EOR | volume 5 | october 2020
DOI: 10.1302/2058-5241.5.200002
www.efortopenreviews.org

EFORT open reviews

Global diversity in bearings in primary THA

Georgios Tsikandylakis[1,2]
Soren Overgaard[3,4,5]
Luigi Zagra[6]
Johan Kärrholm[1,2,7]

- Choice of articulating materials, head size and the design of the articulation will become decisive for the long-term performance of a total hip arthroplasty (THA) and especially in terms of risk for dislocation and wear-related problems. Here we account for common alternatives based on available studies and the evidence that can be derived from them.
- Metal or ceramic femoral heads articulating against a liner or cup made of highly cross-linked polyethylene and ceramic-on-ceramic articulations have about similar risk for complications leading to revision, whereas the performance of metal-on-metal articulations, especially with use of big heads, is inferior. The clinical significance of problems related to ceramic-on-ceramic articulations such as squeaking remains unclear. With use of current technology ceramic fractures are rare.
- Large femoral heads have the potential to increase the range of hip movement before impingement occurs and are therefore expected to reduce dislocation rates. On the other hand, issues related to bearing wear, corrosion at the taper-trunnion junction and groin pain may arise with larger heads and jeopardize the longevity of THA. Based on current knowledge, 32-mm heads seem to be optimal for metal-on-polyethylene bearings. Patients with ceramic-on-ceramic bearings may benefit from even larger heads such as 36 or 40 mm, but so far there are no long-term reports that confirm the safety of bearings larger than 36 mm.
- Assessment of lipped liners is difficult because randomized studies are lacking, but retrospective clinical studies and registry data seem to indicate that this liner modification will reduce the rate of dislocation or revision due to dislocation without clear evidence of clinically obvious problems due to neck-liner impingement.
- The majority of studies support the view that constrained liners and dual mobility cups (DMC) will reduce the risk of revision due to dislocation both in primary and revision THA, the latter gaining increasing popularity in some countries. Both these devices suffer from implant-specific problems, which seem to be more common for the constrained liner designs. The majority of studies of these implants suffer from various methodological problems, not least selection bias, which calls for randomized studies preferably in a multi-centre setting to obtain sufficient power. In the 2020s, the orthopaedic profession should place more effort on such studies, as has already been achieved within other medical specialties, to improve the level of evidence in the choice of articulation when performing one of the most common in-hospital surgical procedures in Europe.

Keywords: dual mobility cup; head size; hip arthroplasty articulations; liner; materials

Cite this article: *EFORT Open Rev* 2020;5:763-775.
DOI: 10.1302/2058-5241.5.200002

Introduction

Despite extensive pre-clinical testing and CE certification marking, all new hip implants should be presumed to be associated with unknown and potentially adverse effects until otherwise proven in well-performed clinical studies. Often, when choosing amongst several types of hip implants, there may be a trade-off between reduced risk of dislocation, which is usually an early complication, and increased risk of wear or loosening, the effects of which usually occur later. As choice of bearing material and articulation design in total hip arthroplasty (THA) will influence the amount of wear, range of motion and joint stability, these properties will affect the risk of complications and the revision rate from the short- and long-term standpoint. Thus, function and stability of a THA is closely related to its articulation. In the clinical decision-making process, patient-related factors such as the status of the soft tissues, activity rate, presence of any neurological impairment or other co-morbidities and costs must be considered. Surgical skills and decisions relating to choice of incision, offset and component positioning and even choice of anaesthesia may have a decisive role for function and risk for complications, but these factors are beyond the scope of this presentation.[1,2]

Sir John Charnley introduced small-diameter femoral heads to reduce friction and wear, whereas bigger heads were favoured by others to maximize stability, but at the expense of increased friction and higher wear and loosening rate when articulating against polyethylene cups of contemporary design.[3] In 1990, Livermore and colleagues suggested a compromise which was the use of a 28-mm head, which, for at least a decade, became a standard in many countries.[4] Introduction of metal-on-metal articulations, ceramic-on-ceramic and, above all later on, highly cross-linked polyethylene opened the possibility for the use of bigger head sizes, but recent studies have suggested limited clinical benefits when head sizes greater than 32 mm are used, and even adverse effects if big metallic heads are used. Lipped, inclined and constrained liners and dual mobility cups (DMC) have been available for decades to improve the stability of artificial hip joints. Numerous studies have documented that these can reduce the risk of dislocation, whereas other studies have failed to do so. Some have reported an increase in adverse effects caused by impingement, loosening, wear and complications, such as intra-prosthetic dislocation. Today, in many countries, there is, however, an increased interest in and greater use of DMC to address the dislocation problem.

Highly cross-linked polyethylene liners or cups articulating against metallic or ceramic heads or ceramic-on-ceramic articulations are today the most commonly used hip articulation material, but there is presently no consensus concerning the optimal combination of materials. Thus, despite decades of evolution, there are still uncertainties concerning the best articulation to use, partially because the choice depends on various patient-related factors, as well as on the surgeon's experience and a compromise between the costs and expected time in situ.

When treating a patient, the main goal is to find the best solution to improve the quality of the patient's life and to fulfil the patient's expectations. In the case of primary total hip arthroplasty, THA surgeons aim for the longest survival for the 'new hip', free of complications in the hopeful setting of a 'forgotten hip'. With the exponential increase in innovations within the orthopaedic and traumatology specialty, and the constant availability of new materials, THA outcomes were expected to be positively influenced. However, compared with implants already in use, most THA prostheses introduced to the market in the past two decades have been shown to lead to similar or even worse results.[5] In Sweden, during the last three years, the frequency of re-operations (not only revision surgery, but all types of hip-related surgical procedures) was reported to be 2.2% within two years after a primary THA. In general, new technologies with proven clinical value have gained in popularity, but it remains difficult to prove that new types of implants globally influence well-established procedures.[2] Navigation, robotic assistance and patient-specific instruments have been shown to reduce the variability of implant positioning, but their cost-effectiveness and clinical benefit still needs to be more firmly proven.

Here we present information about material diversity, head size and articulation design in primary THA with an emphasis on the use of evidence from well-designed and well-conducted research, to address the most common aspects faced by arthroplasty surgeons to optimize decision-making.

Articulating materials

In 2018, *EFORT Open Reviews* published an article on bearing surfaces in primary THA[6] showing the main advantages and drawbacks of various types of tribology, and the similar short- to mid-term survivorship among the best performing bearing surfaces (metal-on-highly cross-linked polyethylene - MoXLPE, ceramic-on-highly cross-linked polyethylene –CoXLPE and ceramic-on-ceramic –CoC) as reported by published studies and registry data. Based on the limited current evidence and paucity of randomized controlled trials (RCTs) when comparing available implants over the long term, this article advised that, as XLPEs are not all the same, and especially in the case of ceramic liners, the metal back features can make a major difference.

Metal-on-metal

Early designs of total hip replacements (THRs) had metal-on-metal articulations (MoM) and some of them, such as the McKee-Farrar prosthesis, were used until the 1970s.[7,8] They were later abandoned due to inferior results compared with metal-on-polyethylene (MoP) THAs and suggestions of an increased risk of cancer when patients with the McKee-Farrar prosthesis were compared with patients with a MoP prosthesis.[9] During the late 1990s there was a renewed interest in metal-on-metal articulations and especially for surface replacements,[10] because of being bone-conservative and due to a large head enabling increased stability of the joint. Improved technology during manufacturing of these devices, resulting in a close to perfect match between the metallic head and cup and less wear, might also have contributed.

The use of MoM articulations soared during the middle of the first decade of the 21st century and then declined during the following 10 years due to reports of adverse events related to metallic wear and especially cobalt toxicity. Numerous reports have shown decreased overall survival of these devices regardless of type[11–13] and some concerns when using small heads.[14] In young male patients some think that hip resurfacing may still be the best option.[11] The short-term risk for cancer does not seem to be elevated,[15] but the long-term effect remains unknown and all patients with MoM articulation run the risk of cobalt intoxication should they any time in the future suffer from diseases which influence the capacity of the kidneys to excrete cobalt. Altogether these factors have contributed to a situation where these articulations have been more or less abandoned in many countries and only a very small number of surface replacements are still implanted.

Metal-on-polyethylene

Since its introduction as an articulating material in THAs in the early 1960s, the wear resistance of polyethylene has gradually increased by replacing high molecular with ultra-high-molecular weight polyethylene, and increased cross-linking by irradiation[16] combined with various processes to make the material more resistant to oxidation (for review see Singh et al)[17]. With use of radiostereometric analysis (RSA) Digas et al[18] observed an average mean wear rate of less than 0.1 mm per year for conventional polyethylene cups or liners sterilized with gamma irradiation. Cups and liners sterilized with ethylene dioxide showed more than 50–100% higher wear rate than the gamma-sterilized implants studied. In a previous study Nivbrant et al[19] had shown that use of alumina ceramic heads could reduce the annual wear rate of gamma-irradiated cups down to around 0.04 to 0.05 mm, but similar wear rates have also been found with use of metallic heads articulating against low-dose gamma-irradiated polyethylene.[20] Jonsson et al could confirm this high annual wear rate with use of ethylene-oxide-sterilized cups, whereas cups made of highly cross-linked polyethylene irradiated with 10 MRa reduced the mean wear rate to 0.01–0.02 mm per year.[21] In this study they also found that use of oxinium heads had no measurable influence on the wear rate.

