TURUN YLIOPISTO
UNIVERSITY OF TURKU

IMPLANT SURVIVAL FOLLOWING PRIMARY TOTAL HIP ARTHROPLASTY

With Special Interest in Uncemented Acetabular Components and Liners

Matias Hemmilä

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To my family

UNIVERSITY OF TURKU
Faculty of Medicine
Department of Clinical Medicine
Orthopaedics and Traumatology
MATIAS HEMMILÄ: Implant survival following primary total hip arthroplasty
With special interest in uncemented acetabular components and liners
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ABSTRACT

Total hip arthroplasty (THA) is regarded as the operation of the century. A successful THA is a combination of adequate surgical technique with appropriate implants performed for carefully selected patients. Orthopedic devices are undergoing continual development towards longer survival and better outcomes. However, development is demanding and time-consuming, because complications can become apparent years after a successful THA. Arthroplasty registers allow us to analyze the survival of implants in large volumes of patients, detect outlier implants, and avoid complications. This study is based on the Finnish Arthroplasty register.

The aims of this thesis were: 1) to compare implant survival and revision risk of a Continuum cup (ZimmerBiomet, Warsaw, USA) with other uncemented cup devices in primary THA; 2) assess the survivorship of ultraporous Tritanium cups (Mahwah, NJ, USA) compared to conventional uncemented cups in primary THA; 3) evaluate revision rates between vitamin E-infused polyethylene liners and moderately crosslinked polyethylene (ModXLPE) liners from the same manufacturer in primary THA; and 4) describe a case report of trunnion corrosion and component failure and clarify risk factors based on the current literature.

We found the Continuum cup component to be associated with an increased risk of revision compared to other uncemented cups in primary THA, mainly due to revisions for dislocation. The risk of dislocation decreased when an elevated liner was used with the Continuum cup. The ultraporous-coated Tritanium cup component for primary THA did not provide an advantage over traditional uncemented cups and was associated with increased revision risk for aseptic loosening of the cup. Vitamin E-infused liners are a durable option; however, we were unable to detect any advantages of this material associated with decreased wear, and further studies with longer follow-up are needed. Mechanically assisted crevice corrosion of the trunnion is a multifactorial phenomenon. Affecting factors can be divided into patient-related, component-related, and surgery-related. Severe trunnion corrosion due to mechanically assisted crevice corrosion (MACC) is a rare complication.

KEYWORDS: Total hip arthroplasty, trabecular metal, high porosity, elevated liner, Tritanium, aseptic loosening, vitamin E, HXLPE, TMFZ

TURUN YLIOPISTO
Lääketieteellinen tiedekunta
Kliininen laitos
Ortopedia ja Traumatologia
MATIAS HEMMILÄ: Lonkan tekonivelen kuppikomponentit ja liukupinnat ensivaiheen tekonivelleikkauksessa – tarkastelussa sementittömät kupit ja muoviliukupinnat
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TIIVISTELMÄ

Lonkan tekonivelleikkausta on pidetty yhtenä vuosisadan lääketieteellisistä toimenpiteistä. Oikea leikkaustekniikka yhdistettynä tarkoituksenmukaisiin tekonivelkomponentteihin tarkkaan valituilla potilailla on menestyksen edellytys. Tekoniveliin kehitetään jatkuvasti uusia ratkaisuja, joilla pyritään vähentämään komplikaatioita ja pidentämään tekonivelten elinkaarta, mutta kehitystyö on haastavaa ja aikaa vievää. Tämän tutkimuksen tarkoituksena oli analysoida lonkan tekonivelinnovaatioiden toimivuutta ja tuloksia. Erityisenä mielenkiinnon kohteena olivat sementittömät kuppikomponentit ja niissä käytettävät polyeteenistä valmistetut liukupinnat. Aineisto kerättiin Suomen Tekonivelrekisteristä.

Vertasimme lonkan tekonivelen tantaalimetallisten Continuum -kuppikomponenttien sijoiltaanmenon ilmaantuvuutta suhteessa muihin yleisesti käytettyihin sementittömiin kuppikomponentteihin. Tutkimme titaanisen Tritanium kuppikomponentin uusintaleikkausmääriä suhteessa muihin sementittömiin primaari kuppikomponentteihin. Selvitimme lonkan tekonivelen E-vitamiinia sisältävän liukupinnan vaikutusta lonkkamaljan muoviliukupintaisten tekonivelten pysyvyyteen ja uusintaleikkausten syihin. Lisäksi raportoimme tapausselostuksen tekonivelen kartioliitoksen korroosiosta ja tekonivelen rikkoutumisesta ja sen riskitekijöistä kirjallisuuden ja oman tapauksemme perusteella.

Tutkimuksessamme Continuum-kupeilla todettiin suurentunut riski uusintaleikkaukseen sijoiltaanmenon vuoksi. Korotettu liukupinta kuitenkin vähensi sijoiltaanmenon riskiä ja sen käyttö on suositeltavaa Continuum kuppia käytettäessä. Tritanium -kuppeihin liittyi tilastollisesti merkittävästi suurentunut uusintaleikkausriski kupin irtoamisen vuoksi. E-vitamiinia sisältävä polyeteeni liukupinta on kestävä valinta lonkan tekonivelleikkauksessa, mutta sen potentiaaliset edut eivät tulleet esiin 7 vuoden seuranta-aikana. Kartioliitoksen korroosio on monitekijäinen ilmiö, jonka riskitekijät voidaan jakaa potilaskohtaisiin, komponenttikohtaisiin ja toimenpidekohtaisiin.

AVAINSANAT: Lonkan tekonivel, tantaalimetalli, poroosipintainen, aseptinen irtoaminen, polyeteeni, ristiinsilloitettu, E-vitamiini, TMZF

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Abbreviations

ALTR	Adverse local tissue reaction
AML	Anatomic medullary locking
AOANJRR	Australian Orthopaedic Association National Joint Replacement Registry
ARMD	Adverse reaction to metal debris
ASA	American Society of Anesthesiologists
BMI	Body mass index
CI	Confidence interval
CoC	Ceramic on ceramic
CoCr	Cobalt-chromium
CoP	Ceramic on polyethylene
DAIR	Debridement-Antibiotics-Irrigation-Retention of component
FAR	Finnish Arthroplasty Register
HA	Hydroxyapatite
HHS	Harris hip score
HR	Hazard ratio
HRA	Hip resurfacing arthroplasty
HXLPE	Highly crosslinked polyethylene
ICD	International Classification of Diseases
KM	Kaplan-Meier
MACC	Mechanically assisted crevice corrosion
MARS MRI	Metal artifact reduction sequence magnetic resonance imaging
ModXLPE	Moderately crosslinked polyethylene
MoM	Metal on metal
MoP	Metal on polyethylene
MoPx	Metal on crosslinked polyethylene
NAR	Norwegian Arthroplasty Register
NARA	Nordic Arthroplasty Register Association
NICE	National Institute for Health and Care Excellence
NJR	National Joint Registry for England, Wales, Northern Ireland and the Isle of Man

OA	Osteoarthritis
OR	Odds ratio
PCA	Porous coated anatomic
PE	Polyethylene
PJI	Periprosthetic joint infections
PMMA	Polymethyl methacrylate
PROM	Patient reported outcome
RA	Rheumatoid arthritis
RSA	Radiostereometric analysis
RR	Risk ratio
ROM	Range of motion
SHAR	Swedish Hip Arthroplasty Register
THA	Total hip arthroplasty
TM	Trabecular metal
TMZF	Titanium-Molybdenum-Zirconium-Fluoride
UHMWPE	Ultra-high-molecular-weight polyethylene
VEPE	Vitamin-E polyethylene
XLPE	Crosslinked polyethylene

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Hemmilä M, Karvonen M, Laaksonen I, Matilainen M, Eskelinen A, Haapakoski J, Puhto A-P, Kettunen J, Manninen M, Mäkelä K. Survival of 11,390 Continuum cups in primary total hip arthroplasty based on data from the Finnish Arthroplasty Register. Acta Orthop, 2019;17:1–10.

