Does Using Autograft Bone Chips Achieve Consistent Bone Ingrowth in Primary TKA?

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Abstract

Background Cementless fixation remains controversial in TKA due to the challenge of achieving consistent skeletal attachment. Factors predicting durable fixation are not clearly understood, but we presumed bone ingrowth could be enhanced by the quantity of host bone and application of autograft bone chips.

Questions/purposes We asked: (1) Did the amount of bone ingrowth exceed the amount of periprosthetic and host bone with the addition of autograft bone chips?

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(2) Did the amount of bone ingrowth increase with implantation time? And (3) did osteolysis along the porous-coated interface and screw tracts progress with implantation time?

Methods We measured the amount of bone in the porous-coated, periprosthetic, and host bone regions in 19 post-mortem retrieved cementless primary total knee implants. The amount of bone in apposition to the implant surface, and alternatively lysed bone, was analyzed radiographically to assess the progression of osteolysis.

Results While bone ingrowth tended to be less than periprosthetic and host bone in all three components, it was only significantly less in the patellar component. Bone ingrowth increased in all three components over time, but progression of osteolysis did not.

Conclusions Even after long-term followup, the amount of bone ingrowth did not surpass host bone levels, suggesting the amount of a patient's host bone is a limiting factor in the amount of bone ingrowth achievable for this cementless design. It remains unknown whether compromised osteopenic bone could achieve the amount of bone attachment necessary to provide durable fixation over time.
Level of Evidence Level IV, therapeutic study. See Guidelines for Authors for a complete description of levels of evidence.

Introduction

The introduction of the cementless Natural-Knee® System (Zimmer Inc, Warsaw, IN, USA) occurred in 1985.

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Fig. 1A–C Gross photographs show (A) the patellar component, (B) tibial component with its asymmetrical design, and (C) femoral component of the Natural-Knee® System and porous-coated surfaces.

The unique features of the design at the time were an asymmetrical tibial tray that matched the resected surface of the human tibia, a metal-backed patella, and a femoral component with a deep-groove titanium alloy ($\text{Ti}_6\text{Al}_4\text{V}$) articulating surface to allow optimal ROM (Fig. 1). Before its introduction, institutional review board (IRB)-approved biocompatibility studies were performed using plugs with the cancellous structured titanium porous coating in a patient population receiving staged bilateral TKAs [4, 18, 19, 21]. During the first operation of a staged bilateral TKA, one of two types of porous-coated plugs were implanted into the patient's opposite medial femoral condyle; the plugs were implanted in such a way as to avoid compromising preparation for femoral component placement at the second operation. In addition, some plugs were implanted with autograft from the underside of the resected tibial wafer for application to the resected host bone surface. The plugs remained implanted until resection at the second staged operation 3, 6, 9, and 12 months later. The resected bone with implanted plugs was subsequently analyzed, demonstrating the potential for human skeletal attachment indicated by bone ingrowth into the cancellous structured titanium of the Natural-Knee® design [4, 18, 19], and reported in the current investigation. The ingrown bone displayed active mineral apposition rates; more bone ingrowth occurred in the cancellous structured titanium

than in hydroxyapatite-coated plugs [4, 18, 19]. These studies also provided support for the use of autograft bone chips [21]; more bone in the porous coating was observed in plugs treated with autologous bone chips. It was believed the autograft bone chips would promote consistent bone ingrowth while limiting fibrous tissue formation at the interface of the components by providing an immediate layer of the patient's own bone tissue at the interface.

Due to the uniqueness of the Natural-Knee® cementless design, there was a question whether backside polyethylene wear would result and lead to subsequent osteolysis, since both the patellar and tibial components had metal backings. There were also initial design questions with the patellar component regarding the possibility of outer-margin metal edge wear and whether the femoral components might have excess surface wear since titanium alloy articulations had subsequently been considered obsolete. Titanium alloys are less wear resistant due to a thin and mechanically weak oxide layer that forms on the surface compared to cobalt-chromium articulations [1, 26].

