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Ceramic-On-Ceramic Joints: A Suitable Alternative Material Combination?

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1. Introduction

Total hip replacement (THR) surgery has been available for several decades and is now a relatively common procedure. Since the introduction of the Charnley metal-on-ultra-high molecular weight polyethylene (UHMWPE) hip prosthesis, THR is seen as one of the most successful orthopaedic operations available today. There are currently over 80,000 hip replacement procedures carried out in England and Wales [1] each year and THR has now become more popular with the younger, more active patient. This is shown in the statistics reported in the National Joint Registry; 12% of the patients who undergo THR are under the age of 55 and 85% of these are recorded as being either fit and healthy (16%) or with mild disease that is not incapacitating (69%) [1]. However, failure of these artificial joints does occur, leading to the need for revision surgery; approximately 10% of the THR procedures reported are revision operations [1].

Failure, in many cases, is due to aseptic loosening [1, 2]. With the conventional metal-on-UHMWPE joint this has been shown to be due to wear particle induced osteolysis [3]. Although 90% of these joints are operating well 15 years after implantation [2] this wear particle induced osteolysis may lead to repetitive revision requirements for the younger, more active patient.

An alternative to the conventional metal-on-UHMWPE type of hip joint is to use ceramic-on-ceramic joints. Ceramic-on-ceramic joints were first introduced in the early 1970s but often resulted in poor performance due to fixation problems, poor quality alumina as a result of inadequately controlled grain size and other material properties (leading to catastrophic wear), and sub optimal design parameters such as too large a clearance. The work of many people over the years, including material scientists and engineers, has improved the quality of these ceramics. Therefore, since the introduction of the standard for ceramic production

(ISO 6474:1981 (second-generation ceramics), which was replaced with ISO 6474:1994 (third-generation ceramics) and has now been replaced by ISO 6474-1:2010 (fourth-generation ceramics)) the performance of these all ceramic bearings has been greatly improved [4, 5]. The third and fourth-generation alumina ceramics are manufactured using hot isostatic pressing. This produces a material that is highly pure with a small grain size ($\leq 2.5 \mu\text{m}$ and many manufacturers produce ceramics with even smaller grain sizes) that provides material strength and minimises the risk of fracture. The majority of the ceramic-on-ceramic joints discussed in this chapter were produced using third-generation ceramics.

Ceramic-on-ceramic hip prosthesis performance will be reviewed in this chapter (*in vitro* and *in vivo*) along with a discussion of the concerns with ceramic-on-ceramic joints that happen in a minority of cases such as joint “squeaking” and component fracture. The majority of articles reviewed discuss the performance of alumina-on-alumina joints. There are, however, other ceramic materials available on the market today for use in orthopaedic surgery, for example BIOLOX® delta (an alumina matrix composite containing 72.5% alumina, 25.5% zirconia, and 2% mixed oxides). The reader will be made aware when joints made from this material are discussed.

2. Ceramic-on-ceramic hip prosthesis performance

The performance of ceramic-on-ceramic hip joints has been evaluated using data obtained from joints operating well within the body, prostheses retrieved due to joint failure and also tests performed within the laboratory. Firstly, the *in vitro* laboratory tests results will be discussed, then the *in vivo* data will be given. In addition to this, “squeaking”, one of the most common concerns relating to ceramic-on-ceramic joints will be discussed.

2.1. *In vitro*

The majority of recent papers discussing the tribology (lubrication, friction and wear) of ceramic-on-ceramic hip joints detail tests done under ‘severe’ conditions such as malpositioning, edge-loading or microseparation. There are, however, some earlier studies that describe how these joints operate under ‘standard’ conditions.