II Palomäki A, Hemmilä M, Laaksonen I, Matilainen M, Eskelinen A, Haapakoski J, Puhto A-P, Kettunen J, Manninen M, Mäkelä KT. Implant survival of 6,080 Tritanium cups in primary total hip arthroplasty based on data from the Finnish Arthroplasty Register. J Bone Joint Surg Am, 2020;102(13):1177–1185.

III Hemmilä M, Laaksonen I, Matilainen M, Eskelinen A, Haapakoski J, Puhto A-P, Kettunen J, Pamilo K, Mäkelä KT. Implant survival of vitamin E-infused highly crosslinked polyethylene liners in total hip arthroplasty based on data from the Finnish arthroplasty register. Acta Orthopaedica, Published online 1st of February 2021, DOI: 10.1080/17453674.2021.1879513

IV Hemmilä M, Karvonen M, Keemu H, Seppänen M, Mäkelä KT. Accolade TMZF trunnion corrosion and mechanical failure 9 yr after primary surgery: A case report and treatment options. Current Orthopaedic Practice, 2020; 31(3):318–321.

1 Introduction

Since its introduction in the 1960s, modern total hip arthroplasty (THA) has gained success and enhanced the quality of life and functional outcome of patients with end-stage hip osteoarthritis. THA is one of the most predictable and cost-effective procedures in orthopedics, and in 2007 was named the "operation of the century" by the Lancet (Learmonth et al. 2007a). THA has satisfactory clinical outcomes at 15 to 20-year follow-up (Learmonth et al. 2007a, Fevang et al. 2010, Mäkelä et al. 2014a). However, despite the improvements in short- and long-term outcomes of THA, orthopedic surgeons still face many of the same problems that pioneering surgeons did in the 1960s and 1970s, including choice of appropriate acetabular and femoral implants, component fixation selection, osteolysis, periprosthetic infection, and fractures. Enhanced results of THA survival are reported (Fevang et al. 2010), but simultaneously THA revision rates have continued to increase in recent years (Kurtz et al. 2007). It has become clear that long-term survival of THA is a multifactorial and complex issue.

The low-friction arthroplasty concept was introduced in the 1960s as a bearing for Charnley's newly invented THA. The bearing combined a high-molecular-weight polyethylene cup with the metal head of a cemented stem, which became the gold standard for THA. Polyethylene (PE) wear and osteolysis around implants soon became a problem (Harris et al. 1976, Maloney et al. 1990), and since then bearing couples have been a target for continuous development. Crosslinking is a method whereby polyethylene is altered to an ionized gas at a dose higher than required for sterilization (Muratoglu et al. 1999), and it has been reported to decrease the rate of revision of THA (Hanna et al. 2016, Moon et al. 2020). However, the crosslinking procedure releases free radicals, which may induce wear (Kurtz 2009). One potential solution to further decrease the amount of free radicals in the liner material is to add vitamin E to highly crosslinked polyethylene (HXLPE), which increases the resistance of polyethylene against these oxidative processes by stabilizing the material (Oral et al. 2006b, 2006a).

In the early days of THA, acetabular components were mainly cemented. Later, porous-coated uncemented cups made of titanium or tantalum achieved great success in total THA due to their unique properties such as strength, corrosion resistance,

and biocompatibility (Nouri et al. 2010). The porous metal surface of the implant mimics the properties of cancellous bone, providing reliable bone ingrowth and a reduced rate of aseptic loosening compared to cemented cups (Naziri et al. 2013). Porous uncemented cups are a heterogeneous group of implants with different properties and manufacturing methods and a broad implant survival spectrum.

The aim of this thesis was to study survival and complications related to uncemented acetabular components and liner design and material, based on data from the Finnish Arthroplasty Register. Further, we report gross trunnion corrosion and component breakage related to material failure.

2 Review of the Literature

2.1 History of hip arthroplasty

Total hip arthroplasty has been called the operation of the century (Learmonth et al. 2007b). The story of hip arthroplasty began in Germany in 1891, when professor Glück used ivory to replace the femoral heads of patients whose hips had been destroyed by tuberculosis. The next experimental endeavor was interpositional arthroplasty in the late 19th and early 20th centuries, when surgeons placed various soft tissues between the articulating surfaces of the hip (Learmonth et al. 2007b). The first more predictable implant developed by Smith-Petersen in 1925 was called mold arthroplasty. The implant was made of glass, but it shattered over time and failed to achieve success. The next attempt was made by Smith-Petersen and Wiles, who chose a stainless steel alloy, Vitallium, to create the first implant fixed with screws and bolts in 1938 (Smith-Petersen 1948). This implant is regarded as a precedent to modern hip implants, and it launched the THA era.

2.2 Development of modern total hip arthroplasty

Early implants often failed due to inferior materials, impractical design and mechanical failure. Sir John Charnley introduced cemented hip arthroplasty in the 1960s, which became the gold standard of modern THA for decades with excellent long-term results (Charnley 1961) (Figure 1). The 25-year survival of the first-generation Charnley arthroplasty was 81% (Berry et al. 2002). Charnley made three major contributions to the evolution of THA: 1) the idea of low friction torque arthroplasty; 2) the use of acrylic cement to fix components to a living bone; and 3) the introduction of high-density polyethylene as a bearing material (Learmonth et al. 2007b). The treatment was originally designed for patients over 65 years of age with end-stage osteoarthritis of the hip. At present, younger and younger patients receive hip prostheses for the treatment of primary or secondary osteoarthritis or rheumatoid arthritis. Patients' expectations have changed a lot since the 1960s. Nowadays, many older people have a more active lifestyle that tends to include physically demanding activities, and they hope that THA will restore their quality of life. High-demand patients, better implant survival, and advances in bioengineering technology have led to improvements and

development in hip arthroplasty, including sustainable materials and design which have allowed orthopedic surgeons to use larger head sizes, providing increased range of motion with enhanced stability and very low wear.

Figure 1. Kerboull stem, replica of the stem from Charnley's hip arthroplasty.

2.2.1 Cemented total hip arthroplasty

German surgeon Glück was the first to use cement fixation with ivory implants. In the late 1950s, sir John Charnley introduced and popularized the use of polymethyl methacrylate bone cement for fixation of total hip prostheses (Charnley 1960).

Although the long-term outcome of the Charnley THA was good, early failure of cemented stems implanted by first-generation cementation techniques was frequent. The failures were associated with local bone resorbing around the implant, and polymethyl methacrylate particles were found in histological studies. This phenomenon was first called cement disease (Harris et al. 1976) and led to the development of uncemented devices in THA (Maloney and Smith 1995). Today, the reaction is well known, as is the fact that it is particulate wear debris from the bearing surface that is the major cause of aseptic osteolysis, not the cement itself (Amstutz et al. 1992, Maloney and Smith 1995).

The early cementing technique was antegrade, the bone was not prepared, and the cement was not pressurized. Poor penetration of cement into the bone resulted in a poor cement mantle and inferior results. Cement is a grout, not a glue, and the stability of the implant is achieved by mechanical interlocking of cement and bone. Krause et al. and Majkowski et al. reported that cleaning the bone surface enhances the cement penetration to cancellous bone and thus results in improved mechanical strength and better long-term results (Krause et al. 1982, Majkowski et al. 1993). These encouraging results led to development of the second-generation cementing technique. It included preparation of the bone surface, intra-medullary plug and retrograde insertion of the cement. Contemporary cementing now includes vacuum centrifugation of the cement, preparation of the bone with jet lavage, suction drainage and packing of the femoral canal, and retrograde cement insertion and pressurization. Finally, the implant is inserted with centralizers to ensure a solid mantle. The benefits of this fourth generation technique have been widely reported by the Swedish Arthroplasty Register (SHAR) (Herberts and Malchau 2000). Although polymethyl methacrylate (PMMA) cement has been reported to have poor resistance to shear (Mirza et al. 2010), the inferior results of cemented devices are at least partly attributable to poor cementing technique. This is consistent with register data showing that regions with long traditions of cemented THA, such as the Nordic countries, have 10- and 15-year results in excess of 90% survival (Mäkelä et al. 2014a, Junnila et al. 2016) (Figure 2).

