Numeric simulation of bone remodelling patterns after implantation of a cementless straight stem

Matthias Lerch · Henning Windhagen · Christina M. Stukenborg-Colsman ·
Agnes Kurtz · Bernd A. Behrens · Amer Almohallami · Anas Bouguecha

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Abstract

Purpose For further development of better bone-preserving implants in total hip arthroplasty (THA), we need to look back and analyse established and clinically approved implants to find out what made them successful. Finite element analysis can help do this by simulating periprosthetic bone remodelling under different conditions. Our aim was thus to establish a numerical model of the cementless straight stem for which good long-term results have been obtained.

Methods We performed a numeric simulation of a cementless straight stem, which has been successfully used in its unaltered form since 1986/1987. We have 20 years of experience with this THA system and implanted it 555 times in 2012. We performed qualitative and quantitative validation using bone density data derived from a prospective dual-energy X-ray absorptiometry (DEXA) investigation.

Results Bone mass loss converged to 9.25 % for the entire femur. No change in bone density was calculated distal to the tip of the prosthesis. Bone mass decreased by 46.2 % around the proximal half of the implant and by 7.6 % in the diaphysis. The numeric model was in excellent agreement with DEXA data except for the calcar region, where deviation was 67.7 %.

Conclusions The higher deviation in the calcar region is possibly a sign of the complex interactions between the titanium coating on the stem and the surrounding bone. We developed a validated numeric model to simulate bone remodelling for different stem-design modifications. We recommend that new

THA implants undergo critical numeric simulation before clinical application.

Keywords Total hip arthroplasty · Dual-energy X-ray absorptiometry · Finite element analysis · Stress shielding · Bone remodelling

Introduction

Aseptic loosening after total hip arthroplasty (THA) is one of the greatest burdens that orthopaedic surgeons will face in the future. This issue has been addressed with the development of new, shorter implants with cementless proximal fixation and proximal load transfer to achieve physiological loading patterns. However, these “short-stemmed” implants are not suitable for every femur or patient. We frequently see cases where we need to implant a straight, “standard” stem, thus providing a more distal, intertrochanteric, metaphyseal/diaphyseal loading, particularly for young and active patients. On the one hand, development of better bone-preserving implants needs to be pushed beyond short stems; on the other hand, we need to look back and analyse established and clinically approved implants to find out what made them successful. Established designs can be assessed by evaluating the redistribution of mechanical forces and femur remodelling around the THA implant. Dual-energy X-ray absorptiometry (DEXA) is the gold standard for this purpose [1] but can be time consuming, expensive and uncomfortable for the patient. In the rapidly developing field of THA implants, DEXA cannot be carried out for every new type of implant, although such investigation would be reasonable before clinical application. Finite element analysis can help with these concerns. This analysis is a numerical method of simulating periprosthetic bone remodelling under different conditions; e.g. after THA. We believe that each new implant should undergo a critical

M. Lerch (✉) · H. Windhagen · C. M. Stukenborg-Colsman ·
A. Kurtz
Department of Orthopaedic Surgery, Hannover Medical School,
Anna-von-Borries Str. 1-7, 30625 Hannover, Germany
e-mail: matthias.lerch@ddh-gruppe.de

B. A. Behrens · A. Almohallami · A. Bouguecha
Institute of Forming Technology and Machines, Leibniz University
Hannover, Hannover, Germany

analysis concerning bone remodelling before clinical application. However, before we can take this step, we need to find out what design and what implant shape will make the bone remodel as it does. Thus, the aim of this study was to establish a numerical model of a cementless straight stem that has provided good, long-term results and been used successfully in its unaltered since 1986/1987 [2–4]. We performed a numeric simulation of the cementless Bicontact® straight stem and validated it with bone density data derived from a prospective DEXA investigation [5].

Patients and methods

The study was conducted using the Bicontact® stem, a cementless, proximal, microporous (plasma-sprayed) titanium-coated implant made of a titanium forged alloy (Ti6Al4V). It has a flat, rectangular shape, lateral fixation fins and a dorsal antirotation wing to give the stem primary stability and proximal force transmission in the intertrochanteric region [5, 6]. The ten to 15-year results of Bicontact® uncemented THA show satisfactory pain relief, good functional results and durable implant stability with excellent stem survival. No revisions for aseptic loosening and no radiographic stem loosening have been documented [4]. We have 20 years of experience with this THA system, and we have implanted it 555 times in 2012.

For numeric investigation, computed tomography (CT) of a physiological male femur was carried out to generate a meshed, solid model using ten-noded tetrahedral elements [7]. The distribution of the apparent bone density (ABD) was calculated from measured Hounsfield units (HU) and then translated into a finite element (FE) model [8]. Young's modulus of the bone was coupled with the ABD using a function described by Carter et al. [9]. Elements of the upper part of the femur were grouped in seven separated sets according to Gruen et al. [10], exactly as done for femurs in clinical DEXA investigations [5, 11] (Fig. 1). The subroutine used in the FE calculation was modified to calculate changes in bone density in each individual zone.

