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CLINICAL RESEARCH

Early Migration Predicts Aseptic Loosening of Cementless Femoral Stems: A Long-term Study

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Abstract

Background Excessive early migration of cemented stems and cups after THA has been associated with poor long-term survival and allows predictable evaluation of implant performance. However, there are few data regarding the relationship between early migration and aseptic loosening of cementless femoral components, and whether early migration might predict late failure has not been evaluated, to our knowledge. Einzel-Bild-Röntgen-Analyse-femoral component analysis (EBRA-FCA) is a validated technique to accurately measure axial femoral stem migration without the need for tantalum markers, can be performed retrospectively, and may be a suitable tool to identify poor performing implants before their widespread use.

Questions/purposes We asked: (1) Is axial migration within the first 24 months as assessed by EBRA-FCA greater among cementless stems that develop aseptic loosening than those that remain well fixed through the second decade; (2) what is the diagnostic performance of implant migration at 24 months postoperatively to predict later aseptic loosening of these components; and (3) how does long-term stem survivorship compare between groups with high and low early migration?

Methods We evaluated early axial stem migration in 158 cementless THAs using EBRA-FCA. The EBRA-FCA measurements were performed during the first week postoperatively (baseline measurement) and at regular followups of 3, 6, and 12 months postoperatively and annually thereafter. The mean duration of followup was 21 years (range, 18–24 years). The stems studied represented 45% (158 of 354) of the cementless THAs performed during that time, and cementless THAs represented 34% (354 of 1038) of the THA practice during that period. No patient enrolled in this study was lost to followup. Multivariate survivorship analysis using Cox's regression model

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.
This work was performed at the University of Heidelberg, Heidelberg, Germany.

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was performed with an endpoint of aseptic loosening of the femoral component. Loosening was defined according to the criteria described by Engh et al. and assessed by two independent observers. Patients with a diagnosis of prosthetic joint infection were excluded. Receiver operating characteristic (ROC) curve analysis was used to evaluate diagnostic performance of axial stem migration 1, 2, 3, and 4 years postoperatively as a predictor of aseptic loosening. Survivorship of hips with high (≥ 2.7 mm) and low (< 2.7 mm) migration was compared using a competing-events analysis.

Results Femoral components that had aseptic loosening develop showed greater mean distal migration at 24 months postoperatively than did components that remained well fixed throughout the surveillance period (4.2 mm ± 3.1 mm vs 0.8 mm ± 0.9 mm; mean difference, 3.4 mm, 95% CI, 2.5–4.4; p ≤ 0.001). Distal migration at 24 months postoperatively was a strong risk factor for aseptic loosening (hazard ratio, 1.98; 95% CI, 1.51–2.57; p < 0.001). The associated overall diagnostic performance of 2-year distal migration for predicting aseptic loosening was good (area under the ROC curve, 0.86; 95% CI, 0.72–1.00; p < 0.001). Sensitivity of early migration measurement was high for the prediction of aseptic loosening during the first decade after surgery but decreased markedly thereafter. Stems with large amounts of early migration (≥ 2.7 mm) had lower 18-year survivorship than did stems with little early migration (29% [95% CI, 0%–62%] versus 95% [95% CI, 90%–100%] p < 0.001).

Conclusions Early migration, as measured by EBRA-FCA at 2 years postoperatively, has good diagnostic capabilities for detection of uncemented femoral components at risk for aseptic loosening during the first and early second decades after surgery. However, there was no relationship between early migration patterns and aseptic loosening during the late second and third decades. EBRA-FCA can be used as a research tool to evaluate new cementless stems or in clinical practice to evaluate migration patterns in patients with painful femoral components.

Level of Evidence Level III, diagnostic study.

Introduction

Aseptic loosening is one of the main reasons for implant failure in THAs [1, 12, 13]. However, prediction of long-term implant performance is difficult and definitive results regarding aseptic loosening are available only after lengthy followup [24, 32, 33]. Widespread use of poor-performing implants might occur before these results are available [7, 8]. Therefore, reliable methods are needed to predict aseptic loosening and allow early evaluation of long-term implant performance during the first years after implantation. Roentgen stereophotogrammetric analysis (RSA) generally is accepted as the gold standard in migration measurement, especially regarding accuracy and three-dimensional (3-D) migration measurement. Another validated and frequently used technique for measurement of distal stem migration is Einzel-Bild-Röntgen-Analyse-femoral component analysis (EBRA-FCA), which also allows accurate measurement of femoral stem subsidence [4] without the need for implanting tantalum markers [5, 38] and can be performed retrospectively using standard radiographs. The EBRA method is a software-based method using digitized radiographs and differs from other non-RSA measurement systems as it contains an algorithm (termed the comparability limit) that excludes radiographs from a patient's measurement series that have more than a preset level of positioning or rotational error and reduces variability secondary to patient positioning [4]. The systemic error of the method when compared with the RSA method is low [4], Cronbach's coefficient α for the interobserver variance is reportedly 0.84 [4], and the method was shown to have sufficient precision to detect clinically relevant migration [39]. EBRA-FCA therefore is well suited especially for large patient cohorts and retrospective studies.