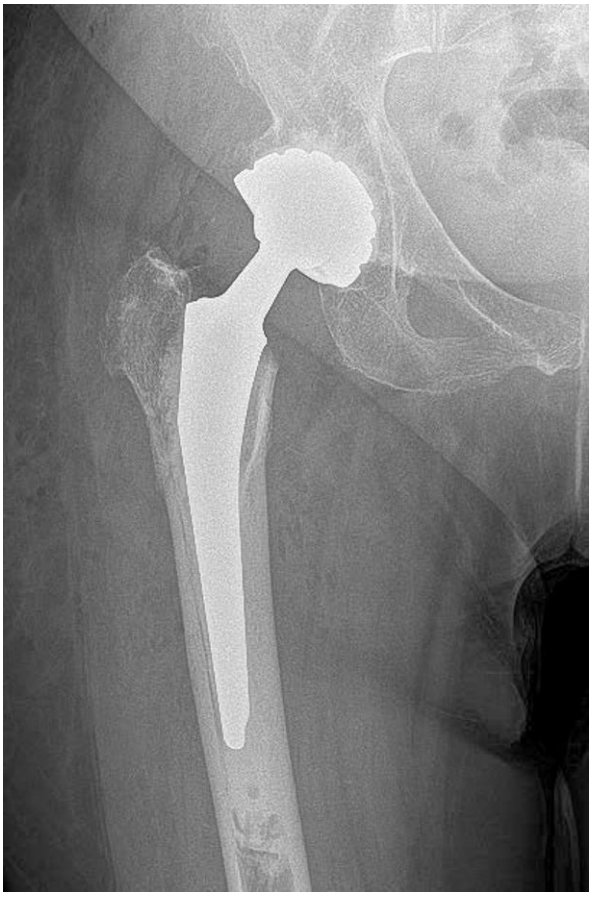

Figure 2. Cemented THA with Müller stem and Avantage shell.

2.2.2 Uncemented total hip arthroplasty

At 12–15 years of follow-up, Charnley reported radiolucent lines around cemented cup implants in 14% of patients (Charnley 1979). More reports of periprosthetic osteolysis and tissue reactions around cemented THA prostheses were published in the 1980s (Jasty et al. 1986), and it was thought that cemented components were not suitable for younger patients (Jones and Hungerford 1987). As mentioned above, this so-called "cement disease" launched the development of uncemented implants (Figure 3).

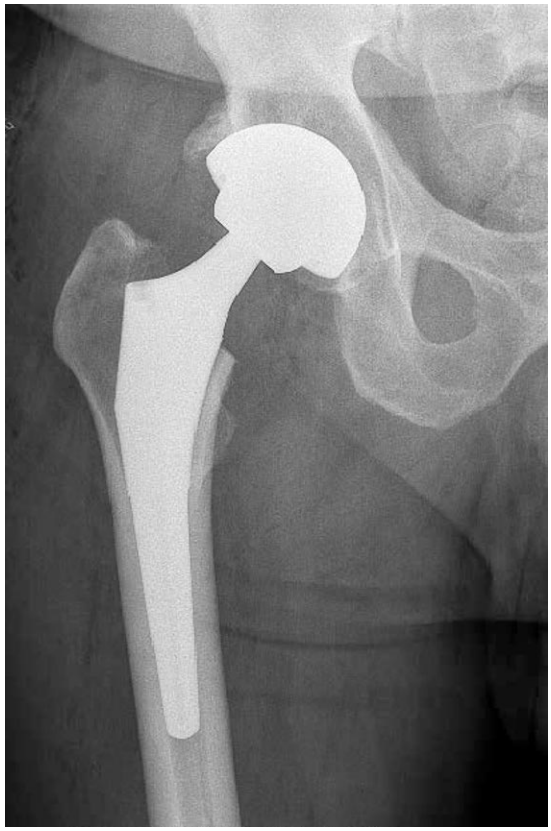

Figure 3. Uncemented THA with M/L taper stem and Continuum cup.

2.2.2.1 Uncemented femoral components

Uncemented components were designed to have instant initial stability to provide the right conditions for osseointegration. In 1979, Lord reported the results of his study on a novel uncemented total hip replacement. He explained that "living bone that undergoes remodeling provides for long-term anchor of the prosthesis" (Lord et al. 1979). Uncemented stems are made of porous material or have at least a roughened surface to allow bone ingrowth. The stem fixation can be based on either metaphyseal, metaphyseal-diaphyseal, diaphyseal or a combination of all three types. The design can be divided into anatomic, tapered or cylindrical.

Early uncemented stems were cylindrical with extensive coating. Diaphyseal bone in-growth occurred, but it was often accompanied by cortical atrophy, proximal stress shielding, and bone loss. Patients frequently reported thigh pain due to elastic mismatch between the rigid stem and the elastic bone (Belmont et al. 2008).

The concept of isoelasticity was introduced in the 1970s by Morscher and Mathys in response to elastic mismatch of rigid stems. The basic idea was that bone and stem should deform as one unit, but the results were poor (Niinimaki et al. 1994).

Link created the Ribbed Stem to provide proximal support without stiffening the component. The stem featured a smooth but extensive ribbed and macrotextured surface and differed from other uncemented stem designs. The stem provided suboptimal canal filling, and primary stability was hard to achieve; thus the results were poor, with a high rate of aseptic loosening (Savilahti et al. 1995) (Figure 4).

Figure 4. Link RS uncemented femoral component. The stem featured a smooth but extensive ribbed and macrotextured surface.

Due to the problems associated with early uncemented stems, research focused on more physiological loading of the proximal femur. The tapered shape of the stem remained essentially the same, but the porous coating was located only in the metaphyseal zone. This innovation came about because it was believed that proximal bone ingrowth would protect the bone against proximal stress shielding and further bone loss (Keaveny and Bartel 1995).

The anatomic medullary locking stem (AML) was one of the first uncemented stems on the market. Although the name included the word ‘anatomic’, the stem had

a straight design, and was made of a cobalt-chrome alloy with extensive porous coating to allow distal, diaphyseal fixation. The stem performed exceptionally well with up to 98% survivorship after 20 years but proximal stress shielding and thigh pain were frequently reported (Belmont et al. 2008).

A porous coated anatomic (PCA) stem was introduced simultaneously with the AML stem. It was made of cobalt-chrome and featured an anatomic sagittal curve and proximal porous coating. The revision rate of the PCA stem has been reported to be favorable, with 7% at 15 years (Bojescul et al. 2003), but a high rate of thigh pain has been reported as well (Knight et al. 1998). The anatomic design was supposed to provide enhanced initial stability and physiological loading but higher frequency of thigh pain has been reported than with cylindrical or tapered designs (McAuley et al. 1998).

Cylindrical stems need distal support to stabilize but diaphyseal fixation provides greater leverage. The stems are canal filling and stiffer, which manifests as thigh pain and stress shielding. The causes of these symptoms are related to the size of the stem, extensive porous coating, and metal- alloy (Lavernia et al. 2004). Longitudinal grooves or coronal slots have been added to the implants to avoid excessive stiffness.

Porous materials have raised concerns about fatigue strength, ion release and adverse femoral canal remodeling leading to a generation of nonporous uncemented femoral components. These devices have surface roughening or some other type of surface modification to provide a macrointerlock with the bone without the ability for true bone ingrowth. An alloclassic stem is a conical straight stem made of titanium alloy with grit-blast; it has a nonporous surface and has been shown excellent results at 25-year follow-up (Cruz-Pardos et al. 2017). Bioactive ceramics such as hydroxyapatite (HA) can be applied to the surface of a metal implant, and it was assumed that such coating could dramatically improve osseus integration of the implant, but arthroplasty registers have reported equal survival to that of other non-HA stems (Hailer et al. 2015, Inacio et al. 2018).

THA has gained popularity among younger patients; thus, it is essential to preserve the bone stock. The focus is to avoid proximal stress shielding to enhance metaphyseal fixation and bone ingrowth. The development of tapered stems has improved the results of uncemented devices (Bourne et al. 2001). Modern stem designs include double taper metaphyseal filling stems or single, medial-lateral (M-L) taper stems, both of which have excellent performance with over 95% survival at 20 years (Khanuja et al. 2011) (Figure 5). Implants are basically made of cobalt-chromium or titanium and both materials have provided equal results (Learmonth et al. 2007a). The modulus of elasticity of titanium stems is closer to that of bone, but the material is more sensitive to notching and cracking.

