Received: 3 November 2023 | Accepted: 2 February 2024

DOI: 10.1002/ksa.12092

KNEE ARTHROPLASTY

Knee Surgery, Sports Traumatology, Arthroscopy WILEY

Microporous titanium and hydroxyapatite improve fixation of the tibial wall in unicompartmental knee replacement

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Funding information
None

Abstract

Purpose: Cementless Oxford unicompartmental knee replacement (OUKR) is associated with less pain than cemented OUKR 5 years postoperatively. This may be due to improved fixation at the tibial wall, which transmits tension and reduces stress in the bone below the tibial component. This study compares tibial wall fixation with three different types of fixation: cemented, cementless with hydroxyapatite (HA) and cementless with a microporous titanium coat and HA (HA + MPC).

Methods: Three consecutive cohorts were identified ($n = 221$ cemented in 2005–2007, $n = 118$ HA in 2014–2015, $n = 125$ HA + MPC in 2016–2017). Analysis was performed on anterior–posterior radiographs aligned on the tibial component taken 1–2 years postoperatively. Aligned radiographs are needed to see narrow radiolucencies adjacent to the wall. Alignment was assessed with rotation ratio (RR = wall width/internal wall height). Perfect RR is 0.3, and a maximum threshold of 0.5 was used. Quality of fixation to the wall was assessed with fixation ratio (FR = bone wall contact height/total wall height). Notable radiographic features at the tibial wall were also recorded.

Results: A total of 33 knees with cement, 37 knees with cementless with HA and 57 knees cementless with HA + MPC had adequately aligned radiographs. Fixation was significantly better with HA compared with cement (55% vs. 25%, $p = 0.0016$). The microporous coat further improved fixation (81% vs. 55%, $p < 0.0001$). FR > 80% was achieved in 3% of the cemented implants, 32% of HA and 68% of HA + MPC. In cementless cohorts, features suggestive of a layer of bone that had delaminated from the wall were seen in 8 (22%) HA and 3 (5%) HA + MPC knees.

Conclusion: Radiographic tibial wall fixation in OUKR is poor with cement. It improves with an HA coating and improves further with an intermediary MPC. Improved tibial wall fixation may explain the lower levels of pain observed with cementless rather than cemented fixation described in the literature, but further clinical correlation is needed.

Abbreviations: ANOVA, analysis of variance; AP, anteroposterior; CoCr, cobalt-chromium; FR, fixation ratio; $H_{Wall\text{-}E}$, external tibial wall height; $H_{Wall\text{-}I}$, internal tibial wall height; HA, hydroxyapatite; HA + MPC, hydroxyapatite with microporous coat; OUKR, Oxford unicompartmental knee replacement; RR, rotation ratio; TWW, tibial wall width; UKR, unicompartmental knee replacement.

Level of Evidence: Level III, retrospective cohort study.

KEYWORDS

arthroplasty, replacement, knee; cemented; cementless; knee replacement, unicompartmental; orthopaedic fixation devices; pain

INTRODUCTION

In mobile bearing unicompartmental knee replacements (UKRs), the tibial component has a vertical wall that abuts the adjacent sagittal bone surface. The cemented and first cementless tibial components of the Oxford UKR were not designed to achieve fixation at this surface, as it was believed that no load would be transmitted through it. Similarly, this sagittal surface was considered unimportant and ignored when radiographic studies of fixation were undertaken [6], even though radiolucencies were commonly observed at this vertical interface [3].

Pain is relatively common early after all types of knee replacement, and in a few patients, it may persist [12, 14, 16]. Following UKR, if early pain occurs, it is usually anteromedial about 2 cm below the tibial component. A study on composite tibia models found that the stress in this region increased when a UKR was implanted [15]. Computational studies demonstrated that the strain in this region increased by 40% after implantation [14]. In most cases it is likely that with time, the bone remodels in response to the increased strain and residual strain returns to normal levels [4], causing the bone-related pain to settle. In some, the pain persists, presumably because the strain remains high. Computational analyses further demonstrated that achieving a mechanical link between the vertical wall of the tibial component and the abutting bone surface significantly reduced bone strain. It was therefore suggested that if a mechanical link could be achieved, the incidence of pain would be reduced [13]. In part based on this analysis, the design of the cementless mobile bearing tibial component was modified. In the initial design, there was a layer of hydroxyapatite (HA) on the cobalt-chromium (CoCr) wall [1]. In the modified design, a microporous titanium coating (MPC) was applied to the wall before the HA coating to enhance fixation. With cemented fixation, bone interfaces with either the CoCr implant surface or bone cement, in this region.

