Densitometric evaluation of periprosthetic bone remodeling

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Summary

The application of Dual-energy X-ray absorptiometry (DEXA) in orthopaedic surgery gradually has been extended from the study of osteoporosis to different areas of interest like the study of the relation between bone and prosthetic implants. Aim of this review is to analyze changes that occur in periprosthetic bone after the implantation of a total hip arthroplasty (THA) or a total knee arthroplasty (TKA).

Introduction

The application of Dual-energy X-ray absorptiometry (DEXA) in orthopaedic surgery gradually has been extended from the study of osteoporosis to different areas of interest like the study of the relation between bone and prosthetic implants. In particular DEXA can be used for the study of:

- the characteristics of bone before surgery to assess patient's global bone mineral density (BMD);
- the reaction of bone to the implant to quantify the entity of bone adaptive remodeling;
- the periprosthetic bone stock to quantify the presence of area of bone loss around the implant;
- the efficacy of antiosteoporotic drugs (i.e. bisphosphonates) in the treatment of periprosthetic bone loss.

Aim of this review is to analyze changes that occur in periprosthetic bone after the implantation of a total hip arthroplasty (THA) or a total knee arthroplasty (TKA).

Total hip arthroplasty

Total hip arthroplasties have been one of the major successes of modern surgery in terms of relieving pain and correcting deformity; each year approximately one million of total hip arthroplasties is performed worldwide. A broad view from the literature shows that 90-95% of hip replacements are successful for 10-15 years but there is still a small significant rate of failure. Most of long term implants failure are due to aseptic loosening, (74.9% of primary hip implant revision), in which periprosthetic bone loss leads to implant instability, pain, and increased risk of periprosthetic fractures. These complications will become significantly more common because today total joint replacements are performed on increasingly younger patients with a very long life expectancy. Proximal bone resorption around femoral stems is commonly seen after cementless total hip arthroplasty. The reasons for this phenomenon include stress shielding (bone remodeling) and an inflammatory reaction to small particles produced by the various wear modes (bone resorption). Serial plain radiographs can provide useful information on periprosthetic bone remodeling, and grading of stress shielding is possible using Engh’s method (1). This radiographic evaluation of the periprosthetic BMD by human eyes, however, is not so sensitive to small changes in BMD and it is not quantitative. Dual-energy X-ray absorptiometry (DEXA) is a precise method to quantifying bone mass and small changes in BMD around femoral implants after total hip arthroplasty.

Stem. Remodeling patterns around a femoral stem are affected by several factors. These include patient-related factors, such as gender, age, initial femoral bone stock, patient activity, and underlying-disease as well as prosthesis-related factors, such as the type of fixation, stem length, stiffness, design, the extent of the coating area, and the method of

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femoral bone preparation (2-7). One of the first authors that studied periprosthetic bone quality and the reaction of bone to the prosthesis was Gruen in 1979 (8). In his work “model of failure” he standardized the 7 zones around the stem that must be studied to evaluate aseptic loosening (Zone 1: Greater trochanter; Zone 2: Proximal lateral; Zone 3: Distal Lateral; Zone 4: Tip; Zone 5: Distal Medial; Zone 6: Proximal Medial; Zone 7: Calcar). This classification was used on first with cemented implant but it became useful also with cementless implant and today it is used with dual energy X-ray absorptiometry (DEXA).

The pattern of BMD changes with different uncemented femoral stems in primary THA is mainly related to the stem’s design and more specifically it is influenced by the region of the stem fixation on bone and thereby where stress is created on the surrounding bone. Cementless femoral stem can be divided in two main types: conventional stem and short stem.

**Conventional stems.** According to Khanuja et al. most of conventional cementless stem can be classified into 6 types (9). In this classification, Types 1 through 4 are straight stems, and as the number increases so does the fixation area. Types 1, 2, and 3 are tapered, designed to obtain more proximal fixation and Type 4 is fully coated to obtain distal fixation. Type 5 is a modular prosthesis, and Type 6 stems are curved with anatomic design. In the following we report the main studies about the densitometric evaluation of periprosthetic bone remodeling in the most implanted stems.