A well positioned ceramic-on-ceramic hip, tested under the loads and motions expected during the standard walking cycle, performs exceptionally well in terms of friction, lubrication and wear [6-24]. Friction tests using different viscosities of carboxy-methyl cellulose (CMC) solution show that these joints operate close to full-fluid film lubrication with very low friction factors (0.002 at physiological viscosities) [6, 12]. These ceramic-on-ceramic joints have been shown to have very low surface roughness values that play a part in this low friction [6]. Tests were also performed using different viscosities of bovine serum [6, 12]. Bovine serum is often used in the laboratory as a replacement for the body’s natural lubricating fluid, synovial fluid, as it contains proteins that act in a similar manner to those present in synovial fluid and although CMC fluids replicate the shear-thinning behaviour of synovial fluid, they do not contain any proteins. The introduction of these proteins into the

lubricating fluid resulted in higher friction (0.03 at physiological viscosities) and mixed lubrication. These results are shown as Stribeck plots in Figure 1. A Stribeck plot shows the measured friction factor plotted against Sommerfeld number (a dimensionless parameter dependent on the lubricant viscosity, the entraining velocity of the bearing surfaces, the joint radius and the load applied). A rising trend of friction factor with increasing Sommerfeld number is indicative of a full-fluid film lubrication regime, whereas a falling trend is normally indicative of mixed lubrication. In full-fluid film lubrication, the surfaces are completely separated by the lubricant and the friction generated is due solely to the shearing of the lubricant film. In mixed lubrication, the load is carried in part by the contact between the asperities of the bearing surfaces and also by the pressure generated within the lubricant. Although the bovine serum tests suggested that these ceramic-on-ceramic joints were operating in mixed lubrication with some asperity contact, there was no surface damage evident on the joints after testing. It was speculated that the proteins that adhere to the ceramic surfaces when using protein-based lubricants produce a sufficiently thick layer to penetrate the fluid film and result in protein-to-protein contact and shearing. It is likely that the subsequent friction developed by the protein-to-protein contact is greater than that due to the shearing of the lubricant film alone. Therefore, although higher friction and mixed lubrication is encountered when testing under more physiological lubricating conditions, there is still little asperity contact during the normal walking cycle [12].

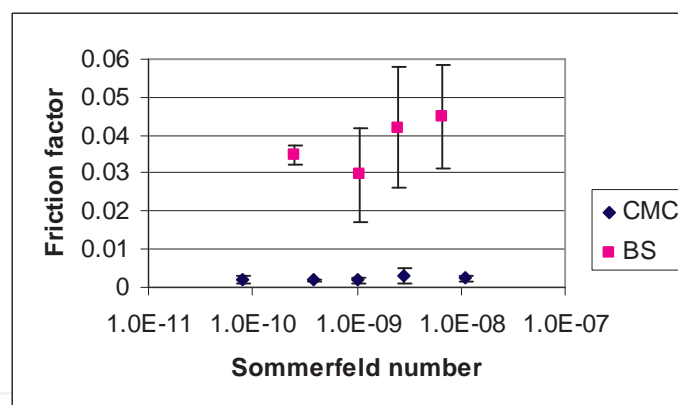


Figure 1. Stribeck plot for ceramic-on-ceramic joints (Scholes *et al* (2006) [12]). CMC: CMC fluids; BS: bovine serum.

With this good lubrication and low surface roughness the wear volumes produced under 'standard' conditions in the laboratory have, inevitably, been shown to be very low (less than 0.4 mg/million cycles cf. approximately 35 mg/million cycles for conventional metal or ceramic-on-UHMWPE joints, see Table 1), and sometimes almost immeasurable. As these ceramic-on-ceramic joints are working close to full-fluid film lubrication there is little or no contacting of the asperities on the joint surfaces leading to this low wear and friction [6, 12]. Also, laboratory studies have shown that cup malpositioning and elevated swing phase load testing have not significantly affected the wear of these joints [21, 22, 25, 26], see Table 2. This combination should, therefore, lead to a very successful artificial joint.

Reference	Material combination	Components	Wear rate (mg/million cycles)
[27]	Metal-on-UHMWPE	UHMWPE cup	47.4
[27]	Ceramic (zirconia)-on-UHMWPE	UHMWPE cup	37.9
[28]	Metal-on-UHMWPE	UHMWPE cup	~33.7
[28]	Ceramic (zirconia)-on-UHMWPE	UHMWPE cup	~29.0
[29]	Metal-on-UHMWPE	UHMWPE cup	~40.9
[29]	Ceramic (zirconia)-on-UHMWPE	UHMWPE cup	~29.5
[13]	Ceramic-on-ceramic	Head and cup	~0.25
[16]	Ceramic-on-ceramic	Head and cup	~0.16
[17]	Ceramic-on-ceramic	Head and cup	< 0.04
[18]	Ceramic-on-ceramic	Head and cup	0.09
[24]	Ceramic-on-ceramic	Head and cup	~0.20

