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Changes in Bone Density in Metal-Backed and All-Polyethylene Medial Unicompartmental Knee Arthroplasty

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Abstract (200 words)

Background: Proximal tibial strain in medial unicompartmental knee replacement (UKR) may alter bone mineral density (BMD) and cause pain. The aims of this retrospective cohort study were to quantify and compare changes in proximal tibial BMD in metal-backed (MB) and all-polyethylene (AP) medial UKRs, correlating these with outcome, particularly ongoing pain.

Methods: Radiographs of 173 MB and 82 AP UKRs were analysed using digital radiograph densitometry at 0, 1, 2 and 5 years. The mean greyscale of 4 proximal tibial regions was measured and converted to a ratio: the GSRb (greyscale ratio b) where GSRb>1 represents relative medial sclerosis.

Results: In both implants GSRb reduced significantly to 1 year and stabilised with no differences between implants. Subgroup analysis showed less improvement in OKS in patients whose GSRb increased by >10% at 1 year (40/255) compared to patients whose GSRb reduced by >10% at both one (8.2 Vs 15.8, p=0.002) and five years (9.6 Vs 15.8, p=0.022). Patients with persistently painful UKRs (17/255) showed no reduction in GSRb at one year compared to a 20% reduction in those without pain (p=0.05).

Conclusions: BMD changes under medial UKAs are independent of metal backing. Medial sclerosis appears to be associated with ongoing pain.

Keywords: Unicompartmental knee arthroplasty; bone mineral density; unexplained pain; digital radiodensitometry.

Footnote 1 Abbreviations:

BMD Bone mineral density; GSRa Grey scale ratio a (digital radiodensitometry ratio of medial to lateral proximal tibial condyles); GSRb Grey scale ratio b (digital radiodensitometry ratio of medial fourth to lateral three fourths proximal tibial

Introduction

Joint registries show higher revision rates for unicompartmental knee arthroplasties (UKAs) compared to total knee arthroplasties (TKAs) [1-3]. Unexplained pain is the second most common reason for UKA revision after aseptic loosening [4, 5], and undoubtedly contributes to the poorer survival of UKA compared to TKA. Elevated proximal tibial strain with repetitive microfracture and remodelling may contribute to this pain [6]. Tibial bone models of UKAs have shown greater microdamage under all-polyethylene tibial components compared to metal-backed components [7]. In TKA, tibial component metal backing distributes stresses more evenly than in all-polyethylene implants, but causes stress shielding along undersurface projections [8]. The clinical significance of this is unclear with equivalent long term outcomes in both types of TKAs [9]. Both overloading and shielding of bone can alter bone mineral density (BMD).

Bone mineral density is routinely measured using dual x-ray absorptiometry (DEXA), but can be measured using digital radiological densitometry. This technique derives changes in BMD from calibrated anteroposterior (AP) radiographs of the knee and has been validated against DEXA [10]. It has been used to assess changes in tibial BMD in TKA [11] and to investigate the role of altered BMD in TKA failure [12]. Stress shielding and low BMD may cause reduced cancellous support to implants resulting in subsidence. Alternatively, proximal tibial microdamage and adaptive remodelling from overload may cause pain and a relative increase in BMD under the implant.

The primary aim of this study was to examine changes in tibial BMD in medial UKAs of two designs: a mobile bearing metal-backed implant (MB) and a fixed bearing all-polyethylene implant (AP). We hypothesized that medial BMD would increase under the less stiff all-polyethylene tibial components due to repetitive microfracture and remodelling. Secondary aims included investigating the effect of patient demographics on BMD and the effect of BMD changes on clinical outcome, with particular reference to unexplained pain.

Materials and Methods

Ethical approval was obtained for this study. Patients who had undergone UKA from 1999-2007 at our institution were identified using our prospectively collected arthroplasty database. All patients who had undergone a cemented Oxford mobile bearing metal-backed UKA (MB) (Biomet, Swindon, United Kingdom) or a cemented Preservation fixed bearing all-polyethylene tibia UKA (AP) (DePuy, Johnson & Johnson Professional Inc., Raynham, Massachusetts, USA) were included in the study. The second of bilateral UKAs were excluded as were patients who had died.

Medical and operation notes were reviewed for all patients. Data recorded included age, sex, weight, and body mass index (BMI).

To assess BMD, anteroposterior weight-bearing knee radiographs were examined at 5 time-points for each patient: pre-operative, immediate postoperative, and at 1, 2 and 5 years post-operatively. All radiographs on radiographic film were digitised using a UMAX Power Look 2100XL flatbed scanner (RSA Biomedical, Naperville, Illinois, USA) at 256 (8-bit) greyscale and 300dpi resolution and were saved as TIFF files for analysis. Digital radiographs from the PACS system (Kodak Carestream, Rochester, NY, USA) were exported for analysis as TIFF files. Image analysis was performed using ImageJ 1.45m, a public domain Java based scientific image processing and analysis package [13]. Implant alignment [14] and pixel value statistics were measured following calibration, producing a range of greyscale values from 0-255 for each pixel. Each image was calibrated such that air (black pixels) had a value of 0 and the femoral component (white pixels) a value of 255 [11]. The mean greyscale value of pixels within user defined regions of interest (ROIs) were calculated. Regions of interest were defined using the tibial anatomical axis and standardised measurements (Table 1) to create 4 ROIs: 2 medial (A1 and A2) and 2 lateral (A3 and A4) (Figure 1). Regional boundaries were selected to maximise trabecular bone content and exclude artefact from fibular head, cement and peripheral cortical bone [11] (Figure 1d).

Regions were transposed to all radiographs of a given patient to ensure the same areas were measured. Mean density measurements were recorded for each ROIs in each patient at each follow up. To facilitate quantitative comparison of radiographs taken at different times, the mean grey scale was represented as a ratio, the greyscale ratio (GSR). This compared the density of medial to lateral ROIs (GSRa, equation 1) and the most medial ROI to the remainder of the proximal tibia (GSRb, equation 2) corrected for area. All measurements were taken by a single observer (CEHS). A GSR>1 reflected a relative medial sclerosis.

