations over different areas of bone.*

Material and Method: *Our study implies a simulation on a computational model using the finite element analysis. The simulation started taking into account arbitrary points because of non-linear conditions of bone-prosthesis interface and it was iterative.. A hundred consecutive situations corresponding to intermediate bone remodelling phases have been calculated according to given loadings. Bone remodelling was appreciated as a function of time and bone density for each constitutive element of the computational model created by finite element method. For each constitutive element a medium value of stress during the walking cycle was applied.*

Results: *Analyse of proximal epiphysis-prosthesis complex slices showed that bone density increase is maintained all over the stem in the immediately post-operative period. At 10 months, the moment considered to be the end of bone remodelling, areas with increased bone density are fewer and smaller. Meanwhile, their distribution with a concentration toward the internal compartment in the distal metaphysis is preserved.*

Conclusions: *After the total knee arthroplasty the tibial bone suffered a process of remodelling adapted to the new stress conditions. This bone remodelling can influence, sometimes negatively, especially in the cases with tibial component varus malposition, the fixation, respectively the survival of the prosthesis. This process has been demonstrated both by clinical trials and by simulation, using the finite elements method of periprosthetic bone remodelling.*

INTRODUCTION

In all cases of total knee arthroplasty, including the case in which the tibial component has been correctly positioned, there are areas of stress concentration, both at the level of the bone - prosthesis interface and at the level of the proximal tibial metaphysis. These observations are in accordance with the X-ray studies, which have shown that following the stress transfer at the level of the subjacent bone, a marginal atrophy parallel with the cortical epiphysis and a bone hypertrophy around the stem, up to the level of

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the cortical metaphysis are being produced. Thus, a by-pass of the epiphysis area that leads to the epiphysis bone atrophy is produced. At the level of the internal tibial plateau, the bone is denser than in the rest of the epiphysis, which leads to an easier transfer of the axial loadings at this level to the metaphyseal area.

The clinical studies have shown that the displacement of the prosthesis components, especially of the tibial one is higher during the first year, after which it reaches an equilibrium position compatible with a good long term functioning. Results showed that for every millimetre increase in migration there was an 8% increase in revision rate, which remained after correction for age, sex, diagnosis, hospital type, continent, and study quality. Consequently, migration up to 0.5 mm was considered acceptable during the first postoperative year, while migration of 1.6 mm or more was unacceptable. TKRs with migration of between 0.5 and 1.6 mm were considered to be at risk of having revision rates higher than 5% at 10 years (1). It is very likely that these displacements are caused by the changes of the bone structure adjacent to the prosthesis, changes that are being induced precisely by these differences between the areas with stress application and the ones at the level of which there is a decrease in the level of stress. Attaining a position that is radiological understood as the ending of the displacement of the components, represents precisely the moment of the finalization of the bone remodelling (2,3). ❑

MATERIAL AND METHOD

In this study a computational model has been made in order to simulate the periprosthetic bone remodelling in the cases of total knee arthroplasty to determine the changes in the periprosthetic bone density up to the moment when there are no more visible changes of it. All 3 prosthesis considered for this study have been cemented. Two of them was in a correct position (tibial component at 90° to tibial mechanical axis) and one in a slight varus (3°).

By using an infra-structural approach, the bone remodelling process has been simulated for more regions of the bone-prosthesis interface. It has been made a computational model which contains a time-dependent interactive function that can prevision changes of bone structure by updating the properties of the model's components using the method of the finite elements (4). By combing all this data, the evolution of the bone-prosthesis interface can be determined on time.

The stress distribution on the bone-prosthesis unit depends on the weight bearing during physical activities, on the muscle activity that ensures the stability of the joint, as well as on the geometry and the properties of the composing materials of the prosthesis components (5). Related to this, the overused areas, the areas of normal use, as well as the areas in which the loading is under the normal value can be located and depending on these values, either the bone resorption or the new bone formation appears (6,7).