Figure 5. A modern single-taper stem: Accolade II. The stem is made of titanium and features proximal surface roughening (@copyrightStyker, courtesy of Stryker).

2.2.2.2 Uncemented acetabular components

As mentioned earlier, problems with cemented THA gave rise to uncemented components and their widespread use starting in the 1970s. First-generation uncemented cups featured geometrical shapes, spikes, screws, large pegs or threaded stems to achieve sufficient stability.

During the 1960s the ring prosthesis, a conical prosthesis with a threaded stem, was one of the most popular uncemented cups. It had a metal-on-metal bearing, a large femoral head, and cup fixation with a single screw. Large bone resections were needed, and this design is still in use in some tumor reconstruction operations.

Threaded cups came into fashion in the early 1970s. Most of the cups were smooth, and fixation was based on the threads interlocking mechanically against the host bone. After promising short-term results, a high rate of aseptic loosening was reported with Links RS and Biomet TTAP threaded cups (Fox et al. 1995, Savilahti et al. 1995, Puolakka et al. 1999) (Figure 6).

In the 1970s, except for threaded cups the surface of most uncemented cups was smooth, the main problems being insufficient initial stability, lack of bony ingrowth, and wear of the bearing surfaces leading to aseptic loosening and revision surgery. The outcome of these implants was poor (Kawamoto et al. 1998).

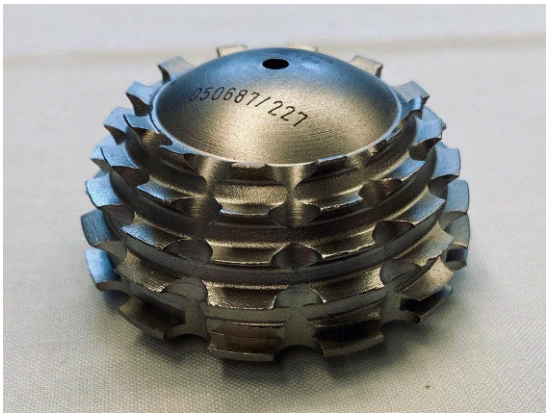

Figure 6. Links RS threaded cup.

Advances in material engineering in the 1980s led to the introduction of porous materials and a new approach to THA. Research focused on gaining sufficient bone ingrowth to achieve good long-term survival (Figure 7). Biocompatibility of the material, optimal pore size and sufficient stability together with adequate contact with the host bone during implantation were the most important factors for bone ingrowth (Bobyn et al. 1980, Crowninshield et al. 1983, McCutchen et al. 1990). Bone ingrowth increased with pore size, but soft tissue also formed simultaneously with increasing pore size. Bobyn et al. determined the optimal pore size to be between 100µm and 400µm (Bobyn et al. 1980). Different materials and methods can be used to manufacture an implant suitable for use in uncemented THA. Sintered beads, fiber mesh and thermal spray have all been used to try to create optimal circumstances for bone ingrowth, but each method has its downsides. Mechanical strength and optimal level of porosity are compromised with sintered beads (Manley et al. 1987), and optimal pore size is not achieved with thermal spray (Hamman and Lemons 1987).

Figure 7. The porous-coated anatomic (PCA) cup component was one of the first uncemented acetabular components. The cup was fabricated from cobalt-chromium alloy and featured a sintered-bead porous surface to allow bone ingrowth. Superiorly placed fixation lugs enhanced primary stability.

Three materials were most commonly used in medical implants in load-bearing situations: titanium alloys, cobalt chrome, and stainless steel. Titanium was the most important material for porous implants due to its unique properties like corrosion resistance, biocompatibility and high strength-to-weight ratio (Santos et al. 2004, Nouri et al. 2010). A porous surface mimics the properties of cancellous bone, providing reliable bone ingrowth and a reduced rate of aseptic loosening compared to cemented cups (Naziri et al. 2013).

The first-generation porous coated cups were introduced in the 1980s. The Harris-Galante uncemented acetabular component featured a titanium fiber mesh surface and an ultra-high-molecular-weight polyethylene (UHMWPE) liner and achieved strong biological fixation and bone ingrowth. Although osseous integration was good, liner dissociation and polyethylene wear were common complications (Maloney et al. 1990, Harris 1995, Puolakka et al. 2001a).

Second generation porous coated cups were launched in the 1990s and featured the same well-proofed porous surface combined with cross-linked liner. Liner wear diminished but pelvic osteolysis were not eliminated totally (Heisel et al. 2005).

Modern uncemented acetabular components are hemispherical single geometry cups. Initial stability is achieved with a press-fit design and additional stability by inserting screws. Recently, ultraporous-coated acetabular components have been developed to further enhance osteointegration (Bourne et al. 2008). It has been suggested that the lower modulus of elasticity of ultraporous-coated cups compared with conventional porous metals minimizes stress shielding and bone loss in the periacetabular region, increasing implant survival (Meneghini et al. 2010b).

Uncemented cups have shown good clinical results (96% survival at 10 years) (Clohisy and Harris 1999). Reasons for revision of an uncemented cup include dislocation, polyethylene wear, osteolysis, or failure of the liner's locking mechanism (Pulido et al. 2011). The widespread preference for uncemented fixation of the acetabulum cannot be explained by a superior survival of uncemented or hybrid components, as both cemented and reverse hybrid THA provide excellent results in both the short and long term (Van Praet and Mulier 2019). Polyethylene wear and osteolysis is still the major reason for cup revisions (Kearns et al. 2006a). Changes and current trends in fixation methods in Finland are shown in Figure 8.

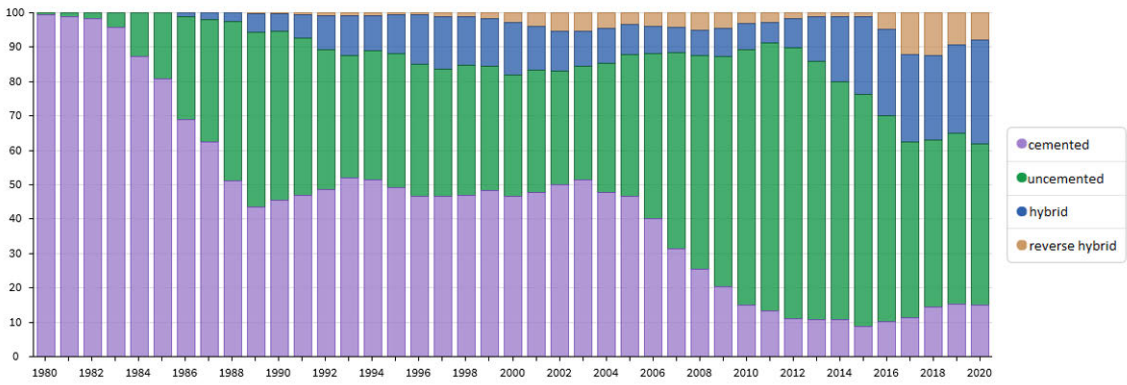

Figure 8. Fixation methods in primary THA in Finland, 1980–2020.

2.3 Bearing surfaces

2.3.1 Metal on polyethylene (MoP)

The use of UHMWPE with a metal head was started in 1960 by Charnley and currently has the longest recorded outcome data. These early polyethylenes were associated with wear particle-induced osteolysis. The failure mechanism is now well known and understood, and no systemic consequences of polyethylene wear have been described (Lachiewicz et al. 2018). Early mechanical failures, such as liner breakage, are rare even though modern liners can be quite thin. MoP bearings have the highest wear rate of all commonly used bearing couples, reported to be in the range of 0.1–0.2 mm/year (Norris et al. 2008), but the development of PE in recent years has reduced the wear rate (Kearns et al. 2006b, Garellick et al. 2018).

2.3.2 Metal on highly crosslinked polyethylene (MoPx)

Crosslinking provides more durable and wear-resistant implants. It is achieved by an irradiation process with inert gas. Different manufacturers have their own techniques, and no registry data prove the superiority of any Px type over another. The annual wear rate of HXLPE has been reported to be <0.06 mm (Callary et al. 2015). Combining a cobalt-chrome head with a MoPx liner has shown 43–100% lower wear rates compared with MoP (Merola and Affatato 2019). Despite their drawbacks, MoPx bearings are still the gold standard for THA and are said to be the most cost-effective option (Lachiewicz et al. 2018) (Figure 9).