Equation1:

$$GSRa = \frac{\overline{(A1}(A1pix) + \overline{A2}(A2pix))}{(A1pix + A2pix)} \Big/ \frac{\overline{(A3}(A3pix) + \overline{A4}(A4pix))}{(A3pix + A4pix)}$$

Equation 2:

$$GSRb = \overline{A1} \,/\, \frac{\overline{\overline{A2}(A2p\imath x) + (A3}(A3pix) + \overline{A4}(A4pix))}{(A2pix + A3pix + A4pix)}$$

$$Where\ \bar{A} = mean\ greyscale\ of\ ROI \quad pix = area\ in\ pixels\ of\ ROI$$

Prior to surgery, all patients completed a Short-form (SF-12) health questionnaire [15] (physical and mental components) and Oxford Knee Score (OKS) [16]. Postoperative questionnaires (SF-12 and OKS) were sent at 12 months. In April 2013 a similar questionnaire was sent to patients with the addition of patient satisfaction measurements [17] and knee specific pain questions. Patients were asked to indicate the pain level from their knee with a visual analogue pain scale (VAS) from no pain (0) to the worst pain imaginable (100). If pain was present, patients were asked to indicate its location by ticking as many boxes as applied from “at the front of the knee”, “at the back of the knee”, “on the inside edge of the knee”, “on the outside edge of the knee”, “at the top of the shinbone”, “all over the knee” and “other”. Patients were asked if they had undergone revision or reoperation of their UKA for any reason with tick-box options. This data was correlated with the notes.

Statistical Analysis

Analysis was performed using SPSS version 19.0 (SPSS Inc., Chicago, IL, USA). Parametric (paired and unpaired T-tests) and non-parametric (Wilcoxon Rank and Mann-Whitney U) tests were used to assess continuous variables for differences between UKA cohorts. Nominal categorical variables were assessed using a Chi square or Fisher’s exact test. Repeated measures ANOVA was used to examine changes in parametric variables over the 5 year study period. Correlation of continuous variables was assessed using Pearson correlation. A p value of <0.05 was considered to be statistically significant. For changes in GSR and PROMs over time, significance was set at $p<0.0125$ incorporating a Bonferroni correction for the 4 timepoints tested. Post-hoc power analyses were performed using the method of Lehr [18]. Subgroup analysis was performed on those with GSRb which increased or decreased by >10% and on those with and without painful UKRs.

Results

The study group consisted of 173 MB and 82 AP UKRs in 255 patients. Table 2 details preoperative patient characteristics. Table 3 details postoperative alignment. Significantly more proximal tibia, as approximated by D4 (as a percentage of the tibial width) was resected to implant the MB implant (mean 21.8%, SD 3.6) compared to the AP (17.9%, SD 2.6, p<0.001 unpaired T-test). Greater overhang was present in the MB group (mean 0.3, SD 1.7) with underhang in the AP group (mean -0.9, SD 1.4, p<0.001 unpaired T-test). There was no difference in resultant femorotibial angle between implants.

Grey Scale Ratios

A total of 945 radiographs were analysed. The greyscale within each ROI was normally distributed, therefore mean greyscale was considered an appropriate measure. Across all UKAs, GSRa did not change significantly with time. However, GSRb decreased significantly in the first postoperative year, remaining stable thereafter (p<0.001, repeated measures ANOVA) (Figure 2).

Prior to surgery, the AP group displayed significantly higher GSRb than the MB. GSRb reduced significantly over the 5 year period in both AP (p<0.001, repeated measures ANOVA) and MB UKAs (p=0.014, repeated measures ANOVA) (Figure 3). In both implants, there was a significant negative correlation between preoperative GSRb and 1 year change in GSRb (Pearson's correlation AP-0.292, p<0.05; MB -0.607, p<0.01). There was no correlation between tibial resection depth and GSRb change in either implant.

Using the method of Lehr, our minimal sample size of 82 would enable detection of a 13% difference in GSRb at 1 year (SD 0.298) as significant at 80% power and a significance level of 0.05.

PROMs

The mean follow-up for the >5year questionnaire was 100 months for all UKAs (62-158). There were significant postoperative improvements in the physical component score (PCS) of the SF-12 for both implants (p<0.001, repeated measures ANOVA) with no change from 1 to 5 years (MB p=0.203, AP p=0.793, paired T-tests). OKS improved significantly in both implants (p<0.001, repeated measures ANOVA). Again this improvement occurred in the first year with no significant changes thereafter and no differences between implants (Table 4).

There was no significant correlation between preoperative GSRb and preoperative OKS (Pearson's correlation 0.105). Nor was there correlation between absolute OKS and absolute GSRb at 1 or 5 years in either implant (1yr: AP 0.09, MB 0.251; 5yrs: AP -0.004, MB 0.11, Pearson's correlation). However, negative linear correlations were found for change in GSRb and improvement in OKS at 1 year (AP -0.312 p=0.044, MB -0.287 p=0.065) (Figure 4).

Overall 81% of MB patients and 78% of AP patients were satisfied with their knee at >5 years. Satisfaction with pain relief was high in both groups: MB 89% and AP 88%. Pain at >5 years (VAS 0-100) did not differ between implants, but did differ significantly between those satisfied (MB 14.6 and AP 14.9) and those dissatisfied (MB 48.0 and AP 47.7, p<0001, unpaired T test). The location of pain reported by patients is shown in Figure 5. The trend towards more medial pain in the AP group was not significant (p=0.127, Chi squared).

Subgroup Analysis

Forty patients (12 AP and 28 MB) displayed a >10% increase in GSRb over 1 year with a mean increase of 0.21 (SD 0.17). A >10% reduction in GSRb occurred in 113 patients with a mean decrease of 0.34 in the first year (SD 0.20). In 103 patients GSRb changed by <10%. Improvement in OKS at 1 and 5 years differed significantly between those with increased and decreased GSRb at 1 year (Table 5).