- **Single-wedge stems (Type 1),** are designed to engage metaphyseal cortical bone in one plane: medial to lateral. They are flat and thin in the anterior-posterior plane. The component narrows proximally, primarily in the medial lateral plane, and tapers distally. The tapered CLS® Sprotorno® (Zimmer) stem is a collarless titanium alloy single wedge design. This design is associated with a moderate bone loss in Gruen zone 7 (calcar). Roth et al. reported a loss of 19% after 1 year (10), Sabo et al. reported a 12% loss after 2 years (11), while in a 10-year comparison of 4 different stems with DEXA, Karachalios et al. reported a progressive recovery in BMD for all 4 designs from 2-10 years postoperatively (12). Gibbons et al. published a comparison study between the CLS® stem and the AML® (DePuy Synthes) stem reporting respectively a 20% (CLS®) and a 38% (AML®) decrease in zone 7 after a mean of 4 years (13). Bone remodeling around the CLS® stem was also evaluated at 12 and 17 years postoperatively reporting the lowest relative BMD values in the calcar region (zone 7) (14).

- The **tapered femoral stems (Type 3A)** use proximal cancellous bony ingrowths and three-point stem fixation to obtain immediate stability. The stems are often straight and wedged in a tight mechanical fit in the lower metaphyseal region. In the Bi-Metric™ (Biotech) uncemented femoral stem bone mineral changes were greatest in Gruen zones 1 and 7, where the losses were 31 and 26%, respectively, after 2 years (15). The authors also reported a continuous decrease in BMD continued in the calcar region after 14 years after implantation. Olof reported a bone mineral density decrease of 19% in both Gruen zones 1 and 7 (16). Bone loss in zones 1, 2, 6, and 7 was also significantly associated with stem size. The authors found a marked proximal BMD loss, especially for the larger stems, which may be specific for this particular implant.

- The **rectangular, tapered stems (Zweymüller Stem)** (Type 3C) have a rectangular cross section that obtains three-point fixation in the metaphyseal-diaphyseal junction and proximal part of the diaphysis. Korovessis et al. and Brodner et al. studied the tapered rectangular titanium cementless Alloclassic® Zweymüller® Stem (Zimmer) which after 4 years in longitudinal studies showed only 7 and 14% loss in zone 7, respectively (17, 18). Albanese et al. in a comparative study between 6 different stem designs confirmed the presence of bone loss in zone 7 (calcar) in the Alloclassic® group (19). The Alloclassic® stem is associated to a significant increase of BMD value in zone 4 under the tip of the stem according to the distal fixation philosophy of this stem design.

- **Anatomic stems (Type 6)** that match the proximal femoral endosteal geometry. They are wider proximally, both laterally and posteriorly (20, 21). In the lateral plane, they bow posteriorly in the metaphysis and anteriorly in the diaphysis. These stems have anteverision of the neck and are produced for right or left femora. Distally, they are either tapered or cylindrical. The use of a titanium anatomic stem coated with hydroxyapatite in the proximal metaphyseal region only (ABG™ Stem Stryker) is associated with a gradual decline in bone mineral density in zone 7 (calcar) to an average of 72.1% of the preoperative value by 24 months. The absence of loading on the calcar explains the bone loss in the area of the lesser trochanter with this type of stem (22). In 2010 Gracia published a densitometric comparison study between ABG-I™ and ABG-II stems (23). The main differences between both stems concern geometrical design and material. The overall length has been reduced by 8% and the proximal and distal diameters by 10%. With the ABG-I™ a decrease in BMD was detected in all zones except zone 4, six months after surgery. Between 6 and 12 postoperative months there was a slight additional loss of BMD in zones 1 and 7. With the ABG-II™ the bone loss was statically significant only in zone 7. The study of both groups using DEXA at 5 years shows less proximal bone atrophy in the ABG-II™ Group (23).

**Short stems.** The new short stems hip implants, with a metaphyseal anchorage, are designed to mimic the physiological load transfer on the proximal femur minimizing the effects of stress-shielding and bone loss especially in younger patients in which further revision surgery are predictable. The maximum preservation of the metaphyseal bone stock is regarded as advisable to facilitate revision surgery when aseptic loosening occurs. All these study showed that the maximum bone remodeling takes place within six months after surgery and reaches a plateau after one year. The use of a short stem is associated to an high load distribution on the medial portion of the femur (calcar region) which is an important region to guarantee long term implant survival. Therefore the correct positioning and good bone quality are important factors for short stem to obtain the best load distribution.

