International Orthopaedics (2020) 44:753–759
https://doi.org/10.1007/s00264-020-04486-0

ORIGINAL ARTICLE

Femoral bone remodeling after short-stem total hip arthroplasty: a prospective densitometric study

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Received: 9 October 2019 / Accepted: 15 January 2020 / Published online: 22 January 2020

Abstract

Purpose Due to improved prosthesis designs and surgical techniques, indications for total hip arthroplasty (THA) now include younger and more active patients. Preserving bone stock and soft tissue in these patients is paramount to allow for future revision. Designed for anatomical reconstruction, short femoral stems have the potential to reduce adaptive bone loss and stress shielding. To confirm this, we evaluated bone remodeling around a short femoral stem and the accuracy of hip joint reconstruction.

Methods This prospective observational study involved 46 patients with short-stem THA for clinical and radiographic analysis. We evaluated bone remodeling by Gruen zone using dual-energy X-ray absorptiometry in 45 patients and assessed the accuracy of hip joint reconstruction using caput-collum-diaphyseal angles. Additionally, we reported functional scores and pain.

Results Patients were followed for a mean of 24.1 (SD 2.2) months. Bone mineral density increased mainly in the lateral region (Gruen zones 2 and 3) and in the distal-medial region (Gruen zone 5), suggestive of lateral loading. Most caput-collum-diaphyseal angles remained stable after surgery, especially in patients with varus hips. Harris Hip Scores improved significantly, from 57.2 (SD 20.0) pre-operatively to 97.2 (SD 4.0) at 24 months post-operatively ($P < 0.0001$). Finally, we encountered one peri-operative dislocation but no post-operative complications.

Conclusion Short femoral stems successfully limited stress shielding and minimized periprosthetic bone loss without compromising primary stability. We were able to accurately reconstruct anatomical relationships in most patients. Finally, excellent clinical outcomes and low complication rates confirmed the favourable results of short-stem THA.

Trial registration: DRKS00017076

Keywords Total hip arthroplasty · Short-stem hip arthroplasty · Bone remodeling · Stress shielding · Bone mineral density · DEXA

Introduction

In its beginnings, total hip arthroplasty (THA) was mainly used in geriatric patients with low demands. However, thanks to improved prosthesis designs and surgical techniques, indications for THA now include younger and more active patients with higher demands. Because these patients are likely to undergo future revision [1], preserving bone stock and soft tissue during the initial surgery is paramount.

Short femoral stems have the potential to preserve more bone stock and soft tissue than conventional stems, since their metaphyseal fixation requires less resection, rendering the implantation less invasive [2, 3]. Owing to their metaphyseal fixation, short femoral stems are thought to provide better physiological load transfer with proximal strain distribution. While normal loading patterns of the proximal femur maintain bone structure, nonphysiological loading can induce adaptive bone changes [2, 4, 5]. In this regard, short femoral stems may reduce adaptive proximal bone loss and stress shielding when compared with conventional femoral stems with distal load transmission [6, 7]. Furthermore, short-stem fixation has the potential to reduce the incidence of nonanatomical reconstruction, periprosthetic fractures, and bone defects [8–10].

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Nevertheless, some uncertainty remains concerning the primary stability of uncemented short-stem fixation. Insufficient diaphyseal stabilization and the smaller bone-implant interface pose a challenge to the primary stability necessary for osseointegration of the prosthesis [9]. Moreover, different short femoral stem designs may result in varying bone remodeling patterns. Consequently, each design requires separate assessment to determine the adaptive bone changes induced.

In this prospective observational study, we therefore evaluated bone remodeling around a calcar-guided short femoral stem using dual-energy X-ray absorptiometry (DEXA). We also investigated the accuracy of hip joint reconstruction by measuring the caput-collum-diaphyseal (CCD) angle. We hypothesized that the prosthesis would limit stress shielding and minimize periprosthetic bone loss while allowing accurate varus/valgus positioning, thus adapting well to the patient's original joint anatomy. Finally, we assessed functional outcomes and complications.

