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A short stem with metaphyseal anchorage reveals a more physiological strain pattern compared to a standard stem – an experimental study in cadavaric bone

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Purpose: The proposed advantages of short stem hip arthroplasties are bone preserving strategies and less soft tissue damage. Bone preserving strategies do not only include a more proximal resection of the femoral neck, but especially for short stem hip arthroplasties with predominantly metaphyseal fixation a presumed more physiologic load transfer and thus a reduction of stress-shielding. However, the hypothesized metaphyseal anchorage associated with the aforementioned benefits still needs to be verified. Unfortunately, mid- to long-term clinical studies are missing. *Methods:* Therefore, the METHA short stem as a short stem with proposed metaphyseal anchorage and the Bicontact® standard stem were tested biomechanically in three pairs of cadaveric femora while strain gauges monitored their corresponding strain patterns. *Results:* For the METHA stem, the strains in all tested locations including the region of the calcar were similar to conditions of cadaver without implanted stem. The Bicontact stem showed approximately half of strain of the non-implanted cadaveric femura with slightly increasing strain from proximal to distal. *Conclusions:* Summarizing, the current study revealed primary metaphyseal anchorage of the METHA short stem and a metaphyseal-diaphyseal anchorage of the Bicontact stem.

Key words: *short stem hip arthroplasty (METHA), standard stem hip arthroplasty (Bicontact), biomechanical testing, strain gauges, strain patterns*

1. Introduction

A number of short stem total hip arthroplasties (THA) were introduced on the market over the last years. The proposed advantages of the short stems are bone preserving strategies as well as less soft tissue damage during implantation. Bone preserving aspects include a more proximal resection of the femoral neck compared to standard stems, and thus, a higher proximal strain distribution rather than transferring the load to the diaphyseal femur. This supposed more physiological load transfer is intended to reduce the stress-shielding effect. It is known that the implantation of a conventional THA into the femur induces an alteration of the physiological strain patterns [13], taking a higher risk of distal locking and proximal offloading into account [3]. Mechanical stimuli regulate the dynamic remodeling of bone, resulting in changes in density and micro-architecture of the proximal femur according to Wolf's law [17]. A previous biomechanical study in synthetic bone showed hints of a primary metaphyseal anchorage of the METHA short stem (Aesculap, Tuttlingen, Germany), as opposed to a metaphyseal-diaphyseal anchorage of a conventional stem. Strain patterns after implantation of the METHA

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short stem or stems with similar biomechanical concepts of anchorage are unknown in cadaveric bone. Therefore, the proposed advantages of short stems are mainly hypothesized. Thus, the aim of this study was to monitor the strain patterns after implantation of the METHA and to compare these strain patterns to the ones of the conventional Bicontact stem (Aesculap), in order to alleviate concerns about deleterious changes in bone quality and implant stability.

2. Materials and methods

Preparation of the femora

Three pair of cadaveric femora (Institute Science Care, Phoenix, Arizona, USA) with caput-collum-diaphysis angle within the physiological range (left/right: 129°/129°; 128°/125°; 134°/135°) were used for biomechanical testing. Each femur was embedded distally in a metallic cylinder. The distance extending from the proximal potting to the fossa piriformis of the femoral neck was 300 mm. A form-fitted mold within an adjustable frame guaranteed a standardized embedding procedure (sagittal and frontal plane at 0°) using Methylmethacrylate (Technovit 4004; Heraeus Kulzer GmbH, Wehrheim, Germany).

Implants

The METHA stem is a short cementless hip stem, which is anchored directly within the closed bony ring of the femoral neck and metaphysis (Fig. 1). The other tested stem is the Bicontact stem. The Bicontact stem is a conventional stem which is meant to be anchored through bone compression, predominantly in the diaphyseal femur (Fig. 1).

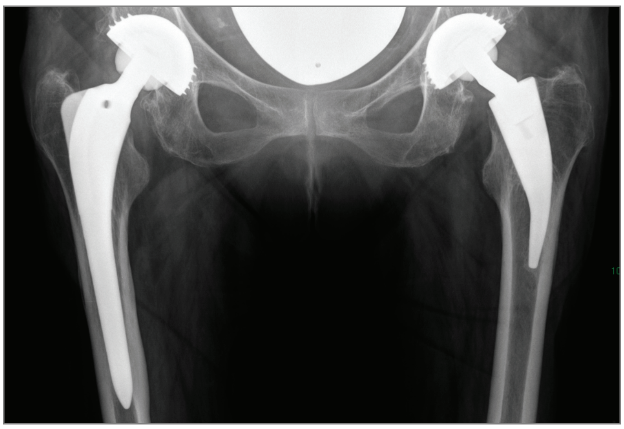

Fig. 1. X-ray of a pelvic overview
with implanted short stem METHA on the left side
and implanted conventional stem Bicontact on the right side