Figure 9. Metal-on-highly-crosslinked polyethylene bearings with Continuum cup.

2.3.3 Metal on metal

Difficulties with polyethylene liners and osteolysis generated the new rise of metal-on-metal (MoM) bearing surfaces (Figure 10). The absence of polyethylene particles, the reported low wear rate compared to MoP surfaces, and the ability to use large heads to prevent dislocations and allow better range of motion were the drivers of this rise. (Schmalzried et al. 1996). After promising short-term results, implant failures were first reported by national joint registers at the end of the 2000s and beginning of the 2010s (AOANJRR 2007, NJR 2009). Raised cobalt and chromium ion levels in the blood were also reported in the early 2010s (Hart et al. 2014). Gluteal muscle necrosis, soft tissue masses and fluid collections were reported around the prosthesis and termed adverse local tissue reaction (ALTR) or adverse reaction to metal debris (ARMD) (Ollivere et al. 2009). Even systemic toxicity due to high metal ion levels and elevated risk of hematopoietic cancer have been reported (Bradberry et al. 2014, Mäkelä et al. 2014b). The 10-year revision rate for large-diameter MoM THA is 19.8% and for MoM (HRA) 12.6% according to the National Joint Registry for England, Wales and Northern Ireland (NJR) (Hunt et al. 2018). In Finland, the use of MoM implants was discontinued in 2012 (Suomen artroplastiayhdistys 2012).

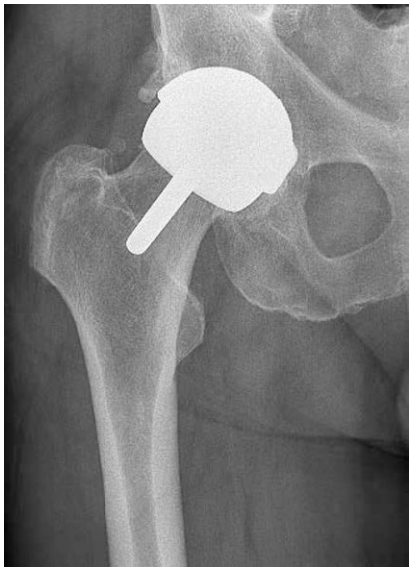

Figure 10. Hip resurfacing arthroplasty with MoM bearings.

2.3.4 Ceramic on polyethylene and ceramic on ceramic (CoP, CoC)

Aluminum oxide, also known as alumina, was introduced in the 1970s and is currently the most frequently used ceramic. Its extreme hardness and smooth surface and hydrophilic properties help create better lubrication and further reduce friction and wear. The released debris is not biologically active and has no potential for ion release (Lerouge et al. 1997). The most important complication with ceramic bearings is risk of breakage. However, according to NJR data, with the currently used 4th generation ceramics the risk of breakage is relatively small, at 0.009% in BIOLOX delta heads and 0.112% in BIOLOX delta liners (Howard et al. 2017). Another CoC-related problem is squeaking. A study of 749 patients with 4th generation CoC bindings found squeaking in 6.4% of patients, although none of them were revised for clicking or squeaking (Lim et al. 2018). Salo et al. reported a high prevalence of squeaking, 17% of patients reported noises, and 48% of them reported that the noise was frequently heard. The only independent risk factor was a specific THA brand. Lower mean OHS was measured in patients with squeaking THAs (Salo et al. 2017).

CoC and CoP bearings (Figure 11) have shown good clinical performance (Kim et al. 2013). It has been stated that CoP results in lower rates of wear and osteolysis, and aseptic loosening is reported to be minimal (Malerba et al. 2015). However, the 2020 AOANJRR Annual Report shows that CoPx and MoPx bearings result in an equally cumulative revision rate percentage. Trunnion corrosion has not been an issue with ceramic heads, but there are reports concerning ceramic heads and

corroded trunnions (Banerjee et al. 2015). Sleeved ceramic heads can also cause trunnion corrosion, but the importance of this phenomenon is thought to be minor (Wyles et al. 2020). CoP is currently the most frequently used bearing in the U.S. (Heckmann et al. 2018).

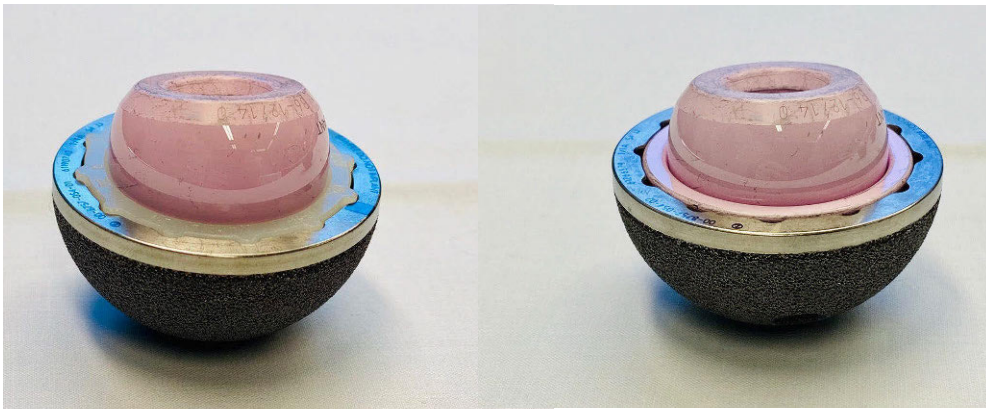

Figure 11. Ceramic-on-polyethylene (left) and ceramic-on-ceramic (right) bearings with Continuum cup.

2.4 Ultra-high-molecular-weight polyethylene (UHMWPE)

Polymerization of UHMWPE was commercialized in the 1950s by the German company Ruhrchemie AG. The original polymer resin was called GUR (Granular UHMWPE Ruhrchemie) resin. It is first polymerized as a fine powder or flake, then must be consolidated into a solid material before it can be used in orthopedic implants. There are generally two methods of polymer consolidation: ram extrusion and compression molding (Blunn et al. 2002, Kurtz et al. 2006). The former provides long UHMWPE bars directly, whereas compression molding can be used to produce large sheets of consolidated bulk, that are then processed into smaller pieces depending on the required product. The final shape of the implant is commonly produced by machining of consolidated UHMWPE bar stock or sheet material. Very few studies have examined the differences between the methods, but molded implants are reported to have a better tensile strength, elongation and hardness compared to ram-extruded devices in some studies (Rieker et al. 2001, Wahyudi et al. 2018).

Sterilization of conventional polyethylene (PE) is most often performed with plasma gas, ethylene oxide or gamma irradiation in air (25–40 kGy). The benefit of this process is molecular crosslinking, which provides improved wear resistance (Hopper et al. 2003). As a downside, the process produces free radicals that decrease

resistance and degradation and thus increase polyethylene wear (McKellop et al. 2000). Gas plasma sterilization was invented in the 1990s. Implants are exposed to ionizing gas at low temperature, resulting in pathogen elimination. This is currently the fastest and most cost-effective method for sterilizing implants.

2.4.1 Crosslinking of UHMWPE

To increase the long-term survivorship of THA, crosslinked polyethylene (XLPE) was introduced in the late 1990s to decrease polyethylene wear and osteolysis (Bragdon et al. 2013). Crosslinking is achieved by irradiating PE at a dose higher than required for sterilization (Muratoglu et al. 1999). This process induces the formation of covalent bonds between the polymer chains of PE (crosslinks), resulting in increased resistance to wear (McKellop et al. 1999). HXLPE has shown lower wear rates in vitro (McKellop et al. 2000) and in vivo (Bragdon et al. 2013) compared to conventional (non-crosslinked) UHMWPE. The amount of crosslinking and thus wear resistance increases with the radiation dose (McKellop et al. 1999). As a downside, the number of free radicals rises, and oxidation is exacerbated.