Materials and methods

Study setup

This was a prospective observational study carried out at a single institution in Austria. The indication for short-stem THA was primary osteoarthritis. We excluded patients who had undergone previous surgery of the affected hip, had received arthroplasty for other joints of the lower limbs, required bilateral THA, suffered from relevant comorbidities, or were either unable or unwilling to participate in the study.

Patients were enrolled from November 2014 to August 2015 and examined clinically and radiographically before surgery and three, 12, and 24 months after surgery. Complications were recorded until the final follow-up examination.

Surgical technique and post-operative rehabilitation

All patients were placed in a supine position and received spinal or general anaesthesia. Five senior orthopaedic surgeons performed the procedures. They used an anterolateral muscle–preserving approach between the tensor fasciae latae and gluteus medius muscles in all cases.

All patients underwent uncemented short-stem THA. They received a calcar-guided femoral short-stem prosthesis with a titanium plasma spray and calcium phosphate coating (optimys stem; Mathys Ltd. Bettlach, Switzerland). This monobloc femoral stem has an osteoinductive coating and is available in 12 sizes with a standard or lateral neck. On the acetabular side, patients received a press-fit, monobloc acetabular cup (RM Pressfit vitamys; Mathys Ltd. Bettlach, Switzerland) made of vitamin E–infused, highly cross-linked polyethylene.

Full weight–bearing under the supervision of a physiotherapist was initiated on the first post-operative day. Patients were allowed to move the joint actively and passively restricting flexion initially. We prescribed rehabilitation for most patients and referred those unable to provide self-care to an inpatient rehabilitation program.

Dual-energy X-ray absorptiometry

We measured the bone mineral density (BMD) around the prosthesis before surgery to establish a baseline and at three, 12, and 24 months after surgery using the bone densitometer Lunar iDXA (GE Healthcare Lunar, Madison, WI, USA). We focused on the 7 Gruen zones adapted for femoral short stems (Fig. 1) [11] and recorded the absolute BMD. Additionally, we calculated the BMD change in each Gruen zone by dividing the measured BMD by the baseline value and expressed the ratio as a percentage. Finally, we calculated the correlation between post-operative CCD angles and DEXA measurements grouped by Gruen zone at 24 months.

For the DEXA scans, we placed the patients in the supine position and secured the operated leg at 20° of internal rotation, which allowed us to prevent measurement errors [12]. One investigator, blinded to the clinical outcome, analyzed all DEXA measurements. This investigator was not involved in the surgery or aftercare of the patients and did not have access to study data.

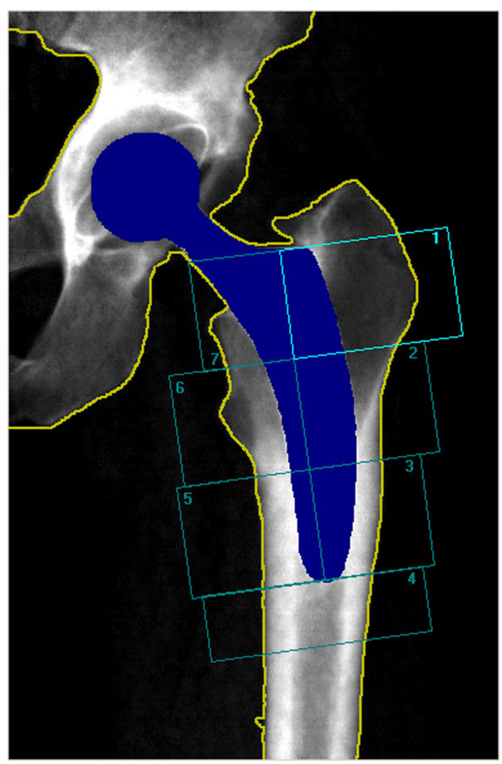

Fig. 1 Dual-energy X-ray absorptiometry image of the short-stem prosthesis with adapted Gruen zones

Radiographic evaluation

Pre-operative and directly post-operative radiographic examinations included a standing anteroposterior radiograph of the pelvis and an axial radiograph of the affected hip; the follow-up examinations consisted of anteroposterior and axial radiographs of the affected hip only. To locate periprosthetic abnormalities and bone loss, we used standardized templates as described by Charnley-Delee et al. and Gruen et al. [13, 14].

