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Primary stability of unicompartmental knee arthroplasty under dynamic compression-shear loading in human tibiae

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ABSTRACT

Background: The objective of our study was to evaluate the impact of a single- (“implant only”) versus a double-layer (“implant & bone”) cementing technique on the primary stability of unicompartmental tibial plateaus under dynamic compression-shear loading conditions in human tibiae.

Methods: Twelve fresh-frozen human knees of a mean donor age of 72.3 years were used to perform medial UKA under a less invasive parapatellar surgical approach. The tibiae were divided into two groups of matched pairs based on comparable trabecular bone mineral density. To assess the primary stability, a new method based on a combination of dynamic compression-shear testing, kinematic analysis of the tibial plateau migration relative to the bone and evaluation of the cement layer by CT-scans and fragments cut through the implant–cement–bone interface in the frontal plane was introduced.

Findings: For the “implant only” cementation technique the mean load to failure was 2600 (SD 675) N and for “implant & bone” it was 2820 (SD 915) N. Between the final load level at failure and the bone mineral density a significant correlation was found for the groups “implant only” ($r_s = 0.875$) and “implant & bone” ($r_s = 0.907$).

Interpretation: From our observations, we conclude that there is no significant difference between a single- (“implant only”) and double-layer (“implant & bone”) cementing technique in the effect on the primary stability of unicompartmental tibia plateaus, in terms of failure load, correlation between final load at failure and bone mineral density, migration characteristics, cement layer thickness and penetration depth.

1. Introduction

Unicompartmental knee arthroplasty (UKA) has become a successful clinical treatment for patients suffering from antero-medial osteoarthritis. It relieves pain, provides fast recovery and restores the function of the joint (Argenson et al., 2002; Emerson and Higgins, 2008; Pandit et al., 2006; Svärd and Price, 2001). Provided there is appropriate patient selection (Argenson et al., 2002; Murray et al., 1998) and surgical experience (Bonutti and Dethmers, 2008) unicompartmental knee arthroplasty has shown excellent long-term results after isolated medial gonarthrosis (Berger et al., 2005; Pandit et al., 2011; Price and Svärd, 2011; Steele et al., 2006).

However, these encouraging clinical results are marred by disturbing findings. Thus, Robertsson et al. (2001) found a negative correlation between the number of UKA treatments performed in a clinical center per year and the risk of revision. Furnes et al. (2005) reported large variations in midterm outcomes between 13 hospitals using the same implant. Analysing a cohort of 23,400 medial cemented Oxford UKA's performed in 366 clinical centers and reported between 2003 and 2010 in the National Joint Registry of England and Wales, Baker et al. (2013) found a significantly lower number of revisions per 100 component years and higher 5 year survival rates for higher-volume surgeons or higher-volume centers and a higher variability in the low-volume surgeons group. These joint registry findings demonstrate that unicompartmental knee arthroplasty is a technically demanding surgery, more sensitive to surgical skills and requires a longer learning curve, particularly with some implant designs (Furnes et al., 2007; Robertsson et al., 2001). Kuipers et al. (2010) investigated factors reducing the early survival of medial UKA and found a greater risk of revision in patients younger than 60. Parratte et al. (2009) reported a survival rate at 12 years of 80.6% in a cohort of 31 UKA patients younger than 50 and concluded that aseptic loosening remains a major factor affecting the outcomes in young and active patients. Overall, the results were inferior to those of tricompartmental knee arthroplasty (Furnes et al., 2007).

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Loosening of the tibial component is one of the main reasons for revision in cemented unicompartmental knee replacements (Furnes et al., 2007; Saenz et al., 2010). Apart from the implant design (Furnes et al., 2007; Robertsson et al., 2001) the applied cementing technique plays a major role. In a consecutive series of 112 cemented Oxford unicompartmental knees, Clarius et al. (2009) compared pulsed lavage ($n = 56$) with syringe lavage as to their effect on the incidence of radiolucent lines under the tibial component 12 months after UKA. They found a substantial reduction of radiolucencies in the cement–bone interface under the plateau and a significantly higher cement penetration in the pulsed lavage group. Using an anatomical open pore sawbone model, Vanlommel et al. (2011) examined the effect of different cementing techniques on the cement penetration in the proximal tibia. Quantifying cement penetration after medial and lateral oblique sagittal cuts through the tibia model, they found instead of applying cement on the implant only a substantially deeper penetration when cement was applied on both the underside of the tibial component and on the tibial bone using a spatula.

To assess the primary stability of tibial plateaus in vitro, different approaches had been undergone: cement penetration depth analysis (Clarius et al., 2012; Maistrelli et al., 1995), static tension (Gebert de Uhlenbrock et al., 2012; Schlegel et al., 2011) or compression loading (Clarius et al., 2010) until interface failure. However, these test conditions do not reflect the in vivo physiologic loading modes, where the unicompartmental tibial plateau is predominantly subjected to combined compression and shear forces in a cyclic profile (Bergmann et al., 2010; Kutzner et al., 2010).

2. Objectives

The objective of our study was to evaluate the impact of a single ("implant only") versus a double-layer ("implant & bone") cementing technique on the primary stability of unicompartmental tibial plateaus under dynamic compression-shear loading conditions in human tibiae.