The size and type of stem was chosen according to preoperative templating as well as to post-implantation X-rays in order to restore the original offset as accurately as possible and consequently to avoid experimental errors due to differences in the lever arm (Table 1). Each stem was implanted according to the manufacturer's recommendation. Thus, the resection height for the METHA stem restored a 5 mm cortical ring of the femoral neck, while the one for the Bicontact was more distal, resecting the femoral neck. The stems were inserted by an experienced orthopaedic surgeon (TF). X-rays were captured to verify correct implant sizes and positioning.

Table 1. Description of the implanted components
(size and type of stem for the METHA and Bicontact;
length of the 32 mm head)

Pair	METHA (Size/CCD-angle/ length of the 32 mm head)	Bicontact (Size/type od stem/ length of the 32 mm head)
1	2/135°/medium	13/H/medium
2	3/135°/medium	16/H/medium
3	4/135°/medium	14/H/short

Strain measurement

Strain measurements represent deformations of the strain gauges, and thus, of the cadaveric bone under loading. Eight strain gauges (3/350 RY91; Hottinger Baldwin Messtechnik GmbH (HBM), Darmstadt, Germany) were bonded to the medial and lateral aspects of the femora at four levels (A-D): 45 (30 mm for the lateral strain gauge), 70, 90, and 150 mm distal to the fossa piriformis. At level A, two additional strain gauges were attached to the anterior and posterior aspects. For the Bicontact stem, two additional strain gauges were bonded 250 mm distal to the notch (level E). The orientation of the strain gauges was thus similar to the previous biomechanical in synthetic bone [8], [9], [12]. Each strain gauge at level A-D should illustrate strain pattern in one of the Gruen zones to enable a possible comparison of strain measurement and DXA scans. Due to different designs of the tested implants, the Gruen zones around the middle and distal part of the stems vary.

The preparation of the cadaveric bone, their surface, as well as the positioning of the strain gauges was performed similarly to the previous biomechanical testing using synthetic bones [8], [9], [12]. However, for the attachment of the strain gauges the soft tissue was removed from the determined locations. The bone surfaces were smoothed with sandpaper with increasing grain size (120, 240, 320, 400; two minutes each). Between each step the surface was covered with 70% propanolol for degreasing. All 30 seconds a new sandpaper was used. The surfaces were carefully cleaned and degreased with ethanol followed by a cleanser (RMS1, HBM). In this process the soft tissue and periosteum was removed. After that the location was cleaned and degreased with ethanol followed by a cleanser (RMS1, HBM) six times with a new cotton stick. A single-component polyurethane-lacquer (PU140, HBM) sealed the location to avoid escape of moistness and fat. The first layer was degraded after drying by sandpaper with grain size of 400 for two minutes. This filled pores and unevenness within the bone. A second layer of cleanser was applied and, after drying, degraded again to create a greater surface. The dust was removed by a non-woven fabric sprayed with cleanser. As the next step, the strain gauges were applied as described previously with a two-component polymethylmethacrylate adhesive (X60, HBM) and covered with a polyurethane protective (PU 120, HBM) [9], [12]. The leads of the gauges were soldered to the wires and connected with a CANHEAD base module (CB1014, HBM) including an amplifier module (CA1030, HBM). The catmanEASY software (Version 3.1, HBM) recorded the data. To avoid heating of the gauges, a bridge excitation voltage of 0.5 V was selected. Data were attained at a frequency of 100 Hz, with a low-pass cut-off frequency of 10 Hz.

Loading configurations (LC)

Under identical set-up and LCs at 8° and 12° adduction (representing single-leg stance), the principal strains were first measured on the non-implanted femora and then with the implanted METHA and Bicontact stems.