Today there are published wear rates based on radiostereometric (RSA) measurements from clinical materials altogether covering at least eight different types of highly cross-linked polyethylene.[20–25] After a bedding in period varying between 3 and 24 months, mean steady state wear amounted to a maximum of 0.02 mm, but was not measurable in several of the studies, not even with use of RSA. One of these studies revealed a lower wear rate after five years for highly cross-linked polyethylene infused with vitamin E (Epoly) than for heat-treated highly cross-linked polyethylene (ArComXL), but the clinical relevance of this finding is at present uncertain.[25]

Wear studies of highly cross-linked polyethylene in joint simulators have shown that a greater volume of smaller and more biologically active particles is produced, which raised some concerns when this material was introduced. In a review from 2011, Kurz et al[26] found a consistent reduction of linear penetration with use of highly cross-linked polyethylene and reduced pooled odds ratio of 0.13 (95% CI 0.06 to 0.27) when compared with the earlier standard (ultra-high-molecular weight polyethylene, UHMWPE). The same year, Kuzyk et al[27] reviewed 1038 THAs included in 12 randomized studies and arrived at the same conclusions. Three years later, Shen et al[28] reviewed eight RCTs including 735 patients comparing highly cross-linked polyethylene with conventional polyethylene. They confirmed the wear-reducing effect of XLPE, but no certain effect concerning reduction of osteolysis or revision rates. Engh et al[29] randomized 230 uncemented THAs to either a gas-plasma-sterilized (non-cross-linked) or a highly cross-linked polyethylene liner, the latter gamma-irradiated with 5.0 MRad and heat treated above melting temperature to eliminate free radicals. After 10 years they observed significantly less wear and fewer re-operations for wear-related complications in the group with highly cross-linked polyethylene.

Paxton et al[30] compared the risk for revision for any reason including only procedures performed in patients 45 to 64 years of age operated on with either a MoP or MoXLPE articulation from six national or regional registries. In the first group, only head sizes smaller than 32 mm were included, whereas all head sizes were included in the XLPE group based on the presumption that head size had a minor influence with use of a more wear-resistant material. They found no evidence to support the theory that use of XLPE liners in this population would reduce the risk of revision within the five-year perspective (Hazard Ratio: 1.20, 95% CI 0.80 to 1.79).

Johansson et al[31] specifically studied cemented and cementless cups of the same design, but with use of either conventional or highly cross-linked polyethylene reported in the Nordic Arthroplasty Register Association (NARA) database. Femoral head sizes of 28 and 32 mm were included, as were both metallic and ceramic heads. Four cup designs were available for this type of analysis, three cemented and one uncemented. Increased revision rate due to aseptic loosening was observed for two of the designs with use of conventional polyethylene and one of them also showed increased risk of revision due to any reason after a follow-up of eight to 10 years.

Ceramic-on-ceramic

Almost 50 years ago, alumina ceramic was introduced in total hip replacements by Boutin.[32,33]

Due to its hardness and wettability it has high resistance against wear. In laboratory studies 50-fold lower wear rates compared with highly cross-linked polyethylene were demonstrated.[34] At this early stage a more widespread use, however, did not occur, probably because of risk of fracture, problems in achieving durable fixation between ceramic implants and bone, and increased costs.[35–37] Progress in the manufacturing process and introduction of alumina matrix composite ceramic heads[38] have substantially decreased the risk of fracture in contemporary studies[35,39] and use of ceramic liners in a metallic shell designed for bony ingrowth has made fixation more reliable. Several studies[40–42] report good long-term results with high survival rate, low rate of complications related to the material and no osteolysis even in young patients.[43–45] These studies are mainly single-centre retrospective analyses.

There have been some concerns regarding risk for edge-fractures (chipping) of the ceramic with use of ceramic on ceramic (CoC) articulations. Tateiwa et al[46] reported this complication in 2.6% of cases during impaction of the liner for a specific design, whereas it was not observed with use of another one. Jeffers and Walter[47] performed an extensive review of 88 publications on ceramic articulations. Chipping during liner insertion was only reported in a few studies with a variation between 0% and 3.7% and differences among implant designs. Ceramic liners are more sensitive to implant positioning and less forgiving to any malorientation.[48]

Squeaking or clicking is another complication, though not specific for CoC articulation, but more common and sometimes more audible when compared with metal-on-polyethylene articulations. Zhao et al[49] performed a systematic review of 14 articles that evaluated occurrence of squeaking in fourth-generation CoC THAs. They arrived at an overall incidence of 3%, with remarkable variations depending on implant design.[50] Kim and Park[51] studied 133 bilaterally operated patients with one CoC THA on one side and a CoXLPE THA on the other after 15 to 18 years. The clinical results were about the same on the two sides, but eight hips had an audible squeak on the side with a CoC articulation. None of the hips developed osteolysis. Lee et al followed 72 patients (86 THAs) with contemporary delta ceramic bearings for a minimum of five years in patients younger than 30 years.[52] Eight hips exhibited squeaking or grinding. The clinical results did not, however, seem to have deteriorated (Harris Hip Score = 96.3, 64 to 100) and there was no case with loosening or osteolysis on either side.

Overall, the revision rates of CoC and CoXLPE seem to be of the same magnitude as reported for MoXLPE bearings. Mihalko et al reviewed 32 studies on MoM and 19 on CoC articulations with at least five years follow-up.[53] Both groups included five registry studies each. In addition, 20 studies of modular stem designs were included. None of the articulations studied were associated with lower revision rates when compared with MoXLPE articulation. As expected, large MoM articulations and modular stem THAs showed lower survival.

Wyles et al reviewed 18 studies (mainly RCTs) that reported survivorship of THAs with CoC, CoXLPE or MoXLPE bearings in patients younger than 65 years and did not observe any differences in the short- or medium-term perspective.[54] Hexter et al reviewed 17 studies to evaluate whether the incidence of periprosthetic joint infection varied depending on the choice of articulation.[55] They observed an overall incidence of 0.85% (1353/158,430) for metal-on-polyethylene, 0.38% (67/17,489) for ceramic-on-polyethylene and 0.54% (94/17,459) for ceramic-on-ceramic bearings without any significant difference between them.

At present there are few studies evaluating ceramic-on-metal articulations (CoM). In a randomized study, Higgins et al observed less metallic wear with use of this articulation, but a tendency to increased chromium levels after three years.[56] In the National Joint Registry the revision rate of CoM articulations is higher than observed for MoXLPE and CoXLPE articulations.[57] This type of coupling, which gained some popularity based on in vitro studies in the early 2000s, has been rapidly withdrawn from the market.

Conclusions: bearing materials

In conclusion, contemporary designs of MoXLPE, CoXLPE and CoC articulations seem to have about equal performance during the first decade after insertion and some studies indicate that this is true up to at least 15 years. With use of contemporary material qualities and implant technology the material-specific complications observed for ceramic heads and liners seem to be small enough not to have a significant influence on these results. Use of well-documented methods, with high resolution to measure linear penetration of the various brands of highly cross-linked polyethylene so far studied, have not revealed differences with certain clinical importance, although the follow-up for most of them is limited. Thus, the choice between MoXLPE, CoXLPE and CoC articulation could be expected to provide similar clinical results up to 10–15 years. To what extent this will be true in the long-term remains to be seen.

Femoral head size

The main argument for using larger heads in THA is that they are expected to decrease dislocation rates. On the other hand, bearing wear, taper-trunnion corrosion and groin pain may occur with larger heads. The use of 32-mm heads (Fig. 1) in MoXLPE or CoXLPE bearings (Fig. 2) is most common, but use of 36-mm heads is increasing.[57–64] In 2018, an article published in EFORT Open Reviews, discussed the pros and cons of larger heads in THA, and concluded that 32 mm seemed to be the optimal head size in MoXLPE bearings and 36-mm ceramic heads could also be used in CoXLPE or CoC bearings.[65] In this update, the short-term outcome of THA related to head size regardless of the

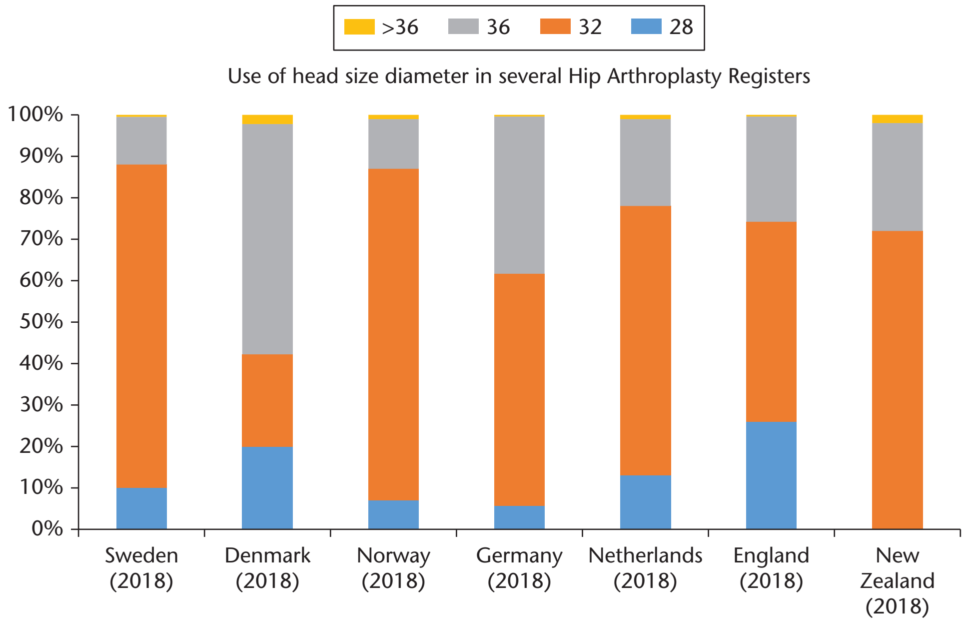

Fig. 1 The current use of different head size diameters in various reported arthroplasty registers across the world.