The prognostic value of excessive early migration within 1 to 2 years postoperatively for early aseptic loosening and mid-term survival has been shown for different cemented stems and cups using different measurement methods [11, 14, 17, 19, 23, 24]. However, there are only a few studies regarding the diagnostic performance of early migration as a predictor for aseptic loosening using uncemented femoral components [11, 17, 19] and, as shown in a recent review by van der Voort et al. [36], the published research is insufficient to support robust conclusions. Furthermore, to our knowledge, there are no long-term data regarding the diagnostic performance of early migration as a predictor for aseptic loosening beyond 10 years, and none of the previous studies focused on this association exclusively for uncemented stems. Therefore, we used EBRA-FCA to evaluate the relationship between early axial migration within 1 to 4 years postoperatively and the long-term survival of an uncemented femoral component regarding failure resulting from aseptic loosening during a mean period of 21 years.

Specifically, we asked: (1) Is axial migration within the first 24 months as assessed by EBRA-FCA greater among cementless stems that have aseptic loosening develop than those that remain well fixed through the second decade; (2) what is the diagnostic performance of implant migration 24 months postoperatively to predict later aseptic loosening of these components; and (3) how does long-term stem survivorship compare between groups with high and low early migration?

Patients and Methods

Between January 1985 and December 1989, we performed 1038 THAs, of which 34% (354/1038 THAs) were cementless. From our institutional database we identified 139 patients with 158 hips (45%, 158/354 THAs) who had undergone cementless THAs and satisfied the following inclusion criteria for this study: (1) THA using the cementless CLS® Spotorno® stem (Zimmer Inc, Warsaw, IN, USA); the FDA has cleared this femoral component for use in the United States; indications for this device were the absence of severe femoral canal deformity and adequate bone stock for uncemented fixation using the Singh index as described by Spotorno et al. [31]; (2) a radiograph made within the first week postoperatively (used as baseline measurement); and (3) sufficient quality of the radiographs assessed by the distinct legibility of the reference points needed for migration analysis with EBRA-FCA.

Of those accounted for, 158 hips underwent analysis for axial stem migration using the EBRA-FCA software (Ein-Bild-Röntgen-Analyse-Femurkomponenten-Analyse, Innsbruck, Austria) [4], as described previously [19]. The EBRA-FCA measurements were performed during the first week postoperatively (baseline measurement) and at the regular followups of 3, 6, and 12 months postoperatively and annually thereafter. Details of the analysis are described below in Statistical Analysis. The mean followup was 21 years (range, 18–24 years). One hundred of the 158 hips included in this study (63%) had at least four radiographs accepted by EBRA-FCA during followup, providing at least three measurements for statistical analysis (first radiograph is set as baseline) and were included for further assessment, whereas 58 hips were rejected by EBRA-FCA for reasons which could not be influenced by the authors (Fig. 1).

To ensure high accuracy ($\leq \pm 1.5$ mm), EBRA-FCA excludes radiographs that do not meet standards determined for comparability, and a minimum of four radiographs per patient is recommended [4, 18].

However, complete clinical and radiologic followup was available for all 139 patients (158 THAs), and no patient was lost to followup. Further, the hips analyzed (n = 100) were not different from those not analyzed (n = 58) in any important or systematic ways (Table 1). At the time of final followup, 50 patients had died after a mean of 14.4 years postoperatively (range, 2–24 years).