As with any new implant design, it was important to study the presence of osteolysis caused by design or materials problems since these might remain asymptomatic in the patient. At the time of the clinical introduction of the cementless Natural-Knee®, the design surgeon (AAH) initiated an IRB-approved postmortem retrieval analysis program allowing the clinical study of successful primary TKA implants in situ at various implantation times for assessment of skeletal attachment and the contribution of autograft bone chips. Over the 25-year period, 19 knees in

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14 patients were donated by individuals and consecutively retrieved after their death. These retrievals came from the first 360 performed surgeries [22].

We asked the following three questions: (1) Did the amount of bone ingrowth exceed the amount of periprosthetic and host bone with the addition of autograft bone chips? (2) Did the amount of bone ingrowth increase with implantation time? And (3) did osteolysis along the porous coating interface and screw tracts progress with implantation time?

Patients and Methods

Over the past 25 years, an IRB-approved program has been in place at the authors' institutions (Department of Veterans Affairs Salt Lake City Health Care System and Department of Orthopaedics, University of Utah School of Medicine) to analyze retrieved postmortem TKAs of the same specific design [2, 3, 8, 19] implanted by one surgeon (AAH) who had clinically followed the patients who ultimately donated [22]. At the time of index operation, between 1985 and 1988, 76 patients consented to the retrievals upon death if possible. Good bone quality and the absence of osteopenic or osteoporotic bone were indications for selection of this implant. Bone quality was assessed by preoperative radiographs and intraoperatively by compressing the bone. During the time of these 76 implantations, the surgeon performed TKA in 360 patients. Clinical followup studies [22] in this type of implant design at 10 to 14 years have demonstrated implant survivorship comparable to that of cemented designs [23, 27, 28]: the initial patient population had high modified Hospital for Special Surgery Knee Score and a 95% survivorship at 10- to 14-year followup [22, 24]. At the time of the current study, we had accumulated 19 postmortem-retrieved primary TKA implants (patellar, tibial, and femoral) from 14 donors (12 men, two women) of which five were bilateral retrievals (Table 1). The average ($\pm$ SD) age at death was 77 ± 7 years (range, 66–91 years). The implants were in situ for an average of 11 ± 7 years (range, 1–25 years) (Table 1). Previous data have been reported on five of these donor retrievals [2, 3]; however, the previous studies did not include analysis of all outcome variables reported in the current study.

A single orthopaedic surgeon (AAH) performed the surgeries according to a standardized operative approach using instruments specifically designed for the implants. The total knee components used in this study were of the Natural-Knee[®] design with a commercially pure titanium porous coating with an average pore size of 530 μ m and 55% porosity. In addition, the surgeon applied a layer of autograft bone chips, similar to milled bone, onto the

Table 1. Clinical data obtained from 14 donors' medical records of which five were bilateral

Donor	Age at death (years)	Sex	Time in situ (months)	Side	Last HSS Knee Score*
1	87	Male	14	Right	100
2	66	Male	17	Left	98
3	72	Male	67	Right	100
4	70	Male	68	Right	100
			83	Left	98
5	77	Male	69	Left	100
6	75	Male	77	Right	100
7	79	Male	84	Right	100
8	78	Male	116	Left	97
			126	Right	97
9	70	Male	120	Right	98
10	81	Male	123	Right	98
			124	Left	97
11	76	Male	136	Right	98
12	81	Male	238	Left	Unknown
			239	Right	Unknown
13	91	Female	243	Left	Unknown
			291	Right	Unknown
14	80	Female	300	Left	Unknown

* Hospital for Special Surgery (HSS) Knee Score was not obtained from the last three donors (n = 5 knee retrievals).

resected host bone surface during the surgery and before implant placement [15, 21, 22]. After preparing the milled bone from the underside surface of the resected tibia, the surgeon placed the bone slurry on the prepared undersurface of the patella and reversed the reamer to uniformly spread the slurry. For the femur and tibia, the surgeon spread the slurry over the surface of the resected bone using the scalpel handle, resulting in a 1.5- to 2-mm-thick layer of milled bone from the implant surface into the trabecular spaces.