2.4.2 Addition of vitamin E to polyethylene

A potential solution to enhance oxidative stability and decrease wear is to add an antioxidant agent, vitamin E (α-tocopherol), which acts as a free-radical scavenger. It stabilizes the material and increases the resistance of polyethylene against oxidation (Oral et al. 2006a, 2006b). The strength of this method is that the mechanical properties of UHMWPE remain uncompromised, because the manufacturing process does not require post-irradiation heating which impairs the mechanical strength of the material (Oral et al. 2008).

There are generally two methods of adding vitamin E to crosslinked UHMWPE: blending the vitamin E with UHMWPE before the irradiation and crosslinking process or infusing it afterwards (Lambert et al. 2018). A higher vitamin E concentration can be achieved by infusing it after crosslinking (Rowell et al. 2011), but improved resistance against wear with higher vitamin E levels has not been demonstrated (S. M. Kurtz et al. 2009). Since the vitamin E-diffused, highly crosslinked polyethylene (VEPE) is quite a recent invention, there are limited data on its efficacy. Although potentially promising mid-term outcomes have been reported (Galea et al. 2018, Nebergall et al. 2017, Scemama et al. 2017, Shareghi et al. 2017), there is a lack of long-term results.

2.4.3 Heating of the polyethylene

Some manufacturers reduce the oxidation potential by heating the material above its melt temperature. This remelting allows the free radicals left in the material to combine, lowering the free radical concentration (Baker et al. 2003). However, this method weakens the mechanical properties of the polyethylene, which may present clinically as cracking and fracture (Bradford et al. 2004). Another method is annealing, where the polyethylene is annealed below the melt temperature after crosslinking. The method does not eliminate all free radicals, and studies have shown that annealed materials can oxidize in vivo (Currier et al. 2007).

2.5 Materials of uncemented cups

2.5.1 Titanium

Porous-coated uncemented cups made of titanium alloy have achieved great success in THA due to their unique properties including strength, corrosion resistance, and biocompatibility (Nouri et al. 2010). The porous metal surface of the implant mimics the properties of cancellous bone, providing reliable bone ingrowth and a reduced rate of aseptic loosening compared to cemented cups (Naziri et al. 2013). Further, ultraporous-coated acetabular components have been developed to further enhance osteointegration (Bourne et al. 2008). It has been said that the lower modulus of elasticity of ultraporous-coated cups compared to conventional porous metals minimizes stress shielding and bone loss in the periacetabular region, thus increasing implant survival (Macheras et al. 2006, Meneghini et al. 2010b, Baad-Hansen et al. 2011, Pakvis et al. 2016).

Titanium fiber metal, titanium beads, plasma spray, and grit blasting are processing methods that have been used to increase the surface roughness and porosity of titanium surfaces. These efforts are intended to enhance initial component stability while encouraging bone ingrowth, leading to a long-term reduction in the rate of aseptic loosening of the acetabular component (Malahias et al. 2020). At present, manufacturing methods of uncemented cups include titanium sintered beads, diffusion bonded fiber metal mesh, cancellous-structured titanium, titanium plasma spray, and 3D printing.

Plasma spray titanium coatings for THA have proven to be a safe, predictable material in long-term follow-up studies (Fabi and Levine 2012). Sufficient primary stability and minimal relative motion between the implant and host bone are the key factors for successful osseointegration of the cup component (Pilliar 1987, Wezel et al. 2005). Several factors affect the primary stability of the component: pore size and surface roughness of the implant, the quality of the underlying bone, and the “snug

fit" between the implant and the host bone (Pilliar 1987, Wezel et al. 2005, Crosnier et al. 2014). Each factor can influence the success or failure of osseointegration of the cup.

Stryker (Mahwah, NJ, USA) introduced the Tritanium primary acetabular component with an ultraporous surface to the U.S. market in 2008 (Figure 12). The porous surface of the Tritanium cup is manufactured by the deposition of commercially pure titanium onto a machined scaffold of reticulated, open-cell, polyurethane foam (Muth et al. 2013). It is designed to have a high porosity and a high coefficient of friction. These properties enhance the biological fixation between the cup and the surrounding bone. Short- to medium-term data have shown good clinical performance for this device (Ramappa et al. 2009, Naziri et al. 2013, Perticarini et al. 2015). Also, the risk of revision of Tritanium cups has been comparable to that of trabecular metal cups (Vutescu et al. 2017). However, a recent study raised concerns about radiolucent lines around the Tritanium cups at 4-year follow-up, even though the revision rate for aseptic loosening was low (Carli et al. 2017).

Figure 12. Tritanium primary acetabular component (@copyrightStyker, courtesy of Stryker).

2.5.2 Tantalum

Tantalum was discovered by the Swedish chemist Anders Ekeberg in 1805. It is a highly porous metal with a porosity of 80%, which is close to that of cancellous bone. Tantalum (trabecular metal, TM) was first introduced to the joint arthroplasty market in 1997. TM cup components were initially indicated especially for cup revisions after THA (Levine et al. 2006). TM cups provide increased bone ingrowth, a better

modulus of elasticity, and better stability due to its porous structure compared to conventional uncemented cup devices made of titanium alloy (Meneghini et al. 2010a) (Figure 13). Since then, TM cups have shown reliable results when used for hip revision arthroplasty and are currently routinely used worldwide (Davies et al. 2011, Mohaddes et al. 2015, Miettinen et al. 2020). Besides revision surgery, TM cups have demonstrated promising mid- to long-term survivorship in primary THA (Baad-Hansen et al. 2011, Howard et al. 2011), and the use of TM cups in primary THA has increased (Wegrzyn et al. 2015, De Martino et al. 2016).

However, a recent register study showed that the early and mid-term revision rate of TM cups was slightly higher compared to other uncemented cups when used in primary THA in Sweden and Australia (Laaksonen et al. 2018). It has been suggested that there might be an increased risk of dislocations associated with the use of primary TM cups due to reduced jumping distance of the femoral head (Pakarinen et al. 2020).

Tokarsi et al. have also suggested that the use of a TM acetabular component in hip revision arthroplasty might be associated with a lower infection rate (Tokarski et al. 2015), but this finding has not been confirmed by register data (Laaksonen et al. 2017, 2018).

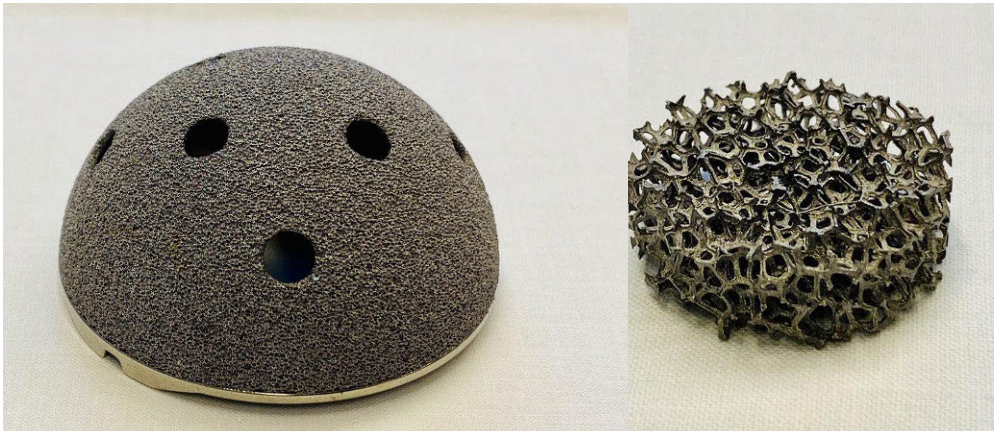

Figure 13. TM revision cup (left). 10-fold enlargement of TM illustrating the porous structure of the metal (right).