All hips without clinical or radiologic signs of aseptic loosening and a radiologic followup greater than 10 years were included in the control group (Group 1), whereas all hips with aseptic loosening were assigned to the case group (Group 2; Table 2). Loosening was defined according to the criteria described by Engh et al. [10] and assessed by two independent observers (MRS, DH) using conventional radiographs (pelvis AP and hip lateral views); in this study, there was agreement between the reviewers in each case. In all hips included in Group 2 (aseptic loosening), loosening was confirmed intraoperatively during revision surgery. Patients with a diagnosis of prosthetic joint infection, defined according to the criteria described by Parvizi et al. [25], were excluded. For inclusion of hips as a control (control group), a minimum radiologic followup of 10 years was required, because we aimed to rule out late aseptic loosening or death before aseptic loosening became evident. If radiographic followup was less than 10 years, in most cases attributable to death before 10 years followup (n =15 hips; Fig 1), these hips were excluded from the control group, as this group should represent the hips that remain well fixed in the long-term (> 10 years). For example, if a patient with a well-fixed hip has only 5 years of followup as the patient died before the next regular followup, but we obtained enough radiographs accepted by EBRA, it would be possible to include the migration results of this patient in the final analysis and to assign this patient to the control group. However, we decided not to do so, as in this case we do not know if the stem would have been well fixed after 10 or more years and therefore this might introduce a bias in our results. As previously described, 15 hips were excluded from the control group because of this criterion; none was lost to followup, leaving 73 hips (67 patients) in the control group (Group 1). Twelve of 158 hips underwent revision surgery during the followup period, one for septic loosening of the implant and two for periprosthetic femoral fracture after trauma unrelated to implant loosening. Nine stems (nine patients) had to be revised because of aseptic stem loosening (Group 2) after a mean of 10 years (range, 3–17 years) (Fig. 1). Complete migration data were obtained for all hips with aseptic femoral loosening. In the final analysis, the axial migration of 82 hips (52%) was included based on a mean of 10.3 (range, 4–23) radiographs per patient (Table 2). The variation in the number of EBRA-FCA measurements was inevitable as some patients were followed into the third decade after surgery and had up to 23 measurements, whereas other patients underwent early revision surgery and had only a minimum of four measurements.

All 139 patients (158 hips) received an uncemented grit-blasted, tapered titanium femoral stem (CLS® Spotorno® stem). The mean age of the patients at surgery was 56 years. Of the 158 hips, 155 (98%) underwent acetabular reconstruction using smooth and uncemented threaded cups: 103 hips (65%) received threaded, spherical, and

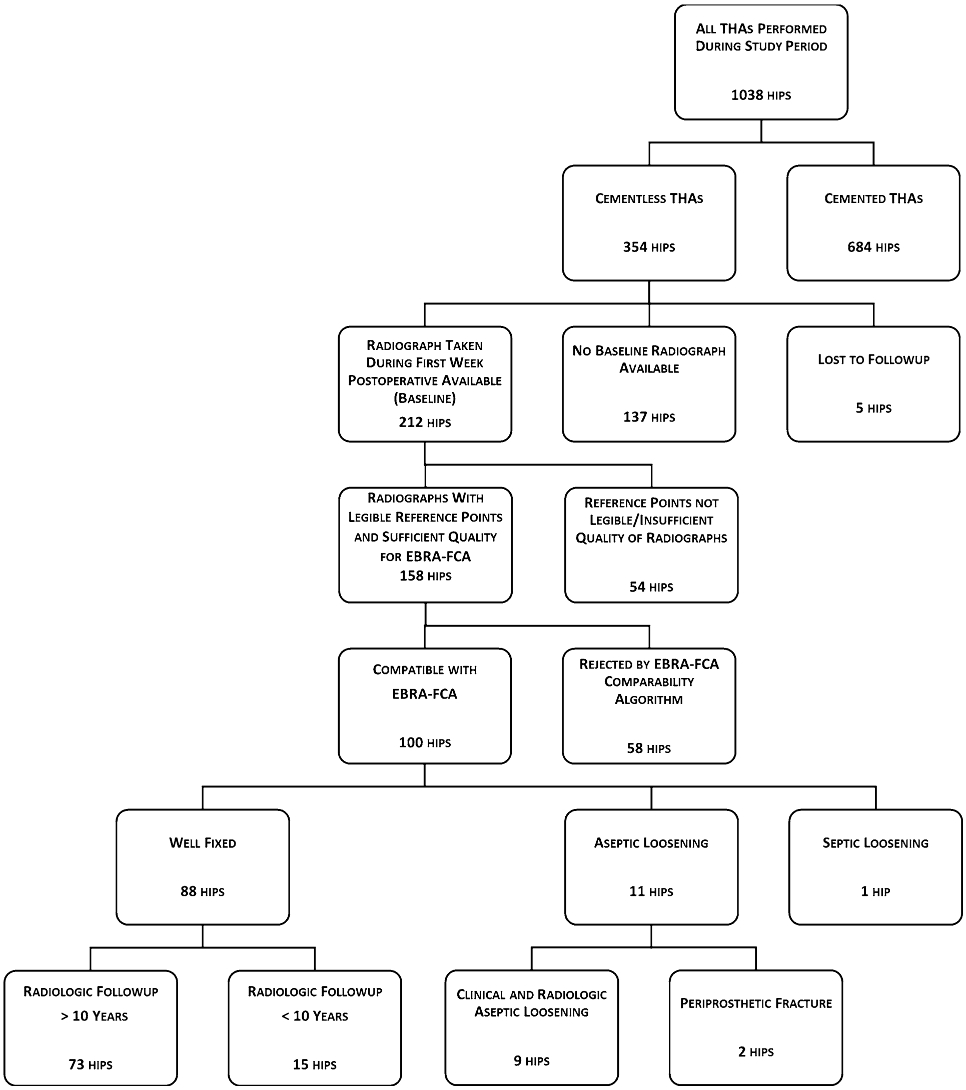

Fig. 1 The flowchart shows the distribution of hips to the different groups.