Table 1. Wear rates found for well-positioned conventional metal or ceramic-on-UHMWPE and ceramic-on-ceramic joints under standard testing conditions

More severe loading conditions have, however, given slightly different results. Microseparation was first introduced during the swing phase of the walking cycle on the Leeds hip wear simulator [30] to replicate the stripe wear sometimes seen on retrieved ceramic-on-ceramic joints. Microseparation was incorporated in the simulator studies at Leeds because a year earlier, it was suggested by Mallory *et al* (1999) [31] that this separation of the femoral head and acetabular cup can occur in conventional metal-on-UHMWPE joints. Nevelos *et al* (2000) [30] hypothesised that a similar mechanism may take place in ceramic-on-ceramic joints resulting in the visible stripe wear found on some retrievals. Microseparation was, therefore, set up in the simulator and involved separation of the femoral head and acetabular cup during the swing phase of walking leading to relocation (with rim contact and edge-loading) during heel strike before the head then relocated in the cup in the stance phase (see Figure 2). The surface damage caused by this rim contact resulted in what is known as stripe wear.

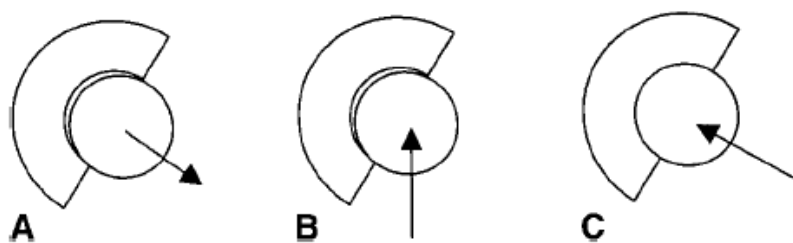


Figure 2. Microseparation as applied in the Leeds simulator by Nevelos *et al* (2000) [30]. (A) Swing phase: microseparation. (B) Heel-strike: rim contact. (C) Stance phase: relocation.

Using this microseparation technique, Nevelos *et al* (2000) [30] found slightly higher wear rates with ceramic-on-ceramic joints than found under 'standard' conditions (see Table 2). This study, however, was relatively short-term (800,000 cycles). Longer-term tests performed by Stewart *et al* (2001) [32] on the same simulator gave similar results to those found by Nevelos *et al* (2000) [30]. Other workers have also found an increase in wear rate with microseparation [33]. More recent work performed by Al-Hajjar *et al* (2010) [25] studied BIOLOX® delta couplings. These joints gave lower wear than that found for alumina-on-alumina joints. Microseparation of the BIOLOX® delta joint surfaces, again, resulted in higher wear. The wear rates found using microseparation are, however, still extremely low in comparison with conventional joints (see Tables 1 and 2).

Reference	Wear conditions	Components	Average wear rate (mg/million cycles)
[11]	Standard	Cup only	< 0.02
[13]	Standard	Not stated	~0.25
[16]	Standard	Head and cup	~0.16
[17]	Standard	Head and cup	< 0.04
[18]	Standard	Head and cup	0.09
[19]	Standard	Cup only	~0.40
[21]	Standard	Not stated	~0.24
[22]	Standard	Cup only	~0.32
[24]	Standard	Head and cup	~0.20
[21]	Elevated cup angle	Not stated	~0.20
[25]	Elevated cup angle	Not stated	0.20
[22]	Elevated swing phase load	Cup only	0.36
[25]	Microseparation	Not stated	0.52
[30]	Microseparation	Not stated	4.78 (after 800,000 cycles)
[32]	Microseparation	Not stated	(mild) ~0.40 (severe) ~5.17
[33]	Microseparation	Head and cup	1.55

Table 2. Wear rates found for alumina-on-alumina joints under standard testing conditions and microseparation

It is still unknown if it is this microseparation that causes the stripe wear that is observed on some retrievals or whether this type of wear is due simply to edge-loading of the head on the cup through a different mechanism. Higher rates of wear including the appearance of stripe wear may also be due to a steep acetabular cup implantation angle or repeated dislocations [34]. Microseparation, or edge-loading, may occur during various different physical activities such as stair climbing, standing from squat position and deep flexion. It may, however, also occur during walking. These simulator studies incorporating microseparation of

the head and cup into the walking cycle are therefore a severe testing method. The resulting rim contact and stripe wear does, however, replicate the more severe conditions that these joints may encounter thus producing the same effect that is seen on some retrievals but not necessarily through the correct corresponding actions.