Early randomised studies comparing cemented and cementless fixation found no difference in outcome scores but had small sample sizes and were underpowered in assessing outcome scores [6]. A much larger comparative cohort study of 546 patients has shown that at 5 years, cementless components were more likely to have no pain at all reported (61% vs. 43%) and less likely to have substantial pain reported (0.41% vs. 4.6%) compared to cemented components [12]. This may be because they are achieving a better mechanical bond between the tibial component wall and the tibial eminence. The best way to assess the fixation of the tibial wall is to determine the incidence and extent of radiolucencies beside the wall when using radiographs aligned on the wall itself.

The aim of the study was therefore to compare the radiolucencies adjacent to the wall of the Oxford UKR (OUKR) tibial component with three clinically used variants of coatings: no coat or bone cement (cemented), HA and hydroxyapatite on an MPC (HA + MPC). The hypothesis that HA and HA + MPC improve tibial wall fixation will be assessed.

PATIENTS AND METHOD

Radiographic measurements

During postoperative follow-up, patients were assessed at 1–2 years and anterior–posterior (AP) standing radiographs, aligned on the tibial component, were obtained. Radiolucencies beside the wall may be obscured in misaligned radiographs, due to the projection being internally or externally rotated relative to the wall (Figure 1).

To assess the amount of internal/external malalignment, a rotation ratio (RR) was defined (Figure 2a) as

$$\mathrm{RR} = \frac{\text{Tibial wall width } (W_{\mathrm{Wall}})}{\text{Internal tibial wall height } (H_{\mathrm{Wall\text{-}I}})} \times 100\%.$$

In the radiographic projection, internal/external rotation will increase W_{Wall} rapidly, while $H_{\mathrm{Wall\text{-}I}}$ remains relatively constant. A perfectly aligned view has an $\mathrm{RR} \approx 30\%$. Radiographs with $\mathrm{RR} < 50\%$ were used to assess fixation at the wall–bone interface.

We have observed that where there is incomplete fixation of the bone to the tibial wall, the radiolucency is always at the top. The extent of the fixation was therefore assessed using the fixation ratio (FR), defined (Figure 2b) as

$$\mathrm{FR} = \frac{\text{External tibial wall height } (H_{\mathrm{Wall\text{-}E}}) - \text{radiolucency height (RLH)}}{\text{External tibial wall height } (H_{\mathrm{Wall\text{-}E}})} \times 100\%.$$

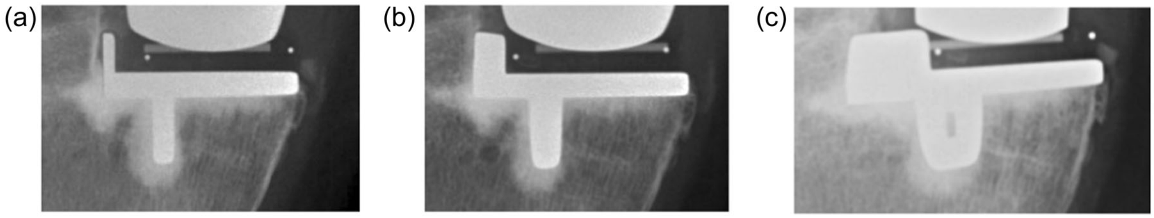


FIGURE 1 Three progressively rotated anteroposterior knee radiographs from a patient, demonstrating how rotation can cause masking of a radiolucency adjacent to the tibial wall. Rotation ratio for (a) 32%, (b) 82% and (c) 223%.