The three-dimensional reconstruction of the joint has been made by combining series of slices obtained from the CT examination made before surgery, to which it has been added the 3D model of the used prosthesis. Its placement at the level of the bone model has been made by using the postoperative X-ray; it has been taken into consideration only the frontal plane positioning of the tibial plateau; the AP slope of the tibial component was not considered, in order to ease the calculation. The import and combination of the imaging has been made by using advanced software (ProEngineer®2002; Parametric Technology Corporation, 2002) of three-dimensional geometric modelling (8). On each slice there have been identified the areas of interest and there have been established points on a precise contour of them. The entire operation has been manually made in order to avoid errors generated by the automatic reconstruction software. The three-dimensional model of the prosthesis joint has been implemented in a model with finite elements, by using specialised software (Ansys). The bone density and the Young module are particularly important for a precise simulation of the bone remodelling. The bone density of each component has been established by its correspondence towards the grey scale of the CT sections (the density of the cortical is of about 1.95 g/cm^3 and that of the medullar bone is of about 0.05 g/cm^3. The Young module for composing bone elements of the used bone model has been determined in accordance with their apparent density (9). The elasticity module of the femoral component (chrome-cobalt-molybdenum alloy) has been assessed at 200 GPa and also, the material has been considered to be linear elastic.

In order to obtain a correct cinematic of the prosthesis joint, a system of acquisition and image analyse, SIMI0 Motion (SIMI Reality Motion Systems GmbH) has been used. The image recording has been made with two high-speed video cameras following in two perpendicular planes some markers attached onto well established points at the level of the both legs of the patient during walking (10, 11). By processing this data, cinematic curves have been obtained. The model has been subjected to stress-loading according to these cinematic data resulted from the post - arthroplasty walk analysis. The loading is assessed by the femur displacement over the tibial plateau as a function of time for a walking cycle, as well as by the corresponding axial weight bearing (12). The analysis is dynamic and it has been made by using a specialised software (LS - DYNA).

The simulation of bone remodelling

The simulation of bone remodelling has been made starting from the theory according to which the bone structure adapts to the values and directions of the forces it is subject to (13,14). This simulation has had an iterative character, taking into consideration some random points because of non-linear conditions present at the level of the bone – prosthesis interface.

It has been assessed only the remodelling of the spongious bone, the cortical bone being kept unaltered in order to preserve the shape of the bone subjacent to the prosthesis. The simulation has been applied to the model described above, 100 subsequent situations corresponding to the intermediate phases of bone remodelling being calculated in accordance with the given stress.

The bone remodelling has been assessed according to the time and particular density of each component of the mathematical model, created with the method of the finite elements (15). For each component it has been applied, in particular, an average value of the stresses developed at its level during the walking cycle (16).

In this study it has been used a relation in which the adaptation of the elasticity module of the bone is directly connected with the von Misses type stresses (the level of the stresses where the deformations are no longer elastic, but they become plastic). Two different structures have been put up to discussion for the study of the simulation process of bone remodelling: the tibial plateau and a quadrilateral structure, used as witness (17-19). The bone remodelling process and the finite element code have been associated into one image. ❑