CCD angles were measured pre- and postoperatively in the anteroposterior radiographs and organized into five categories: A (less than 125°), B (125° to 130°), C (130° to 135°), D (135° to 140°), and E (more than 140°).

Clinical outcomes

We used the Harris Hip Score (HHS) to evaluate pain, functionality, and range of motion. The questionnaire included a visual analog scale (VAS) from 0 to 10 to assess pain at rest and under load. We also asked the patients to indicate their overall satisfaction on a scale of 0 to 10, with 10 representing the highest patient satisfaction.

Statistics

The power analysis predicted that relative mean differences of the DEXA value of 17.4% or more would be detectable in a paired t test with a power of 99.7% when including 45 patients.

Descriptive statistics included means, medians, standard deviations, 25% and 75% percentiles, and ranges. We compared between-group differences, such as in Gruen zones and CCD categories, with respect to DEXA values using nonparametric tests: the Wilcoxon rank-sum test in the case of two groups and the Kruskal-Wallis test in the case of more than two groups. We used chi-square tests to evaluate association between discrete variables and paired t tests to evaluate differences to baseline. The level of significance was set at 0.05 (two-sided) for all tests. All statistical analyses were performed with SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

Results

Study participants

Forty-seven patients were enrolled consecutively over the study period. Of these, one patient did not attend follow-up examinations and was lost, leaving 46 patients for the clinical and radiographic analysis. The DEXA analysis was based on 45 patients, censoring one outlier due to a very low baseline BMD. Lastly, one patient missed the 24-month follow-up examination due to terminal illness; this patient was included for all other follow-up time points.

Patients were followed for a mean of 24.1 (SD 2.2) months. They had a mean age of 65.7 (SD 9.3) years and a male-to-female ratio of 21:25.

Dual-energy X-ray absorptiometry

We found a significant increase in BMD in Gruen zones 2, 3, and 5 ($P < 0.0001$), where the mean absolute and relative differences from baseline were 1.3 g/cm^2 (12.1%), 2.3 g/cm^2 (25.5%), and 2.3 g/cm^2 (17.6%), respectively (Table 1). On the other hand, the BMD of Gruen zones 4, 6, and 7 remained relatively stable and did not change significantly from baseline ($P > 0.05$).

We further observed that Gruen zone 3 had the most pronounced BMD increase at every given time point, followed by Gruen zones 5 and 2 (Fig. 2). Additionally, we found a slight positive correlation between CCD angles and DEXA measurements averaged over all Gruen zones ($P = 0.046$).

Radiographic evaluation

Comparing pre- and postoperative CCD categories, we found most outcomes in or around the diagonal row, while CCD category A was restored in all cases (Table 2). This indicates that the categories remained stable after surgery, especially in patients with a low pre-operative CCD angle.

Clinical outcomes

The mean HHS improved significantly: from 57.2 (SD 20.0) pre-operatively to 97.2 (SD 4.0) at 24 months post-operatively ($P < 0.0001$) (Table 3). At the final follow-up examination, all other scores had also significantly improved compared with the baseline. The mean VAS for pain at rest decreased by 4.3 points ($P < 0.0001$), the mean VAS for pain under load decreased by 6.8 points ($P < 0.0001$), and the VAS for satisfaction increased by 7.7 points ($P < 0.0001$).

Complications

One patient experienced a peri-operative dislocation during relocation from the operating table. The dislocation was treated with closed reduction immediately. No post-operative complications were reported during the observation period, and no revision surgery was required.