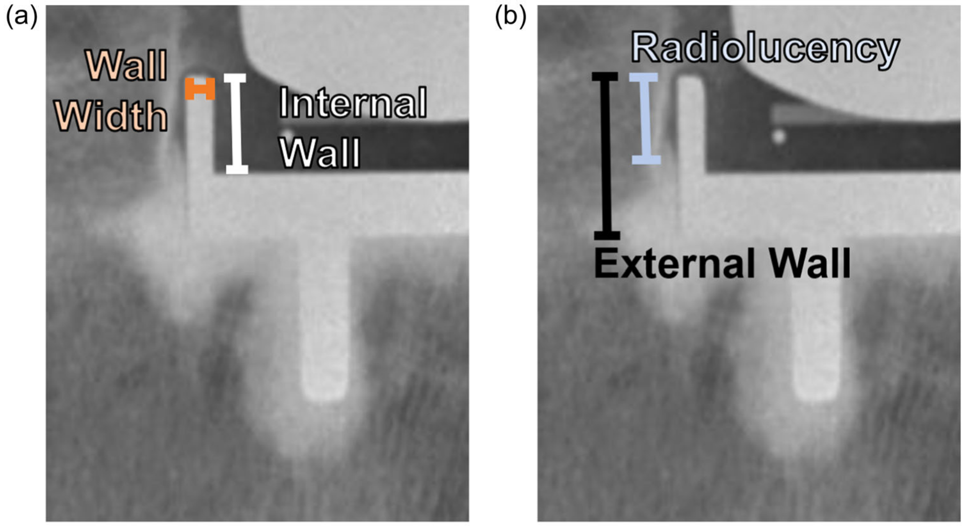


FIGURE 2 Samples of rotation ratio and fixation ratio (FR) measurements. (a) Measures of wall width (W_{wall}) and internal wall height ($H_{\mathrm{Wall\text{-}I}}$) used to measure rotation ratio. (b) Measures of radiolucency height and external wall height ($H_{\mathrm{Wall\text{-}E}}$) used to measure FR.

FR represents the proportion of the wall where there is bone contact. FR = 0% shows no direct contact between bone and the wall, and FR = 100% if bone appeared to be in direct contact with the full height of the wall. The presence of any radiological features or patterns observed during radiograph analysis by operators was noted. A key feature, sometimes seen, was two parallel radiolucent zones between the component wall and tibial eminence, between which appeared to be bone with a characteristic hemilenticular shape (Figure 6). The presence of this hemilenticular structure was assessed in all radiographs.

Knees

From a database of OUKRs performed by two high-volume surgeons in one centre in the United Kingdom, three separate consecutive cohorts were retrospectively identified ($n = 221$ cemented in 2005–2007; $n = 118$ HA in 2014–2015; $n = 125$ HA + MPC in 2016–2017).

AP knee radiographs taken for routine clinical follow-up, between 1 and 2 years (10–26 months) postoperatively, were collected. Measurements to calculate RR were made for all radiographs. Radiographs with RR ≤ 50% (i.e., adequately aligned) were obtained in 33 knees with Nil/cement, 37 knees with HA, and 57 knees with HA + MPC. Adequately aligned radiographs were assessed by two independent observers to calculate FR. Interobserver correlation was assessed, and the average FR of both observers was used for each radiograph. Observers were blinded to implant type.

Software and statistics

Radiograph measurements were made using ImageJ (Rasband, W. S., ImageJ; US National Institutes of Health) based on an in-house protocol for measurements. Interobserver correlation was performed using SPSS 25.0 (IBM SPSS Statistics for Windows, Version 25.0.0.1; IBM Corp.). Data were analysed and visualised using GraphPad Prism (GraphPad Software LLC) and Excel (Microsoft).

All data were classified by knee. Radiographic measurements were compared between cohorts using

TABLE 1 Baseline characteristics of cemented, HA and HA + MPC cohorts.

	Cemented	HA	HA + MPC
Age			
Mean (Standard Deviation)	66.0 (9.7)	66.0 (10.2)	67.7 (8.6)
Sex			
Male (n, %)	112 (51%)	60 (51%)	63 (50%)
Female (n, %)	109 (49%)	58 (49%)	62 (50%)

Abbreviations: HA, hydroxyapatite; HA + MPC, hydroxyapatite with microporous coat.