If, and when, wear of these ceramic components occurs it is important to understand how the body is likely to react to these wear particles. It is well known that wear particle induced osteolysis is a major concern for conventional metal-on-UHMWPE joints [3] but is this the case for ceramic-on-ceramic prostheses? Promisingly, several workers have shown that the cellular response to ceramic particles is less severe than that due to polyethylene particles [35, 15]. An important point to note with the laboratory tests discussed above is that, even under extreme loading and motion conditions, these joints provide low wear with a minimal adverse tissue reaction to these wear particles. As stated by Fisher *et al* (2006) [15], the combination of low wear and low reactivity means that ‘...ceramic-on-ceramic bearings address the tribological lifetime demand of highly active patients.’

2.2. *In vivo*

As shown above, the laboratory test results for ceramic-on-ceramic joints are very promising. Is this mirrored by the *in vivo* performance? There are many publications detailing the performance of ceramic-on-ceramic hip joints in the body. A selection of these papers is discussed below to give a general overview of joint performance using this material combination.

The short-term (mean follow-up of 50.4 months) performance of ceramic-on-ceramic joints was compared to that of metal-on-highly cross linked polyethylene (XLPE) joints in a study reported by Bascarevic *et al* (2010) [36]. Seventy-five metal-on-highly XLPE hips (72 patients) and 82 ceramic-on-ceramic hips (78 patients) were assessed. Both were found to work well with no revisions performed on the ceramic-on-ceramic joints compared with 2 revisions necessary for the metal-on-highly XLPE group. The authors commented that ceramic-on-ceramic components manufactured using third-generation ceramics were “especially suited for hip arthroplasty in young and active persons”.

A comparative study was also performed by Amanatullah *et al* (2011) [37]. The short-term performance (60 months) of 125 ceramic-on-ceramic hip joints was assessed against 95 ceramic-on-UHMWPE prostheses. In this study both the material combinations performed well and no statistically significant difference was found between the clinical outcome scores for the two types of prosthesis, however, one important point to note is that audible noise such as “squeaking” did occur in 3.1% of the ceramic-on-ceramic hips. “Squeaking” is a phenomenon reported by others and this will be discussed later. It was noted that this is a short-term study (five years) and, as the metal-on-UHMWPE hips did not produce as low wear rates in the radiographic analysis, osteolysis may occur at a later stage.

Another short-term study comparing the results of 525 hips (421 ceramic-on-ceramic and 104 metal-on-UHMWPE) was reported by Johansson *et al* (2011) [38]. These joints had been implanted for an average of 59 months. The survival rates were 98% and 92% for the ceramic-on-ceramic and metal-on-UHMWPE hip joints respectively.

A short-term study (60 month follow-up) reported by Nikolaou *et al* (2012) [39] assessed and compared the performance of 36 metal-on-UHMWPE, 32 metal-on-highly XLPE and 34 third-generation ceramic-on-ceramic hip joints. The apparent wear of the bearing surfaces was assessed radiologically. The ceramic-on-ceramic joints showed the lowest wear (mean linear wear 0.035 mm) and the metal-on-highly XLPE gave nearly 3 times lower wear than the metal-on-UHMWPE joints (0.329 mm cf. 0.869 mm). At 60 months, no difference in clinical outcome was found for these three different material combinations. "Squeaking" was observed in 3 (8.8%) of the ceramic-on-ceramic joints; no revision procedures were necessary as a results of this squeaking though.

Early to mid-term results were also reported by Stafford *et al* (2012) [40]. At a mean follow-up of 59 months six of these 250 ceramic-on-ceramic hips were revised. Two were revised for recurrent dislocation secondary to impingement, two for deep infection, one for recurrent dislocation and one due to fracture of the femoral head. Although no patients experienced "squeaking", six described a grinding or crunching noise that was experienced mainly during deep flexion. One of these "squeaking joints" was a BIOLOX® delta ceramic prosthesis. Again, no revision surgery was performed on these noisy joints.