Discussion

In this study, we evaluated bone remodeling around a short femoral stem and the accuracy of hip joint reconstruction. We

Table 1 Absolute and relative changes of bone mineral density by Gruen zone and follow-up time point, expressed as means (standard deviations)

Gruen zone	Pre-operative	3 months		12 months		24 months		*P* value*
	Absolute value	Absolute value (g/cm^2)	Relative change (%)	Absolute value (g/cm^2)	Relative change (%)	Absolute value (g/cm^2)	Relative change (%)	
1	0.9 (0.2)	0.8 (0.2)	− 2.3 (10.9)	0.8 (0.2)	− 6.0 (10.4)	0.9 (0.2)	− 5.4 (12.6)	0.007
2	1.2 (0.3)	1.4 (0.3)	20.4 (14.8)	1.4 (0.4)	14.7 (17.1)	1.3 (0.4)	12.1 (18.4)	< 0.0001
3	1.9 (0.3)	2.2 (0.3)	20.1 (9.9)	2.3 (0.3)	23.7 (12.2)	2.3 (0.3)	25.5 (10.7)	< 0.0001
4	2.1 (0.3)	2.1 (0.2)	− 1.3 (3.7)	2.1 (0.3)	− 1.1 (4.7)	2.1 (0.3)	− 1.1 (4.8)	0.148
5	2.0 (0.2)	2.2 (0.2)	13.4 (8.2)	2.3 (0.2)	16.0 (8.2)	2.3 (0.2)	17.6 (7.8)	< 0.0001
6	1.5 (0.3)	1.4 (0.3)	− 0.8 (11.0)	1.4 (0.4)	− 0.7 (14.3)	1.5 (0.3)	0.1 (14.2)	0.976
7	1.2 (0.2)	1.3 (0.2)	3.9 (18.0)	1.3 (0.2)	4.6 (16.2)	1.3 (0.3)	5.1 (17.8)	0.063

*Difference to baseline at 24-month follow-up examination. Number of observations at baseline, 45

hypothesized that the prosthesis used would limit stress shielding and minimize periprosthetic bone loss and that it would allow accurate varus/valgus positioning. Indeed, we observed favorable adaptive changes during the follow-up period. While BMDs remained statistically unchanged in Gruen zones 4, 6, and 7, Gruen zones 2, 3, and 5 evolved positively with mean BMD increases of 12.1 to 25.5% after 24 months of follow-up.

Similar results were reported by Chen et al. who found significant relative BMD increases of 9% in Gruen zone 2 and of 21% in Gruen zone 3 at a mean follow-up of close to six years after THA with a metaphyseally fixed femoral short stem [5]. Other studies with different short femoral stems mostly reported decreased BMD values [9, 11, 15] or mixed patterns of BMD increases and decreases in the different Gruen zones [16]. Additionally, comparative studies showed that conventional femoral stems induced more pronounced bone loss than short femoral stems [9, 15]. With uncemented conventional stems, bone loss was found to be most prominent in the proximal region (Gruen zones 1 and 7) after 24 months of follow-up [17–19]. Specifically, one study reported a BMD loss of 18% in Gruen zone 1 [18], while another study found a loss of 8.5% in Gruen zone 7 [17]. In addition, stem size has been associated with proximal bone loss, with larger stems leading to higher proximal bone loss [19].

In contrast to uncemented conventional stems, we found more stable BMDs in the proximal periprosthetic region (Gruen zones 1 and 7) and saw increasing BMDs in the lateral and distal-medial regions (Gruen zones 2, 3, and 5). Although