During the study period, 16/173 MB and 7/82 AP UKAs were revised. Figure 6 details modes of failure. Revisions for pain (2MB and 5AP) were performed at mean 34 months (range 18-45). Despite no preoperative differences in GSRb, patients revised for pain had a mean increase in GSRb of 10% in year 1 compared to a mean decrease of 20% in those not revised for pain (p=0.017, unpaired T-test, 95%CI 0.06 to 0.6) (Figure 7).

Combining revisions for pain (2MB and 5AP) with patients "poorly" satisfied with pain relief but not offered revision (6MB and 4AP), absolute GSRb at 1 year was higher compared to non-painful UKAs, and this approached significance (p=0.051, Table 6). Mean GSRb reduced over 1 year in patients without painful UKAs, but remained unchanged in painful

UKAs. Again, this approached significant (p=0.052, Table 6). Significantly less improvement in the 1 year OKS (4.25, SD 11.1) was found following revision for pain compared to revisions for all other modes of failure (19.4, SD 10.6, p=0.026 unpaired T-test).

Alignment

Though there was no difference in resultant femorotibial angle (FTA), the AP tibia was implanted significantly more varised and with greater PTS than the MB (Table 3). The mean tibial component coronal alignment for all UKAs was 86.7° (range 78-93). There was no correlation between GSRb and tibial component coronal alignment (-0.073) or FTA (0.106, Pearson's correlation). There was no significant difference in GSRb between patients with varus tibial components and those without using both 87° (1.0 Vs 0.96, p=0.263 student T-tests) and 85° (0.98 Vs. 0.99, p=0.865, student T-tests) definitions. There was no difference in the tibial coronal alignment in those with painful UKAs (+/- revision) (mean 86.6°) and those without (86.2°, p=0.684 student T-tests). Similarly there was no difference in sagittal alignment between those dissatisfied with painful UKAs (+/- revision) (mean 87.6°) and those without (86.7°, p=0.237 Mann Whitney U test). Femorotibial angle did not differ significantly in those with painful UKAs and those without (177.4 Vs 177.5, p=0.882, student T-test).

Sex, Age and BMI

Females displayed a higher GSRb (higher relative medial BMD) in both groups at every time point. In the MB group, the mean preoperative GSRb in women was 0.99 compared to 0.85 in men (p=0.005, 95%CI -0.25 to -0.05). These differences remained significant at 1 year. There was no significant difference in the *change* in GSRb over the first year between men and women in the MB group (p=0.602, unpaired T-test). In the AP group, again women had a higher mean preoperative GSRb of 1.13 compared to men, 0.93 (p=0.001, 95% CI -0.33 to -0.08, unpaired T-test). Once again these differences remained at 1 year, with no significant differences in the *change* in GSRb over the years between the sexes.

Preoperative GSRb negatively correlated with age (Pearson's correlation -0.440, p<0.01). Younger patients displayed greater relative medial sclerosis preoperatively. No significant correlation was apparent between change in GSRb at 1 year and age, absolute BMI, weight or tibial resection depth in either implant.

Patients with a BMI >30 had significantly higher preoperative GSRb (1.03, SD 0.28) than those with BMI <30 (0.93, SD0.27, p=0.025, 95%CI -0.2 to -0.01 unpaired T-test). BMI above or below 30 had no effect on *changes* in GSRb in the MB group. In the AP group, the differences in preoperative GSRb for patients with BMIs above or below 30 (BMI >30 GSRb 1.13 compared to BMI<30 GSRb 0.96, p=0.012, unpaired T-test) resolved by 1 year postoperatively.

Discussion

The greatest changes in BMD were found immediately below the UKA tibial components at the most medial quadrant measured, reflected by GSRb being the most reactive measure. This is consistent with the findings of previous medial UKA DEXA studies [19]. The most significant finding of this study was an overall decrease in medial sclerosis (GSRb) after medial UKA with no differences apparent between all-polyethylene and metal-backed implants. This finding contradicts our original hypothesis that greater medial sclerosis would occur under the all-polyethylene components. This hypothesis was based upon biomechanical data showing greater proximal tibial microdamage under all-polyethylene compared to metal-backed UKA implants [7]. The relationship between implant and bone turnover appears more complex *in vivo* than simply less stiff implants creating greater cancellous bone overload, and thus sclerosis, via microfracture and adaptive remodelling or avascularity. A number of confounding variables (age, weight, BMI, bone size, resection depth, activity level, preoperative BMD and bone quality) affect loading and the response of bone to this. We have attempted to investigate some of these variables here, but small subgroups increase the possibility of type 2 errors and significant relationships may have been missed.

Using the same digital radiological densitometry method, a similar reduction in medial BMD has been found following TKA [11]. In isolated medial compartment osteoarthritis, progressive medial tibial condyle overload elevates medial BMD compared to lateral [20]. Restoring medial compartment height and femorotibial angle with a UKA offloads the medial condyle. This would be expected to reduce medial BMD, and thus GSRb as occurred here during the first postoperative year. This concurs with the hypothesis of Simpson et al [6] and with the DEXA findings of others [19, 21]. To our knowledge is the first study to correlate such changes with outcome in UKA.

The modes of failure differed between implants. The commonest mode of failure for the AP implant was pain, whereas development of lateral OA predominated in the MB implant. There were no cases of tibial collapse, but tibial loosening was more common in the MB implant. These revisions were performed before tibial radiolucencies in the Phase III Oxford UKA implant were recognised as non-pathological lesions. Though revisions for pain were greater in the AP group, the proportion of painful UKAs was the same for both implants. The difference in revision rate may represent different approaches to painful AP and MB UKAs due to concerns for implant stiffness in AP tibias and for bone loss management in MB revisions [7]. Proximal tibial adaptive remodelling following TKA continues up to 2 years postoperatively, evident on bone scans. It has been suggested that if adaptive remodelling stabilises at 2 years, painful UKAs should settle then too [6]. This is not supported by our results where 18-26% of patients reported ongoing medial pain at >5 years, with most revisions for pain (6/7) were performed after 24 months. National Joint Registry data shows revisions for unexplained pain to occur consistently up to 7 years [5]. Revisions for pain had poorer postoperative outcomes than revisions for other reasons and this supports the findings of others [22].