Mesko *et al* (2011) [41] assessed the outcome of 930 ceramic-on-ceramic hips over 10 years that were implanted by nine different surgeons. The survivorship at 10 years (96.8%) was referred to as 'excellent' with 0.9% fracture, 2.3% dislocation and 2.5% reported incidents of noise such as clicking, squeaking, popping, or creaking.

Another 10 year follow-up was reported by Yeung *et al* (2012) [42]. The clinical information was available for 244 hips (227 patients) and the radiographic information was available for 184 hips (172 patients). The success of these joints led to an overall survival rate of 98% (again, with revision for any reason as the end point).

In a multicentre study performed by Capello *et al* (2008) [43], 452 patients (475 hips) were assessed. The majority of the hips implanted were ceramic-on-ceramic (380) whilst the remainder (95) were conventional metal-on-UHMWPE and used as a comparison. The average patient age was 53 years and there was an average 8 year follow-up period. The authors found the clinical results to be excellent. The ten-year Kaplan-Meier survivorship (with revision of either component for any reason given as the end-point) was stated as 95.9% for the ceramic-on-ceramic hip joints and 91.3% for metal-on-UHMWPE. The ceramic joints, therefore, performed better than the conventional joints and because one of the major causes of failure for conventional metal-on-UHMWPE joints is late aseptic loosening due to osteolysis, a longer term study is likely to give a greater difference in survivorship ratings. Of the ceramic-on-ceramic failures requiring revision, only 2/380 (0.5%) were due to ceramic fractures. Therefore, overall it was concluded that the third-generation ceramic-on-ceramic hip joints performed well clinically and radiographically in this young patient group. Although these joints performed relatively well "squeaking" was reported in 3/380 (0.8%) cases for the ceramic-on-ceramic joints.

In the study reported by Lee *et al* (2010) [44], the ten year survival rate of 88 ceramic-on-ceramic hip joints, with revision of either the head or the cup for any reason being as the end

point, was 99.0%. These results were taken after a minimum of 10 years postoperatively and are, indeed, very promising.

A long-term study on earlier generation ceramic joints was performed by Hernigou *et al* (2009) [45]. This was a comparative study which investigated the wear and osteolysis of 28 bilateral arthroplasties (one ceramic-on-ceramic and the contralateral ceramic-on-UHMWPE). All of these joints (ceramic-on-ceramic and ceramic-on-UHMWPE) had lasted 20 years without the need for revision surgery. Computer tomography (CT scan) was used to assess the number and volume of osteolytic lesions present. Fewer osteolytic lesions were found on the side with the ceramic-on-ceramic joint; there were 13 cases of pelvic osteolysis found and 15 joints showed evidence of femoral osteolysis (cf. 24 joints with pelvic osteolysis and 23 with femoral osteolysis for the ceramic-on-UHMWPE joints). Also, in each patient, the diameter, surface and volume of osteolysis was substantially lower on the side with the ceramic-on-ceramic hip implant than the ceramic-on-UHMWPE joint. It must also be remembered that these joints were manufactured using first-generation ceramics and the ceramics produced to the standard expected for third and fourth-generation ceramics are expected to perform even better.

Another longer-term study (mean 20.8 years), again with earlier generation ceramics, performed by Petsatodis *et al* (2010) [46] also showed good results. There were 100 patients in this study, all with at least one ceramic-on-ceramic hip joint (109 hips) and, again, a young patient population (average age 46 years). The cumulative rate of survival was quoted as being 84.4% at 20.8 years.

Although these results are promising, in the majority of cases, the follow-up period particularly for the third generation ceramics, was only short-term. It will, therefore be very interesting to evaluate the performance of these third and fourth-generation ceramic-on-ceramic joints, along with the metal and ceramic-on-highly XLPE, on a longer-term basis. These results are eagerly anticipated.

The papers discussed so far have shown exceptional performance of ceramic-on-ceramic joints and suggests that these joints may perform better than metal or ceramic-on-UHMWPE. This, however, is not reflected in the data described in the National Joint Registry (NJR) of England and Wales (2011) [1]. Promisingly though, the NJR states that there is 'little substantive difference' in the risk of revision for ceramic-on-ceramic, ceramic-on-polyethylene or metal-on-polyethylene joints. It is, however, not stated whether this polyethylene is UHMWPE or XLPE and the differences in performance between these two materials is not listed.