At postmortem retrieval, the knee components (patella, tibia, and femur) were recovered in situ while ensuring the interface between the implants and host bone tissues remained undisturbed. We accessioned, photographed, and radiographed each component and removed all soft tissues and excess bone without compromising the bone-implant interface. Components were then fixed in 70% ethanol, dehydrated in ascending grades of ethanol, infiltrated, and embedded in methylmethacrylate using standard techniques [6]. We then cut the components into the maximum number of 3-mm-thick sections (Fig. 2), averaging seven patellar, eight tibial, and 10 femoral wafers per component, on a custom water-cooled, high-speed cutoff saw [5] equipped with a diamond-edged blade (Rockazona Inc, Peoria, AZ, USA). The number of sections was dictated by the size of the individual components. The sections were

Fig. 2 The image shows high-resolution contact radiographs of 3-mm-thick sections from the right patella of one of the donors used to measure the ABI. This patellar implant had been in situ for 84 months and had a high percentage of bone in apposition to the porous-coated interface (original magnification, $\times 1$).

ground and polished to a scratch-free finish using a variable-speed grinding wheel (Buehler Inc, Lake Bluff, IL, USA) using standard techniques. All histologic analyses were conducted in a blinded fashion by two observers (BMW, KEK).

We sputter-coated each 3-mm-thick section with a conductive layer of gold for approximately 1 minute (Hummer VI-A; Anatech Ltd, Alexandria, VA, USA) and examined it using a scanning electron microscope (JSM 6100; JEOL Inc, Peabody, MA, USA) with a backscattered electron (BSE) detector (Tetra; Oxford Instruments Ltd, Cambridge, UK) and associated image capture software (ISIS; Oxford Instruments) at $\times 40$ magnification. The entire length of the porous coating along the implant surface dictated the number of images captured from each component. We performed BSE imaging analysis to determine the percent area of bone present in the porous-coated region, periprosthetic interface region, and host bone region. The porous-coated region was defined as the 2-mm region within the porous coating. The periprosthetic region was defined, as in previous studies [6], as being directly adjacent to the porous coating and extending for 2 mm from the coating surface. The periprosthetic interface region was composed of the autograft bone chips. The host bone region was defined as starting 3 mm from the porous coating surface and also extending 2 mm with the 1-mm distance between the periprosthetic and host bone region serving as a buffer to differentiate between these two regions (Fig. 3). The total space imaged included

Fig. 3A–C BSE images illustrate the three regions used for analysis of bone ingrowth: (A) porous-coated region, (B) periprosthetic region, and (C) host bone region (original magnification, $\times 40$). The periprosthetic interface region was in direct apposition to the porous-coated interface, whereas the host bone was 3 mm from the porous-coated interface.

the area occupied by implant porous coating, bone, and marrow [6]. We calculated the percent void area within the porous coating, or area available for bone ingrowth that was not occupied by the implant, as the area occupied by bone divided by the available void in the pore space of the image field and multiplied by 100. Additional calculations of percent void area in the porous coating filled with bone and percent total area filled with bone were also performed for comparison with previously reported bone ingrowth literature utilizing BSE imaging [11, 14, 20, 25, 29, 31].

We took high-resolution contact radiographs (Fig. 2) of each 3-mm-thick section using high-resolution film (Kodak SO253; Eastman Kodak, Rochester, NY, USA) at 55 kV, 1.0 mA for 1800 seconds in a radiography cabinet (Torrex 120D; Scanray, Hawthorne, CA, USA) [3, 6, 7]. The appositional bone index (ABI) of each component [3, 6, 7] was measured by viewing the high-resolution contact radiographs at $\times 8$ magnification on a radiographic light box and taking measurements using a calibrated, hand-held digital caliper (CD-6B; Mitutoyo Corp, Painesville, OH, USA). Radiolucencies interposed between the bone and implant (ΣL_2) were subtracted from the total linear length of the porous-coated interface (ΣL_1). We then calculated the ABI for the entire component as the percentage of bone that appeared in direct contact with the porous-coated regions of the components using the following equation:

$$ABI = \frac{\sum L_1 - \sum L_2 \times 100\%}{\sum L_1}.$$

This method was developed to better discriminate the tissue response and fibrous tissue formation at the interface of each component and for inspection of regional analysis to determine the extent of osteolysis compared to the

limitations of gross radiographs, which interfere with visibility due to projection effects (Fig. 4). These contact radiographs were then used to document regional osteolysis (Fig. 5). After this process, the 3-mm-thick sections were subsequently ground down to 50 μm to confirm the presence of wear particulate in the osteolytic region using transmitted and polarized light microscopy.

The area of bone (bone ingrowth, periprosthetic bone, and host bone) from sections of femur, patella, and tibia were averaged to obtain a single regional value per donor ($n = 19$: patellas, tibias, and femurs). A paired t-test was used when comparing regions (percent bone ingrowth, percent periprosthetic bone, and percent host bone) within the patellar, tibial, or femoral components. Univariable regression was performed with implantation time as the independent variable and percent bone ingrowth or ABI as the dependent variable, with $n = 19$ donor implants for each of the three types of components (patellar, tibial, and femoral). We performed all analyses with SAS[®] software (SAS Institute, Inc, Cary, NC, USA).

Fig. 4A–B (A) A gross radiograph and (B) high-resolution contact radiograph from the same specimen show projection effects inherent with gross radiography, making detailed regional observations difficult but showing the superior detail with high-resolution contact radiographs.

Fig. 5A–C High-resolution contact radiographs of the (A) femur, (B) tibia, and (C) patella show the regions used for reporting osteolysis (Table 4).

Results

The percent area of bone ingrowth into the porous coating was never greater than the percent of either periprosthetic or host bone in any of the components. There was less ($p = 0.018$) bone ingrowth relative to the host bone in the patellar component but no difference in the ingrowth of the tibial component ($p = 0.274$) and femoral component ($p = 0.861$) relative to the host bone. There was less ($p < 0.001$) bone ingrowth when compared to periprosthetic bone in the patellar component but no difference between the bone ingrowth of the tibial component ($p = 0.155$) and femoral component ($p = 0.197$) when compared to the periprosthetic bone (Table 2).

For every 10-month increase in the implantation time, there was a 0.5% increase in the percent bone ingrowth in the patellar components ($p = 0.007$), 0.4% increase in the percent bone ingrowth for the tibial components ($p = 0.007$), and 0.2% increase in the percent bone ingrowth for the femoral components ($p = 0.049$), suggesting continued remodeling of the bone within the porous coating with a net bone formation over time (Fig. 6). Implantation time did not correlate to the ABI in the patellar component ($p = 0.837$), tibial component ($p = 0.322$), or femoral component ($p = 0.528$), thus indicating osteolysis did not progress with time. The femoral component had a lower ABI than either the tibial ($p = 0.012$) or patellar component ($p < 0.001$) (Table 3), and for every 10-month increase in implantation time, there was a 0.4% decrease in ABI, suggesting increase in fibrous tissue formation in the femoral component (Fig. 6).

The gross analysis of the polyethylene inserts, metal-backed patellas, and femoral components showed, at approximately 10 years time in situ, osteolysis was occurring in various regions and along the screw tracts (Table 4). Metal back edge wear was observed in one of the 19 knee retrievals (Donor 12, right; Fig. 7). We noted there was minimal burnishing of the femoral components'

Table 2. Bone percent data for the three components and the three regions

Value	Bone percent								
	Patella			Tibia			Femur		
	PC (%)	PP (%)	HB (%)	PC (%)	PP (%)	HB (%)	PC (%)	PP (%)	HB (%)
Average	13.69	25.98	19.81	9.92	13.49	8.06	8.10	10.90	7.85
SD	7.26	12.10	7.17	6.35	7.31	3.74	5.43	5.02	3.15
Median	12.90	25.09	19.30	9.50	14.80	7.00	7.27	10.10	7.80
Maximum	28.16	47.90	32.90	21.90	29.00	16.20	18.90	24.10	13.90
Minimum	2.60	6.04	9.56	2.10	1.65	1.95	1.40	2.64	1.82