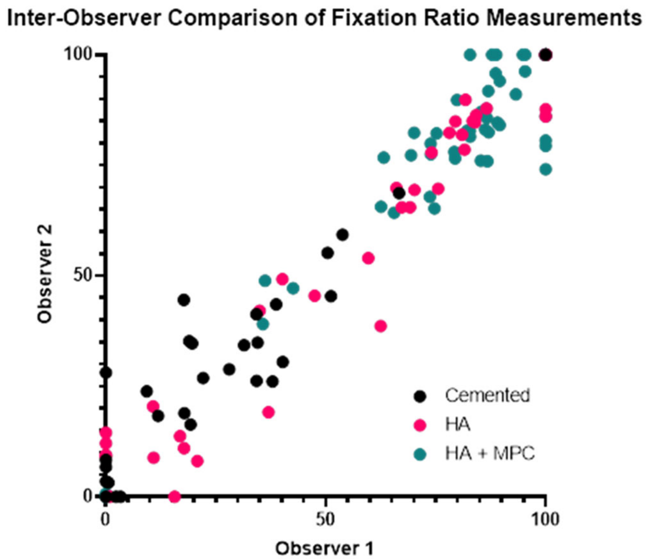


FIGURE 3 Comparison of fixation ratio measured by both observers, separated by coating type. HA, hydroxyapatite; HA + MPC, hydroxyapatite with microporous coat.

the unpaired Student's *t*-test for parametric (Shapiro–Wilk $p > 0.05$), and the Mann–Whitney *U*-test for nonparametric (Shapiro–Wilk $p < 0.05$) distributions. Intraclass correlation coefficient (ICC) was calculated using a two-way mixed-effects model for average measures.

RESULTS

There were no significant differences between the patient groups for age and sex across the three study groups (Table 1). In the cemented, HA and HA + MPC cohorts, the number of radiographs was 33, 37 and 57 and the average time between the operation and the radiograph was 13.9, 16.7 and 15.5 months, respectively. There was no significant difference in the time

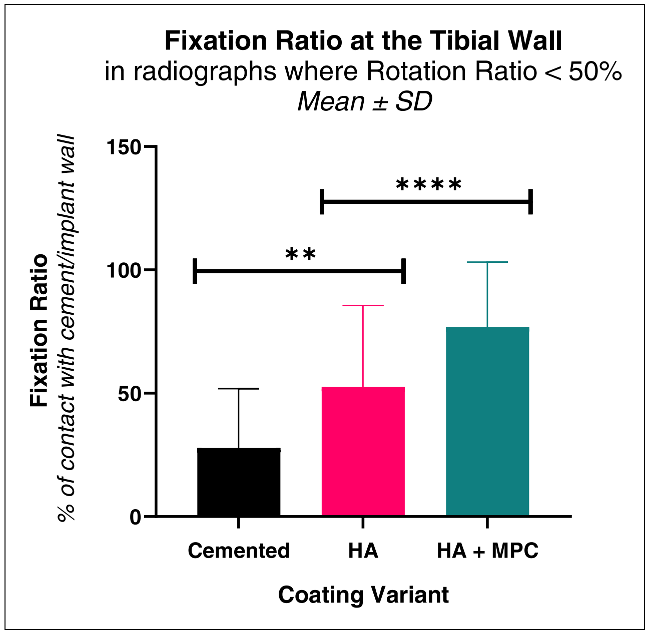


FIGURE 4 Mean fixation ratio at the tibial wall in all aligned radiographs (where rotation ratio is ≤0.5), separated by coating at the tibial wall. $^{**}p < 0.01$; $^{****}p < 0.0001$. HA, hydroxyapatite; HA + MPC, hydroxyapatite with microporous coat.