uncemented Mecron cups (Mecron GmbH, Berlin, Germany) and 52 hips (33%) received a threaded, conical, uncemented Weill ring (Zimmer Inc); two hips (1%) received cemented cups (B. Braun Aesculap, Tuttlingen, Germany). The surgical procedures were performed by multiple surgeons at one institution. The operative technique and postoperative regimen with this implant have been described [32].

Followup

Patients were followed at regular intervals of 3, 6, and 12 months postoperatively and annually thereafter. At the time of final followup, 50 patients had died. No patients were lost to followup. Conventional AP pelvis and lateral radiographs of the hip were obtained during the first week after surgery, at the followups, and when indicated. Analog radiographs were digitalized at 150 dpi (ScanMaker 1000XL; Microtek, Hsinchu, Taiwan) resolution, converted to jpeg format, and integrated in the clinical database.

Statistical Analysis

Data were interpolated using a polynomial regression model fitted to each patient's migration data received by EBRA-FCA to calculate the migration rate at equal times as described previously [3, 27, 28]. We used a polynomial-based analysis to account for the fact that the stem subsides somewhat during the first weeks or months after implantation, but that later migration usually slows down and

Table 1. Distribution of characteristics in analyzed and not analyzed cases

Variable	Hips analyzed	Hips not analyzed	Mean difference (95% CI)	p value
Total number of hips	100	58		
Male	44 (44%)	32 (55.1%)		
Female	56 (56%)	26 (44.9%)		0.176#
Mean age of patients at time of surgery (years)	56 ± 9.0	55 ± 11.0	1.1 (−2.0 to 4.3)	0.489§
Clinical followup (years)	21 ± 2.0	21 ± 1.5	0.4 (−0.4 to 1.2)	0.364§
Cumulative incidence of aseptic stem loosening at 20 years (%)	9.9% (5.3–18.3)	6.3% (2.1–18.5)		0.420¶

95% CI in parentheses; # chi-square test; § t-test; ¶ log-rank test.

Table 2. Distribution of characteristics in both groups

Variable	Total cohort (number; %)	Group 1 (number; %) (control group)	Group 2 (number; (%) (aseptic loosening)
Hips	82 (100%)	73 (89%)	9 (11%)
Male	39 (48%)	33 (45%)	6 (67%)
Female	43 (52%)	40 (55%)	3 (33%)
Age of patients at time of surgery (years)	55 (23–74)	56 (33–74)	53 (23–63)
Mean clinical followup (months)	228 (36–288)	246 (144–288)	120 (36–204)
Mean radiologic followup (months)	198 (36–293)	211 (116–293)	94 (36–154)
Mean number of radiographs per hip	10.3 (4–23)	10.7 (5–23)	7.3 (4–11)

Ranges in parentheses.

stem subsidence usually does not follow a linear pattern. Data interpolation was necessary as postoperative radiographs were not always taken exactly at 12, 24, 36, and 48 months. Multivariate survivorship analysis using Cox' regression model was performed with an endpoint of aseptic loosening of the femoral component for the risk factors migration rate at 1, 2, 3, and 4 years postoperatively and age at surgery. Receiver operating characteristic (ROC) curve analysis was used to evaluate diagnostic performance of axial stem migration 1, 2, 3, and 4 years postoperatively as a predictor of late aseptic loosening. The optimal cutoff to determine acceptable early migration in this cohort was calculated by the Youden index [2]. A competing risk model [15, 21] was used to estimate long-term survival of stems with large early distal migration compared with stems with little early distal migration at 2 years with the endpoint "aseptic stem loosening", stems were assigned to groups of high and low early migration according to the calculated cutoff. We considered p values less than 0.05 to be significant. SPSS® Version 17.0 (SPSS Inc, Chicago, IL, USA), GraphPad Prism® Version 6.01 (GraphPad Software, La Jolla, CA, USA), Bias für Windows 11.02® (Epsilon-Verlag, Darmstadt, Germany), and the R Statistical Software Package (http://www.r-project.org) were used to record and analyze the data.

Informed consent for inclusion in our center's research database was obtained from all patients. Procedures followed were approved by the institutional review board of the University of Heidelberg (346/2004) and the study was conducted in accordance with the Helsinki Declaration of 1975, as revised in 2008.