PC = porous-coated ingrowth; PP = periprosthetic; HB = host bone.

articulating surfaces except in the patient with patellar metal back edge wear. Gross analysis demonstrated articulating surface and backside wear was visible in the gamma-in-air-treated conventional polyethylene and also appeared to progress during the 10- to 25-year period. Contact radiographs were useful in determining none of the 57 rotational stabilizing smooth pegs in the patellar components, none of the 76 smooth pegs in the tibial components, and none of the 38 smooth pegs in the femoral components had preferential bone attachment that might have led to stress shielding.

Discussion

Cementless fixation remains controversial in TKA due to the challenge of achieving consistent skeletal attachment. We assumed the patient's host bone may act as a limiting factor in the ability to obtain successful attachment and the addition of autograft bone chips would limit fibrous tissue formation, presumably facilitating bone ingrowth. We evaluated the *in vivo* performance of 19 human post-mortem-retrieved clinically successful primary knee systems to better understand the biologic principles of skeletal fixation and the use of autograft bone chips in a unique porous-coated implant design. Previous studies [9, 10, 12, 13, 16] had not attempted to compare the amount of bone ingrowth with the amount of periprosthetic or host bone to understand connectivity with the skeleton. We therefore asked the following three questions: (1) Did the amount of bone ingrowth exceed the amount of periprosthetic and host bone with the addition of autograft bone chips? (2) Did the amount of bone ingrowth increase with implantation time? And (3) did osteolysis along the porous coating interface and screw tracts progress with implantation time?

The authors acknowledge several limitations to the current study. First, the study had a lower number of female donors ($n = 2$) compared to the number of male donors ($n = 12$). This discrepancy can be explained simply

by the fewer number of female patients in the Veterans Affairs population. Second, it was unknown how long the patients in this series had been compromised by declining health, a possible onset of osteoporosis, or their individual activity levels, which may have affected the interpretation of the data. Third, the patients who chose to enroll in this study were dedicated to the doctor-patient relationship and there may have been skeletal attachment failures in the larger clinical series, although clinical followup studies were favorable [22]. It should also be noted, although a single blinded observer performed a particular outcome measure, this may introduce a systematic bias even if the observer is experienced. Despite these limits and after a careful literature review, this appears to be the largest postmortem donor series of a single-surgeon-implanted and designed knee system performed with corresponding translational research and clinical followup studies [2–4, 17–19, 21, 22].

We found the percent area of periprosthetic bone was greater than the percent area of bone ingrowth in the patellar, tibial, and femoral components. This was particularly apparent in the patellar component, which had the highest absolute ingrowth, despite having the least ingrowth relative to adjacent bone. This may be explained by the mechanical impaction of the autograft bone chips into the resected bone using the unique procedure of reversing the patellar reamer to mechanically apply the milled autograft bone chips uniformly over the surface of the patellar host bone as compared to the less efficient manual spreading by hand using the scalpel handle for the application to the femoral and tibial resected host bone [15, 22, 30]. The apparent strength of the postmortem analysis was the ability to determine the efficacy of using autograft bone chips at the time of implantation to help achieve consistent skeletal attachment. Although clinical radiographs had suggested bone ingrowth had been achieved, the postmortem analysis using BSE imaging was definitive and absent of the inherent projection effects seen in clinical, gross, and contact radiographs.

Although implantation time predicted the percent bone ingrowth in all three components, these data suggest, even

Fig. 6A–F Graphs show (A, C, E) the mean bone percent in each region (porous-coated ingrowth [PC], periprosthetic interface [PP], and host bone [HB]) and (B, D, F) the mean ABI data as they vary over time of implantation for each of the components: (A, B) patella, (C, D) tibia, and (E, F) femur.