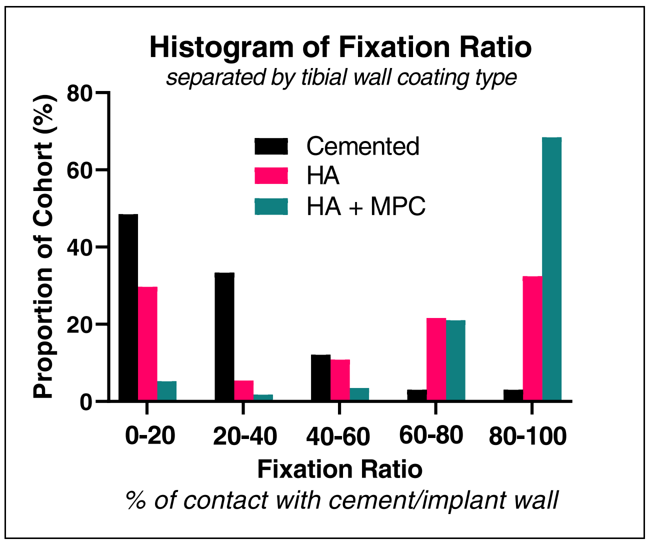
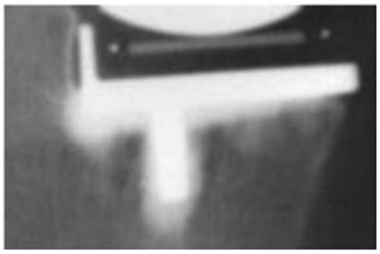
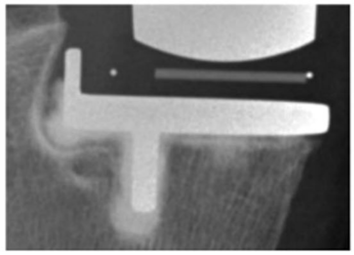
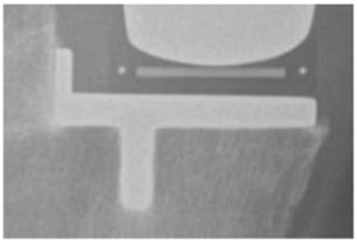
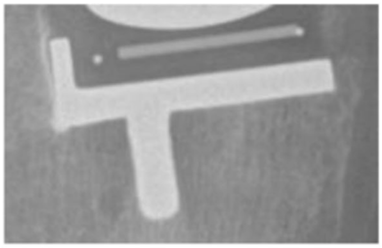
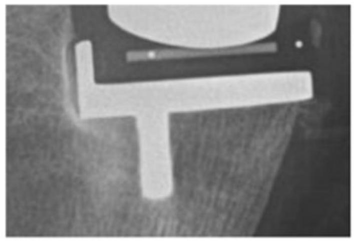
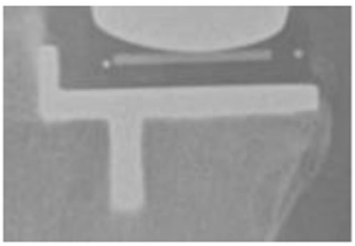
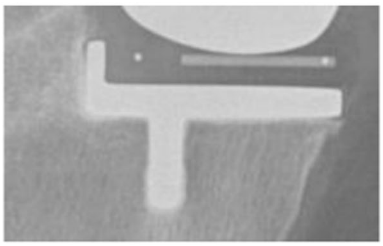
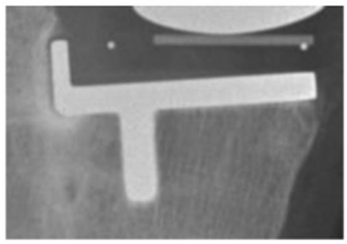


FIGURE 5 Histogram of fixation ratio (FR) at the tibial wall in all aligned radiographs (where rotation ratio is ≤0.5), separated by coating at the tibial wall. FR is split into 20% groups from poor fixation (FR = 0%–20%) to excellent fixation (FR = 81%–100%). HA, hydroxyapatite; HA + MPC, hydroxyapatite with microporous coat.

between surgery and radiography across the three cohorts (one-way analysis of variance, $p = 0.0835$).

FR from the two independent observers were compared (Figure 3). ICC for all cohorts separate and combined, were excellent: cemented 0.959, HA 0.982, HA + MPC 0.972 and combined 0.985.

TABLE 2 Sample images of the OUKR tibial component and bone–implant interface at the tibial wall, separated by coating type.

	Highest FR	Mean FR	Lowest FR
	Image and Fixation Ratio (nearest 10%)		
Nil/Cement	 100%	 30%	 0%
HA	 100%	 50%	 0%
HA + MPC	 100%	 80%	 0%

Abbreviations: FR, fixation ratio; HA, hydroxyapatite; HA + MPC, hydroxyapatite with microporous coat; OUKR, Oxford unicompartmental knee replacement.

FR was significantly better in the HA group compared to cemented (mean FR 55% vs. 25%, Mann–Whitney $p = 0.0016$). The group with the added microporous coat (HA + MPC) had a higher FR compared to the HA-only group (mean FR 81% vs. 55%, Mann–Whitney $p < 0.0001$) (Figure 4). FR > 80% was found in 3% of the cemented implants, 32% of HA implants and 68% of HA + MPC implants (Figure 5 and Table 2).

