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Bone remodeling in the resurfaced femoral head: Effect of cement mantle thickness and interface characteristics

M.A. Pérez[a,*], P.-A. Vendittoli[c], M. Lavigne[c], N. Nuño[b]

[a] *Aragón Institute of Engineering Research (I3A), University of Zaragoza, Zaragoza, Spain*
[b] *Département de génie de la production automatisée, École de technologie supérieure, Laboratoire de recherche en imagerie et orthopédie, Université du Québec, Montreal, Quebec, Canada*
[c] *Department of Surgery, Université de Montréal, Maisonneuve-Rosemont Hospital, Montreal, Quebec, Canada*

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Metal-on-metal hip resurfacing prostheses were re-introduced during the last 10–15 years. These prostheses have the potential to better restore normal function with limited activity restriction, being an option for younger and more active patients. Resurfacing procedures have demonstrated high failure rates in national registers [1,2]. Multiple factors may affect early and long-term HR performance. The influence of femoral cement mantle thickness and different interface characteristics between the prosthesis components on the long-term performance of resurfacing prostheses is still unknown. In the present work, a model was used to predict bone remodeling with different mantle thicknesses and interface characteristics. A very thin cement mantle (0.25 mm) increased bone resorption at the superior femoral head, while greater thickness (1 or 3 mm) had a lesser effect. In all cases, bone apposition was predicted around the stem and at the stem tip. Bone formation and resorption were observed clinically in good agreement with the predictions calculated in simulations. Computed results showed that 1-mm cement mantle thickness combined with a bonded bone–cement interface and a debonded implant–cement interface was an appropriate configuration. Bone remodeling results and computed equivalent strains were correlated. In conclusion, we have been able to demonstrate the importance of choosing an adequate cement mantle thickness. Additionally, computational studies should consider realistic interface characteristics between the components in order to perform simulations closer to reality.

1. Introduction

Metal-on-metal hip resurfacing prostheses (HR) are used nowadays as an alternative to total hip arthroplasty (THA), especially for young and active patients [3,4]. HR have some improvements over THA, i.e., minimal femoral bone resection, easier revision, reduction of stress shielding in the proximal femur, more reliable restoration of physiological biomechanics and a lower dislocation rate [5–9]. However, some resurfacing implants presented high failure rates in national registers and published cases series [1,2,10–12]. Klotz et al. [13] obtained that the survival rate after 5–6 years was 96.3%, after 7–8 years 93.8% and after 9–10 years 90%. They detected two major problems: aseptic loosening (34.4%) and fracture of the proximal femur (31.9%). Jameson et al. [14] observed that 96.4% of HR 7 years post-op did not undergo revision surgery. Murray et al. [15] reflected a ten-year survival of 74% in some particular designs in female patients and in small size joints due to the materials used in the bearing surfaces and the biological reactions they can elicit. These reactions are also responsible for the largest shift away from HR clinically. Multiple factors may affect early and long-term HR performance, for example, surgical technique problems, such as femoral neck notching, improper implant position/seating or poor cementing techniques [16,17], could occur with consequent aseptic loosening or neck fracture [16]. Narrowing of the femoral neck has been observed after HR, although in most cases associated with no adverse clinical or radiological outcome up to a maximum of six years after the initial operation [18]. In the long-term, migration of the femoral component was observed and the femoral components which had not migrated had radiological changes of unknown significance [19]. Previous observations could be directly related with bone remodeling around the HR components. The cementing technique is one of the speculated factors that might contribute to the long-term survival of HR [20,21]. Krause et al. [21] demonstrated that most failures were cemented inappropriately. Among the possible causes were both biological (thermal necrosis or interface biological reactions) or mechanical (inadequate initial fixation).

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* Corresponding author at: Mechanical Engineering, University of Zaragoza, Ed. Betancourt-Campus Río Ebro, C/María de Luna, 50018 Zaragoza, Spain.
Tel.: +34 876 55 52 13; fax: +34 976 76 26 70.
E-mail addresses: angeles@unizar.es, mangelespa@hotmail.com (M.A. Pérez).

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In the latter respect, computational studies could help to predict implant behavior after surgery, mainly when long-term clinical results are still not available. Finite element analysis (FEA) is a well-established method for assessing changes in mechanical stress and strain in complex structures [22]. Kuhl and Balle [23] and Gupta et al. [24] undertook bone remodeling analysis by comparing HR and THA performance. They reported that HR improved bone density distribution in the long-term with respect to THA. Some computational studies have focused on determining post-surgery changes in femoral bone stress and strain that resurfacing prostheses produce [24–32]. Most of previous FE studies have shown that fixing the full length of metallic stems, either by using cement or as a result of osseointegration leads to decreases in stress and strains in the femoral head bone [27,29,33,34].

Gupta et al. [24] concluded that resurfacing caused a reduction of strain in the bone underlying the implant (bone resorption) and elevated strains around the proximal femoral region indicating a potential risk of fracture. Pal et al. [29] indicated that resurfacing led to strain shielding of the bone of the femoral head and periprosthetic bone resorption for all interface stem–bone contact conditions. Taylor [27] observed that increasing the stem diameter and increasing the percentage stem length is in contact with bone both increased the degree of strain shielding. He also concluded that cement mantle thickness had a negligible effect on the load transfer. Similar results were predicted by Pal et al. [30]. They investigated the influence of a short-stem resurfacing component on load transfer and bone remodeling. The short-stem led to a more physiological stress distribution and bone resorption was considerably lower than with a long-stem. They also analyzed the effect of different bone–stem interface conditions. Little et al. [28] found that HR FE models showed bone strains closer to the intact conditions and that bone stresses predicted after resurfacing in both normal and aged femoral neck were not sufficient to be a potential cause of fracture.