Table 3. Appositional bone index data for the three components

Value	Appositional bone index		
	Patella	Tibia	Femur
Average	90.8	75.3	64.4
SD	10.2	13.7	13.2
Median	92.4	72.7	61.6
Maximum	100	96	96.7
Minimum	59.4	51.3	45.1

Table 4. Osteolysis data obtained from contact radiographic analysis for the three components

Donor	Side	Time in situ (months)	Osteolysis per region*		
			Patella	Tibia	Femur
1	Right	14			
2	Left	17			
3	Right	67			1
4	Right	68			8
	Left	83		10	4, 5, 6
5	Left	69		Around stem	1
6	Right	77			
7	Right	84			
8	Left	116		Screw (1×)	8, 9
	Right	126			
9	Right	120			
10	Right	123	18	Around stem	8, 9
	Left	124		Around stem	7
11	Right	136			2, 9
12	Left	238	19	Screw (1×)	2, 3, 8, 9
	Right	239		10, around stem, screw (1×)	
13	Left	243	19	10, screw (2×)	1, 2, 3, 4
	Right	291	18, 19	Around stem, screw (2×)	1, 2, 3
14	Left	300	19	10, screw (2×)	8, 9

* For the regions and the region numbers used for reporting osteolysis, see Figure 5; osteolysis appeared to progress at the later time periods (> 10 years) for all three components.

after long-term followup, the amount of bone ingrowth does not reach host bone levels. Results from these clinically successful postmortem retrievals suggest cementless TKA remains a reasonable option in the active healthy patient with good bone quality [15], considering the advantages of bone preservation and the ease of revision. It remains unknown whether compromised osteopenic bone could achieve the amount of bone attachment necessary to provide durable fixation over time since osteopenic and osteoporotic bone are contraindications for porous-coated TKAs.

Implantation time did not predict ABI in any of the components. The femoral component had a lower ABI than

either the patellar or tibial component. Additionally, contact radiographic analysis was useful in determining none of the pegs in any of the components had preferential attachment that might have led to stress shielding. This has occurred in some other designs with porous-coated stabilizing pegs, which can lead to preferential bone ingrowth attachment to the porous-coated pegs, causing the remainder of the undersurface face of the porous coating to be limited by fibrous tissue attachment [32].

The use of a titanium alloy articulating surface on the femoral component is no longer available with this design. This is despite the fact, at least in this series of retrievals, that the clinical outcomes were not apparently compromised. The metal-backed patella is now rarely used in most total knee designs. It should be noted, when the design surgeon (AAH) initially observed edge wear on the metal-backed patella in early clinical followup studies, the minimum edge of the polyethylene thickness was increased and medialization of the metal-backed component was performed to avoid edge wear [15]. As seen in this study, only one of the 19 knees had evidence of edge wear. It is important to note this observation since, although some questions can be better answered by postmortem donor analysis, earlier operative and design corrections can be made clinically and at revision surgery with subsequent implant analysis without waiting for postmortem analysis [3, 8].

In summary, this 25-year postmortem study demonstrated consistent bone ingrowth and skeletal attachment with the use of autograft bone chips. The osteolysis along the interface and screw tract appeared to be limited in scope to the longer-term (> 10-year) retrievals. This was similar to cemented total knee studies using gamma-in-air-treated UHMWPE. When reviewing the few stemmed components, the stem seemed to facilitate osteolysis beneath the tibial component. This observation was speculative due to the small number of components with stem osteolysis in this series (stems, $n = 9$; without stems, $n = 10$). Further analysis must be conducted to confirm these findings, as these observations have also not been reported in clinical followup studies using this design [23, 27, 28].