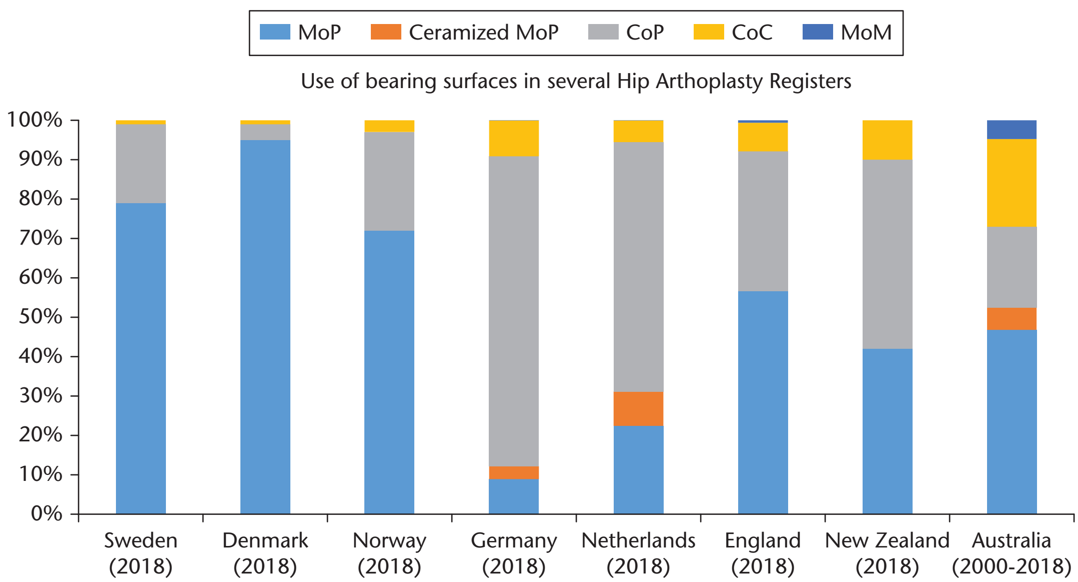

Fig. 2 The current use of different bearing surfaces reported in various arthroplasty registers across the world.
Note. MoP, metal-on-polyethylene; CoP, ceramic-on-polyethylene; CoC, ceramic-on-ceramic; MoM, metal-on-metal.

bearing material is analysed, as well as the long-term outcome considering both head size and bearing material.

Head size and risk of THA dislocation

There are two geometrical factors that will contribute to reduced risk of dislocation with use of large heads: increased range of hip movement before impingement between the neck of the stem and the socket occurs, and increased jumping distance of the head before disengaging from the socket. The effect of femoral head size on the jumping distance will, however, vary depending on cup abduction angle. Increasing the head diameter from 22 mm to 40 mm increases the impingement-free range of hip movement by about 30°, if surrounding anatomical structures of the hip are disregarded.[66] Clinical studies confirmed the increased hip movement, especially for flexion, abduction and internal rotation when smaller than contemporary (26- vs. 32-mm[67]) or non-adjacent (28- vs. 40-mm[68]) head sizes were compared. Considering the surrounding tissues, hip movement did not increase further with 38-mm or bigger heads because bone-to-bone or implant-to-bone impingement occurred.[69] To avoid the latter, increasing the femoral offset rather than the head size had a better effect.[70] Moreover, a study comparing THRs with 36-mm CoC heads and 40–54-mm MoM heads found no difference in the gain of hip range of motion.[71] Jumping distance, the amount of lateral translation of the femoral head before dislocation occurs, acts like a 'safety belt' in case of impingement and depends on the head size. Jumping distance increases linearly by 1.6 mm for each 4 mm increase of head diameter, provided the cup is placed in 45° of abduction. However, the net gain in jumping distance decreased if the abduction angle was 60°.[72] Moreover, a cadaver study compared the torque as well as the degree of internal rotation at 90° of flexion needed for dislocation to occur, among 28-, 32-, 36-, 40- and 44-mm heads. There was a positive association between head size and least torque to accomplish dislocation, but the degree of internal rotation before dislocation did not differ between adjacent head sizes, only in non-adjacent such as 28 mm vs. 44 mm.[73]

The increased impingement-free range of hip movement and jumping distance observed with larger heads should theoretically lead to lower dislocation rates. In an RCT, the use of 36-mm heads reduced the dislocation rate by 3.6 % ($p = 0.012$) in primary THA compared with 28-mm.[74] In another RCT performed on patients undergoing revision THA, the use of 36–40-mm heads reduced the dislocation rate by 7.6 % ($p = 0.035$) compared with 32-mm heads.[75] A third RCT that compared 36-mm heads with 32-mm heads found no difference in the revision rates, but the study was underpowered.[76] In registry studies, head diameters below 28 mm have been associated with greater revision risk due to dislocation compared to 28 mm.[77,78] The use of 32-mm heads has been associated with further decrease of risk for revision due to dislocation.[78–81] Thirty-six-mm heads have also been associated with lower revision rates due to dislocation compared with non-adjacent smaller sizes such as 28 mm,[81] but a similar effect compared with the adjacent 32-mm heads[80] was not found, unless stratifying for posterior surgical approach.[79] When 38-mm or larger heads were used in a case control study[82] and in a study on patients at high risk for dislocation,[83] the dislocation rates were lower compared with 36-mm or smaller heads.

Head size and bearing wear, taper-trunnion corrosion and groin pain

The downside of larger heads includes bearing wear, corrosion of the taper-trunnion junction and increased incidence of groin pain. In vitro, wear rates in MoXLPE THA have not been related to head size (22–46 mm).[84] In RSA studies, early (3–5 years) XLPE linear wear rates were not different between 28- and 36-mm metal heads in an RCT,[85] as well as between two cohorts of 32-mm[86] and 36–40-mm heads.[87] However, in series with a longer follow-up (11 years), 36- and 40-mm metal heads had higher volumetric XLPE wear rates compared with 28-mm even though linear wear rates were comparable.[88] In a cohort of 107 large MoXLPE THAs there were no differences in wear rates between 36- and 40-mm heads, and no cases of liner fracture, implant loosening or symptomatic taper-trunnion corrosion.[89] The use of ceramic heads could potentially reduce the volumetric XLPE wear in larger bearings. Long-term reports are currently not available, but an early RCT report has shown no difference between 32- and 36-mm CoXLPE bearings for wear.[90] In large head MoM THA and surface replacements, bearing wear seems to be a greater problem due to issues with elevated serum metal ions[91] as well as the development of pseudotumours.[92] Large head MoM THA has demonstrated higher and earlier failure rates compared with smaller heads and alternative bearings such as CoC.[92]

Another drawback with larger heads is the increased frictional torque reported in ≥ 36-mm MoXLPE bearings, though not in CoXLPE, compared with smaller ones.[93] Increased torque due to higher friction can be transmitted to the bone–implant interface and compromise implant stability. Stresses in the acetabular cortical bone/cement interface were found to increase by 9% as the head size increased from 28 to 32 and 36 mm in cemented MoXLPE THA.[94] Furthermore, larger metal heads increase trunnion-taper moments that may lead to fretting and corrosion.[95] Trunnion corrosion has been reported in MoM[96] and MoXLPE bearings,[97] and has been associated with larger heads.[98,99] However, other studies have not verified this association but found other factors related to trunnion corrosion, such as length of implantation, taper design and use of different alloys in the stem and the head.[100,101] XLPE wear, increased frictional torque and trunnion corrosion associated with larger metal heads might be a possible explanation for the higher overall revision risk up to 15 years of follow-up for 36-mm heads compared with 32-mm in MoXLPE THA in the Australian registry.[64] In the same registry, larger than 32-mm CoC bearings had no increased revision risk. On the contrary, the risk was lower for ≥ 40-mm ceramic heads compared with 32-mm. Similarly, 36-mm metal and ceramic heads on polyethylene seem to perform worse in the National Joint Registry compared to 32-mm heads, especially for cemented cups, while in CoC bearings 40-mm heads seem to perform better than 32- and 36-mm.[57]