All radiographs were assessed for the presence of a hemilenticular bone growth. These structures were only observed where FR < 20%. Of these, zero of 16 (0%) cemented, eight of 12 (67%) knees in the HA cohort and three of three (100%) knees in the HA + MPC cohort had this hemilenticular feature (Figure 6 and Table 3). The thickness, height and distance from adjacent surfaces of this hemilenticular feature varied between cases.

DISCUSSION

Cementless OUKR has substantially better fixation at the tibial wall than cemented OUKR. A cemented implant fixes to, on average, 25% of the height of the wall. A cementless implant with an HA coat significantly increases wall fixation to 55%, and an MPC with HA (HA + MPC) significantly increases fixation to 80%.

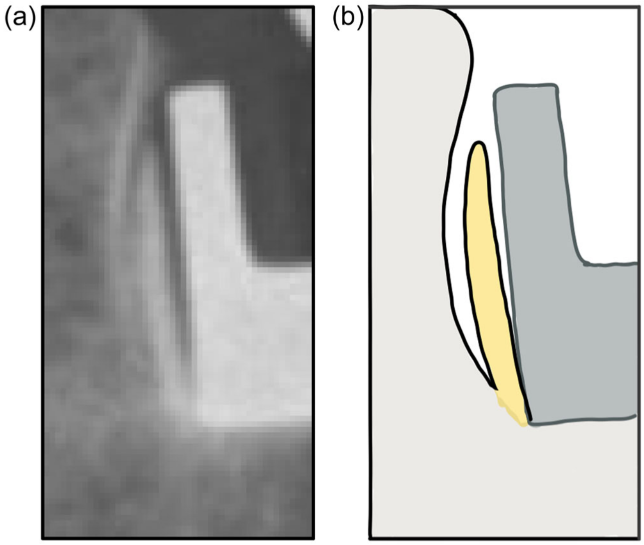


FIGURE 6 (a, b) Bone growth found in some radiographs where fixation to the tibial wall is poor fixation ratio (<20%). The feature is radiographically characterised as a generally hemilenticular opacity between the implant and sclerosed vertical bone surface. (a) Radiograph of a cementless implant; (b) graphical representation with hemilenticular opacity highlighted in yellow.

Despite varying outcomes in the early postoperative period [2, 11], it has been shown that there is significantly less pain at five years following cementless rather than cemented OUKR [7]. This pain is typically anteromedial below the tibial component. A computational study of the OUKR found that the strain in the bone in this area increased postoperatively, and a bond that could transmit tension between the wall and the tibial eminence would reduce bone strain in the painful area [13, 14]. It therefore seems likely that the improved fixation in the region of the wall with cementless components may have resulted in the improvement in the pain. The components that were assessed for pain in the clinical study were those with an HA coat alone. A further study is needed to assess pain in patients with HA + MPC. This study suggests that they might have similar or even better clinical results than HA alone.

In the cemented cohort, the amount of cement covering the wall was variable. When it only partially covered the wall, it tended to be at the bottom, with exposed CoCr at the top. It was generally observed that the bone was rarely in contact with the CoCr but was more often in contact with the cement (Table 2). Cement is placed between the transverse cut and the undersurface of the component. When pressured during implantation, it can be forced up between the CoCr wall and the vertical cut bone, and into the cancellous bone. The cancellous bone may resorb, causing a radiolucency to form around the cement. The uncoated CoCr wall abutting the sagittal bone cut has no mechanical interaction with the bone and does not have a surface that stimulates bone formation [4].