Finally, postmortem analysis can contribute to the basic understanding of TKA design performance, skeletal attachment, and confirmation of the use of autograft bone chips or other biologic additives. It must be emphasized, however, clinical followup and implant analysis at the perioperative time of revision surgery are essential for making early corrections such as the operative medialization of the metal-backed patella in this implant system [15]. Also, the femoral component was subsequently changed to a bimetal design (cobalt-chrome articulation with titanium porous coating) to allow for a more wear-resistant

Fig. 7A–D (A, C) Full-sized and (B, D) detailed gross images taken from the bilateral patellas of Donor 12 show differences in wear patterns in the patellas of the same patient. (A, B) The left patella was implanted for 238 months (> 19 years) and showed extensive delamination of the surface with edge damage. (C, D) The right patella was implanted for 239 months and showed extensive metal back edge wear with metallosis.

articulating surface with improved wear performance, although the titanium alloy femoral component did not appear to be a major compromise to the clinical success in this retrieval series.

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References

1. Bischoff UW, Freeman MA, Smith D, Tuke MA, Gregson PJ. Wear induced by motion between bone and titanium or cobalt-chrome alloys. *J Bone Joint Surg Br.* 1994;76:713–716.
2. Bloebaum RD, Bachus KN, Jensen JW, Hofmann AA. Post-mortem analysis of consecutively retrieved asymmetric porous-coated tibial components. *J Arthroplasty.* 1997;12:920–929.
3. Bloebaum RD, Bachus KN, Jensen JW, Scott DF, Hofmann AA. Porous-coated metal-backed patellar components in total knee replacement. *J Bone Joint Surg Am.* 1998;80:518–528.
4. Bloebaum RD, Bachus KN, Momberger NG, Hofmann AA. Mineral apposition rates of human cancellous bone at the interface of porous coated implants. *J Biomed Mater Res.* 1994;28:537–544.
5. Bloebaum RD, Merrell M, Gustke K, Simmons M. Retrieval analysis of a hydroxyapatite-coated hip prosthesis. *Clin Orthop Relat Res.* 1991;267:97–102.
6. Bloebaum RD, Mihalopoulos NL, Jensen JW, Dorr LD. Post-mortem analysis of bone growth into porous-coated acetabular components. *J Bone Joint Surg Am.* 1997;79:1013–1022.
7. Bloebaum RD, Rhodes DM, Rubman MH, Hofmann AA. Bilateral tibial components of different cementless designs and materials: microradiographic, backscattered imaging, and histologic analysis. *Clin Orthop Relat Res.* 1991;268:179–187.
8. Bloebaum RD, Rubman MH, Hofmann AA. Bone ingrowth into porous-coated tibial components implanted with autograft bone chips: analysis of ten consecutively retrieved implants. *J Arthroplasty.* 1992;7:483–493.
9. Bobyn JD, Cameron HU, Abdulla D, Pilliar RM, Weatherly GC. Biologic fixation and bone modeling with an unconstrained canine total knee prosthesis. *Clin Orthop Relat Res.* 1982;166:301–312.
10. Bobyn JD, Pilliar RM, Cameron HU, Weatherly GC. The optimum pore size for the fixation of porous-surfaced metal implants by the ingrowth of bone. *Clin Orthop Relat Res.* 1980;150:263–270.
11. Bobyn JD, Stackpool GJ, Hacking SA, Tanzer M, Krygier JJ. Characteristics of bone ingrowth and interface mechanics of a new porous tantalum biomaterial. *J Bone Joint Surg Br.* 1999;81:907–914.
12. Collier JP, Colligan GA, Brown SA. Bone ingrowth into dynamically loaded porous-coated intramedullary nails. *J Biomed Mater Res.* 1976;10:485–492.
13. Collier JP, Mayor MB, Chae JC, Surprenant VA, Surprenant HP, Dauphinais LA. Macroscopic and microscopic evidence of prosthetic fixation with porous-coated materials. *Clin Orthop Relat Res.* 1988;235:173–180.
14. Deglurkar M, Davy DT, Stewart M, Goldberg VM, Welter JF. Evaluation of machining methods for trabecular metal implants in a rabbit intramedullary osseointegration model. *J Biomed Mater Res B Appl Biomater.* 2007;80:528–540.
15. Evanich CJ, Tkach TK, von Glinski S, Camargo MP, Hofmann AA. 6- to 10-year experience using countersunk metal-backed patellas. *J Arthroplasty.* 1997;12:149–154.