Mechanical application and measurement protocol

The setup and measurement protocol were in accordance with previous studies [9], [12]. The femora were placed on a 15 kN load cell of a materials testing system (MTS Mini Bionix 858; MTS Systems Corporation, Eden Prairie, Minnesota, USA) using a custom-made jig. For vertical loading, a floating bearing was attached to the MTS to avoid undesired horizontal forces and moments. After zeroing the load cell and strain gauges the femur was loaded in a ramp profile up to an axial force of 800 N at a rate of 10 N/s. Using load control during the axial force of 800 N was kept constant for 90 s to reduce the influence of a creep effect. After 30 s, an interval during which creep was observed in preliminary experiment, strains were recorded for the following 60 s. The measurement procedure was repeated five times, the femora was allowed to elastically recover for eight minutes between repetitions.

This procedure was first conducted on three pairs of femora cadaver. Subsequently, the METHA and Bicontact stems were each implanted in one of the femora of each pair, and the measurement protocol was repeated.

Statistical analysis

The mean values of the principal strains and the angles of the principal strains during the five load repetitions were determined. For further statistical analysis, a multivariate linear mixed regression model was used. The gained data of the strain measurements were analyzed using a model equation existing of the logarithm of strain as target variable, of device, angle and position of the strain gauges as influencing variable, as well as a correlation term from device and position of strain gauges, which provides device specific pattern of the position of the strain gauges. Side and cadaveric bone were considered as random variable. Each analysis revealed a linear equation including a term of error. This results in a linear system of equations with unknown coefficients. These coefficients are adjusted by a software, so that the sum of the squares of the terms of error is minimal (ordinary least squares method). The estimated mean value and standard deviation of each coefficient allows for the analysis of whether this is significantly different from 0. Thus, the strains with significant changes can be identified. The confidence interval was set to 5% (p-value < 0.05). Graphics were used to illustrate the results where the values of the implanted femora were expressed as a percentage of the strains in the corresponding non-implanted femur.

In addition, a post-hoc test was used to determine the p-values for the comparison within the position of the strain gauges.

3. Results

Strain patterns after insertion of stems

The gained data showed fewer changes in the strain patterns after implantation of the METHA short stem, compared to the conventional Bicontact stem. Except for the region of the greater trochanter (AL) and the anterior part of the level A (AA), the alteration after METHA, compared to the non-implanted condition, never exceeded 25%. For both stems, an obvious decrease of strain in the region of the greater trochanter (AL) was observed. The alteration in the region of the greater trochanter after implantation of the conventional stem was by far greater than for the short stem (METHA: – 30%; Bicontact: – 73%). The strain values for the conventional stem were similar to the non-implanted condition in level D, but less in the more proximal levels A, B and C (Fig. 2).

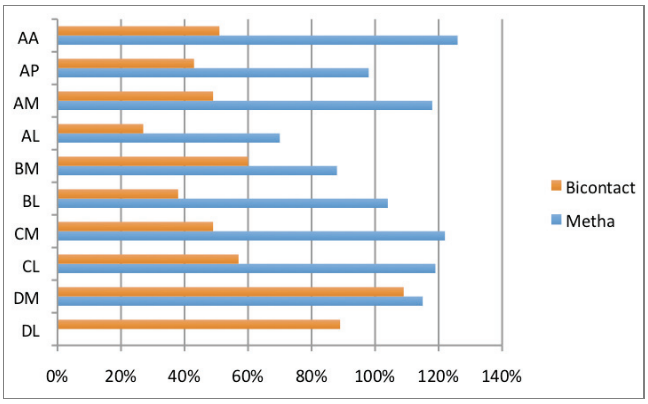

Fig. 2. Changes in mean principal compressive (medial, anterior, lateral) and tensile strains (lateral) after implantation of the two stems (METHA and Bicontact) in comparison with the strains without implanted stems (in % of the principal strain values in the intact femora). 100% denotes the strain values in the intact femora. The first letter represents the level (A, B, C or D). The second letter represents the position within the level (anterior (A), posterior (P), medial (M) or lateral (L). Due to problems during testing the value at DL for the METHA is missing

Table 2. Comparison of the strains of the METHA and Bicontact, compared to the nonimplanted ("Anatomic") setting at each strain ($p > 0.05$). Due to problems during testing the value at DL for the METHA is missing