A study of BMD changes in matched failing and non-failing TKAs (measured using digital radiological densitometry) has shown a mean reduction in medial BMD in non-failing knees, but a significant increase in medial BMD in those going on to fail by medial collapse [12]. In medial UKAs, we found postoperative elevation of (or maintenance of high) medial BMD to be associated with pain, but not collapse. If painful UKAs had been left without revision, more may have failed by tibial collapse. Pain was associated with younger age and elevated BMI, an association reported before [22] with no differences between fixed and mobile bearing UKAs [5]. The association between medial sclerosis and pain has not been reported previously. It suggests that younger, heavier patients may experience persistent overload even in MB implants. Interestingly, preoperative GSRa (reflecting medial to lateral proximal tibial BMD) was less in those patients who went on to increase their BMD and develop pain. This lends support to the concept of avoiding UKA in those with osteopenic bone.

GSRb was greatest preoperatively in women. Previous TKA studies show men to have higher lateral condyle BMD than women [11]. This falsely reduces the GSRb in men. Patient selection may have biased this further by excluding women with osteoporosis/radiographic osteopenia from undergoing UKA. The greater proportion of women in the AP group undoubtedly contributed to the higher starting GSRb in this group. The lesser tibial resection used in the AP implant may also have led to measurement of a more sclerotic region. Younger patients, and those with BMI>30, displayed greater preoperative medial sclerosis, suggesting that GSRb may reflect medial load.

Three previous studies have examined BMD in UKAs. Hooper et al [23] used DEXA in 79 uncemented Oxford UKAs comparing operated and non-operated knees at 2 years. They found a mean decrease in BMD in all regions of the operated tibia, greatest medially (corresponding to ROI A1). Changes over time were not examined and comparisons were not with the preoperative knee. Soininvaara et al [19] performed DEXA scanning on 21 metal-backed fixed bearing UKAs up to 7 years reporting a mean increase in medial tibial condyle BMD of 9% at 1 year. The ROIs used did not exclude cement, cortical condensations or fibular head composite shadowing. Richmond et al [21] used quantitative CT to asses tibial BMD in 26 MB and 24 AP UKAs reporting a mean reduction in BMD medially under the tibial component of <5% in both UKAs, but significantly greater in the AP implant. Though studies are few, there is little consistency in findings regarding BMD in UKA. It appears that BMD increases in some patients and decreases in others. The bigger sample size in our study has facilitated a more detailed examination of this than has been possible previously.

The digital radiodensitometry method used in this study can be used on any digital radiograph using the public access software Image J, making it more accessible and cheaper than DEXA scanning [13]. However, whilst this technique can be used to compare relative BMDs, it is unsuitable for absolute values and requires validation before use as a clinical decision making tool could be recommended. There is often reluctance to offer UKA to patients with poor BMD due to concerns regarding tibial subsidence. Our results suggest that caution may also be required in young, heavy patients who are at risk of continued sclerosis and ongoing pain following UKA.

This study has a number of limitations, including its retrospective design. The tibial component material is not the only design difference between these UKA implants as one is fixed and the other mobile bearing. Digital radiological densitometry is an inferred rather than a true measure of BMD, though it has been validated against DEXA scanning [10]. We have tried to strengthen this methodology by representing our findings as a ratio of medial to lateral ROIs rather than as absolute values. This methodology can be used retrospectively facilitating examination of a greater sample size. It also avoids additional radiation required by quantitative CT. Implant alignment was measured on short leg radiographs, not hip-knee-ankle radiographs, and as such may be less accurate. Subgroup analysis may be underpowered raising the possibility of type 2 errors, but was performed to try to better understand the clinical consequences of altered BMD. The 10% level used in subgroup analysis to define patients with increased or decreased BMD is arbitrary, but lies within the 7.3 to 17.4% range that BMD is thought to decrease by in TKA [12], and is above the mean 9% increase reported in UKA previously [19]. However, until further studies have been performed to determine what constitutes a clinically significant change in BMD, this remains an arbitrary, though informed, limit.

Conclusions

This retrospective cohort study has shown no difference in proximal tibial BMD between medial UKAs with and without tibial component metal backing. Despite a mean reduction in medial tibial BMD following medial UKAs, some patients display a localised increase in medial tibial density with sclerosis. This may reflect ongoing microdamage and adaptive remodelling in overloaded and overstrained bone and here was associated with younger age, elevated BMI and persistent pain with worse Oxford Knee Scores.

Table 1. Standardisation of the ROIs

Step	Figure	Description
1	1a	Tibial diaphysis measured at 2 points (green lines)
2	1a	Tibial anatomical axis (AA, red line) drawn by bisecting green lines
3	1a	Line D1 drawn through lateral corner of implant perpendicular to AA
4	1a	Vertical distance from lateral tibial spine to D1 measured as D4. This is a proxy measure of tibial resection depth and is represented as a % of D1
5	1b	D4 used to transpose D1 on to a preoperative radiograph
6	1b	Line D2 drawn parallel to D1 at a distance 0.5 D1 to mark distal boundary
7	1b	2 vertical lines (D3s) drawn where D2 intersects the cortices
8	1c	4 ROIs thus created: A1, A2, A3, A4.
9	1d	ImageJ polygon tool used to select each region for analysis, excluding the fibular head, cortical condensations and cement.

Table 2. Preoperative patient characteristics.