Results

Stems that had aseptic loosening develop during the long-term followup showed greater early mean axial stem migration as measured by EBRA-FCA at 1, 2, 3, and 4 years postoperatively than did stems that remained well fixed (Fig. 2). Mean migration at 1 year postoperatively was 0.5 mm ± 0.7 mm among stems without loosening (Group 1) and 2.2 mm ±1.5 mm among stems with aseptic loosening (Group 2), respectively (mean difference, 1.7 mm; 95% CI, 1.1–2.3; $p \leq 0.001$). Two years postoperatively, a mean migration of 0.8 mm ± 0.9 mm was measured in Group 1 and 4.2 mm ± 3.1 mm in Group 2, respectively (mean difference, 3.4 mm; 95% CI, 2.5–4.4; $p \leq 0.001$) (Table 3). Evaluation of the individual migration pattern of the failed stems revealed the differences between early and late aseptic loosening (Fig. 3). Five of nine failed stems showed excessive migration during the first 4 postoperative years. These implants showed a mean migration of 6.7 mm ± 1.1 mm 2 years postoperatively and had to be revised after a mean of 80 months (range, 37–153 months) after implantation. Four stems showed a result similar to those of the well-performing stems with a mean migration of 1.1 mm ± 0.5 mm 2 years postoperatively (mean difference, 5.6 mm; 95% CI, 4.2–7.0; p < 0.001). These stems had to be revised markedly later owing to late aseptic loosening after a mean of 175 months (range, 117–207 months). The axial stem migration 1 and 2 years postoperatively appeared to be the strongest risk factor for aseptic loosening. The Cox' regression model showed a hazard ratio of 2.39 (95% CI, 1.95–3.46; p < 0.001) for axial stem migration per millimeter 1 year after implantation and 1.98 (95% CI, 1.51–2.57; p < 0.001) for migration 2 years postoperatively.

The diagnostic performance of migration measurement using EBRA-FCA at 2 years postoperatively for predicting later aseptic loosening was good (area under the curve, 0.86; 95% CI, 0.72–0.99; p < 0.001) (Fig. 4). Using a maximum Youden index, we determined a cutoff value of 2.7 mm at 2 years postoperatively, detecting future aseptic loosening with a sensitivity of 56% and a specificity of 99%. In a second analysis, this cutoff was used to calculate sensitivity of migration measurement 2 years postoperatively in prediction of aseptic failure regarding the entire observation period (Fig. 5). The sensitivity of the threshold decreased subsequently with a prolonged period between primary and revision surgeries because excessive migration was the predominant pattern for short-term and mid-term failure.

Stems with large amounts of early distal migration (≥ 2.7 mm) had lower 18-year survivorship than did stems with little early distal migration (29% [95% CI, 0%–62%] versus 95% [95% CI, 90%–100%], log-rank test, p < 0.001) (Fig. 6).

Discussion

Aseptic loosening is a common cause of late revision after THA [1, 12, 13]. Reliable and clinically applicable methods are needed to predict aseptic loosening and allow early

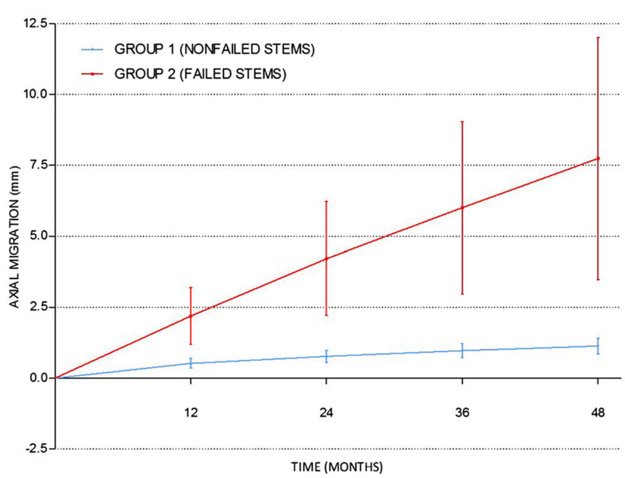

Fig. 2 This graph shows the mean axial migration of the failed (n = 9) and nonfailed stems (n = 73) during the first 48 postoperative months. Mean migration of the failed components is shown by the solid red line, whereas the mean migration of the well-performing stems is indicated by the solid blue line.