The stem was virtually implanted according to the manufacturer's manual using the preprocessor software HyperMesh (Altair Engineering GmbH, Böblingen, Germany). The proximal coating was given a higher friction coefficient ($\mu=0.2$; $\mu_{\text{coating}}=0.8$), and the implant had consistent volumetric meshing to simulate full bonding to the bone when equilibrium is reached. The strain-adaptive bone remodelling was computed following Behrens et al. [7], simulating physiological loading patterns with the use of the entire gait cycle and the boundary conditions described by Speirs et al. [8]. The bone-adaption law used was that previously described by Behrens et al. [7]. Hip-contact forces and muscle forces were taken from the investigations of Bergmann and Duda [12, 13].

Fig. 1 Finite element model of the femur after virtual implantation of the Bicontact stem; seven separated sets according to Gruen et al. [10] were calculated

We used a reduced muscle system, with the acting points of the forces being those of Heller et al. [14]. The system consisted of abductor muscles (gluteus muscles), the tensor fascia latae muscle and the medial and lateral vasti of the quadriceps muscle. The final state was reached when the convergence criterion was achieved (Fig. 2).

For clinical validation of our numeric model, DEXA data from a previous investigation on the same implant were taken [5]. In brief, a consecutive series of 25 patients with unilateral Bicontact® stem implantation was prospectively analysed by DEXA preoperatively and at one week, six months, one year and two years after surgery. Mean age was 68 (range 51–77) years, and mean preoperative body mass index was 27.5 (range 20.0–35.0). The bone mineral density (BMD, g/cm^2) of

Fig. 2 Bone mass change (g/cm^3 and %) over the course of 52 computation steps

the operated hip was measured in seven conventional Gruen zones [10] using a HOLOGIC Discovery A S/N 80600 device (Hologic Inc., Waltham, MA, USA) in metal-removal hip-scanning mode. Data collected one week after surgery served as baseline values for the following DEXA examinations. In a second review of the scan sheets, the detected bone area was analysed in each region. Shapiro–Wilk tests showed no normal distribution for DEXA measurements; a Wilcoxon signed-ranks test was used to statistically compare density changes. A p value <0.05 was considered significant. Data analysis was performed using SPSS software (11.05 SPSS Inc. Chicago, IL, USA).

Results

Figure 2 shows the evolution of the ABD over the course of 52 increments. The loss of bone mass converged to 9.25 % for the entire femur. No change in ABD was calculated distal to the tip of the prosthesis. The decrease in ABD around the proximal half of the implant was 46.2 %; diaphyseal bone density decreased

by 7.6 % (Fig. 3). To compare calculated and measured bone remodelling, changes in BMD obtained from the DEXA investigation [5] and changes in bone density calculated using the FE model in each region of interest are given in percentages, and the difference is taken (Table 1). In regions R2, R3, R4 and R5, the difference between measured and calculated bone densities is around 5 %; this increases to 10 % in R1 (greater trochanter). The best agreement between numeric data and DEXA values is observed for the smooth aspect of the implant. The deviation between the FE calculation and DEXA data is especially noticeable in R6 (distal minor trochanter region) and R7 (calcar region). Overall deviation in all regions is 17.7 %. Only R7 showed a significant decrease ($p < 0.005$) in scanned bone area (Fig. 4), whereas the area remains constant in the FE. DEXA recorded a baseline BMD of $1.08 \text{ g}/\text{cm}^2$ in R7 with a scan area of 3.3 cm^2 . This equates to a bone mass of 3.546 g. In the final scan, we found a BMD of $0.99 \text{ g}/\text{cm}^2$ on 1.9 cm^2 , for a bone mass of 1.88 g. Hence, the adjusted bone mass reduction is 47.4 %, for a deviation to the FE calculation of only 28.6 %.

Fig. 3 Apparent bone density changes in the proximal and diaphyseal regions directly after implantation (initial state) and after reaching convergence (final state)

Discussion

Although good results after THA are reported, THA implants need to be further improved. We need to ask how can we make what could be the first major revision in 20 years as successful as the primary procedure. New revision techniques have been developed alongside new grafting techniques and modern implants. However, we believe that the best results of revised arthroplasty can be achieved by keeping the revision procedure in mind when performing the primary THA. An important step was the introduction of real-neck-retaining short-stemmed implants, but the application of this implant is not easy in daily practice. There are numerous patients who should be treated

with a strategy of preserving bone, but the short-stemmed implant would fail in most of their femurs. In our research, we search for stem design and shape that will make the bone remodel as it does in reality. The objective of this study was thus to develop a validated numeric model of a relatively successful cementless, standard straight-stem implant to establish a basic numeric model for further simulations.

For a realistic simulation of bone remodelling in the periprosthetic femur, several important factors need to be considered. Firstly, the entire gait cycle should be used to obtain physiological loading patterns. We know from Speirs et al. [8, 15] that loading constraints play an important role in numerical load computations for the femur. Behrens et al. [7] examined several loading cases and then considered the entire gait cycle in the loading regime. Their results varied widely and showed that it is necessary to examine all loadings of a gait cycle in a realistic numeric calculation. In similar investigations conducted by Bitsakos et al., only static loading cases at 10 %, 30 % and 45 % of the gait cycle were considered, and the constraint at the femoral head was missing [16]. As in other research [17–20], only the proximal femur was considered in their study. However, this does not correspond to physiological reality [13]. We therefore carried out the calculation for the entire femur in our study in order to represent the physiological situation. Furthermore, it is of great importance to calculate the proximal rough portion of the implant with a high friction coefficient. We are aware that there will be micromotion in the months following implantation and that full bonding of the bone should be simulated to obtain correct data representing long-term conditions.