	Variable	MB (n=173)	AP (n=82)	P value	95% CI
Demographics	Female Sex	79 [45.6]	49 [59.8]	0.044 ^{T}	
	Age	66.4 (7.8)	68.3 (9.1)	0.127*	-4.2 to 0.53
	BMI	28.8 (4.3)	28.7 (4.8)	0.886*	-1.24 to 1.4
	Weight	81.4 (14.5)	78.7 (15.1)	0.218*	-1.6 to 7.2
PROMs	*OKS*	*20.8 (7.8)*	*20.1 (6.0)*	0.614*	-3.2 to 1.9
	PCS	30.3 (6.39)	31.23 (7.11)	0.400*	-3.12 to 1.25
	MCS	50.5 (11.78)	50.8 (11.51)	0.957 $^{\infty}$	-4.07 to 3.65
Alignment	FTA (lateral angle)	181.7 (2.9)	181.6 (2.6)	0.952*	-0.83 to 0.88
	TPA	85.0 (3.6)	85.6 (2.5)	0.023 §	
	PTS	3.5 (11)	3.5 (4)	0.458 §	
BMD	Time of XR (months preop)	1.18 (6)	0.79 (6)	0.938 §	
	GSRa	0.98 (0.19)	1.10 (0.18)	<0.001*	-0.18 to -0.07
	GSRb	0.91 (0.28)	1.05 (0.26)	0.002*	-0.22 to -0.05

OKS=Oxford Knee Score, PCS = physical component score of SF-12, MCS = mental component score of SF-12, FTA = femorotibial angle, TPA = native tibial plateau angle, PTS = native posterior tibial slope, XR = radiograph, GSR = greyscale ratio

Mean (SD), number [%], median (IQR) for TPA, PTS, comorbidities, time of XR

^{T} Chi squared test, *Two-tailed student T-test, § Kruskal Wallis test, $^{\infty}$ Mann-Whitney U-test

Table 3. Postoperative alignment recorded according to Sarmah et al [14]

		MB (n=173)	**AP (n=82)**	**P value**	**95% CI**
Overhang (mm)		0.3 (1.7)	-0.9 (1.4)	<0.001*	0.75 to 1.6
Resection depth D4 (% of tibial width)		21.8 (3.6)	17.9 (2.6)	<0.001*	3.15 to 4.74
FTA (lateral angle)		177.3 (2.6)	178.2 (3.1)	0.06*	-1.59 to 0.04
Change in FTA		4.5 (4.1)	3.75 (3.2)	0.111§	
Tibia	Coronal (Valgus +ve)	-2.9 (4.0)	-3.6 (3.7)	0.186§	
	Sagittal (Additional slope +ve)	0.5 (5.5)	-1.5 (3)	<0.001§	
Femur	Coronal (Valgus +ve)	2.9 (5.2)	-0.5 (5.1)	<0.001*	-4.7 to -2.0
	Sagittal (Flexion +ve)	2.65 (6.5)	-1.5 (7.1)	<0.001*	2.2 to 6.2

FTA = femorotibial angle, MPTA = medial proximal tibial angle, PTS = posterior tibial slope

Mean (SD), number [%], median (IQR) change in FTA, tibial angles

*Two-tailed student T-test, § Kruskal Wallis test

Table 4. Postoperative PROMs by UKR implant.

		MB (n=158)	**AP (n=75)**	**P value**	**95% CI**
OKS	Improvement to 1 yr	15.6 (9.90)	13.4 (8.17)	0.208*	-1.22 to 5.56
	Improvement to 5 yrs	14.1 (10.29)	14.73 (8.82)	0.727*	-4.27 to 2.99
PCS	Improvement to 1 yr	11.0 (10.66)	9.6 (10.89)	0.486*	-2.65 to 5.54
	Improvement to 5 yrs	8.6 (11.61)	9.6 (11.01)	0.652*	-5.08 to 3.20
MCS	Improvement to 1 yr	1.1 (11.41)	0.13 (9.06)	0.644*	-3.16 to 5.08
	Improvement to 5 yrs	-2.08 (12.27)	-1.45 (12.04)	0.777*	-5.07 to 3.79
Pain VAS	5 yr	20.2 (25.69)	22.2 (26.99)	0.525∞	-10.41 to 6.47

Mean (SD), number [%]

* Two sample T-test, ∞ Mann-Whitney U-test

Table 5. Relationship between change in GSRb at 1 year and PROMs at 1 and 5 years.

		↑GSRb at 1 year	**↓GSRb at 1 year**	**P value**	**95% CI**
Both UKRs		**(n=40)**	**(n=113)**		
	OKS Imp at 1yr	8.2 (9.99)	15.8 (8.3)	0.002*	-12.4 to -2.8
	OKS Imp at 5 yrs	9.6 (11.4)	15.8 (9.1)	0.022*	-11.4 to -0.9
	VAS Pain at 5 yrs	20.1 (24.5)	23.0(27.1)	0.712*	-18.8 to 12.9
MB		**(n=28)**	**(n=64)**		
	OKS Imp at 1yr	9.0 (11.6)	16.6 (6.5	0.023*	-14.2 to -1.1
	OKS Imp at 5 yrs	10.2 (11.3)	15.6 (9.9)	0.129*	-12.5 to 1.7
	VAS Pain at 5 yrs	16.2 (21.9)	19.7 (25.3)	0.647*	-18.7 to 11.7
AP		**(n=12)**	**(n=49)**		
	OKS Imp at 1yr	6.4 (4.6)	14.9 (8.2)	0.033*	-16.2 to -0.7
	OKS Imp at 5 yrs	8.2 (11.8)	8.4 (16.0)	0.086*	-16.7 to 1.2
	VAS Pain at 5 yrs	19.6 (33.8)	23.7 (24.7)	0.698*	-25.4 to 17.2

Imp = improvement in, Mean (SD), *=unpaired T-tests

Table 6. Characteristics of painful (+/- revision) and not painful UKR (MB and AP included) patients.