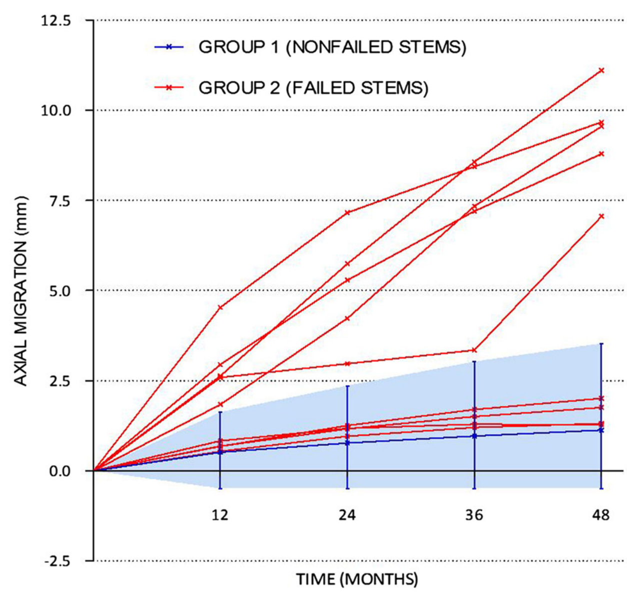

Fig. 3 This graph shows the axial migration of the individual components during the first 48 postoperative months. All failed components (n = 9) are shown by solid red lines. Mean migration of well-performing stems (n = 73) is shown by the solid blue line. The blue shaded area contains the 95% range of axial migration shown by all well-performing stems.

Table 3. Mean migration (± SD) in both groups at different times (95% CI)

Point of measurement in months	Mean migration in Group 1 (control group) (mm)	Mean migration in Group 2 (aseptic loosening) (mm)	Mean difference (95% CI)	p value (Wilcoxon)
12	0.5 ± 0.7	2.2 ± 1.5	1.7 (1.1–2.3)	0.001
24	0.8 ± 0.9	4.2 ± 3.1	3.4 (2.5–4.4)	< 0.001
36	1.0 ± 1.1	6.0 ± 4.7	5.0 (3.8–6.3)	< 0.001
48	1.1 ± 1.1	7.7 ± 6.5	6.8 (5.2–8.4)	0.001

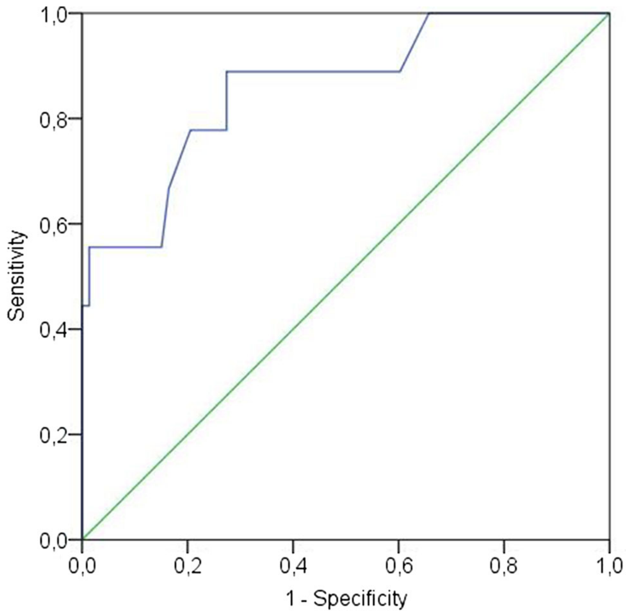

Fig. 4 The receiver operating characteristic (ROC) curve for axial stem migration at 24 months postoperatively is shown.

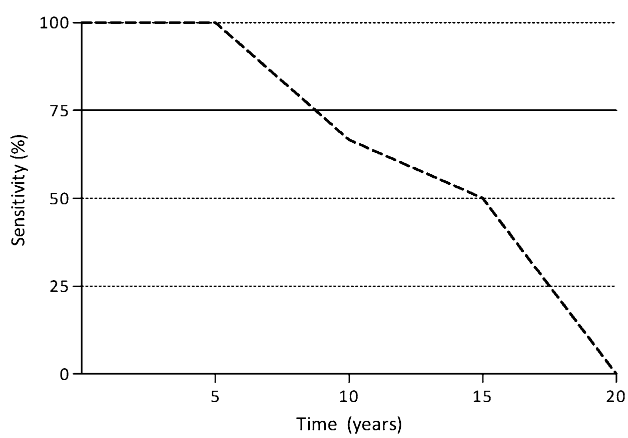

Fig. 5 This graph shows the sensitivity of early migration measurement to predict later aseptic implant failure with a cutoff of 2.7 mm at 2 years postoperatively. Sensitivity decreases with an extended period between implantation and aseptic failure.