16. Galante J, Rostoker W, Lueck R, Ray RD. Sintered fiber metal composites as a basis for attachment of implants to bone. *J Bone Joint Surg Am.* 1971;53:101–114.
17. Hofmann AA. Response of human cancellous bone to identically structured commercially pure titanium and cobalt chromium alloy porous-coated cylinders. *Clin Mater.* 1993;14:101–115.
18. Hofmann AA, Bachus KN, Bloebaum RD. Comparative study of human cancellous bone remodeling to titanium and hydroxyapatite coated implants. *J Arthroplasty.* 1993;8:157–166.
19. Hofmann AA, Bloebaum RD, Bachus KN. Progression of human bone ingrowth into porous-coated implants. *Acta Orthop Scand.* 1997;68:161–166.
20. Hofmann AA, Bloebaum RD, Koller KE, Lahav A. Does Celecoxib have an adverse effect on bone remodeling and ingrowth in humans? *Clin Orthop Relat Res.* 2006;452:200–204.
21. Hofmann AA, Bloebaum RD, Rubman MH, Bachus KN, Plaster R. Microscopic analysis of autograft bone applied at the interface of porous-coated devices in human cancellous bone. *Int Orthop (SICOT).* 1992;16:349–358.
22. Hofmann AA, Evanich JD, Ferguson RP, Camargo MP. Ten- to 14-year clinical followup of the cementless Natural Knee system. *Clin Orthop Relat Res.* 2001;388:85–94.
23. Hofmann AA, Murdock LE, Wyatt RW, Alpert JP. Total knee arthroplasty: two- to four-year experience using an asymmetric tibial tray and a deep trochlear-grooved femoral component. *Clin Orthop Relat Res.* 1991;269:78–88.
24. Insall JN, Dorr LD, Scott RD, Scott WN. Rationale of The Knee Society Rating System. *Clin Orthop Relat Res.* 1989;248:13–14.
25. Jasty M, Bragdon CR, Haire T, Mulroy RD Jr, Harris WH. Comparison of bone ingrowth into cobalt chrome sphere and titanium fiber mesh porous coated cementless canine acetabular components. *J Biomed Mater Res.* 1993;27:639–644.
26. La Budde JK, Orosz JF, Bonfiglio TA, Pellegrini VD Jr. Particulate titanium and cobalt-chrome metallic debris in failed total knee arthroplasty: a quantitative histologic analysis. *J Arthroplasty.* 1994;9:291–304.
27. Nafei A, Nielsen S, Kristensen O, Hvid I. The press-fit Kinemax knee arthroplasty: high failure rate of non-cemented implants. *J Bone Joint Surg Br.* 1992;74:243–246.
28. Ranawat CS, Flynn WF Jr, Saddler S, Hansraj KK, Maynard MJ. Long-term results of the total condylar knee arthroplasty: a 15-year survivorship study. *Clin Orthop Relat Res.* 1993;286:94–102.
29. Sumner DR, Bryan JM, Urban RM, Kuszak JR. Measuring the volume fraction of bone ingrowth: a comparison of three techniques. *J Orthop Res.* 1990;8:448–452.
30. Whiteside LA. Long-term followup of the bone-ingrowth Ortholoc knee system without a metal-backed patella. *Clin Orthop Relat Res.* 2001;388:77–84.
31. Willie BM, Bloebaum RD, Bireley WR, Bachus KN, Hofmann AA. Determining relevance of a weight-bearing ovine model for bone ingrowth assessment. *J Biomed Mater Res A.* 2004;69:567–576.
32. Wright TM, Rimnac CM, Stulberg SD, Mintz L, Tsao AK, Klein RW, McCrae C. Wear of polyethylene in total joint replacements: observations from retrieved PCA knee implants. *Clin Orthop Relat Res.* 1992;276:126–134.