Variable	**Painful UKR (n=17)**	**Not painful (n=237)**	**P value**	**95% CI**
Female Sex	8 [47]	120 [51]	0.961[T]	
Age	60.4 (7.6)	67.4 (8.2)	0.001*	-11.2 to -2.8
BMI	32.7 (5.1)	28.5 (4.2)	<0.001*	1.9 to 6.5
Wt	88.1 (17.6)	79.8 (14.4)	0.034*	0.6 to 16.1
Pre-op OKS	*15.9 (7.5)*	*20.8 (7.1)*	0.061*	-0.2 to 10.0
Pre-op GSRb	1.04 (0.30)	0.96 (0.28)	0.334*	-0.09 to 0.26
1 yr GSRb	1.09 (0.17)	0.98 (0.21)	0.051*	0.01 to 0.24
1 yr Change in GSRb	0.02 (0.2)	-0.21 (0.3)	0.052*	0.005 to 0.363

Mean (SD), number [%]

[T] Chi squared test, * two sample T-test

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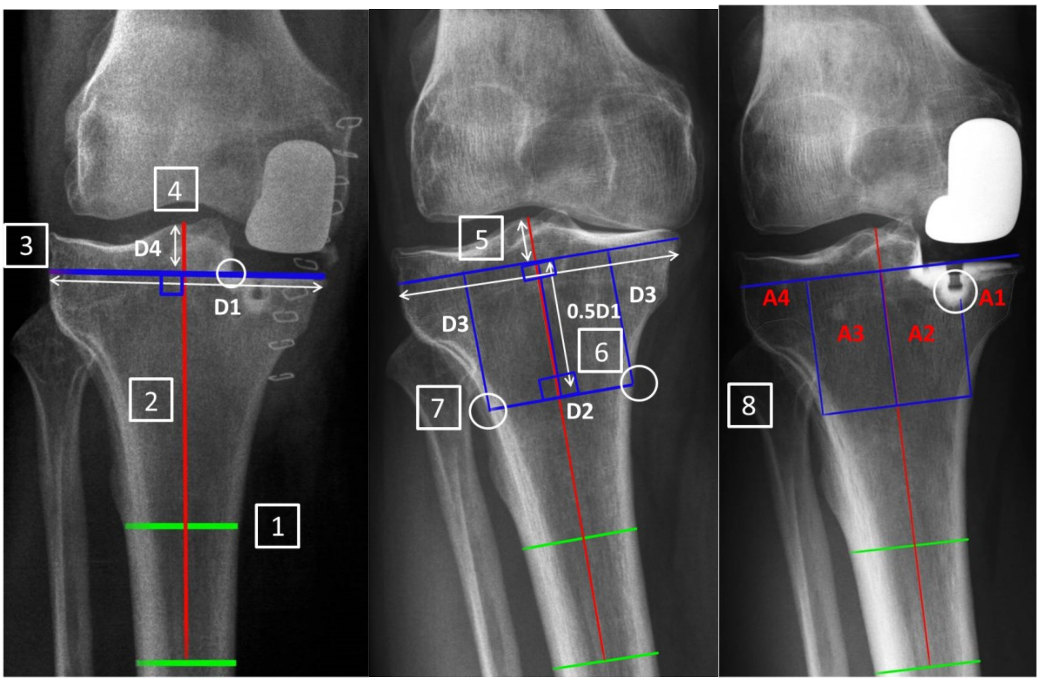

Figure 1a-c. Delineating the regions of interest (ROIs).

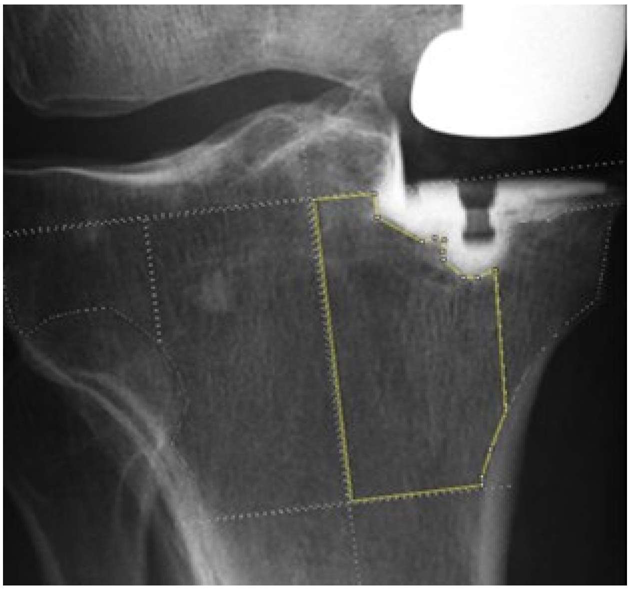

Figure 1d. ROIs for analysis with exclusion of fibular head, cortical condensation and cement (magnified).

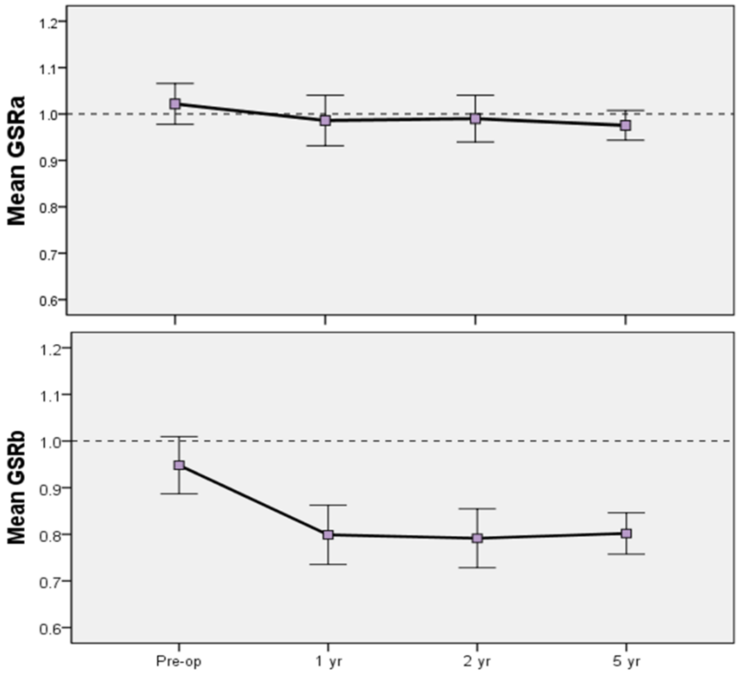

Figure 2. Changes in GSRa and GSRb over 5 years of follow up across the entire UKA population showing significant reductions in the mean GSRb in the first postoperative year (p<0.001, ANOVA)