Although, as discussed above, many of these ceramic-on-ceramic hip joints perform exceptionally well, early dislocation is seen as a possible concern due to limited modular neck length and other factors. In the majority of the published literature referred to in this text [47, 36, 48, 43, 49, 50, 46, 51-57, 41, 40], the occurrence of dislocation is 0% - 2.3%. The number of dislocations was higher (6%) in a study reported by Chevillotte *et al* (2011) [58], however, no reoperation was required for any of these cases. Colwell *et al* (2007) [53] summarised other published literature detailing the number of dislocations in ceramic-on-

ceramic hip joints in comparison with metal-on-polyethylene and found no difference between the two material combinations. In addition to this Amanatulla *et al* (2011) [37] and Bascarevic *et al* (2010) [36] showed no difference in the number of dislocations for ceramic-on-ceramic and ceramic-on-UHMWPE or metal-on-highly XLPE hip prostheses. Often there is no need for revision surgery after dislocation, unless it is recurrent dislocation.

Component fracture in ceramic-on-ceramic hips is another cause for concern for many surgeons and patients. The fracture rates of ceramic joints have been dramatically reduced since the introduction of third and fourth-generation ceramics with the new material processing methods. Ceramic-on-ceramic joints have strict regulations that must be abided by with regard to material properties such as burst strength; as discussed in work reported by Salih *et al* (2009) [59]. However, fracture of these components does still occur, leading to catastrophic joint failure and revision surgery. In the majority of cases though, this fracture rate is extremely low (0% - 0.5%) [60, 61, 43, 49, 45, 50, 46, 51, 48, 55, 57, 40]. Some reports do, however, give a higher rate of post-operative fracture (1-2.3%) [62, 44, 37, 42, 47, 39]. Fracture is often associated with trauma, however a multicentre review reported by Park *et al* (2006) [63] discussed the performance of 357 third-generation ceramic-on-ceramic THRs and fracture occurred under normal activities in six of these hips (1.7%). This design used a polyethylene-ceramic composite liner within a titanium alloy shell and the high rate of fracture led to the authors discontinuing its use. It must be recognised though that, in general, the rate of fracture for ceramic-on-ceramic hip joints is very low. In fact, an article describing the fracture of ceramic joints (Hannouche *et al* (2003) [64]) stated that during a 25 year period (1977 – 2001) 11 (less than 0.004%) of the 3300 ceramic-on-ceramic joints reported on failed due to fracture. This low rate of fracture is from ceramics produced using earlier versions of the ISO standard and, so, this is expected to reduce even further and many studies using third-generation ceramics have reported no failures due to fracture [51, 36, 65, 66], Fracture must, however, still be recognised as a risk (albeit very low) with ceramic-on-ceramic joints.

For what other reasons does failure occur? Savarino *et al* (2009) [67] analysed the clinical, radiographic, laboratory and microbiological data from 30 retrieved ceramic-on-ceramic hip components. They concluded that failure was due to malpositioning of the joint during surgery leading to mechanical instability, or trauma or infection. Loosening in this selection of joints was not due to wear debris induced osteolysis. They indicated that the wear debris produced by these joints and the osteolysis present were the effect of the loosening, rather than the cause. It is stated that correct positioning of the implant is crucial. This has also been stated by other workers [54].

A case study was reported by Nam *et al* (2007) [68] discussing a failed ceramic-on-ceramic hip joint where failure was stated as being caused by alumina debris-induced osteolysis. A sixty-three year old woman underwent bilateral THR in 1998. Eight years later the patient returned to the clinic for routine follow-up and was experiencing no discomfort or worrying symptoms. However, the radiographs taken showed expansive osteolytic lesions. After revision surgery a histologic analysis of the retrieved tissues showed alumina particles within the cytoplasm of macrophages and in intercellular tissue suggesting wear particle induced osteolysis. Alumina wear particle-induced osteolysis is, however, a very rare phenomenon.