3. Methods

We performed a medial UKA under clinical conditions on twelve fresh-frozen human knees of a mean donor age of 72.3 years (range 53–90) with the distal third of the femur and the proximal third of the tibia and intact surrounding tissue. To determine bone mineral density (BMD) CT-scans (Sensation 64 Somatom, Siemens AG Munich, Germany) were made of all tibiae prior to the implantation. The BMD was determined on the medial tibial head in 7 layers of 3 mm thickness in the region of trabecular bone, using a relative calibration to water (0 Hounsfield units (HU)) and calcium (200 HU). We divided the tibiae into two groups of matched pairs (Table 1).

Table 1
Human knee specimen characteristics, bone mineral density and implanted tibial tray size.

Specimen	Sex	Age	Leg (medial)	BMD (mg/mm^3)	Cementation technique	Tibial tray size
640	male	54	Right	183	"implant & bone"	T4RM
380	male	78	right	98	"implant only"	T4RM
K01A	male	83	right	79	"implant & bone"	T6RM
K08A	male	82	left	71	"implant only"	T4LM
K02B	female	84	left	76	"implant & bone"	T2LM
K06B	female	84	right	81	"implant only"	T2RM
K03B	male	53	right	89	"implant & bone"	T2RM
K04B	male	53	left	108	"implant only"	T6LM
K07A	male	58	right	117	"implant & bone"	T4RM
K07B	male	58	left	118	"implant only"	T4LM
K09B	male	90	right	135	"implant & bone"	T4RM
K09A	male	90	left	143	"implant only"	T4LM

A less invasive parapatellar surgical approach without eversion of the patella with a 7–8 cm skin incision was chosen. The bone preparation and implantation of the tibial plateau, the femur and the gliding surface (Univation® XF, Aesculap Tuttlingen, Germany) was done as described in the OR manual. Once the appropriate implant size was determined, tibial resection was performed (7 mm below the joint line) with an anatomical posterior slope. Pulsed lavage was used (500 ml, 2 minutes purging time) to clean the trabecular bone of the medial resected knee joint before cementation. A high viscosity bone cement (Palacos® R 20 g powder/10 ml monomer, Heraeus Medical Wehrheim, Germany) was mixed with bowl and spatula for cement fixation of the tibia and femur implants. On one specimen of each pair, bone cement was applied on both the undersurface of the tibial tray and the resected tibial bone using a double-layer technique ("implant & bone"); on the other one, bone cement was applied only on the surface of the tibial tray using the single-layer technique ("implant only"). In the double-layer technique, approximately 10 g of cement was applied in equal parts on both the tibial component and the tibial bone, by fingerpacking. In the single-layer technique, also approximately 10 g of cement was spread over the inferior surface of the tibial component. The tibial tray was inserted in the knee and the posterior part was seated first to avoid posterior cement extrusion. Then the implant component was placed and impacted onto the tibia using the specific impactor (Univation® F instruments, Aesculap, Germany). For pressurisation of the bone cement during polymerisation the knee was positioned in 45° flexion and a spacer was inserted for compression until the cement was cured. After implantation, the surrounding soft tissue was removed and the specimens were dissected, aligned in the sagittal plane to the tibia axis in 0° extension and imbedded with polyurethane casting resin, 70 mm distally from the anterior tibial tray surface (Fig. 1).

To assess the primary stability at the implant–bone interface, three points of interest were defined around the rim of the tibial plateau (P1 ventral (5 mm from the sagittal rim), P2 medial ($0.4 \times$ AP distance from dorsal), P3 dorsal (5 mm from the sagittal rim)) in relation to a defined global coordinate system. The coordinate system was defined with the origin in the direction of the tibia axis, in the mid-sagittal plane and situated in the plane of the imbedding level. The positive x-axis pointed in the posterior direction, the y-axis in the lateral or medial direction depending on the legs' side and the z-axis in the proximal direction. To make the motion of left or right side implants comparable, the orientation of the y-axis was for left knees transformed to right side. The point translations in x, y and z direction were measured with a 3D ultrasonic motion analysis system (customised JMA system Zebris medical Isny, Germany) with an accuracy of 0.01 mm in translation and 0.1° in rotation. The points (P1, P2, P3) were set with an pointer, which was fixed on a sender of the measurement system. This defined the initial position of the points (P1, P2, P3) in the described global coordinate system. Due to the fixation of the sender at the implant the movements of the points could be followed.

The tibiae were fixed on the test machine in a flexed position to simulate peak joint loading during mid-stance phase at 15° flexion in the walking gait cycle (Franta et al., 2011; Muendermann et al., 2008; Ngai and Wimmer, 2009; Taylor et al., 2004) (Fig. 2).

The tibio-femoral contact force was applied in a sinusoidal waveform with a frequency of 1 Hz via the femoral component acting on the vertical axis of the condylar contact point, which was determined with an anterior offset of $0.32 \times$ AP distance of the tibial plateau from the dorsal outer rim (T2 = 14 mm; +1 mm additional offset per size) (de Jong et al., 2010). In five TKA patients Kutzner et al. (2010) measured in vivo an average tibio-femoral force of approximately 2700 N during level walking. In case of UKA treatment as in our study, it seemed reasonable to assume that the medial compartment is subjected to 55 percent of this load (1485 N) (Zhao et al., 2007). For all patients in all trials, Kutzner et al. (2010) found an absolute maximum load of 400 %BW during descending stairs. With a patient weight of 100 kg and a load share on the medial compartment of up to 90% in varus knee alignment