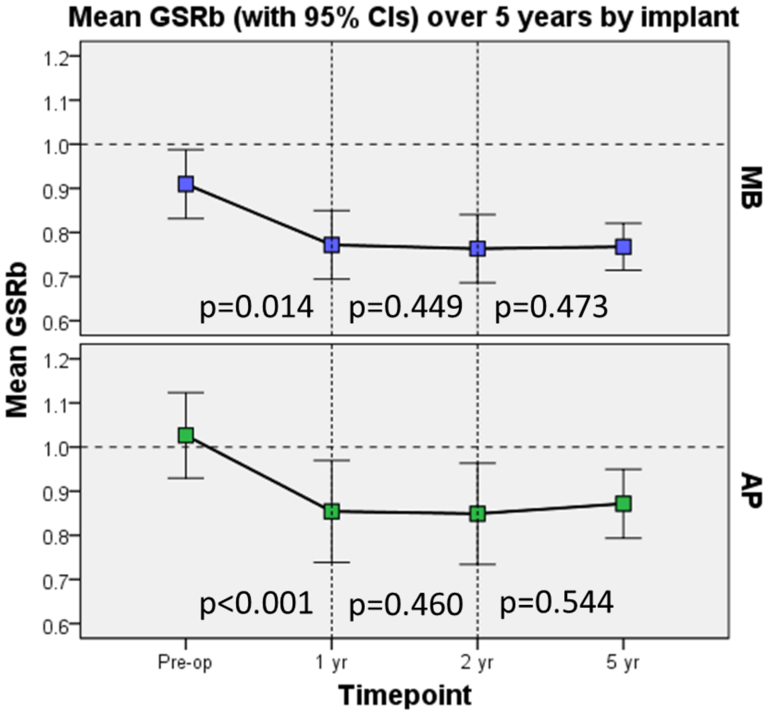

Figure 3. GSRb over time by implant showing reduced GSRb in both implants, ie a GSR <1. This change is significant in the first postoperative year in both the MB (p=0.014, ANOVA) and AP (p<0.001) implants, with no signifcant changes beyond this (Paired T-tests).

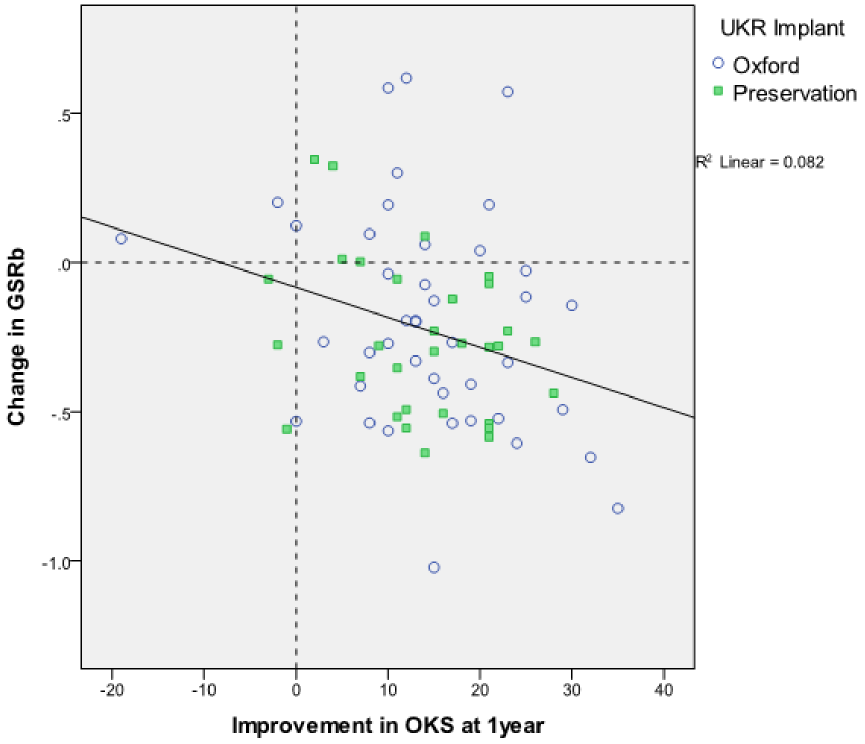

Figure 4. Scatter graph of improvement in OKS at 1 year and change in GSRb at 1 year.