2.6 Complications after THA

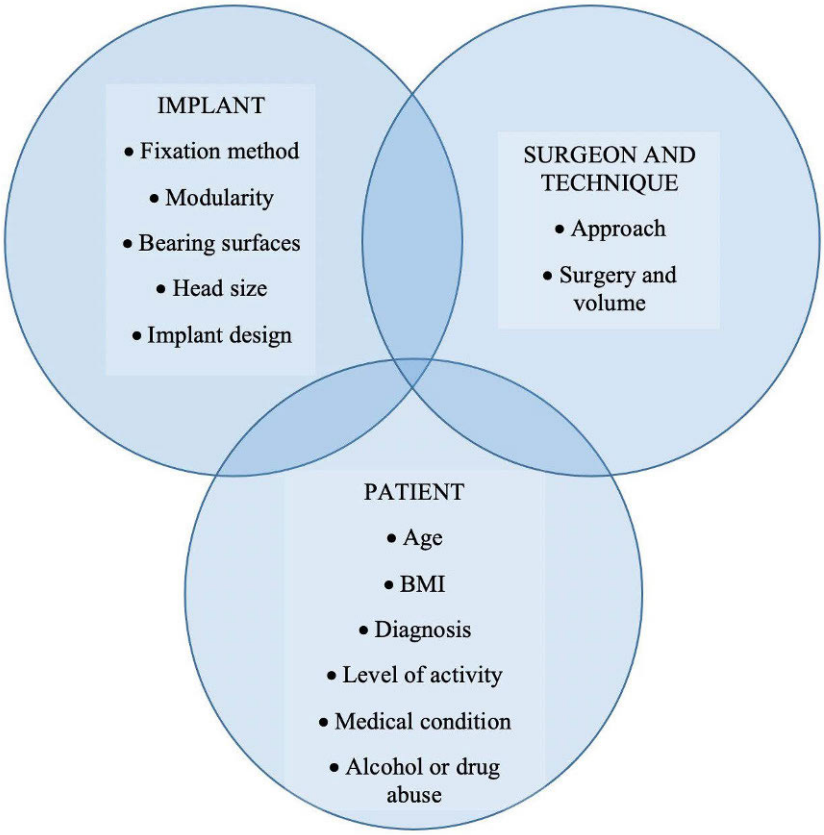

Figure 14. Factors related to hip arthroplasty failure modes.

According to the criteria of the National Institute for Health and Care Excellence (NICE), modern THA should have a revision rate of 10% or less at 10 years (NICE 2014). The modes of failure discussed here are fracture, infection, instability/dislocation, liner wear, aseptic loosening, osteolysis and trunnionosis. Other remarkable complications include failure of fixation, heterotrophic ossification, squeaking, vascular injury, nerve injury, MoM-related problems, and limb length discrepancy. Complication after THA is often a multifactorial phenomenon. Factors can be divided into implant-related, patient-related, and surgery-related (Figure 14). Infection following THA is currently the most important challenge, because infection rates are rising not only in Finland but worldwide (Figure 15).

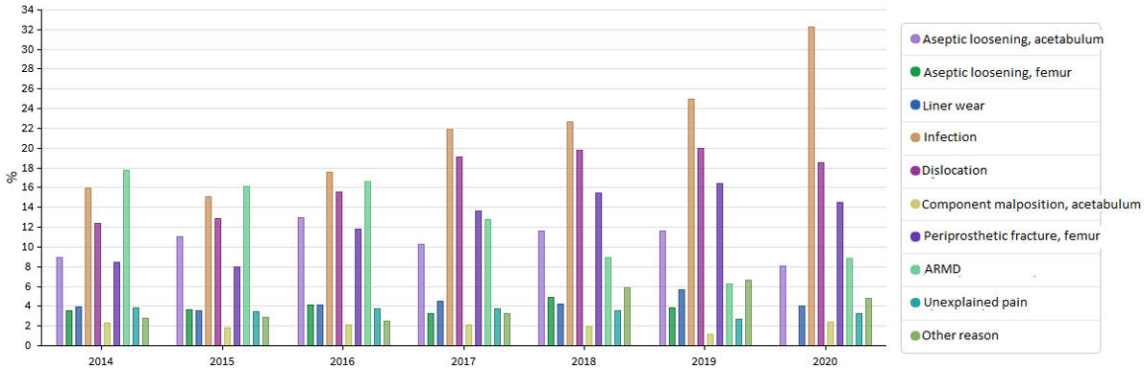

Figure 15. Reason for THA revision in Finnish Arthroplasty Register, 2014–2020.

2.6.1 Periprosthetic joint infection

Periprosthetic joint infections (PJI) are a growing medical challenge, as an increasing number of joint arthroplasties are being performed and the life expectancy of patients is increasing (Huotari et al. 2015). Indeed, the cumulative incidence of PJI in the U.S. and the Nordic countries is reportedly growing. The risk of PJI following THA rose from 1.99 to 2.18% from 2001 to 2009 in the U.S. (Kurtz et al. 2012), and the Nordic Arthroplasty Register Association (NARA) has reported increased 5-year revision rates due to infection. Between 1995 and 1999, the 5-year revision rate due to infection was 0.46% compared to 2000-2004, when the rate increased to 0.71% according to the NARA report (Dale et al. 2012). Despite the increased risk, the overall incidence of PJI is relatively low but is still the most common reason for revision in Finland and the third most common reason in the U.S. (FAR, Ong et al. 2009).

Infections are divided into acute and chronic. Acute infections are further classified into acute post-operative (Figure 16) and late hematogenous infection. In case of acute infection, DAIR (debridement, antibiotics, irrigation and retention of the component) has shown encouraging results (Anagnostakos and Schmitt 2014). Chronic periprosthetic infections are treated with a one-stage or two-stage revision, which is the gold standard. Resection arthroplasty and chronic suppressive antibiotic therapy can be used if the patient is, for example, medically unfit for multiple demanding surgeries.

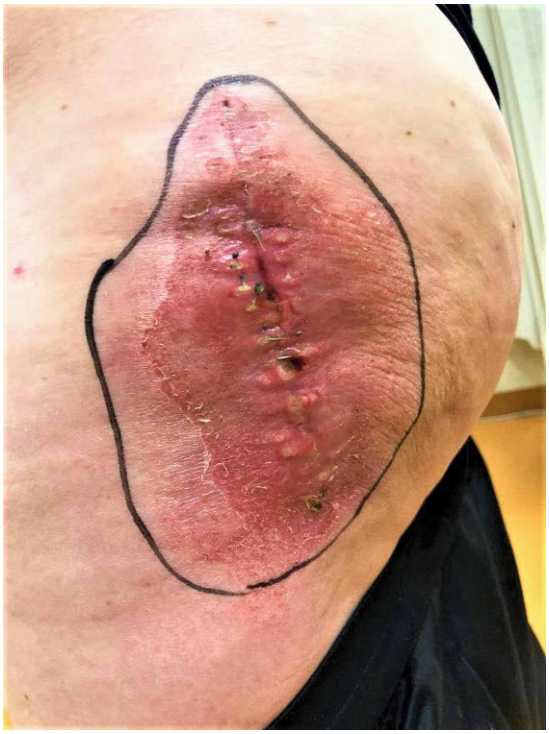

Figure 16. Acute post-operative PJI 3 weeks after primary THA.

2.6.2 Dislocation

Dislocation is one of the most common early complications of primary THA (Hailer et al. 2012) (Figure 17). Dislocation was the third most common reason for revision in the AOANJRR 2020 annual report, with a 20.3% cumulative percent revision after primary conventional THA (AOANJRR 2020). Dislocation rates have varied from 1.7% to 3% in the U.S. (Mahomed et al. 2003, Khatod et al. 2006). Dislocation does not automatically need a revision operation, and single episodes can be treated successfully with closed reduction, whereas recurrent dislocations often need a revision. Blom et al. described the incidence of recurrent dislocations in a cohort study of 1727 primary THAs, and reported 58.5% of dislocations to be recurrent (Blom et al. 2008).

Dislocation is often multifactorial: patient-related, surgery-related and component-related factors have been reported (Howie et al. 2012). The posterior approach, implant choice, poor repair of soft tissues, and little surgeon experience have generally been accepted as surgery-related risk factors for dislocation (Brian C Werner 2012, Hailer et al. 2012, Zijlstra et al. 2017). Poor acetabular component positioning is generally thought to be a reason for dislocation, but a systematic review by Seagrave et al. revealed that most studies could not identify a statistically significant difference between dislocating and non-dislocating THA with regard to

mean angles of cup anteversion and inclination (Seagrave et al. 2017). Patient-related risk factors include femoral neck fracture, osteonecrosis, decreased muscle tone, and proprioception and spinopelvic mechanics (AOANJRR 2018, Vigdorchik et al. 2019). Implant-related factors are, for example, femoral head size and cup or liner design.