Setting	Setting	Location of strain gauge	Strain ratio	Percentage after implantation of stem	Probability
Anatomic	Bicontact	AA	1.95	51%	0.0092
Anatomic	Bicontact	AL	3.66	27%	<0.0001
Anatomic	Bicontact	AM	2.03	49%	0.0015
Anatomic	Bicontact	AP	2.34	43%	0.0034
Anatomic	Bicontact	BL	2.62	38%	<0.0001
Anatomic	Bicontact	BM	1.66	60%	0.019
Anatomic	Bicontact	CL	1.76	57%	0.0096
Anatomic	Bicontact	CM	2.02	49%	0.0014
Anatomic	Bicontact	DL	1.13	89%	0.5768
Anatomic	Bicontact	DM	0.92	109%	0.6886
Anatomic	Metha	AA	0.80	126%	0.2976
Anatomic	Metha	AL	1.43	70%	0.1232
Anatomic	Metha	AM	0.85	118%	0.4723
Anatomic	Metha	AP	1.02	98%	0.9455
Anatomic	Metha	BL	0.97	104%	0.8681
Anatomic	Metha	BM	1.14	88%	0.5476
Anatomic	Metha	CL	0.84	119%	0.4146
Anatomic	Metha	CM	0.82	122%	0.3585
Anatomic	Metha	DL			
Anatomic	Metha	DM	0.87	115%	0.51

Unfortunately, a technical problem occurred for the measurement of the strain in level D laterally for the METHA, so that for this location a value is missing.

Regarding the differences of implanted condition compared to the non-implanted conditions, the METHA short stem did not show any significant difference in any of the strain gauges, while the conventional Bicontact stem induced significant differences in all regions except level D (Table 2).

Comparing the alteration of strain in the different region after insertion of the METHA and the Bicontact stem, in all locations except for the medial region in level B (BM) and the medial region of level D (DM) significant difference were determined (Table 3).

Table 3. Comparison of the strains of the two different stems METHA and Bicontact at each location ($p > 0.05$). Due to problems during testing the value at DL for the METHA is missing

Setting	Setting	Location of strain gauges	Percentage after implantation [%]	Probability
Bicontact	METHA	AA	245	0.0017
Bicontact	METHA	AL	256	0.0016
Bicontact	METHA	AM	241	0.0011
Bicontact	METHA	AP	230	0.0098
Bicontact	METHA	BL	272	0.0001
Bicontact	METHA	BM	146	0.1365
Bicontact	METHA	CL	211	0.0036
Bicontact	METHA	CM	247	0.0004
Bicontact	METHA	DL		
Bicontact	METHA	DM	106	0.8247

4. Discussion

Although there is a lack of evidence that bone remodeling as a result of stress-shielding directly influences clinical results, it is of predominate concern that a resorption of proximal femoral bone stock may negatively affect the stability and survival of femoral implants [6], [15], [23]. Therefore, in a previous study on synthetic bone, we determined the alteration in strain after implantation the METHA short stem and the conventional Bicontact stem. The results gave hints of a primary metaphyseal anchorage of the short stem and a meta-diaphyseal anchorage of the conventional stem. As the study was conducted on synthetic bone, it was of great interest whether the insights could be confirmed on cadaveric bones. Therefore, the aim of this study was to determine the strain patterns in a proximal femur after implantation of a short stem with supposed primary metaphyseal anchorage, and to compare the strain pattern with the one after implantation of a conventional stem.

The results suggest a greater level of metaphyseal anchorage for the METHA short stem compared to the conventional Bicontact stem. Based on the analysis, it can be hypothesized that the short stem induced less stress-shielding effect, compared to a conventional device. Furthermore, the data in cadaveric bone revealed less reduction in the region of the greater trochanter for the short stem. While it was about 50% in synthetic bone, in cadaveric bone it was only 30%. The conventional Bicontact stem displayed a metaphyseal-diaphyseal anchorage. There was a reduction in strain in the proximal level and similar to the non-implanted conditions only in level D, the diaphyseal area. In summary, the METHA short stem seems to induce a metaphyseal anchorage. The bone stock preserving resection of the femoral neck, the tapered shape and the bracing of the distal tip of the METHA on the lateral cortex are all intended to restore the load transfer of the non-implanted conditions. The risk of stress-shielding seems to be negligible. For the Bicontact stem, the different resection height may explain the severe decrease of strain around the calcar. Nevertheless, the strains in the lower levels demonstrate a combination of metaphyseal and especially diaphyseal load transfer.

The insights of the biomechanical studies on synthetic as well as cadaveric bone confirm the results of other biomechanical studies examining the strain patterns of standard (anatomical) and customized stems [1], [6], [14], [17], [23]. These studies uniformly showed a severe reduction of the principal strains in the proximal femur for both stem types with the greatest decreases at the calcar, especially for the standard stems. Along with that, also customized proximal fit stems and traditional stems all display non-physiological strain patterns within the proximal femur, with a slight tendency to more physiological patterns for customized stems. Comparing the data with the current study, the METHA short stem seems to reproduce more physiological load transmission to the proximal femur than traditional stems or customized implants.