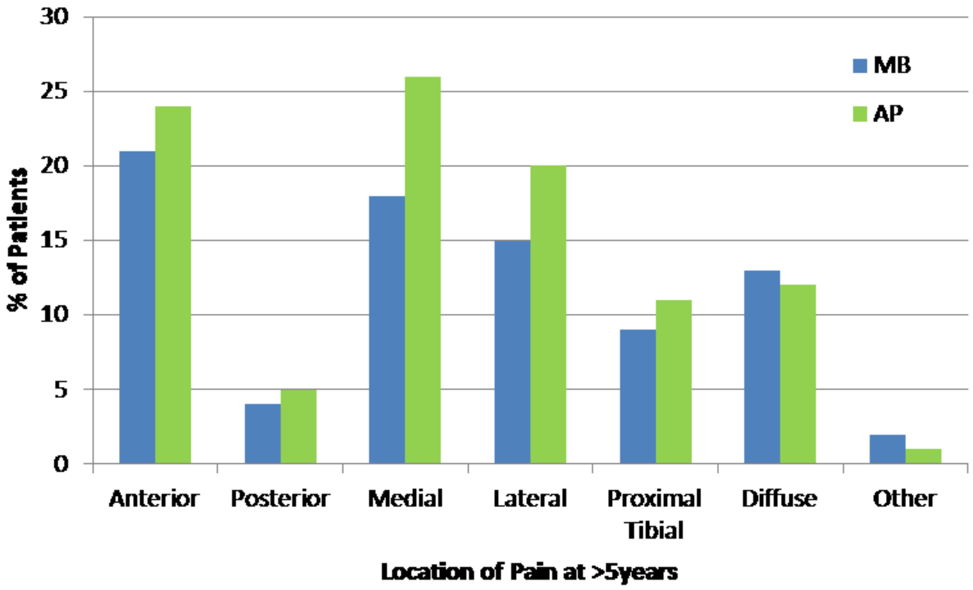

Figure 5. The location of pain by implant at >5years in patients with unrevised UKRs.

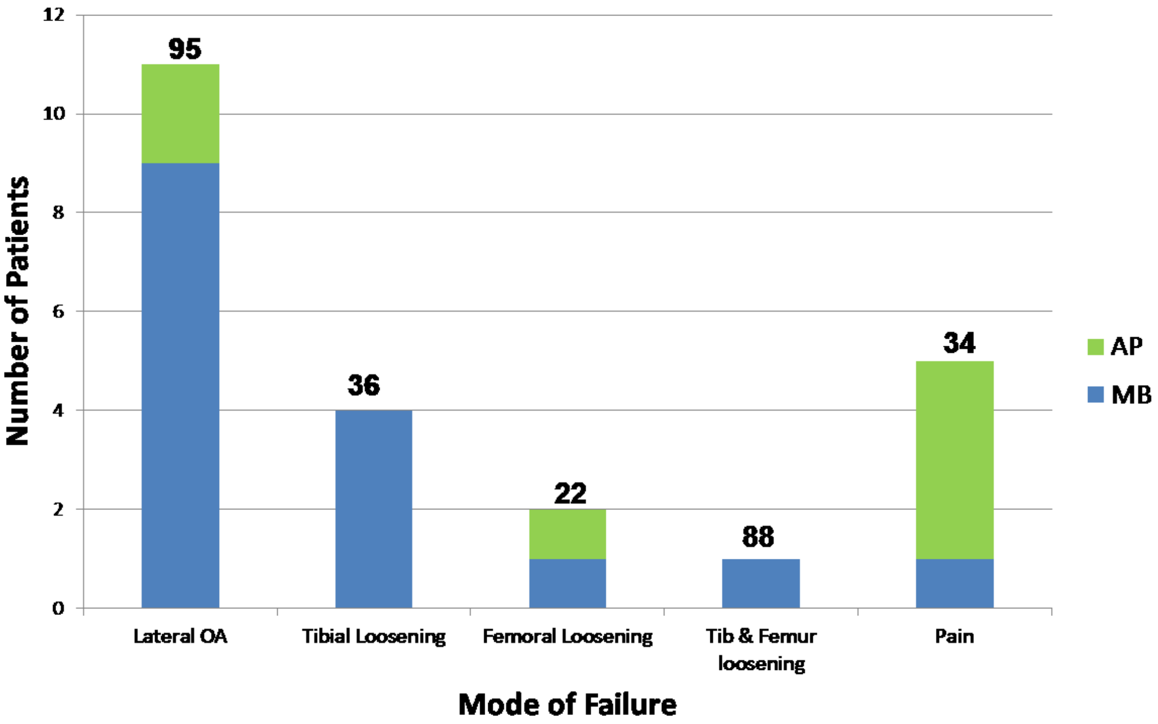

Figure 6. Modes of UKA failure by implant with mean survival times for each mode in months.

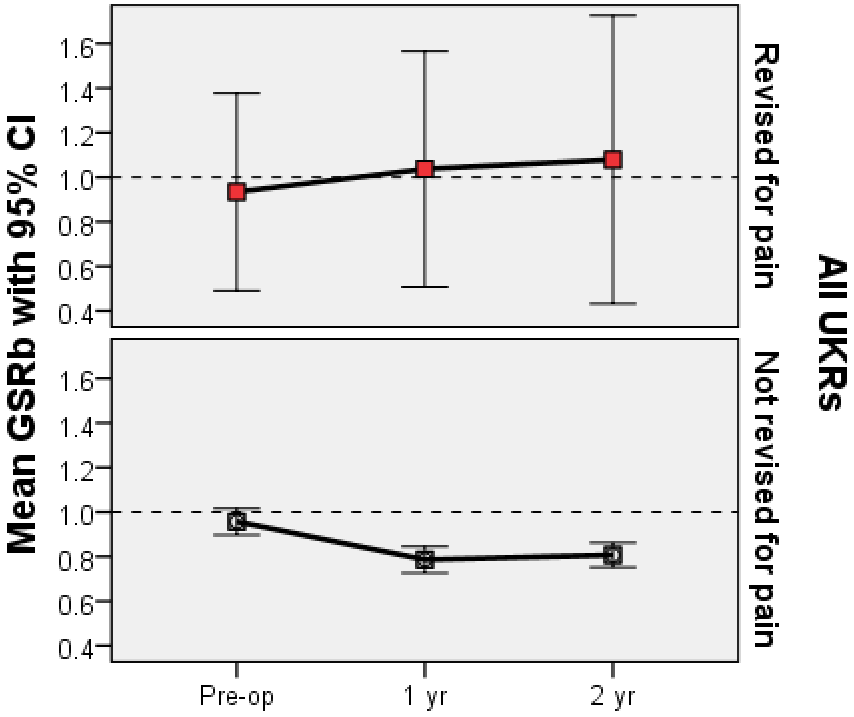

Figure 7. GSRb in patients with and without painful UKAs (both AP and MB implants).