Big heads could also negatively affect the outcome of THA due to groin pain. Although originally an issue in large head MoM THA and surface replacements,[102] groin pain has also been reported in 36-mm MoXLPE THA,[103] as well as in 7% of larger head (38–44-mm) CoC THA.[104] It is speculated that large heads overstuff the anterior joint capsule and impinge the iliopsoas tendon.[105] Noise generation such as squeaking has also been associated with increasing head size in CoC THA from 7% with 36-mm up to 44% with 48-mm heads, although reportedly without influence on patient satisfaction.[106]

Finally, an RCT using gait analysis showed no difference in gait recovery after THA when the head diameter is increased from 28 mm to 36 mm up to more than 42 mm.[107]

Conclusion: head size

There are only a few RCTs comparing dislocation rates or polyethylene wear rates between different head sizes. Our conclusions are therefore based mainly on observational studies. Present evidence supports increased THA stability with larger heads, but also suggests increased risk of long-term complications for metallic head sizes above 32 mm. Long-term registry reports suggest against the use of larger than 32-mm heads in MoXLPE bearings due to uncertainties concerning issues related to polyethylene wear and taper-trunnion corrosion. The use of 32-mm heads has shown a quite clear superiority compared with smaller sizes in terms of lower dislocation risk and increased implant survival as well as no issues with polyethylene wear, corrosion or groin pain. Therefore, and at present, the choice of 32-mm heads seems to be optimal for MoXLPE THA. In CoC and possibly CoXLPE THA, 36-mm heads seem to provide a better balance between stability and long-term failure, although studies with longer follow-up are needed to confirm their safety in routine use, especially to show any advantage of 40-mm heads in CoC bearings over 32-mm and 36-mm.

Design of the articulation

Lipped liners

On the acetabular side the cup construction can be modified in various ways with the intention of making it more resistant to dislocation. In 1972, Charnley started to use his LPW cup (long posterior wall) with the intention of reducing the risk of posterior dislocation.[108] Use of the same principle for liners (lipped or elevated rim liners) became common as an alternative for many uncemented cup designs during the 1980s and early 1990s, despite some concerns about increased risk for impingement between the neck and liner resulting in more wear, and in cases with suboptimal placement of the liner, also increased risk of dislocation.

Despite widespread use the clinical documentation of the effect on risk for dislocation after use of elevated rim liners is scarce. Cobb et al[109] compared the cumulative probability of dislocation in 5157 primary and revision THAs (2469 with elevated rim, 2698 with standard acetabular components). Follow-up consisted of physical examination, questionnaire or telephone interview. In the primary group the cumulative probability of dislocation was almost 1% higher if a standard cup had been used. In the revision group (520 with elevated rim, 530 without) the corresponding difference amounted to about 5%.

Insull et al[110] evaluated the risk for revision due to dislocation for three of the most frequently used designs of uncemented acetabular cup reported to the New Zealand Joint Registry. In total, 8023 lipped and 4088 non-lipped components were included. Non-lipped components had 2.4 times (95% CI 1.6 to 3.7) higher risk for revision due to instability than non-lipped components after adjusting for femoral head size, surgical approach, gender and age. They also observed a slightly higher revision rate (0.76 vs. 0.62 per 100 component years, $p = 0.046$) due to any reason with use of non-lipped liners.

In a comparative analysis of almost 50,000 uncemented cups reported to the Finnish Arthroplasty Register, Hemmilä et al performed a subanalysis of Continuum cups (Zimmer, Warsaw) inserted with or without liner elevation.[111] (There were 11,390 Continuum cups at the start and an unreported number of cups with other than polyethylene inserts were excluded). After adjustment for possible confounders they reported 1.7 times (hazard ratio –HR, 95% CI 1.2 to 2.5) higher risk for hips with neutral liners being revised due to dislocation when compared to the group with elevated liners.

Unfortunately, studies showing long-term effects on wear, osteolysis or liner breakage due to the risk of neck-elevated rim impingement are lacking.

Constrained liners

Cups with an inner circumference wider than a hemisphere in which a 32-mm or bigger femoral head was snap-fitted at reduction were used as standard implants in some departments during the 1970s and early 1980s. They were abandoned mainly because of increased rate of loosening when compared with cups without snap-fit and a smaller femoral head.[112,113] Later, still more constrained liners were developed where the femoral head is locked into the socket with use of a metal locking ring. Even in these designs the inner diameter of the rim has to be expanded to seat the femoral head into the bottom of the liner and before the locking ring is applied. Due to the firm locking of the head inside the cup, distracting forces from the femur generated during various patient activities will be transferred to the cup–bone interface necessitating a secure cup fixation. Constrained liners will to various extents compromise range of motion depending on head size and shape and when the joint reaches the end of possible motion, impingement will become unavoidable.[114] Since these devices place high demands on the fixation of the cup, they have been recommended in revisions due to dislocation provided that the shell is well-fixed and properly placed and especially in salvage procedures.[1,115]

The reported clinical results of constrained liners vary. Hernigou et al[116] compared 144 patients (164 hips) with neuromuscular disease who had been operated on with a constrained liner and 120 patients (132 hips) with the same disease but who had been operated with a conventional insert. Follow-up was minimum five years and 25 patients in the first and 17 in the second group were lost to follow-up. There were three dislocations in the group with constrained liners and 33 in the control group. Interestingly and contrary to what could be expected, only one acetabular component was revised due to loosening in the group with constrained liners, whereas 10 cups were revised due to the same reason in the group with conventional liners.

Williams et al[117] reviewed eight studies including 1199 hips in 1148 patients operated on with constrained devices after two to 10 years follow-up. The mean dislocation rate was 10% and the reoperation rate for other reasons 4%. Clavé et al studied 155 THAs (73% revisions) after an average 6.2 years follow-up which were operated on with a constrained liner (Lefèvre retentive cup).[118] At 10 years the survival rate due to non-infectious cup revision was 92.3% (CI 87.3 to 97.2) and due to dislocation 98.7% (CI 96.8 to 100). Berend et al evaluated 667 patients, mainly revisions with constrained THAs up to 10 years.[119] Of these, 117 dislocated during follow-up and in total 42.1% failed due to various reasons in the long term. In 2006 Fricka et al stated that the dislocation problem could be addressed in a better way with the use of large femoral heads rather than constrained liners due to problems such as cup loosening, dissociation of the liner/shell interface, implant fracture, wear, and the requirement for open surgery should dislocation occur.[120]

Dual mobility cups

The dual mobility cup was developed during the 1970s by Giles Bousquet, a French surgeon and the engineer André Rambert. The first designs functioned as bipolar hemi-arthroplasties, but due to erosion problems a cemented bipolar cup was developed in 1977 followed by an uncemented design in 1979.[121] The scope was to increase stability with use of a big head of polyethylene with its outer surface articulating against a highly polished inner surface of a metallic cup and the inner surface of the polyethylene head articulating against a small femoral head, which originally had the same diameter as the Charnley hip (22.2 mm). Low dislocation rates were found by the inventor, but concerns about wear and wear-related problems such as intra-prosthetic dislocation, a complication almost unique for DMC designs, together with poor fixation capability of the first generations of DMCs,[122] probably counteracted the spread of use of this type of device outside France. The introduction of more wear-resistant polyethylene, including new designs of highly cross-linked and improved fixation and bone ingrowth properties of the metal back,[122] with the introduction of modular DMCs (a cobalt-chromium metal liner inserted in an uncemented cup-shell made of metal), made this type of implant much more attractive for surgeons. During the last 10–15 years the popularity and use of DMCs has increased almost exponentially as reflected in reports from National Registers and an increasing number of publications in scientific journals (Fig. 3).[60,123,124]

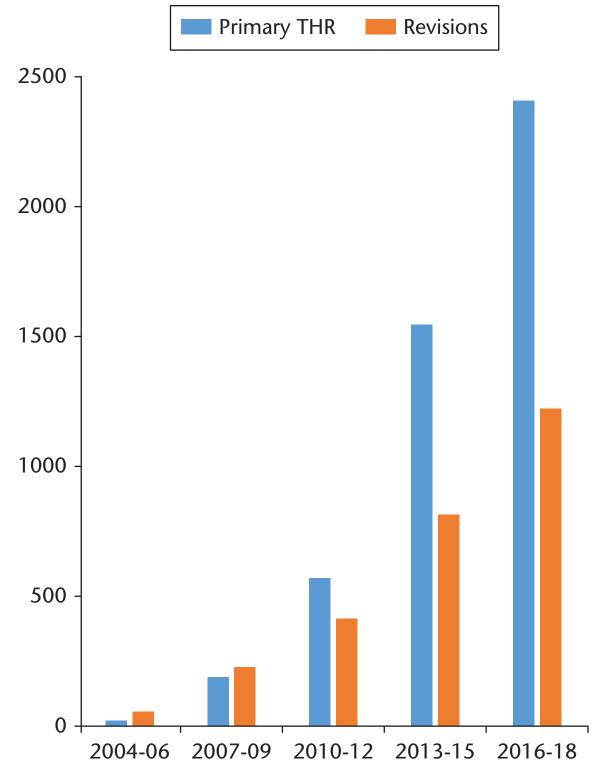

Fig. 3 Dual mobility cups reported to the Swedish Hip Arthroplasty Register 2004 to 2018 per periods of three years in primary and revision hip arthroplasties.