Chang *et al* (2009) [69] reported on the clinical and radiographic outcomes when using third-generation ceramic-on-ceramic joints in revision THR of 42 failed metal-on-UHMWPE hips. This was an interesting study as most published literature discuss the choice of bearing material for primary surgery and, as stated by the authors, ‘...few studies have focussed on the choice of bearing surface in revision...’. This was a young patient group (mean age: 48.8 years, range: 32 – 59 years) and the mean length of time between primary and revision surgery was 9.5 years (range: 3.3 – 16.1 years). The mean duration of follow-up after this revision surgery was 64 months (range: 38 – 96 months). At the time of publication of this article, no hips needed additional revision surgery and no hips showed radiolucent lines, acetabular cup migration or osteolysis. This study gives very favourable results for the use of ceramic-on-ceramic hip joints in revision surgery, especially for the younger patient as the likelihood of the need for further revision is greater.

3. The “squeaking” hip

Another concern with hard-on-hard bearing couples such as ceramic-on-ceramic and metal-on-metal is the incidence of noise or “squeaking” in these joints. Audible sounds such as squeaking, clicking, snapping, cracking, grinding, rustling, crunching and tinkling are all referred to in this text as “squeaking”. “Squeaking” can be present during different kinds of activity including stair climbing, bending forward, squatting, standing from a chair and walking. The occurrence of this “squeaking” has been reported by many workers to different degrees.

Jarrett *et al* (2009) [52] described a group of 131 patients from which 14 (10.7%) suffered an audible “squeak” during normal activities (however, only 4 of these patients were able to reproduce the “squeak” during the clinical review session). They stated that none of the patients had undergone revision surgery specifically because of “squeaking”, however, longer-term follow-up was needed to monitor this noise.

Mai *et al* (2010) [70] reported noise or “squeaking” in 17% of 320 ceramic-on-ceramic hips and Keurentjes *et al* (2008) [71] found “squeaking” in 20.9% of cases. From their study they concluded that short neck length of the femoral component was a potential risk factor for “squeaking”.

A study performed by Cogan *et al* (2010) [72] reported on the occurrence of “squeaking” in a patient population with at least one ceramic-on-ceramic hip; 10.6% of 265 hips demonstrated “squeaking”. Two other published studies report on “squeaking” in 15% and 8.8% of the patient population [44, 39]. Other published literature suggests that “squeaking” occurs in 0% - 6% of patients [73-75, 40, 65, 50, 61, 56, 76, 43, 49, 51, 37, 58, 41, 77]. The “squeaking” phenomenon tends to appear at an average of 28.8 months (range of averages 5.7 - 66 months) post-operatively.

After 10 years of follow-up Chevillotte *et al* (2012) [73] discussed the performance of 100, third-generation ceramic-on-ceramic joints. By use of a questionnaire, 5% of these patients reported

the occurrence of “squeaking”. All of these patients were active, sporty and heavy men. “Squeaking” was not related to any malpositioning, wear or loosening of the joint and none of the 100 patient group suffered from any component fracture. In this paper it was stated that “squeaking” noise seems to be an isolated phenomenon with no consequences for the patient regarding functional results and on the implant longevity at 10 years of follow-up’.

The largest study to date (Sexton *et al* (2011)) [75] reported on the occurrence of “squeaking” and the role of patient factors and implant positioning in 2406 ceramic-on-ceramic hips at a mean follow-up of 10.6 years. Seventy-four hips (73 patients, 3.1%) made “squeaking” sounds at a mean time post-operatively of 40 months. Taller, heavier and younger patients with higher activity levels were found to be more at risk of developing a “squeaking” hip. However, there was no relationship between BMI and the prevalence of “squeaking”. Interestingly, it was found that at a mean follow-up of 9.5 years, 11 of these hips (15%) had stopped “squeaking”. Therefore, “squeaking” is not necessarily a permanent complication.

There is great debate over the cause of “squeaking” in ceramic-on-ceramic THRs. Several possible causes of “squeaking” are edge-loading [78], component malpositioning [78-80] or component or stem design [74, 81, 70, 77]. Other workers have also related “squeaking” to patient weight, height or age [70, 78, 79]. It is possible that a number of factors need to be present to initiate the “squeaking” phenomenon. The occurrence of “squeaking” has not been found to compromise the results of ceramic-on-ceramic hip joints; however, some patients do request revision surgery in order to solve the “squeaking” issue [82].