Several studies have proposed solutions to previous HR limitations. Pal et al. [35] used a ceramic prosthesis instead of metallic. High stress coupled with increased strain shielding in the proximal femoral next region appeared to be a major concern regarding its use as an alternative material. Caouette et al. [36] incorporated a biomimetic stem which did not eliminate the strain shielding effect but reduced it significantly versus a metallic cemented stem. Radcliffe and Taylor [33] analyzed the effect of different cementing techniques on load distribution in the resurfaced proximal femur, reporting that thicker cement mantles increase strain shielding. Others investigated the effect of varus–valgus orientation on load transfer and concluded that valgus alignment is preferential to varus alignment [34,37]. Ong et al. [38] studied the effect of extreme implant orientation and stem canal overreaming on initial bone remodeling stimulus. Rothstock et al. [39] investigated different interior implant geometries, cemented and uncemented solutions predicting that an uncemented press-fit implant could limit bone resorption. A more complex study was performed by Dickinson et al. [40] where they simulated prosthesis-bone interface healing with bone remodeling observing the progressive gap filling at the implant–bone interface.

To date, there are few published works on the effect of the cement mantle thickness and interface characteristics on HR [27,30,33]. Cementing technique affects not only cement penetration but also the initial stability of the femoral component [41]. Previous studies did not simulate bone remodeling [27,33], but analyzed the load transfer, i.e., strains for an immediate post-surgery situation. Additionally, little is known about the effect of the bone–cement and cement–implant interface conditions on bone remodeling. Bone–cement interface has always been assumed as completely bonded [27,30,33], and cement–implant interface was mainly assumed as bonded [27,33].

Therefore, the main goal of this study is to investigate the effect of different parameters on bone density increase and/or bone resorption evolution using bone remodeling on a three-dimensional (3D) FEA of a resurfaced cemented prosthesis. In particular, different cement mantle thicknesses (0.25, 1 and 3 mm) and interface conditions between the components were varied. A previously developed phenomenological bone remodeling model was tested to predict the bone response post-operatively [42]. The methodology presented in this paper is intended to improve the understanding on previous parameters (cement mantle thickness and interface characteristics between components).

2. Materials and methods

The 3D FEA model used in the present study was generated from CT scans of a single right male femur (46 years old). The medical images were segmented using Mimics software (Materialize, Leuven, Belgium) to obtain a personalized geometry of the femur. Finally, the proximal femur was reconstructed using Catia V5 (Dassault Systèmes, Suresnes, France) and the resurfacing prosthesis was implanted. The implant design is based on the clinically used Zimmer Durom implant. While this implant is no longer commercially available, owing to failures related to the acetabular cup, the femoral component geometry of this implant is similar to all the other implants, hence its use in this study. Arthroplasty simulation was oriented at 5° valgus with respect to the neutral axis line of the femoral neck (Fig. 1), as recommended by Amstutz et al. [16]. The resurfacing prosthesis was composed of a small and polished stem attached to the spherical component, hereinafter referred to as ‘the implant’. To investigate the effect of cement mantle thickness, three different models were created to represent different gaps between the femoral head and the inner face of the implant: 0.25, 1 and 3 mm keeping the stem geometry constant (diameter of 6 mm). One milimeter is the closest to a current clinically achieved cement mantle thickness [16]. The three different configurations were modeled for a constant femoral component with outer diameter of 50 mm and inner diameter of 42 mm. In reality, the cement is interdigitated with cancellous bone, however for simplicity this was modeled by a layer of cement. The 0.25- and 1-mm configurations ensured no notching of the femoral neck, although notching was necessary for implantation in the 3-mm configuration (Fig. 1).

Four-noded tetrahedral solid elements were used in automatic finite element mesh generation with Harpoon v2 (Harpoon Sharc Ltd., Manchester, UK). The different models consisted of approximately 220,000 elements and 40,000 nodes each (Fig. 2). The element size used is inside the asymptotic region of convergence and represents a good trade-off between numerical accuracy and computational cost (results not shown).

Bone tissue was considered to be anisotropic and heterogeneous. Mechanical properties of bone were predicted by means of a remodeling computational model, able to evaluate the evolution of bone porosity and anisotropy as a function of the mechanical conditions [42,43]. Following the scheme proposed by Doblaré and García [42] to simulate bone remodeling, three different forces that simulate the gait cycle were considered as loading conditions, specially the forces when the foot touches the floor and the other two alternative situations of abduction and adduction, respectively [42,43]. Hip contact forces were imposed as a uniform load on nodes of the femoral head surface (see Table 1). Only abductor muscle force was considered. Loading configuration, including hip-joint contact force and abductor force, can adequately reproduce in vivo loading [44].

Initially with the femur intact, all elements were considered as bone, presenting an initial homogeneous isotropic density of 0.5 g/cm^3 (Fig. 3). After the application of the forces defined above