Several publications have reviewed the results of DMCs.[115,121,125,126] Batailler et al concluded that 'dual mobility cups are a significant indication for managing instability following primary and revision hip arthroplasty' and that the overall survivorship of the cup was comparable to conventional primary cups, whereas a similar comparison could not be performed in the revision situation.[123] Darrith et al reported a high survival rate of DMC cups used in primary THR, revisions and in patients treated with THA due to femoral neck fracture after the short and mid-term follow-up.[125] De Martino et al included 59 articles in their systematic review comprising 12,844 primary and 5064 revision THAs with mean follow-ups of 6.8 and 4.4 years, respectively.[126] The overall rate of revision was 0.9% in primaries and 3.0% in revisions, probably reflecting revision due to dislocation although not explicitly stated. Later, they regarded the overall quality of the articles studied as low.

Recently Kreipke et al performed an analysis of DMCs in the Nordic Arthroplasty Register Association (NARA) database. All patients were operated on due to primary OA between 1995 and 2013.[127] To reduce the risk of bias, 2277 hips with DMC cups were matched with 2227 hips with conventional cups based on age, gender, cup and stem fixation, and year of surgery. The overall risk of revision did not differ, but patients who had received a DMC had a lower risk of revision due to dislocation, but a higher risk of revision because of infection. In the same year, Jobory et al used a similar study design and evaluated 4520 hip fractures treated with DMC and matched those cups to 4520 THAs operated on with a conventional cups during the period 2001 to 2014, also in the NARA database.[128] The overall risk for revision due to any reason and due to dislocation was lower with use of the DMC design. Risk for revision due to infection did not differ between the two groups.

Mohaddes et al evaluated 984 first-time revisions performed due to dislocation and reported to the Swedish Hip Arthroplasty Register from 2005 to 2015.[129] A total of 436 hips received a cemented DMC, and in the control group there were 355 first-time revisions operated on during the period with a cemented conventional cup, with or without impaction grafting. Lower re-revision rate due to dislocation and due to any reason was observed after four years with use of DMCs. The role of DMCs in revisions with more severe bone defects is still unclear, but these devices seem to work well if used with a Kerboull cross-plate[130] or if cemented into an uncemented cup of trabecular metal.[131]

Conclusions

Dislocation is one of the leading causes of revision after primary THA accounting for about 14% of all revisions during the last 10 years in the Swedish Hip Arthroplasty Register and for about 20% of the revisions in the Danish Hip Arthroplasty Register.[60] It is typically an early complication, and of those who suffer from a first dislocation about 40% will experience one or more further dislocations.[132] Patients who have had their first dislocation frequently develop anxiety about further dislocations and have significantly reduced quality of life,[132] which underlines the need to perform well-designed studies to optimize the decision-making for each patient category.

Most studies support the view that lipped liners, constrained liners and DMCs will reduce the risk of revision due to dislocation. These devices suffer from implant-specific problems, which seem to be more common for the constrained liner designs and has resulted in more restrictive use of this design and mainly for salvage. The majority of studies of lipped liners lack long-term results which consider impingement and wear issues, and studies of DMCs suffer from various methodological problems, not least selection bias, which calls for randomized studies preferably in a multi-centre setting to obtain sufficient power.

AUTHOR INFORMATION

[1]Department of Orthopaedics, Institute of Clinical Sciences, Sahlgrenska Academy, University of Gothenburg, Sweden.

[2]Region Västra Götaland, Sahlgrenska University Hospital, Department of Orthopaedics, Gothenburg, Sweden.

[3]The Danish Hip Arthroplasty Register, Aarhus, Denmark.

[4]Department of Orthopaedic Surgery and Traumatology, Odense University Hospital, Odense, Denmark.

[5]Institute of Clinical Research, University of Southern Denmark, Odense, Denmark.

[6]Hip Department, IRCCS Istituto Ortopedico Galeazzi, Milan, Italy.

[7]The Swedish Hip Arthroplasty Register, Gothenburg, Sweden.

Correspondence should be sent to: Johan Kärrholm, Department of Orthopaedics, Sahlgrenska Hospital Mölndal, Göteborgsvägen 31, R-huset, 431 30 Mölndal, Sweden.

Email: johan.karrholm@vgregion.se or johan.karrholm@gmail.com

ICMJE CONFLICT OF INTEREST STATEMENT

GT reports employment at Sahlgrenska University Hospital/Orthopaedic department and travel grants for participation in international orthopaedic meetings during 2017 and 2018 from the Medical Society of Gothenburg, outside the submitted work.

SO reports grants/grants pending from Zimmer-Biomet to their Institution, outside the submitted work.

JK reports institutional support for research received from Link, Germany, Zimmer-Biomet, USA and DePuy, and is also a board member of RSA Biomedical, Umeå, Sweden, outside the submitted work.

LZ declares no conflict of interest relevant to this work.

FUNDING STATEMENT

Although none of the authors has received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article, benefits have been or will be received but will be directed solely to a research fund, foundation, educational institution, or other non-profit organization with which one or more of the authors are associated.

REFERENCES

1. **Rowan FE, Benjamin B, Pietrak JR, Haddad FS.** Prevention of dislocation after total hip arthroplasty. *J Arthroplasty* 2018;33:1316–1324.

2. **Zagra L.** Advances in hip arthroplasty surgery: what is justified? *EFORT Open Rev* 2017;2:171–178.

3. **Ritter MA, Campbell ED.** Long-term comparison of the Charnley, Muller, and Trapezoidal-28 total hip prostheses: a survival analysis. *J Arthroplasty* 1987;2:299–308.

4. **Livermore J, Ilstrup D, Morrey B.** Effect of femoral head size on wear of the polyethylene acetabular component. *J Bone Joint Surg Am* 1990;72:518–528.

5. **Anand R, Graves SE, de Steiger RN, et al.** What is the benefit of introducing new hip and knee prostheses? *J Bone Joint Surg Am* 2011;93:51–54.

6. **Zagra L, Gallazzi E.** Bearing surfaces in primary total hip arthroplasty. *EFORT Open Rev* 2018;3:217–224.

7. **August AC, Aldam CH, Pynsent PB.** The McKee-Farrar hip arthroplasty: a long-term study. *J Bone Joint Surg Br* 1986;68:520–527.

8. **Jacobsson SA, Djerf K, Wahlström O.** A comparative study between McKee-Farrar and Charnley arthroplasty with long-term follow-up periods. *J Arthroplasty* 1990;5:9–14.

9. **Visuri T, Pukkala E, Paavolainen P, Pulkkinen P, Riska EB.** Cancer risk after metal on metal and polyethylene on metal total hip arthroplasty. *Clin Orthop Relat Res* 1996;(329):S280–S289.

10. **Amstutz HC, Grigoris P, Dorey FJ.** Evolution and future of surface replacement of the hip. *J Orthop Sci* 1998;3:169–186.

11. **Smith AJ, Dieppe P, Vernon K, Porter M, Blom AW; National Joint Registry of England and Wales.** Failure rates of stemmed metal-on-metal hip replacements: analysis of data from the National Joint Registry of England and Wales. *Lancet* 2012;379:1199–1204.

12. **Hart AJ, Sabah SA, Henckel J, Lloyd G, Skinner JA.** Lessons learnt from metal-on-metal hip arthroplasties will lead to safer innovation for all medical devices. *Hip Int* 2015;25:347–354.

13. **Pijls BG, Meessen JM, Schoones JW, et al.** Increased mortality in metal-on-metal versus non-metal-on-metal primary total hip arthroplasty at 10 years and longer follow-up: a systematic review and meta-analysis. *PLoS One* 2016;11:e0156051.

14. **D'Angelo F, Tanas D, Gallazzi E, Zagra L.** Adverse reaction to metal debris after small-head diameter metal-on-metal total hip arthroplasty: an increasing concern. *Hip Int* 2018;28:35–42.

15. **Gaillard MD, Gross TP.** Metal-on-metal hip resurfacing in patients younger than 50 years: a retrospective analysis: 1285 cases, 12-year survivorship. *J Orthop Surg Res* 2017;12:79.

16. **Oonishi H, Kadoya Y, Masuda S.** Gamma-irradiated cross-linked polyethylene in total hip replacements: analysis of retrieved sockets after long-term implantation. *J Biomed Mater Res* 2001;58:167–171.

17. **Singh G, Klassen R, Howard J, Naudie D, Teeter M, Lanting B.** Manufacturing, oxidation, mechanical properties and clinical performance of highly cross-linked polyethylene in total hip arthroplasty. *Hip Int* 2018;28:573–583.

18. **Digas G, Thanner J, Nivbrant B, Röhrl S, Ström H, Kärrholm J.** Increase in early polyethylene wear after sterilization with ethylene oxide: radiostereometric analyses of 201 total hips. *Acta Orthop Scand* 2003;74:531–541.