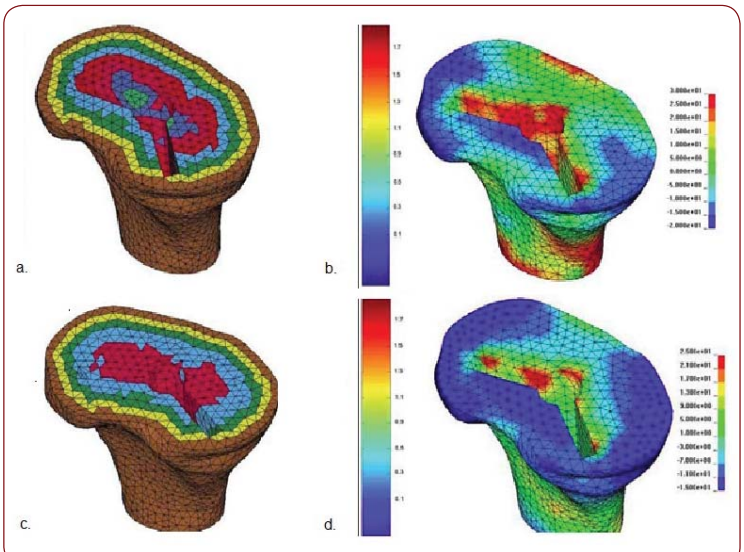

FIGURE 1. The distributioin of the bone density and the stress concentrations at the level of the bone-prosthesis interface and of the prosthesis proximal tibial extremity, immediately after arthroplasty (a, b) and after 10 months of bone remodelling (c,d).

RESULTS

The simulation process is carried on until there are no more observed changes of the density of the components of the model created by the method of the finite elements (20, 21).

In the Figure 1A and 1B it can be observed an increased periprosthetic bone density immediately after surgery, due to the bone compaction secondary to the keel hole preparing. In the same time, it can be observed an area of stress concentrations at the level of the internal compartment not only at the bone – prosthesis interface and to the metaphysic level, but also at the level of the antero-medial contour of the tibial plateau, corresponding to an area of cortical support of the tibial component.

In Figure 1C and 1D, considerated to represent the evolution of the bone remodelling process and stress redistribution at 10 months after surgery, it can be observed a reduction of the areas with stress concentration, these being preserved almost point like at the level of the internal compartment, probably by finding an equilibrium position. However, there are still areas at the level of the internal compartment at which the stress is of about 25 MPa, almost equal with the initial stress. The increase of the bone density is found on a larger area at the level of the internal compartment, corresponding with the areas of stress concentrations (the areas of contact with the femoral condyles, during the mid-stance interval). At the level of the external compartment, where the axial loadings are reduced, it can be observed an area of bone density reduction, especially antero-external.

At the level of the entire tibial plateau, the bone density decrease is of 13%, which corresponds to a decrease of 1.5% per month. This density decrease is related to the stress-shielding phenomenon, generated by a decrease of the axial loading at this level. It is very likely that in the case of a varus malposition, by concentrating the stress at the level of the internal compartment, the external compartment to be even less solicited and in consequence, to the decrease of bone density at this level. The decrease of bone density has unfavourable effects on the component fixation on a long term evaluation, by decreasing the number of connections between the cement and the subjacent bone (22,23).

The series of sections of the prosthesis-proximal tibial epiphysis complex have shown that immediately after the surgery the periprosthetic bone density growth is preserved on the entire length of the metaphyseal extension of the tibial component (keel) (Figure 2A,B,C). At 10 months after the surgery, the moment when it is considered that the bone remodelling process has been finished, it is observed a reduced surface where the bone density is increased. In the same time, it has been observed the preservation of the distribution of these areas towards the internal compartment, especially at the distal part of metaphysis, fact that confirms the presence of stress concentration areas at the level of the internal cortical metaphysis. (Figure 2C,D,E).

At the metaphysis level, the increased bone density is present only towards its internal slope, most likely because of the reception and transmission of the axial loading by the stem of the tibial component. At the level of the extremities of the lateral "wings" of the stem there are not noted neither stress bearings, nor changes of bone density. This is in connection with its building properties, meaning that the reception and transmission of loading is made by the central axis of the stem, and the lateral wings have the role to rotationally stabilise the tibial component. At the level of the external compartment it has been noticed a decreased bone density, especially at the antero-external angle which is in accordance with the above data. In addition, it has been noticed a progressive enlargement of decreased bone density areas in comparison with the postoperative status (24). ❑

DISCUSSIONS

In practice, the contact between the prosthetic margin and the cortical bone (essential fact for a correct prosthesis implantation) ensures a transfer of the stress from the prosthesis towards the cortical area. In case this contact is not achieved, the cortical not being stressed, it suffers an atrophy process. It is not very clear if the cortical bone has a different pattern from the spongious one regarding its behaviour on stress, from the point of view of the speed with which the process is being made.