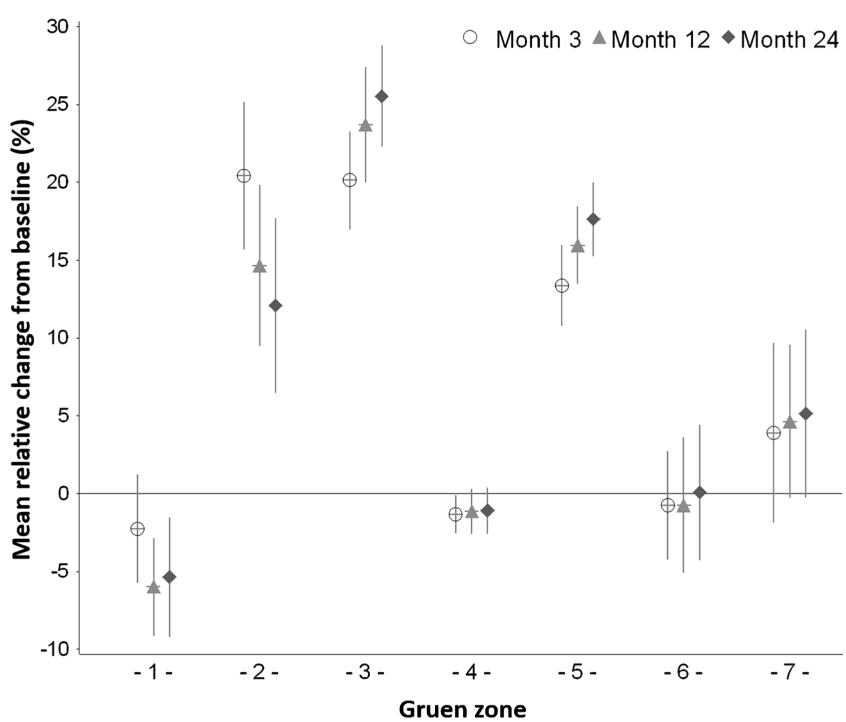

Fig. 2 Mean relative changes from baseline and 95% confidence intervals of bone mineral density by Gruen zone and follow-up time point

Table 2 Cross-table of pre- and post-operative CCD angle categories: A (less than 125°), B (125° to 130°), C (130° to 135°), D (135° to 140°), and E (more than 140°)

		Post-operative CCD[a] category				
		A	B	C	D	E
Pre-operative CCD[a] category	A	14	0	0	0	0
	B	0	3	10	2	0
	C	0	1	7	4	0
	D	0	1	0	1	0
	E	0	0	0	3	0

[a] Caput-collum-diaphyseal

the increases suggest loads transferred mainly to the lateral region and to a lesser extent to the distal-medial region, we did not observe proximal bone loss suggestive of stress shielding. To our knowledge, this is the first study where BMD was preserved in the proximal region, which is known to be prone to stress shielding [2, 20–22].

Brinkman et al. suspected lateral loading to be a consequence of the stem design on the one hand and stem positioning on the other. According to them, valgus positioning of the stem may lead to increased lateral loading and influence bone remodeling patterns [16]. In fact, we found a similar remodeling pattern with increased BMD in the lateral regions (Gruen zones 2 and 3), suggestive of lateral loading. We believe, however, that valgus implantations lead to higher BMD and varus implantations to lower BMD on the lateral side. Therefore, radiographic results of short-stem THA from different studies cannot be compared when the CCD angles are unknown.

Our DEXA results confirmed that the short femoral stem we used limited stress shielding and minimized bone loss. Given this and the fact that short stems require less bone resection in the first place, we believe that short femoral stems are more successful in preserving bone stock than conventional femoral stems. This preservation of bone stock would be especially advantageous for THA in young patients, who are likely to undergo revision surgery later in life [23].

Looking at CCD angles, we accurately reconstructed the varus/valgus positioning, and thereby the anatomical relationship of the hip joint. In most cases, the pre-operative CCD angle was retained after surgery, confirming a stable implant position. While reconstruction of varus hips is known to be challenging with conventional stems [24], varus hips (CCD category A) were restored accurately in all cases in this study. These data support the fact that the prosthesis used in this series adapts well to the patient's original joint anatomy.