19. **Nivbrant B, Kärrholm J, Röhrl S, Hassander H, Wesslén B.** Bone cement with reduced proportion of monomer in total hip arthroplasty: preclinical evaluation and randomized study of 47 cases with 5 years' follow-up. *Acta Orthop Scand* 2001;72:572–584.

20. **Röhrl SM, Li MG, Nilsson KG, Nivbrant B.** Very low wear of non-remelted highly cross-linked polyethylene cups: an RSA study lasting up to 6 years. *Acta Orthop* 2007;78:739–745.

21. **Jonsson BA, Kadar T, Havelin LI, et al.** Oxinium modular femoral heads do not reduce polyethylene wear in cemented total hip arthroplasty at five years: a randomised trial of 120 hips using radiostereometric analysis. *Bone Joint J* 2015;97-B:1463–1469.

22. **Digas G, Kärrholm J, Thanner J, Herberts P.** 5-year experience of highly cross-linked polyethylene in cemented and uncemented sockets: two randomized studies using radiostereometric analysis. *Acta Orthop* 2007;78:746–754.

23. **Gascoyne TC, Petrak MJ, Turgeon TR, Bohm ER.** Wear of a sequentially annealed polyethylene acetabular liner. *Acta Orthop* 2014;85:470–473.

24. **Flatøy B, Rydinge J, Dahl J, Röhrl SM, Nordsletten L.** Low wear, high stability: promises of success in a moderately cross-linked cup? *Hip Int* 2015;25:199–203.

25. **Shareghi B, Johanson PE, Kärrholm J.** Wear of vitamin E-infused highly cross-linked polyethylene at five years. *J Bone Joint Surg Am* 2017;99:1447–1452.

26. **Kurtz SM, Gawel HA, Patel JD.** History and systematic review of wear and osteolysis outcomes for first-generation highly crosslinked polyethylene. *Clin Orthop Relat Res* 2011;469:2262–2277.

27. **Kuzyk PR, Saccone M, Sprague S, Simunovic N, Bhandari M, Schemitsch EH.** Cross-linked versus conventional polyethylene for total hip replacement: a meta-analysis of randomised controlled trials. *J Bone Joint Surg Br* 2011;93:593–600.

28. **Shen C, Tang ZH, Hu JZ, Zou GY, Xiao RC, Yan DX.** Does cross-linked polyethylene decrease the revision rate of total hip arthroplasty compared with conventional polyethylene? A meta-analysis. *Orthop Traumatol Surg Res* 2014;100:745–750.

29. **Engh CA Jr, Hopper RH Jr, Huynh C, Ho H, Sritulanondha S, Engh CA Sr.** A prospective, randomized study of cross-linked and non-cross-linked polyethylene for total hip arthroplasty at 10-year follow-up. *J Arthroplasty* 2012;27:2–7.e1.

30. **Paxton E, Cafri G, Havelin L, et al.** Risk of revision following total hip arthroplasty: metal-on-conventional polyethylene compared with metal-on-highly cross-linked polyethylene bearing surfaces: international results from six registries. *J Bone Joint Surg Am* 2014;96:19–24.

31. **Johanson PE, Furnes O, Ivar Havelin L, et al.** Outcome in design-specific comparisons between highly crosslinked and conventional polyethylene in total hip arthroplasty. *Acta Orthop* 2017;88:363–369.

32. **Bizot P, Nizard R, Lerouge S, Prudhommeaux F, Sedel L.** Ceramic/ceramic total hip arthroplasty. *J Orthop Sci* 2000;5:622–627.

33. **Hannouche D, Hamadouche M, Nizard R, Bizot P, Meunier A, Sedel L.** Ceramics in total hip replacement. *Clin Orthop Relat Res* 2005;430:62–71.

34. **Essner A, Sutton K, Wang A.** Hip simulator wear comparison of metal-on-metal, ceramic-on-ceramic and crosslinked UHMWPE bearings. *Wear* 2017;259:992–995.

35. **Lee GC, Kim RH.** Incidence of modern alumina ceramic and alumina matrix composite femoral head failures in nearly 6 million hip implants. *J Arthroplasty* 2017;32:546–551.

36. **Fritsch EW, Gleitz M.** Ceramic femoral head fractures in total hip arthroplasty. *Clin Orthop Relat Res* 1996;328:129–136.

37. **Snorrason F, Kärrholm J, Löwenhielm G, Hietala SO, Hansson LI.** Poor fixation of the Mittelmeier hip prosthesis: a clinical, radiographic, and scintimetric evaluation. *Acta Orthop Scand* 1989;60:81–85.

38. **Hannouche D, Zingg M, Miozzari H, Nizard R, Lübbeke A.** Third-generation pure alumina and alumina matrix composites in total hip arthroplasty: what is the evidence? *EFORT Open Rev* 2018;3:7–14.

39. Howard DP, Wall PDH, Fernandez MA, Parsons H, Howard PW. Ceramic-on-ceramic bearing fractures in total hip arthroplasty: an analysis of data from the National Joint Registry. *Bone Joint J* 2017;99-B:1012–1019.

40. Petsatodis GE, Papadopoulos PP, Papavasiliou KA, Hatzokos IG, Agathangelidis FG, Christodoulou AG. Primary cementless total hip arthroplasty with an alumina ceramic-on-ceramic bearing: results after a minimum of twenty years of follow-up. *J Bone Joint Surg Am* 2010;92:639–644.

41. Hamadouche M, Boutin P, Daussange J, Bolander ME, Sedel L. Alumina-on-alumina total hip arthroplasty: a minimum 18.5-year follow-up study. *J Bone Joint Surg Am* 2002;84:69–77.

42. Toni A, Giardina F, Guerra G, et al. 3rd generation alumina-on-alumina in modular hip prosthesis: 13 to 18 years follow-up results. *Hip Int* 2017;27:8–13.

43. Kim YH, Park JW, Kim JS. Long-term results of third-generation ceramic-on-ceramic bearing cementless total hip arthroplasty in young patients. *J Arthroplasty* 2016;31:2520–2524.

44. Solarino G, Zagra L, Piazzolla A, Morizio A, Vicenti G, Moretti B. Results of 200 consecutive ceramic-on-ceramic cementless hip arthroplasties in patients up to 50 years of age: a 5–24 years of follow-up study. *J Arthroplasty* 2019;34:S232–S237.

45. Kang BJ, Ha YC, Ham DW, Hwang SC, Lee YK, Koo KH. Third-generation alumina-on-alumina total hip arthroplasty: 14 to 16-year follow-up study. *J Arthroplasty* 2015;30:411–415.

46. Tateiwa T, Clarke IC, Williams PA, et al. Ceramic total hip arthroplasty in the United States: safety and risk issues revisited. *Am J Orthop (Belle Mead NJ)* 2008;37:E26–E31.

47. Jeffers JR, Walter WL. Ceramic-on-ceramic bearings in hip arthroplasty: state of the art and the future. *J Bone Joint Surg Br* 2012;94:735–745.

48. Traina F, De Fine M, Bordini B, Toni A. Risk factors for ceramic liner fracture after total hip arthroplasty. *Hip Int* 2012;22:607–614.

49. Zhao CC, Qu GX, Yan SG, Cai XZ. Squeaking in fourth-generation ceramic-on-ceramic total hip replacement and the relationship with prosthesis brands: meta-analysis and systematic review. *J Orthop Surg Res* 2018;13:133.

50. Parvizi J, Adeli B, Wong JC, Restrepo C, Rothman RH. A squeaky reputation: the problem may be design-dependent. *Clin Orthop Relat Res* 2011;469:1598–1605.

51. Kim YH, Park JW. Eighteen-year follow-up study of 2 alternative bearing surfaces used in total hip arthroplasty in the same young patients. *J Arthroplasty* 2019. doi:10.1016/j.arth.2019.09.051 [Epub ahead of print].

52. Lee YK, Kim KC, Yoon BH, Kim TY, Ha YC, Koo KH. Cementless total hip arthroplasty with delta-on-delta ceramic bearing in patients younger than 30 years. *Hip Int* 2019. [Epub ahead of print].

53. Mihalko WM, Wimmer MA, Pacione CA, Laurent MP, Murphy RF, Rider C. How have alternative bearings and modularity affected revision rates in total hip arthroplasty? *Clin Orthop Relat Res* 2014;472:3747–3758.

54. Wyles CC, Jimenez-Almonte JH, Murad MH, et al. There are no differences in short- to mid-term survivorship among total hip-bearing surface options: a network meta-analysis. *Clin Orthop Relat Res* 2015;473:2031–2041.

55. Hexter AT, Hislop SM, Blunn GW, Liddle AD. The effect of bearing surface on risk of periprosthetic joint infection in total hip arthroplasty: a systematic review and meta-analysis. *Bone Joint J* 2018;100-B:134–142.

56. Higgins JE, Conn KS, Britton JM, Pesola M, Manninen M, Stranks GJ. Early results of our international, multicenter, multisurgeon, double-blinded, prospective, randomized, controlled trial comparing metal-on-metal with ceramic-on-metal in total hip arthroplasty. *J Arthroplasty* 2019. doi:10.1016/j.arth.2019.08.002 [Epub ahead of print].