evaluation of long-term implant performance. RSA is accurate, but expensive, feasible only for prospective study designs, and impractical for long-term studies with large patient populations. EBRA-FCA may be a suitable alternative as it also allows accurate measurement of femoral stem subsidence [4] without the need for implanting tantalum markers [5] and can be performed retrospectively using standard radiographs. However, to our knowledge there are only four studies that investigated the association between early migration of the femoral component in THAs and stem survival [11, 14, 17, 19]. Whereas early migration measurement is commonly recommended as a valuable tool to detect unsafe and poor-performing implants early and to prevent their widespread use [16, 30], there is a lack of studies that correlate early migration and late implant loosening in the same patient cohort, particularly regarding long-term observations (> 10 years) [36]. Furthermore, and even more important, none of these previous studies [11, 14, 17, 19] investigated this relationship exclusively for cementless femoral stems. All femoral stems, cemented or cementless, migrate to some extent during the first year, but thereafter, the migration slows in well-functioning stems. Continuing rapid early migration is said to be predictive of loosening [22]. However, the absolute early migration is different depending on the stem design [6, 22, 23, 29, 34–37]. We found that early migration, as measured by EBRA-FCA at 2 years postoperatively, can identify uncemented femoral components at risk for aseptic loosening during early and mid-term followup, but did not predict aseptic loosening in the late second and third decades.

There are several limitations to this study. First, EBRA-FCA is able to measure only distal implant migration and differences in the stem axis to varus position, whereas RSA is able to measure 3-D migration, notably posterior head migration, and it has a higher accuracy. However, when compared with the RSA-based migration data published on the CLS® stem [23, 24], our mean migration found at 1 and 2 years compares well with that from RSA studies using the CLS® stem; therefore, we believe our measurements are accurate. Second, the high dropout rate is a limitation of our study. However, the dropout rate is influenced mainly by exclusion of noncomparable radiographs resulting from the EBRA algorithm, which is unlikely to inject any sort of systematic bias (Table 3). Specifically, the hips analyzed were not different from those not analyzed in key areas such as age, sex, duration of followup, and cumulative incidence of stem loosening. In addition, when compared with other migration analysis studies using EBRA-FCA [9, 19, 38], our dropout rate was lower. We also recognize a possible bias because the acetabular components used in this cohort showed a high rate of aseptic loosening [7, 8], as patients with cup loosening might reduce their activity which could influence wear and aseptic loosening of the stem; surgery for cup loosening also might have an influence on stem revision rate. Further, the migration threshold of 2.7 mm in this study using a single stem design might not apply to other stem designs, since such thresholds are almost certainly implant-specific. However, the concept that such a threshold exists may be a generalizable principle, and large amounts of early subsidence likely will be found that could predict loosening in other designs, although future studies will need to evaluate this in more-specific terms. Finally,

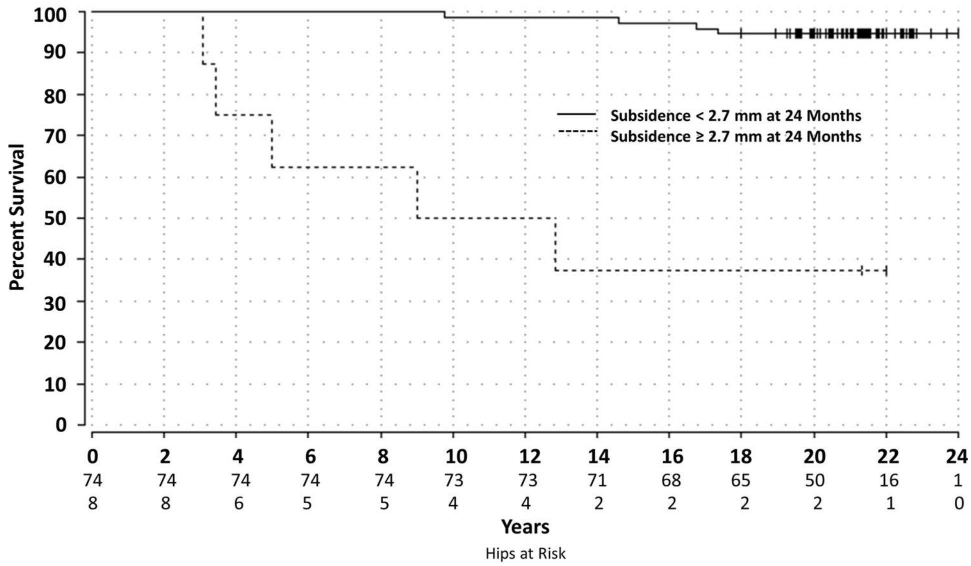

Fig. 6 The survivorship curve obtained by competing risk analysis for stems migrating more or less than 2.7 mm during the first 2 years with femoral revision for aseptic loosening as the endpoint is shown. Eighteen-year survival was estimated at 95% for hips with less than 2.7 mm axial migration at 2 years postoperatively and at 29% for hips migrating 2.7 mm or more, respectively (log-rank test, $p < 0.001$).

we are aware that early migration can predict only aseptic loosening, whereas other failure mechanisms (such as wear and osteolysis) are not evaluated by implant migration measurements.