This goes along with other biomechanical studies, comparing the strain distributions of short-stemmed or stemless prosthesis with stem prosthesis [6], [10], [20], [24]. For example, Decking et al. [6] showed that, in contrast with two conventional stems, revealing an increase of measured strains on the lateral side of the greater trochanter after implantation of the stemless CUT prosthesis (ESKA Implants), while the medial strains were closer to physiological values in the "stemless" prosthesis than those of the two full-stem prosthesis. Furthermore, Bieger et al. [3] evaluated the stress-shielding effect in the proximal femur for the Fitmore short stem in comparison with the Mayo short stem and standard CLS stem prosthesis (all Zimmer). The results indicated that the reduction of longitudinal cortical strains in the proximal femur was less pronounced for the shorter stems. Piao et al. [18] compared the stress shielding effects of implantable anatomical and traditional stem after in vitro total hip joint replacement simulation. They concluded that the rates of proximal femoral stress shielding were significantly higher in the traditional femoral prosthesis transplantation group than in the anatomical prosthesis group ($p < 0.05$). According to all these studies including the present study, the stemless, the anatomical as well as short-stemmed prostheses reveal a significantly less alteration of strain pattern after implantation compared to traditional stem prostheses, indicating a more physiological load transmission and thus probably a reduced stress-shielding effect.

Clinical midterm results exist for only a few short stems. A meta-analysis by Liang et al. [16] was conducted to determine the proximal bone remodeling, revision rate, Harris Hip Score, radiolucent line and maximum total point motion values of both short and conventional stems for primary THA. The authors concluded that short stem provide superior bone remodeling and similar survival rates and clinical outcomes compared to conventional stems. Nevertheless, mid- and long-term results need to prove this statement.

Furthermore, contemporary short stem devices have a completely different principal design. Falez et al. [7] published paper providing possible classifications for short stems. Regarding the METHA short stem, the indication has been enlarged over the years to secondary osteoarthritis (e.g., rheumatoid arthritis, hip dysplasia). The clinical data suggest good outcome and high survival rates: Thorey et al. [22] published a study with a survival rate of 98% in 148 cases after 5.8 years, and Wittenberg et al. [25] – with a survival rate of 96.7% for 250 cases after 4.9 years for the short stem tested in this study. Along with that, Schnurr et al. [19] observed a 7-year revision rate for the monoblock METHA stem was 1.5%. By changing the biomechanical concept, short stems are intended to improve the load transfer pattern, potentially reducing the failure rate.

However, existing long-term results after implantation of a conventional stem like the Bicontact provide excellent survival rate even after more than 10–20 years [2], [21]. The greater diaphyseal anchorage of the Bicontact stem, compared to the METHA short stem, seems to support very good implant longevity and only few problems of stress shielding within that follow-up period.

A main limitation of the previous study with the biomechanical testing in synthetic bone could be solved by the current study on cadaveric bone. The problem in cadaveric bone due to a wide interspecimen variability regarding bone geometry and mechanical properties, which directly affects the results of strain measurements, was considered by using three pairs of cadaveric femora. The two different stems were implanted in the left or right femur after randomization. A repeatable positioning of the strain gauges is highly relevant for the different femora. This was guaranteed by applying a well-defined reference system including an optical tracking system. Thus, this device accounts for very little variability between the left and right femora.

In order to avoid bone damage due to repeated loading an axial force of 800 N was applied according to Ganapathi et al. [11]. However, as the linearity between force and strain previously was proved [9], [12], the strain patterns do not depend on the absolute amount of the applied load, as the results of the implanted femora were expressed as a percentage of the strains in the identical non-implanted femora. Forces and muscles provided by other soft tissue were not simulated during this biomechanical testing. However, it has been reported previously that biomechanical studies, in which the testing set-up did not feature muscles [4], [5], can reliably analyze the strain patterns of the proximal femur.

5. Conclusion

Our data indicate that the METHA short stem induced a proximal load transfer, which supports a primary metaphyseal anchorage. This is in contrast to the strain pattern following implantation of the conventional Bicontact stem, which demonstrated a metaphyseal-diaphyseal anchorage. Whether the different strain patterns observed in the present study are correlated to the clinical outcome has to be shown by mid- and long-term clinical follow-up especially of short stems.

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