57. NJR. National Joint Registry for England, Wales, Northern Ireland and the Isle of Man. *16th annual report 2019*. https://reports.njrcentre.org.uk/Portals/0/PDFdownloads/NJR%20 16th%20Annual%20Report%202019.pdf (date last accessed 3 December 2019).

58. SHAR (The Swedish Hip Arthroplasty Register). *Annual report* 2018. https://registercentrum.blob.core.windows.net/shpr/r/Arsrapport_2018_Hoftprotes_final_web-rJgg8LvkOB.pdf (date last accessed 23 October 2019).

59. NAR (The Norwegian Arthroplasty Register). Report June 2019. http://nrlweb.ihelse.net/eng/Rapporter/Report2019_english.pdf (date last accessed 23 October 2019).

60. DHR (The Danish Hip Arthroplasty Register). *Annual report* 2019. http://danskhoftealloplastikregister.dk/wp-content/uploads/2019/09/DHR-%C3%A5rsrapport-2019_til-offentligg%C3%B8relse-1.pdf (date last accessed 23 October 2019).

61. The New Zealand Joint Registry. *January 1999 to December 2018. 20-year report*. https://nzoa.org.nz/system/files/DH8328_NZJR_2019_Report_v4_7Nov19.pdf (date last accessed 14 November 2019).

62. LROI. Online LROI annual report 2019. *Annual report of the Dutch Arthroplasty Register*. http://www.lroi-rapportage.nl/ (date last accessed 14 November 2019).

63. EPRD. Mit Sicherheit mehr Qualität. *Jahresbericht 2019*. https://www.eprd.de/fileadmin/user_upload/Jahresbericht_2019_doppelseite_2.0.pdf (date last accessed 14 November 2019).

64. AOANJRR. Hip, Knee & Shoulder Arthroplasty. *Annual report 2019*. https://aoanjrr.sahmri.com/documents/10180/668596/Hip%2C+Knee+%26+Shoulder+Arthroplasty/c287d2a3-22df-a3bb-37a2-91e6c00bfcf0 (date last accessed 14 November 2019).

65. Tsikandylakis G, Mohaddes M, Cnudde P, Eskelinen A, Kärrholm J, Rolfson O. Head size in primary total hip arthroplasty. *EFORT Open Rev* 2018;3:225–231.

66. Crowninshield RD, Maloney WJ, Wentz DH, Humphrey SM, Blanchard CR. Biomechanics of large femoral heads: what they do and don't do. *Clin Orthop Relat Res* 2004;429:102–107.

67. Matsushita I, Morita Y, Ito Y, Gejo R, Kimura T. Activities of daily living after total hip arthroplasty: is a 32-mm femoral head superior to a 26-mm head for improving daily activities? *Int Orthop* 2011;35:25–29.

68. Tsuda K, Haraguchi K, Koyanagi J, Takahashi S, Sugama R, Fujiwara K. A forty millimetre head significantly improves range of motion compared with a twenty eight millimetre head in total hip arthroplasty using a computed tomography-based navigation system. *Int Orthop* 2016;40:2031–2039.

69. Burroughs BR, Hallstrom B, Golladay GJ, Hoeffel D, Harris WH. Range of motion and stability in total hip arthroplasty with 28-, 32-, 38-, and 44-mm femoral head sizes. *J Arthroplasty* 2005;20:11–19.

70. Jinno T, Koga D, Asou Y, Morita S, Okawa A, Muneta T. Intraoperative evaluation of the effects of femoral component offset and head size on joint stability in total hip arthroplasty. *J Orthop Surg (Hong Kong)* 2017;25:2309499016684298.

71. Delay C, Putman S, Dereudre G, et al. Is there any range-of-motion advantage to using bearings larger than 36 mm in primary hip arthroplasty: a case-control study comparing 36-mm and large-diameter heads. *Orthop Traumatol Surg Res* 2016;102:735–740.

72. Sariali E, Lazennec JY, Khiami F, Catonné Y. Mathematical evaluation of jumping distance in total hip arthroplasty: influence of abduction angle, femoral head offset, and head diameter. *Acta Orthop* 2009;80:277–282.

73. Dietz MJ, Moushmoush O, Samora WP, Kish VL, Hamlin BR. The effect of increasing femoral head size on the force required for dislocation. *Surg Technol Int* 2019;35:426–429.

74. Howie DW, Holubowycz OT, Middleton R; Large Articulation Study Group. Large femoral heads decrease the incidence of dislocation after total hip arthroplasty: a randomized controlled trial. *J Bone Joint Surg Am* 2012;94:1095–1102.

75. Garbuz DS, Masri BA, Duncan CP, et al. The Frank Stinchfield Award: dislocation in revision THA: do large heads (36 and 40 mm) result in reduced dislocation rates in a randomized clinical trial? *Clin Orthop Relat Res* 2012;470:351–356.

76. Lee YK, Ha YC, Koo KH. Comparison between 28 mm and 32 mm ceramic-on-ceramic bearings in total hip replacement. *Bone Joint J* 2014;96-B:1459–1463.

77. Hailer NP, Weiss RJ, Stark A, Kärrholm J. The risk of revision due to dislocation after total hip arthroplasty depends on surgical approach, femoral head size, sex, and primary diagnosis: an analysis of 78,098 operations in the Swedish Hip Arthroplasty Register. *Acta Orthop* 2012;83:442–448.

78. Byström S, Espehaug B, Furnes O, Havelin LI; Norwegian Arthroplasty Register. Femoral head size is a risk factor for total hip luxation: a study of 42,987 primary hip arthroplasties from the Norwegian Arthroplasty Register. *Acta Orthop Scand* 2003;74:514–524.

79. Zijlstra WP, De Hartog B, Van Steenbergen LN, Scheurs BW, Nelissen RGHH. Effect of femoral head size and surgical approach on risk of revision for dislocation after total hip arthroplasty. *Acta Orthop* 2017;88:395–401.

80. Tsikandylakis G, Kärrholm J, Hailer NP, et al. No increase in survival for 36-mm versus 32-mm femoral heads in metal-on-polyethylene THA: a registry study. *Clin Orthop Relat Res* 2018;476:2367–2378.

81. Kostensalo I, Junnila M, Virolainen P, et al. Effect of femoral head size on risk of revision for dislocation after total hip arthroplasty: a population-based analysis of 42,379 primary procedures from the Finnish Arthroplasty Register. *Acta Orthop* 2013;84:342–347.

82. Miettinen SSA, Mäkinen TJ, Laaksonen I, et al. Dislocation of large-diameter head metal-on-metal total hip arthroplasty and hip resurfacing arthroplasty. *Hip Int* 2019;29:253–261.

83. Haughom BD, Plummer DR, Moric M, Della Valle CJ. Is there a benefit to head size greater than 36 mm in total hip arthroplasty? *J Arthroplasty* 2016;31:152–155.

84. Muratoglu OK, Bragdon CR, O'Connor D, et al. Larger diameter femoral heads used in conjunction with a highly cross-linked ultra-high molecular weight polyethylene: a new concept. *J Arthroplasty* 2001;16:24–30.

85. Howie DW, Holubowycz OT, Callary SA. The wear rate of highly cross-linked polyethylene in total hip replacement is not increased by large articulations: a randomized controlled trial. *J Bone Joint Surg Am* 2016;98:1786–1793.

86. Callary SA, Field JR, Campbell DG. Low wear of a second-generation highly crosslinked polyethylene liner: a 5-year radiostereometric analysis study. *Clin Orthop Relat Res* 2013;471:3596–3600.

87. Callary SA, Field JR, Campbell DG. The rate of wear of second-generation highly crosslinked polyethylene liners five years post-operatively does not increase if large femoral heads are used. *Bone Joint J* 2016;98-B:1604–1610.

88. Lachiewicz PF, Soileau ES, Martell JM. Wear and osteolysis of highly crosslinked polyethylene at 10 to 14 years: the effect of femoral head size. *Clin Orthop Relat Res* 2016;474:365–371.

89. Lachiewicz PF, O'Dell JA, Martell JM. Large metal heads and highly cross-linked polyethylene provide low wear and complications at 5–13 years. *J Arthroplasty* 2018;33:2187–2191.

90. Lindalen E, Nordsletten L, Høvik Ø, Röhrl SM. E-vitamin infused highly cross-linked polyethylene: RSA results from a randomised controlled trial using 32 mm and 36 mm ceramic heads. *Hip Int* 2015;25:50–55.

91. Smith J, Lee D, Bali K, et al. Does bearing size influence metal ion levels in large-head metal-on-metal total hip arthroplasty? A comparison of three total hip systems. *J Orthop Surg Res* 2014;9:3.

92. Reito A, Elo P, Puolakka T, Pajamäki J, Eskelinen A. Femoral diameter and stem type are independent risk factors for ARMD in the large-headed ASR THR group. *BMC Musculoskelet Disord* 2015;16:118.

93. Meneghini RM, Lovro LR, Wallace JM, Ziemba-Davis M. Large metal heads and vitamin E polyethylene increase frictional torque in total hip arthroplasty. *J Arthroplasty* 2016;31:710–714.

94. Alonso-Rasgado T, Del-Valle-Mojica JF, Jimenez-Cruz D, Bailey CG, Board TN. Cement interface and bone stress in total hip arthroplasty: relationship to head size. *J Orthop Res* 2018;36:2966–2977.