- **Femoral neck preserving prosthesis.** In 2008 Decking published the results obtained with a femoral neck preserving prosthesis (24). This stem is made of CoCrMo alloy and has a macroporous surface structure. The highest decrease of BMD, more than 3%, was recorded in the three proximal regions 1 and 7, while the smallest decrease was observed in region 3, where the lateral flare...
of the implant pushes against the lateral cortex of the femur. The change in all regions of interest were statistically significant at three months. However, 12 months postoperatively the BMD was similar to the initial values recorded shortly after the surgery. All regions on the lateral proximal femur showed a significant change with the highest increase recorded in region 3 (+2.84%) (24).

In a prospective dual-energy X-ray absorptiometry study BMD around a short stem (Metha® B-Braun) was examined (25). This stem has a proximal rough titanium, plasma-sprayed, microporous coating and an additional 20 micrometric osteoinductive dicalcium phosphate coating. The stem is anchored metaphysically within the closed ring of the femoral neck. Bone mineral density (BMD) in the greater trochanter decreased significantly from 0.78 g/cm² postoperatively to 0.72 g/cm² two years after surgery. Marginal changes were seen in the lateral distal regions (R4-R5). In the minor trochanter region BMD increased significantly after two years by 12.9%. In the calcane region BMD decrease was 7.6% in the first six months but recovered in the following 18 months and exceeded the baseline value by 6.1% two years after implantation. The authors concluded that the use of the Metha® stem is associated with a concentrated load distribution on the medial portion of the femur while a limited stress shielding seems to occur at the greater trochanter due to the vast cross-section of the stem (25).

In 2013 Lazarinis published a prospective study of 30 patients receiving the collum femoris-preserving (CFP® Link) stem (26). CFP® stem is a curved hydroxyapatite-coated stem introduced by Pipino and Calderone in 1987. In Gruen zone 7 the decrease 1 year after surgery was 31% (p<0.001), whereas a decrease of 19% was seen in Gruen zone 6 after 1 year (p<0.001). 2 years after insertion of the stem, periprosthetic bone loss remained substantial in Gruen zone 7 (28% reduction after 2 years; p<0.001) and 6 (19% reduction after 2 years; p<0.001), without any signs of recovery when compared with baseline values. In contrast, periprosthetic BMD did recover to baseline values in Gruen zones 1 and 3. A modest recovery was also found in Gruen zone 5 although the reduction in BMD in this region after 2 years remained compared to baseline values (p=0.03). Authors conclude that substantial loss in proximal periprosthetic BMD cannot be prevented by the use of CFP® stem, and forces appear to be transmitted distally (26). Other study have found similar pattern of BMD reduction in the proximal femur around the CFP stem (27, 28). However this bone loss does not appear to influence clinical outcome in the medium term (29, 30).

Zeh et al. in 2013 report the results obtained with the Nanos® (Smith&Nephew) short-stemmed femoral prosthesis (31). The evaluation of the DEXA scan preoperatively and on average 3 months and 1 year postoperatively showed a significant and constant decrease of the BMD in zone 1 (15%), 2 (5%) and 7 (15%), and a significant moderate increase of BMD in Gruen zone 6 (12%). These finding are interpreted as a result of a distally located load transfer and a moderate proximally located stress-shielding with only a limited increase or preservation of bone mass at the calcane region (31). These results are in accordance with the report of Gotze et al. who found with the Nanos® prosthesis a bone loss of approximately 7% at the calcane region and 6% at the major trochanter (32).

Compared to results of other analyses, these findings suggest only a moderate bone loss at the calcane region after implantation of the Nanos® stem approximately one year postoperatively. The authors conclude that Nanos® prosthesis can reduce the loss of BMD of the proximal aspect of the femur compared with conventional stems and other short-stemmed implants (31).