Brinkmann et al. suggested that bone remodeling could be affected by prosthesis positioning [16]. Since we suspected that the accuracy of hip joint reconstruction would influence bone remodeling, we investigated the relationship between post-operative CCD angles and DEXA measurements grouped by Gruen zone. This revealed a slight positive correlation between the post-operative CCD angle and BMD of moderate significance ($P = 0.05$); however, the clinical impact of this finding was not found in the literature.

In terms of clinical results, functional outcomes evaluated by the HHS improved substantially over the first three months and remained favorable during the follow-up period. With a mean HHS of 97.2, our results compare well to those of other authors reporting clinical outcomes of short femoral stems in the short and midterm [9, 15, 16, 25] and to studies reporting clinical outcomes of uncemented conventional stems [17, 18]. Finally, we observed no complications apart from one perioperative dislocation. Specifically, there were no cases of aseptic loosening, post-operative dislocation, or periprosthetic fracture, all commonly encountered after conventional uncemented THA [26, 27]. Short-stem THA has therefore the potential to reduce prosthesis-related complications while achieving excellent clinical outcomes.

Our study had several strengths. Its prospective design provided us with an uninterrupted and complete dataset. Additionally, DEXA measurements have proven to be reliable and not prone to subjective bias, which allowed us to compare our results with other studies and generalize our findings [28]. Furthermore, we reported post-operative CCD angles, which are known to affect DEXA results [16], to ensure that our findings are comparable with other studies.

Nevertheless, our study did have some limitations. Patients were followed for only two years. Despite adaptive bone remodeling having been described as occurring primarily during the first three to six months post-operatively and lessening

Table 3 Clinical outcomes by follow-up time point, expressed as mean (standard deviation)

Clinical outcome		Pre-operative	3 months	12 months	24 months	*P* value*
HHS[a]		57.2 (20.0)	94.2 (6.0)	95.4 (5.4)	97.2 (4.0)	< 0.0001
VAS[b] for pain	at rest	4.5 (2.9)	0.5 (1.7)	0.3 (1.2)	0.2 (1.2)	< 0.0001
	under load	7.2 (1.9)	0.9 (1.1)	0.4 (1.1)	0.4 (1.1)	< 0.0001
VAS for satisfaction		2.0 (2.0)	9.4 (0.7)	9.6 (1.1)	9.7 (1.1)	< 0.0001

*Difference to baseline at 24-month follow-up examination

[a] Harris Hip Score

[b] Visual analog scale

after the first year [28, 29], longer follow-up periods may have provided a more complete picture. Additionally, our study lacked a control group. Direct comparison with patients receiving a conventional femoral stem may have provided a more detailed clinical profile of the short-stem prosthesis use.

In conclusion, the short femoral stem used in our study successfully limited stress shielding and minimized periprosthetic bone loss without compromising primary stability. In particular, the proximal zones, which are prone to stress shielding, remained stable over the follow-up period, while the lateral zones even showed increased BMD. Furthermore, we were able to accurately reconstruct the anatomical relationships of the hip in most patients, confirming that the prosthesis used in this series adapts well to the patient's original joint anatomy. Finally, we saw excellent clinical outcomes and encountered few prosthesis-related complications, supporting the favorable short-term results of short-stem THA.

Acknowledgments Medical Minds GmbH provided medical writing and editorial support. Dominik Pfluger carried out the statistical analysis.

Author contributions All authors contributed equally to the study.

Funding information The work was partially supported by Mathys Ltd. Bettlach. Funds sponsored statistical analysis through an independent consultant as well as medical writing and editorial support from a medical writing agency. No other external sources were involved.

Compliance with ethical standards

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

Ethical approval The local ethics committee reviewed and approved the study protocol; the institutional review board also approved the study (ethics approval registration number: EK 19/14; issue date: 16 June 2014). Additionally, the study was registered with the German Clinical Trials Register (clinical trial registration number: DRKS00017076). We conducted the study in accordance with the study protocol, the latest Helsinki Declaration, and good clinical practice guidelines.

Informed consent Informed consent was obtained from all individual participants included in the study.

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