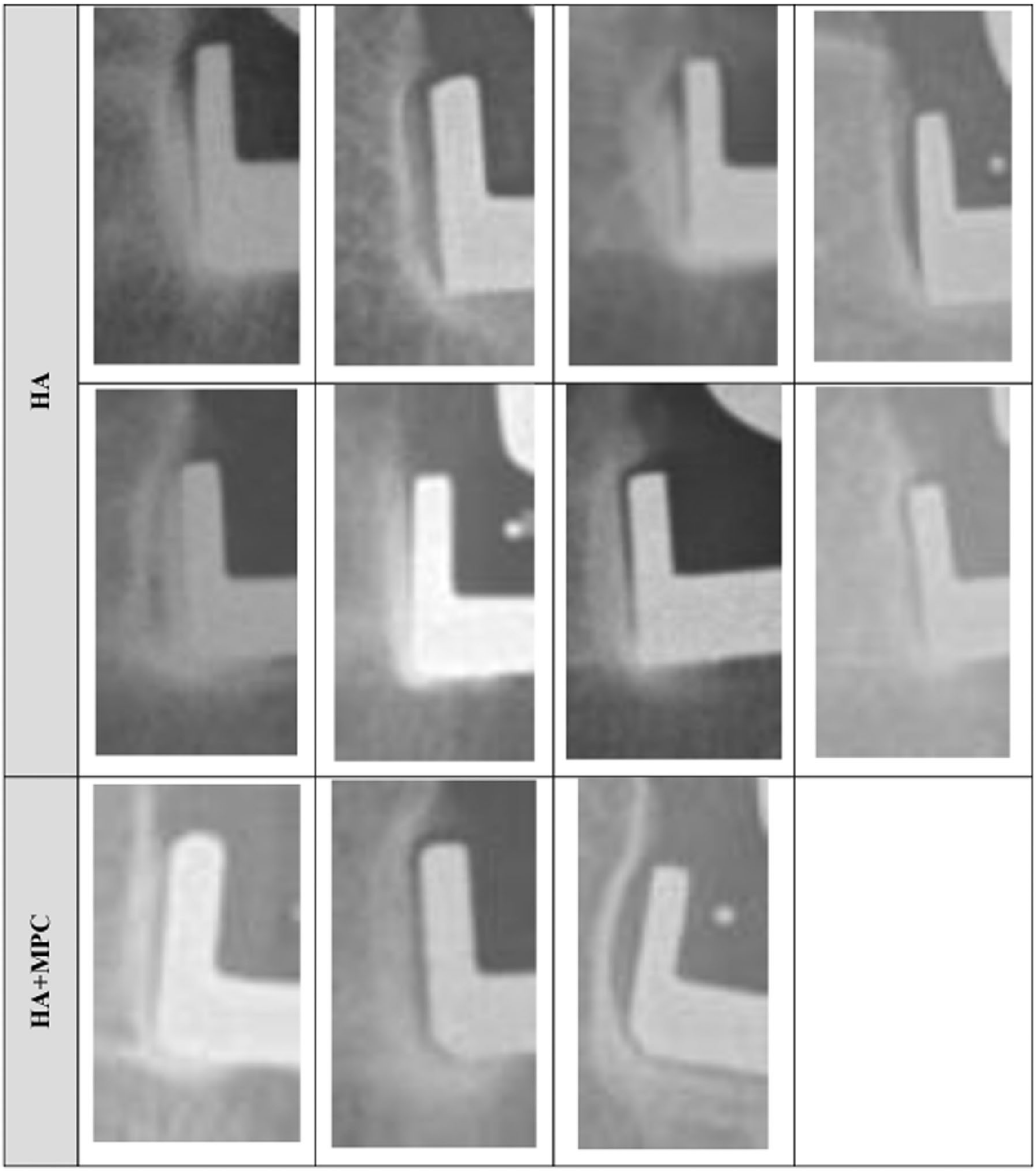
In implants with the HA coating only, the tibial wall fixation was bimodal—bone was either likely to have near-complete fixation at the implant wall (FR > 80% in one third of cohort), or if not, poor fixation (FR < 20% in one third of cohort). This may be indicative of the variability in benefit provided by HA signalling. Osseous interfacing has been shown to occur in gaps of up to 1 mm between bone and HA, but this does not occur in all patients [1]. This seems to depend on how successful HA signalling and osteoblast activation is [8–10]. However, even if bone grows to abut the surface, the strength of the attachment and ability to transmit tension is limited as the surface is smooth.

The HA + MPC cohort (with an HA coat on an MPC at the tibial wall) showed the best wall fixation of all three groups, with over 60% of all radiographs showing near-complete tibial wall fixation (FR > 80%). The addition of the MPC provides a coarser surface. A coarse surface has been shown to increase the release of prostaglandin E_2 and transforming growth factor-β1, which induce osteoblast differentiation [17]. The combination of HA + MPC has been further shown to benefit cell proliferation and provide a more favourable biomimetic microenvironment for osseointegration [5]. In addition, the bone can potentially grow into the microporous surface providing strong fixation, which is able to transmit tension.