Recently, laboratory studies have been performed in an attempt to re-create the conditions required to generate this “squeaking”. Some authors have observed “squeaking” with ceramic-on-ceramic hip joints lubricated under dry conditions [83, 84, 73]. However, such an extreme lubrication regime is not expected to occur *in vivo* [85]. Work performed by Currie *et al* (2010) [86] suggested that the rolling/sliding mechanism of the bearing surfaces can induce vibration, of an audible frequency, resulting in “squeaking”. Under lubricated conditions, Sanders *et al* (2012) [85] were able to reproduce the “squeak” using edge-loading during short-term wear tests. The “squeaking” was found to occur with a high contact force centred above or near the margin of the wear patch on a previously edge-worn femoral head. The authors state ‘the results reveal key conditions that yield recurrent squeaking *in vitro* in various scenarios without resorting to implausible dry conditions’. In support of this, Walter *et al* (2011) [87] analysed 12 ceramic-on-ceramic components retrieved from “squeaking” joints and compared these with 33 ‘silent’ ceramic-on-ceramic hip retrievals. All 12 “squeaking” hips showed evidence of edge-loading with up to 45 times greater wear than that reported for then the 33 ‘silent’ hips [54]. The authors suggested that although the causes of “squeaking” are unknown, the high contact pressures experienced during edge-loading may result in a breakdown of the fluid film lubrication leading to some asperity contact and an increase in friction. Also, any surface damage, which may have been caused by the edge-loading, will result in an increased roughness of the bearing surfaces thus leading to possible destruction of the fluid film leading to asperity contact.

Although there are a few reports on poor ceramic-on-ceramic hip prosthesis performance, the majority of authors give good and optimistic results. There have been little or no frac-

tures, dislocation, infection or osteolysis. Also, the few patients suffering from “squeaking” hips have, in the majority of cases, had no need for revision surgery. These are, therefore, excellent results, but Lee *et al* (2010) [44] did suggest that these small risks should be a concern to surgeons and that patients should also be made aware of these before surgery. In addition to this, they mentioned that longer-term follow-up is needed to assess the effects of these small risks on the prosthesis performance.

4. The younger patient

As these artificial hip joints have been found to perform well in the younger patient (45 to 55 years), some surgeons have chosen to replace the diseased joints of even younger patients with this material combination.

A case study was reported by Capello and Feinberg (2009) [88] where ceramic-on-ceramic joints were implanted in a 13 year-old child with bilateral end-stage arthritis of the hip. Seven and eight years post-operatively the patient had no pain, no limp, and was able to walk long distances. The radiographs showed no implant loosening, osteolysis or wear. This is a very encouraging result, however, it was stated that the patient is still very young (20 years of age at the time of report) and, therefore, the need for revision surgery will be more than likely.

Other studies on younger patients have not had as good results as those reported by Capello though. Nizard *et al* (2008) [89] reported on ceramic-on-ceramic hips that had been implanted in a group of 101 patients (132 hips) younger than 30 years old (mean age: 23.4 years, range: 13 – 30 years). These joints were implanted from 1977 to 2004 and, because of this, different implant designs and modes of fixation were used. Of these 132 joints, 17 were revised for aseptic loosening leading to a survivorship of 82.1% at 10 years and 72.4% at 15 years. These survivorship rates are quite low and may create cause for concern. It was, however, found that the higher rate of failures of joints replaced for treatment of slipped capital epiphysis or trauma influenced the survivorships greatly. Also, these artificial hip joints were implanted over a period of 26.5 years, during which time the ceramic materials have been improved and the fixation methods have changed. It is hoped that ceramic of the new generation with improved prosthesis design and mode of fixation will perform better and provide improved longer-term results.

5. Overview

From the results reported here it is clear that ceramic-on-ceramic hip joints have good tribological results: low friction, good lubrication and very low wear *in vitro* and *in vivo*. In addition to this, ceramic particles are biologically inert. Also, the fracture risk is relatively low. With good implant positioning these joints have the potential to perform incredibly well. These bearings, therefore, deserve to be high on the list for both primary and revision implants, especially for

the younger, more active patient. However, for the best results, the choice of bearing combination/design should be patient-specific; as one design does not suit all.

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