Short-stemmed prosthesis. Chen et al. in 2009 published the results obtained with the use of a double-tapered short stem (Mayo® Conservative Hip Zimmer®) designed to obtain a metaphyseal fixation (33). After 5.7 years of FU a significant decrease was found proximally in zone 1 (-14.4%), zone 6 (-14.4%) and zone 7 (-17.9%). In zone 4 (distal region) and zone 5 (medial-distal region), the BMD was also decreased by 5.3% and 1.0%, respectively. As suggested from the authors these pattern of periprosthetic bone changes were defined by design characters of the short-stemmed implant: in the implant cortex contact areas, high stress occurred with increased bone density (zones 2 and 3). In other areas in which stress transfer was minimal, significant bone resorption was found (33). Kim et al. reported the results obtained with the use of a metaphyseal fitting cementless anatomical short femoral stem (Proxima™ DePuy) (34). After 4.5 years the BMD was slightly decreased in Gruen zone 7, but it was increased slightly in zone 1. In a study published in 2011 the Proxima stem was compared with the Nanos stem in terms of osteointegration after one year (35). In Nanos stem a significant higher BMD values were observed in region of interest (ROI) 3 and 4 (p<0.05). No differences were found in ROIs 1, 2, and 5 between the 2 stem.

In a multicentre clinical study published in 2006 the DXA method was used to compare bone mass after un cemented THA between custom made stemless design (Santori custom made, DePuy) and five types of conventional stems (Alloclassic®, Mayo®, CFP®, IPS™, ABG®) after 3 years (36). Significant differences were found between stemless implants and the other five groups in zone 1, 4 and 7. In comparison with custom-made Santori, in zone 1 (greater trochanter) a significant BMD decrease was detected in CFP®, IPS® and ABG® groups respectively. The lowest value of BMD was also detected in zone 7 (calcane) in Mayo®, IPS™, ABG® and Alloclassic® groups. These last groups also showed higher value of BMD in zone 4 (under the tip of the stem) (36).

In a further study published in 2009 two types of custom made stem designs with a large lateral flare, a fully coated stem with a short distal tip (type 1) and a ultra-short stem without distal tip (type 2), were compared by DEXA 3 years after surgery (37). Increased bone mass in the stemless implant was found in medial ROIs 4 and 5 and in lateral and medial regions when compared to the contralateral femur. In the stemless implant group, calcane bone loss was only 7% as compared to 24% loss in the short-stem group. The authors concluded that the ultra-short implant can provide a more physiological load distribution, thus increasing periprosthetic BMD in the medial regions over time (37).

Acetabular cups. Although two thirds of all revisions for aseptic loosening comprises an exchange of the cup poor attention has been paid to the study of periacetabular bone remodeling (38). Wilkinson and co-workers performed a study...
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on acetabular periprosthetic Bone Mineral Density measurements, by using a DEXA-scanner (39). They proposed a model with four regions of interest “The Wilkinson Regions” to offer the highest precision in BMD measurements. Laursen compared a porous coated Trilogy ® (Zimmer) versus Trilogy Calcicoat® (HA/TCP coated) (Zimmer) (40). Measurements revealed no differences between the two groups after 3 years either in the clinical outcome or in terms of periprosthetic bone density.

Hydroxyapatite coatings. An advantage of Hydroxyapatite Coating (HA) has been proposed by Rosenthall et al. who demonstrated that the Multiloc HA stem caused less bone loss after 2 years than the same stem with only porous coating (41). In a retrieval study by Coatham et al. the Bi-Metric stem was analyzed with and without HA and they noted more ingrowth and more proximal attachment of bone to the HA-coated implant surface than to the porous-coated implant (42). The use of a proximally HA-coated BI-Metric stem is associated to the same degree of proximal bone loss with time, suggesting that geometric design has a greater importance in periprosthetic bone remodeling. This is exemplified by the work of Rahmy et al. they compared 2 proximally HA-coated designs, the anatomic (ABG®) and the tapered (Mal- lory-Head™ Biomet) stems, and found 10% greater bone loss in zone 7 in the anatomic group after 3 years (43).