Table 1 Calculated and measured changes in bone density (negative values indicate decreases). DEXA data are derived from [5]

Gruen zone (R)	DEXA (%)	FEM (%)	Deviation (%)
R1	− 12.9	− 23.5	10.5
R2	− 6.3	− 9.1	2.8
R3	− 0.6	− 8.8	8.2
R4	+ 1.1	− 3.3	4.3
R5	− 4.7	− 1.8	2.9
R6	+ 4.2	− 23.2	27.5
R7	− 8.3 (− 47.4 ^a)	− 76.0	67.7 (28.6 ^a)

R regions of interest DEXA dual-energy X-ray absorptiometry, FEM finite element method

^a Values adjusted to area reduction

Fig. 4 Analysis of scan area of R7 (calcar region) over the study period in the dual-energy X-ray absorptiometry (DEXA) analysis [5]; the detected bone area decreases significantly ($p < 0.005$) by 42.4 %

The numeric model agrees well with DEXA data in the smooth sections of the implant. However, areas with a rough titanium surface tend to have greater deviation between numeric and DEXA data. As a consequence, physiological influences of the proximal microporous structure of the prosthesis surface must be considered. Li et al. [21] found that the proximal properties of their investigated implant encourage bone ingrowth in the plasma-sprayed layer, which mitigates stress concentration and thus the unloading as well as the overloading ratio of bone tissue. Titanium-coated implants will behave differently when bone ingrowth has taken place, particularly in terms of stress shielding [21]. Proliferation of bone cells will increase as another consequence of these coating properties [22]. From a mathematical point of view, both effects might explain why bone in the proximal regions (R7, R6) does not lose density on DEXA as it does in FE analysis. In other words, bone remodelling as a reaction to unloading would be first activated by a higher unloading ratio in regions where bone tissue grows at the microporous surface of the prosthesis. However, the interactions between the titanium coating, bone reaction and the implant itself are complex and not yet fully understood. Therefore, we are not yet able to incorporate such data in our model. A careful analysis of DEXA data reveals another possible reason for the significant difference between calculated and measured changes in bone density in R7 and R6; i.e., stress shielding in the proximal calcar might be so strong (as indicated in the numerical data) that the DEXA system is unable to record the remaining bone surface and thus excludes the bone from the measured BMD in this area. Hence, the remaining bone density is recorded and gives a falsely high value for the measured affected area (Fig. 4). This increases the

effect of a load shift to a more distal area (R6) where even positive values were recorded on DEXA. This phenomenon was previously seen in an investigation of a short stem [23, 24] but has not yet been seen in densitometric studies of straight stems. A stress concentration at the medial proximal part of the femur (R6) was previously described as a possible contribution to long-term implant survival of short-stemmed implants [23], but it is unclear whether this hypothesis can be assigned to a straight stem.

In a former DEXA investigation, Braun et al. [25] studied bone mineral changes lateral (corresponding to R1) and medial (corresponding to R6) of the proximal, plasma-sprayed, rough area of the same implant. The phenomenon of scan area reduction was not reported, but their results 12 months after surgery are similar to ours. We thus conclude that our measurements are correct and reproducible for this implant.

We observed an area reduction of 42.4 % in R7 (Fig. 4) in which we anticipate the bone density to be zero. We adjusted the recorded bone density to the area reduction and calculated a bone mass loss of 47.4 % in R7. After this, deviation to our model was only 28.6 %. Excluding the regions with false measurements, mean deviation is only 4.5 %, which is an excellent result that highlights the accuracy of our calculations.

There are some limitations to this study. Only one physiological femur geometry was modelled; hence, we cannot predict how different femur morphologies would remodel under the influence of the investigated implant. The most important and time- and money-consuming procedure in FE is the development of a representative model. This consumed most of the available capacity for the study's subproject. However, a next step must be the development of multiple

pathological femur models to aid the surgeon in defining the limits of an implant. Also, relevant patient-related factors (obesity; osteoporotic bone stock) were not included in the model; however, they will be important when defining the longevity of the implant. The data available for computing these biological factors is vague and would have caused considerable bias and weakened the model's predictability. However, we developed a basic model by which to investigate femoral pathologies and patient-related factors when reliable biological data is available.

In conclusion, the numeric model reported here is able to anticipate bone remodelling after implantation of the Bicontact® stem with good accuracy. In future work, we will further improve our FE model for the proximal rough titanium coating. We have developed a numeric model with which to simulate different stem-design modifications and find the optimal geometry for avoiding stress shielding and enhancing physiological remodelling patterns in the periprosthetic femur. This will help in analysing bone remodelling for new implant designs before their clinical application.

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Conflict of interest The authors declare that they have no conflict of interest.

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