The increased periprosthetic bone density distribution is in accordance with the 3-D model obtained by the method of finite elements of the stress concentrations both at the immediately subjacent to the prosthesis level

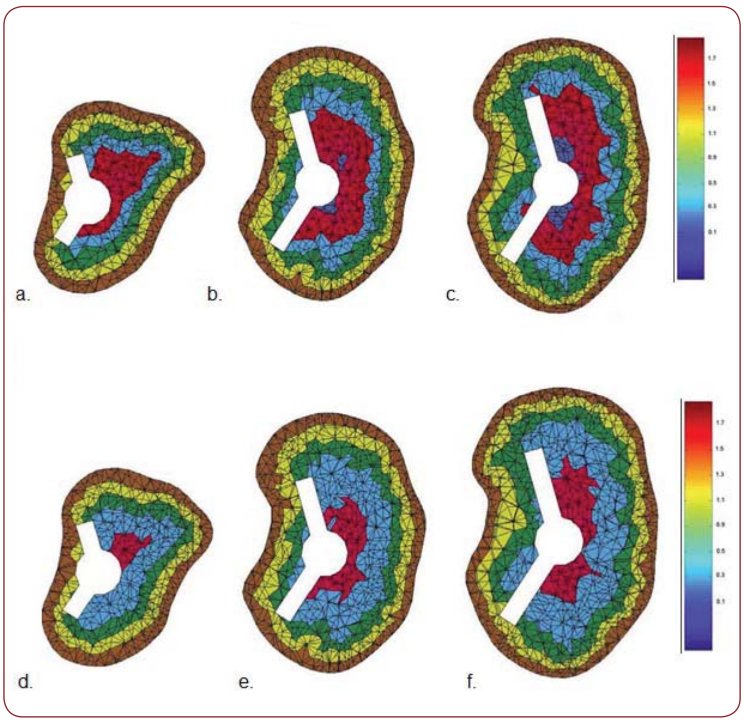

FIGURE 2. Series of sections of the prosthesis tibial epiphysis, with bone density distribution before (a,b,c) and after 1- months of bone remodelling (d,e,f).

and at the level of the entire tibial proximal extremity. Therefore, it is confirmed the relation postulated by Wolff, between the intimate structure of the bone and the stress that it is subjected to.

At 10 months after the surgery, the moment when it is considered that the bone remodelling process is finished, it is observed a reduced area of increased bone density. In the same time, it has been observed the preservation of the distribution of these areas towards the internal compartment, especially at the distal level of methaphysis, fact that confirms the presence of areas of stress concentration at the level of the internal cortical metaphysis. The stress decrease in the external compartment leads to the reduction of the bone density at this level, especially at the level of the antero-external angle through the stress-shielding phenomenon.

In the case of a varus malposition, by concentrating the stress at the level of the internal compartment, the external compartment is even less solicited, which would lead to the decrease of bone density at this level, secondary to the higher stress-shielding. ❑

CONCLUSIONS

After arthroplasty, the model of stress distribution at the level of the subjacent bone has suffered radical changes. As consequence, the bone tissue has suffered a process of remodelling, thus it has suffered a change both in density and in resistance, adapted to the new stress conditions. This bone remodelling can influence, sometimes negatively, the fixation of the prosthesis by the gradual disappearance of the bone tissue at the bone-prosthesis interface. This has been demonstrated both by clinical trials and by simulation, using the finite elements method of periprosthetic bone remodelling (25,26).

The decrease of bone density has unfavourable effects on a long-term fixation of the prosthesis, by decreasing the number of connections between the cement and the subjacent bone. In the case of malpositioned prosthesis, especially in varus, this effect would be even more dramatic, the decreased quality of the subjacent bone leading to the fast deterioration of the prosthetic fixation.

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