95. Norman TL, Denen JE, Land AJ, Kienitz DM, Fehring TA. Taper-trunnion interface stress varies significantly with head size and activity. *J Arthroplasty* 2019;34: 157–162.

96. Lanting BA, Teeter MG, Howard JL, MacDonald SJ, Van Citters DW. Metal-on-metal compared with metal-on-polyethylene: the effect on trunnion corrosion in total hip arthroplasty. *J Arthroplasty* 2017;32:2574–2579.

97. Lachiewicz PF, O'Dell JA. Trunnion corrosion in metal-on-polyethylene hip arthroplasty: a simple diagnosis and treatment? *Bone Joint J* 2018;100-B:898–902.

98. Dyrkacz RM, Brandt JM, Ojo OA, Turgeon TR, Wyss UP. The influence of head size on corrosion and fretting behaviour at the head-neck interface of artificial hip joints. *J Arthroplasty* 2013;28:1036–1040.

99. Del Balso C, Teeter MG, Tan SC, Howard JL, Lanting BA. Trunnionosis: does head size affect fretting and corrosion in total hip arthroplasty? *J Arthroplasty* 2016;31: 2332–2336.

100. Triantafyllopoulos GK, Elpers ME, Burket JC, Esposito CI, Padgett DE, Wright TM. Otto Aufranc Award: large heads do not increase damage at the head-neck taper of metal-on-polyethylene total hip arthroplasties. *Clin Orthop Relat Res* 2016;474:330–338.

101. Siljander MP, Baker EA, Baker KC, Salisbury MR, Thor CC, Verner JJ. Fretting and corrosion damage in retrieved metal-on-polyethylene modular total hip arthroplasty systems: what is the importance of femoral head size? *J Arthroplasty* 2018;33:931–938.

102. Bartelt RB, Yuan BJ, Trousdale RT, Sierra RJ. The prevalence of groin pain after metal-on-metal total hip arthroplasty and total hip resurfacing. *Clin Orthop Relat Res* 2010;468:2346–2356.

103. Baumgarten KM, McKenzie MJ. Case reports: iliopsoas tendon impingement after total hip arthroplasty with use of a large-diameter femoral head. A case report. *JBJS Case Connect* 2012;2:1–5.

104. Lavigne M, Vendittoli PA, Virolainen P, et al. Large head ceramic-on-ceramic bearing in primary total hip arthroplasty: average 3-year follow-up of a multicentre study. *Hip Int* 2019; Jul 11:1120700019863376.

105. Cobb JP, Davda K, Ahmad A, Harris SJ, Masjedi M, Hart AJ. Why large-head metal-on-metal hip replacements are painful: the anatomical basis of psoas impingement on the femoral head-neck junction. *J Bone Joint Surg Br* 2011;93:881–885.

106. Blakeney WG, Beaulieu Y, Puliero B, et al. Excellent results of large-diameter ceramic-on-ceramic bearings in total hip arthroplasty: is squeaking related to head size. *Bone Joint J* 2018;100-B:1434–1441.

107. Zagra L, Anasetti F, Bianchi L, Licari V, Giacometti Ceroni R. No difference in gait recovery after THA with different head diameters: a prospective randomized study. *Clin Orthop Relat Res* 2013;471:3830–3837.

108. **Charnley J.** *Low friction arthroplasty of the hip*. Berlin, Heidelberg: Springer, 1979.

109. **Cobb TK, Morrey BF, Ilstrup DM.** The elevated-rim acetabular liner in total hip arthroplasty: relationship to postoperative dislocation. *J Bone Joint Surg Am* 1996;78:80–86.

110. **Insull PJ, Cobbett H, Frampton CM, Munro JT.** The use of a lipped acetabular liner decreases the rate of revision for instability after total hip replacement: a study using data from the New Zealand Joint Registry. *Bone Joint J* 2014;96-B:884–888.

111. **Hemmilä M, Karvonen M, Laaksonen I, et al.** Survival of 11,390 continuum cups in primary total hip arthroplasty based on data from the Finnish Arthroplasty Register. *Acta Orthop* 2019;90:312–317.

112. **Carlsson AS, Lindberg HO, Sanzén L.** Loosening of the socket in a 35-mm snap-fit prosthesis and the Charnley hip prosthesis: a roentgenographic evaluation of 321 cases operated upon because of osteoarthritis. *Clin Orthop Relat Res* 1988;228:63–68.

113. **Johnsson R, Thorngren KG, Persson BM.** Revision of total hip replacement for primary osteoarthritis. *J Bone Joint Surg Br* 1988;70:56–62.

114. **Van der Merwe JM.** Comprehensive review of current constraining devices in total hip arthroplasty. *J Am Acad Orthop Surg* 2018;26:479–488.

115. **Zagra L, Caboni E.** Total hip arthroplasty instability treatment without dual mobility cups: brief overview and experience of other options. *Int Orthop* 2017;41:661–668.

116. **Hernigou P, Filippini P, Flouzat-Lachaniette CH, Batista SU, Poignard A.** Constrained liner in neurologic or cognitively impaired patients undergoing primary THA. *Clin Orthop Relat Res* 2010;468:3255–3262.

117. **Williams JT Jr, Ragland PS, Clarke S.** Constrained components for the unstable hip following total hip arthroplasty: a literature review. *Int Orthop* 2007;31:273–277.

118. **Clavé A, Maurer D, Tristan L, Dubrana F, Lefèvre C, Pandit H.** Midterm survivorship of the Lefèvre constrained liner: a consecutive multisurgeon series of 166 cases. *J Arthroplasty* 2016;31:1970–1978.

119. **Berend KR, Lombardi AV Jr, Mallory TH, Adams JB, Russell JH, Groseth KL.** The long-term outcome of 755 consecutive constrained acetabular components in total hip arthroplasty examining the successes and failures. *J Arthroplasty* 2005;20:93–102.

120. **Fricka KB, Marshall A, Paprosky WG.** Constrained liners in revision total hip arthroplasty: an overuse syndrome: in the affirmative. *J Arthroplasty* 2006;21:121–125.

121. **Noyer D, Caton JH.** Once upon a time. . . . Dual mobility: history. *Int Orthop* 2017;41:611–618.

122. **Massin P, Orain V, Philippot R, Farizon F, Fessy MH.** Fixation failures of dual mobility cups: a mid-term study of 2601 hip replacements. *Clin Orthop Relat Res* 2012;470:1932–1940.

123. **Batailler C, Fary C, Verdier R, Aslanian T, Caton J, Lustig S.** The evolution of outcomes and indications for the dual-mobility cup: a systematic review. *Int Orthop* 2017;41:645–659.

124. **Caton JH, Ferreira A.** Dual-mobility cup: a new French revolution. *Int Orthop* 2017;41:433–437.

125. **Darrith B, Courtney PM, Della Valle CJ.** Outcomes of dual mobility components in total hip arthroplasty: a systematic review of the literature. *Bone Joint J* 2018;100-B:11–19.

126. **De Martino I, D'Apolito R, Soranoglou VG, Poultsides LA, Sculco PK, Sculco TP.** Dislocation following total hip arthroplasty using dual mobility acetabular components: a systematic review. *Bone Joint J* 2017;99-B:18–24. Erratum in: *Bone Joint J* 2017;99-B:702–704.

127. **Kreipke R, Rogmark C, Pedersen AB, et al.** Dual mobility cups: effect on risk of revision of primary total hip arthroplasty due to osteoarthritis: a matched population-based study using the Nordic Arthroplasty Register Association database. *J Bone Joint Surg Am* 2019;101:169–176.

128. **Jobory A, Kärrholm J, Overgaard S, et al.** Reduced revision risk for dual-mobility cup in total hip replacement due to hip fracture: a matched-pair analysis of 9,040 cases from the Nordic Arthroplasty Register Association (NARA). *J Bone Joint Surg Am* 2019;101:1278–1285.

129. **Mohaddes M, Cnudde P, Rolfson O, Wall A, Kärrholm J.** Use of dual-mobility cup in revision hip arthroplasty reduces the risk for further dislocation: analysis of seven hundred and ninety one first-time revisions performed due to dislocation, reported to the Swedish Hip Arthroplasty Register. *Int Orthop* 2017;41:583–588.

130. **Langlais FL, Ropars M, Gaucher F, Musset T, Chaix O.** Dual mobility cemented cups have low dislocation rates in THA revisions. *Clin Orthop Relat Res* 2008;466:389–395.

131. **Brüggemann A, Mallmin H, Hailer NP.** Do dual-mobility cups cemented into porous tantalum shells reduce the risk of dislocation after revision surgery? *Acta Orthop* 2018;89:156–162.

132. **Hermansen LL, Viberg BL, Hansen LT, Overgaard S.** True frequency of and risk factors for hip dislocation within two years after primary total hip arthroplasty due to osteoarthritis: a nationwide population-based study from the Danish Hip Arthroplasty Register. Danish Orthopedic Society (DOS) Bulletin 2019. 48th edition. www.ortopaedi.dk/abstractbog/2019/152/ (date last accessed 16 February 2020).