The appearance of a hemilenticular structure (Figure 6 and Table 3) usually with a radiolucency on either side is seen in eight of the 12 HA-coated tibial walls, where fixation was measured to be low (FR < 20%). The medial side of the structure facing the implant is flat but angled away from the implant wall. This structure is suggestive of initial bone growth on the surface of the implant wall, which had later delaminated from the implant wall surface. Such delamination would explain, in part, the radiographs where poor tibial wall fixation is seen in the HA cohort. With the HA + MPC cohort, the increased fixation at the implant wall suggests reduced delamination, with bone growth less likely to be sheared off the wall. In contrast, none of the uncoated cemented tibial walls demonstrated this sign, likely because bone never grew against the wall surface.

All radiographs assessed in this study had fixation at the superior aspects of the tibial wall only if the inferior aspects of the tibial wall were also fixed. No radiographs were found to have fixation at a superior aspect of the wall if a more inferior aspect was not fixed. It is not clear why this happens. It may relate to the amount of micromotion occurring at the interface, with more micromotion at the top rather than the bottom. Alternatively, cancellous bone may be more likely to fix to the implant than cortical bone and the lower part of the wall is in contact primarily with cancellous bone and the upper part with cortical bone.

TABLE 3 HA and HA + MPC radiographs with features of delaminated bone growth.



Abbreviations: HA, hydroxyapatite; HA + MPC, hydroxyapatite with microporous coat.

One limitation of this study is that it was conducted on radiographs collected from three separate (though each consecutive) cohorts from 2005 to 2007, 2014 to 2015 and 2016 to 2017, so other factors that changed with time may have influenced the outcomes assessed. However, identical indications were used for all cohorts and identical techniques were used for the two cementless cohorts. With cemented fixation, the technique was the same as the cementless, apart from a wider keel slot and the use of cement, and it is unlikely this would have influenced wall fixation. A novel finding of the study was the hemilenticular structure at the interface that was most common in the HA cases. It is postulated that this was caused by bone forming on the wall and then delaminating. To determine how it formed would require a time-course analysis of serial radiographs.

Importantly, this radiographic study does not directly compare clinical outcomes between the cohorts—further study of these findings between cohorts, including fixation in other implant surfaces, needs to be performed with clinical and patient-reported data to determine the effect on outcomes. Nonetheless, novel and potentially important radiographic patterns have been described in this study and biomechanical implications have been discussed.

CONCLUSION

This study has shown that tibial wall fixation in OUKR is poor with cement. It improves with an HA coating and improves further with an intermediary MPC. Fixation at the wall is consistently 'bottom-up', with fixation at the superior aspect of the wall present only when the inferior aspect is fixed. The implications of load transmission across the wall, caused by the improvements to radiographic fixation shown in this study, require further assessment. While this study does not compare radiographic findings to clinical data, improved tibial wall fixation may provide a possible explanation for the lower levels of pain observed with cementless rather than cemented fixation found in the literature. This requires further assessment.

AUTHOR CONTRIBUTIONS

Azmi Rahman and Gabrielle Omoregie carried out the acquisition of data. All authors made substantial contributions to the conception, design, analysis and interpretation of data. All authors have been involved in drafting and critically revising the manuscript, have given final approval of the version to be published and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

ACKNOWLEDGEMENTS

We would like to thank Barbara Marks and Jo Brown from the Oxford Orthopaedic Engineering Centre for supporting the conduct of this study, and the radiographers from the Nuffield Orthopaedic Centre for the consolidation of the radiographs needed for this study. No study-specific funding was obtained.

CONFLICT OF INTEREST STATEMENT

The author or one or more of the authors have received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article. In addition, benefits have been or will be directed to a research fund, foundation, educational institution, or other nonprofit organisation with which one or more of the authors are associated.

ETHICS STATEMENT

Not applicable.

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How to cite this article: Rahman A, Omoregie G, Mellon S, Murray DW. Microporous titanium and hydroxyapatite improve fixation of the tibial wall in unicompartmental knee replacement. Knee Surg Sports Traumatol Arthrosc. 2024;32:704–12. https://doi.org/10.1002/ksa.12092