This study shows a clinically relevant association between early distal migration of cementless femoral stems, as measured with EBRA-FCA, and aseptic femoral loosening at long-term followup. Each millimeter of distal migration at 2 years postoperatively was associated with an approximately twofold greater risk for aseptic loosening. The prognostic value of excessive early migration within 1 to 2 years postoperatively for early aseptic loosening and mid-term survival has been shown for different cemented stems and cups using different measurement methods [11, 14, 17, 19, 23, 24, 26]. Krismer et al. [19] reported an association between early migration and loosening during the first decade after surgery in a mixed study combining cemented and uncemented stems. However, we are not aware of any previous study focusing on this association exclusively for uncemented stems. In a recent review and meta-analysis, van der Voort et al. [36] found a clinically relevant association between early subsidence of cemented shape-closed femoral stems and late revision for aseptic loosening. For every 0.1 mm increase in 2-year subsidence, there was a 4.2% increase in the aseptic revision rate at 10 years. They also concluded that the published research is not sufficient to allow any conclusions regarding such an association for cemented force-closed and uncemented stems [36]. Considering our findings, we believe that the observed association in our study between early migration and long-term aseptic loosening on uncemented femoral stems should be adopted in phased evidence-based market introduction of new cementless stems, particularly of short-stem prostheses.

The overall diagnostic performance of early distal migration calculated during the entire timespan to predict aseptic loosening was good. However, if calculated for early- and mid-term failure only, it would be excellent because the sensitivity was very high during the first decade and decreased during the second decade (Fig. 5). This finding is consistent with those of a previous study in which a decrease in the sensitivity of early migration as a predictor of later failure in the long term was reported [20]. Implants with late aseptic failure rarely showed early-onset migration and would not have been detected even by a very low migration threshold. We found that the early migration pattern in these stems was not different from the pattern observed in well-functioning stems (Fig. 3). Therefore, we believe that primary stability was sufficient, and initial osseointegration was effective, but secondary stability was compromised by other factors such as bone loss and remodeling or osteolysis. Late-onset migration represents a fatigue failure of the bone-implant interface in cementless stems. Our study shows that if late-onset migration occurs with the cementless stem we studied, it also might exist for others. However, because of the high sensitivity of detecting failure in the short- and mid-term, early migration measurements of cementless femoral components are a reliable screening method. Various migration thresholds have been proposed for different cemented stem designs [11, 14, 17, 19]. Compared with previous migration thresholds proposed for cemented implants, we found that a relatively high threshold of 2.7 mm at 2 years postoperatively had the best diagnostic performance to predict aseptic loosening using a cementless stem. The lower thresholds proposed mainly for cemented prostheses were inappropriate in this long-term study. As previously shown, migration of cementless stems is related to several design features and minor modifications might have an important effect on their early migration rate. One example is the higher migration of the Furlong® Active stem (JRI Orthopaedics Ltd, London, UK) without a collar compared with the Furlong® H-A.C. stem with a collar [29, 37]. Because several factors influence the extent of early migration, we believe it is difficult to define definite limits on absolute implant early migration to predict long-term survival. Stabilization of early migration might be more appropriate than the absolute value of migration for identification of unsafe uncemented stems [36].

Compared with stems with low early distal migration, those with migration of 2.7 mm or greater had a markedly lower survival at long-term followup. The obvious difference in survival rates after 18 years in both groups illustrates the clinical significance of predicting long-term results using short-term migration data (Fig. 6). To our knowledge, there are two published studies reporting stem survival data after early migration analysis in the same cohort. Krismer et al. [19] reported a significantly lower 10-year survival in an EBRA-FCA analysis for stems (mixed cohort of cemented and uncemented prostheses) subsiding more than 1.5 mm after 2 years. Freeman and Plante-Bordeneuve [11] found a significantly lower 8-year survival for femoral stems subsiding more than 1.2 mm after 2 years, again in a mixed cohort of cemented and uncemented stems.

Our study shows that early migration analysis, especially the individual analysis of early migration patterns, is a potentially useful tool to predict long-term survival of cementless femoral components. Although its diagnostic performance to predict loosening in the early- and mid-term was excellent, aseptic loosening during the late second and third decades could not be predicted by early migration measurement with EBRA-FCA. Future studies should evaluate more implant-specific migration data for uncemented stem designs in large patient cohorts, either retrospectively using EBRA-FCA, preferably in cohorts that were closely followed into the second or third decade postoperatively, or prospectively using RSA for implants with known long-term results, so that the association between early migration and late aseptic revision can be assessed using a weighted regression model [36].

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