Cement fixation. To understand better the difference in periprosthetic BMD between cemented and uncemented implant Chandran et al. compared two different stems: one cemented (Charnley® Stem) and the other one uncemented and hydroxyapatite coated (Furlong® Stem) (44). They found a greater preservation of bone density in the distal medial and distal lateral cortex with the uncemented stem. This is in contrast with other studies that show a significant bone resorption in the lesser trochanter and in the medial and lateral femoral bone loss after 2 years than the same stem with only porous coating (41). In a retrieval study by Coatham et al. the Bi-Metric stem was analyzed with and without HA and they noted more ingrowth and more proximal attachment of bone to the HA-coated implant surface than to the porous-coated implant (42). The use of a proximally HA-coated BI-Metric stem is associated to the same degree of proximal bone loss with time, suggesting that geometric design has a greater importance in periprosthetic bone remodeling. This is exemplified by the work of Rahmy et al. they compared 2 proximally HA-coated designs, the anatomic (ABG®) and the tapered (Mal- lory-Head™ Biomet) stems, and found 10% greater bone loss in zone 7 in the anatomic group after 3 years (43).

Total knee arthroplasty

Total knee arthroplasty implantation alters mechanical loading of both femur and tibia and it could lead to implant loosening, periprosthetic fractures (i.e. supracondylar femur fractures) (45). Adaptive bone remodeling around the implant could also complicate the revision surgeries procedure of failed implant (46). In the current clinical practice the results of a TKA can be evaluated clinically (postoperative evaluation of knee function, pain ...) and radiographically. X-rays can be used to assess the implant position, the knee alignment, to evaluate the bone-implant interface and reveal the presence of knee infection or implant loosening (but often not at an early stage). However plain radiographs are not useful to evaluate the quantitative changes in periprosthetic bone especially at early stages. Like in total hip arthroplasty a DXA analysis could be used also in the assessment of bone remodeling of the tibial plateau and/or the femoral condyles after total knee arthroplasty (TKA). Robertson et al. have shown the superiority of DXA, compared to other methods, in assessing changes in bone mass after TKA (47). Liu 1995 reported a reduction of distal femur BMD after TKA ranging from 7% to 27% at 1 year after the operation (48). Soininvaara evaluated the bone mineral density changes in the distal femur and in the proximal tibia after total knee prosthesis implantation. This is exemplified by the work of Rahmy et al. they compared 2 proximally HA-coated designs, the anatomic (ABG®) and the tapered (Mal- lory-Head™ Biomet) stems, and found 10% greater bone loss in zone 7 in the anatomic group after 3 years (43).

Conclusion

The poor sensitivity of plain radiography has led DEXA becoming the method of choice to quantify periprosthetic bone loss after a prosthetic implant. Many factors may affect bone remodeling after total knee arthroplasty. The most important modifiable patient’s related factor seems to be the presence of a low systemic BMD before surgery (57). The pattern of adaptive bone remodeling with different cementless femoral stems varies and it appears to be strictly related to the design and more specifically to where the femoral stem is fixed on bone. Conventional cementless stem have shown a constant decreased of periprosthetic bone mineral density especially over the course of the first year following surgery. Short stems with metaphyseal fixation allow the maintenance of a more physiologic load transfer to the proximal femur decreasing the entity of bone loss. However a certain amount of stress shielding seems to occur also with short stems and
it seems to be related not only to the stem geometry, but also to the stem final position (varus/valgus). As shown by an in vitro study on composite femora, changes in strain patterns of the Metha® stem are induced by variation in the varus/valgus positioning of the implant and by different offsets (58).

As emerged from the literature review we believe that the main factors related to the entity of bone remodeling after THA are the patient’s preoperative bone stock, stem design and type of fixation and the presence and the extension area of bioactive coatings.

In total knee arthroplasty there were a constant decreased of periprosthetic bone mineral density especially at femoral level over the course of the first 3-6 months following surgery. Femoral bone loss after TKA seems to be related to the stress shielding induced by the implants especially at the level of the patello-femoral joint while tibial bone remodeling seems to be related to postoperative changes in knee alignment (varus/valgus) and consequently in tibial load transfer. Thus after both THA and TKA stress shielding seems to be an inevitable phenomenon that occurs mainly in the first year after surgery which suggests that pharmacotherapy should be considered as method for inhibiting the postoperative decrease of periprosthetic BMD. Bisphosphonate therapy seems to be effective in reducing periprosthetic resorption during the first decade after total hip arthroplasty: a DXA study at 12 and 17 years. Os- teoporos Int. 2011 Nov;22(11):2879-86.


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