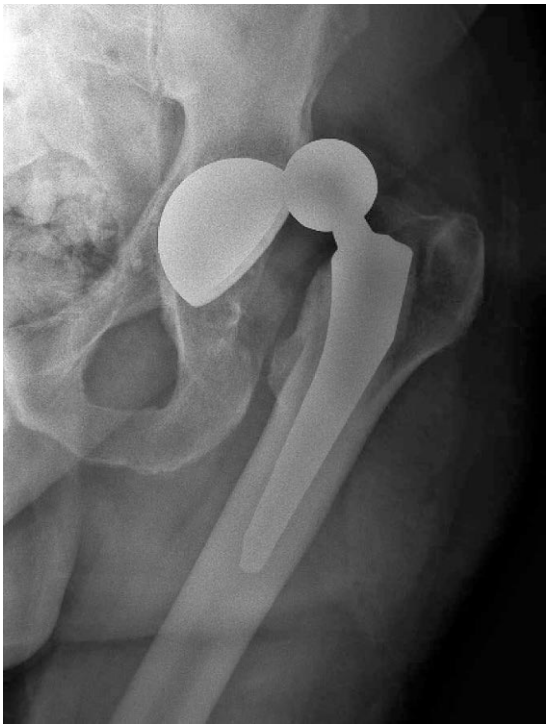

Figure 17. Radiograph of left hip demonstrating dislocation of THA.

2.6.3 Periprosthetic fracture

Intraoperative periprosthetic fractures occur in surgery during rasping of the femoral stem or reaming of the acetabular shell, or during implantation of components. Postoperative periprosthetic fractures are a consequence of external force leading to bone breakage around the implants. The rate of this complication is increasing as a result of increased numbers of THA procedures and the high demands of elderly patients (Kurtz et al. 2007). Surgeons can manage the risk with individual implant selection. According to register data, cemented or hybrid THA can offer better survival for patients aged 65 years or more, whereas uncemented THA can provide good results in younger patients (Mäkelä et al. 2014a, AOANJRR 2018). Fractures are classified according to the Vancouver classification (Figure 18). Type A fractures are peritrochanteric, which are further divided into two classes: greater trochanteric

(AG) and lesser trochanteric (AL) fracture. Type B fracture is located around or just below the tip of the stem. Type B fractures again are divided into three subgroups: in type B1 the stem is well fixed, in type B2 the stem is loose, but the proximal bone stock is good, and in type B3 the stem is loose with poor-quality bone stock. Type C fracture is located well below the stem.

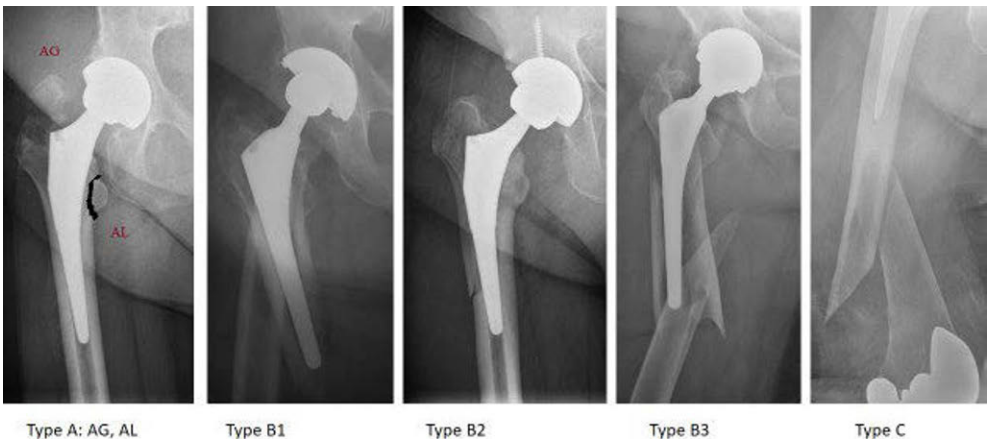

Figure 18. Vancouver classification of femoral stem periprosthetic fractures (Type A–C). Type A: Peritrochanteric fractures. AG: Greater trochanter, AL: Lesser trochanter. Type B: Around or just below the tip of the stem. Type B1: Well-fixed stem. Type B2: Loose stem with good proximal bone quality. Type B3: Loose stem with poor-quality bone stock. Type C: Fracture well below the stem.

2.6.4 Liner wear, aseptic loosening and osteolysis

Wear is described as a result of local mechanical damage due to articulating surfaces and unwanted loss of material and production of wear particles. Conventional wear includes fatigue and interfacial (bearing surface) wear. Fatigue wear is a result of repetitive mechanical stress of bearing couples. Interfacial wear is further divided into abrasive and adhesive wear (Bhatt and Goswami 2008). The wear of UHMWPE in THA is mainly adhesive and abrasive, and this phenomenon produces wear particle debris (McKellop et al. 1995). Abrasive wear occurs when bearing surfaces mechanically grinds against others. If another material is softer, the harder surface cuts into the softer one. Adhesive wear occurs when bonding of microcontacts exceeds the inherent strength of either material. As a result, the weaker material may tear off and adhere to the stronger material. Other wear-affecting factors include surface roughness, material hardness, contact areas, and loads applied (Jasty et al. 1997, Bhatt and Goswami 2008).

Wear of bearing surfaces is thought to be the main limiting factor for long-term survival of THA. Polyethylene particles induce a chronic inflammation reaction,

which causes osteolysis around implants (Green et al. 1998). Polyethylene wear was a serious problem in first-generation PE liners. Santavirta et al. reported aggressive granulomatous lesions in uncemented THA in 1990, and further alarming wear rates of first-generation PE- liners have been published (Amstutz et al. 1992, Schmalzried and Callaghan 1999, Puolakka et al. 2001a, Dumbleton et al. 2002). Gross liner wear can even lead to metallosis if a broken liner allows contact between the metal parts of an implant. The properties of polyethylene liners have improved significantly due to crosslinking, and massive polyethylene wear is rarely seen in crosslinked polyethylene liners (Hanna et al. 2016).

Aseptic loosening is a result of a biological response to polyethylene wear debris, which sets up a chronic inflammation reaction (Merola and Affatato 2019). The mechanism of the phenomenon was first described in the mid-1990s as a macrophage-transmitted biological response to polyethylene wear debris (Harris 1995, Green et al. 1998). The steps of the process include 1) particulate debris formation, 2) macrophage activated osteolysis, 3) prosthesis micromotion and loosening, and 4) particulate debris dissemination.

Particulate debris formation is caused by different types of wear in bearing surfaces; adhesive wear is the most important in regard to osteolytic processes. Other types include abrasive wear, which has a cheese-grater effect of the prosthesis scraping off particles; third-body wear; volumetric wear, which is directly associated with femoral head size, which is the main determinant of the number of particles created; and finally liner wear, which can be measured by the distance that the femoral head has penetrated into the liner (Schmalzried and Callaghan 1999).

Next, polyethylene debris formation activates macrophages, inducing osteoclasts to resorb bone around the implant and leading to osteolysis (Green et al. 1998). Osteolysis leads to implant micromotion and thus an increase in particle wear and further loosening of the prosthesis (Green et al. 1998). In the final step, increased hydrostatic pressure leads to further dissemination of debris within the periprosthetic space (Green et al. 1998).

The intensity of the osteolytic reaction varies, and patient susceptibility to aseptic loosening may be affected by host-, genetic-, surgical-, and implant-related factors, but their relative importance is not known (Karachalios et al. 2018). It is also worth noting that chronic infection has been found in 4–13% of patients with a preoperative diagnosis of aseptic loosening (Moojen et al. 2010).

2.6.5 Trunnionosis

Preserving the patient's anatomy in THA is important for achieving good functionality and patient satisfaction. Modular heads are designed with this in mind, as limb length, offset and soft tissue balancing can be managed, and normal anatomy

more easily preserved. Furthermore, exposure of the acetabular component can be done by removing the femoral head in revision surgery. However, modularity increases risk for mechanically assisted crevice corrosion (MACC) (also called trunnion corrosion) and may lead to trunnionosis, ALTR, and even early femoral head dissociation and implant failure (Figure 19).

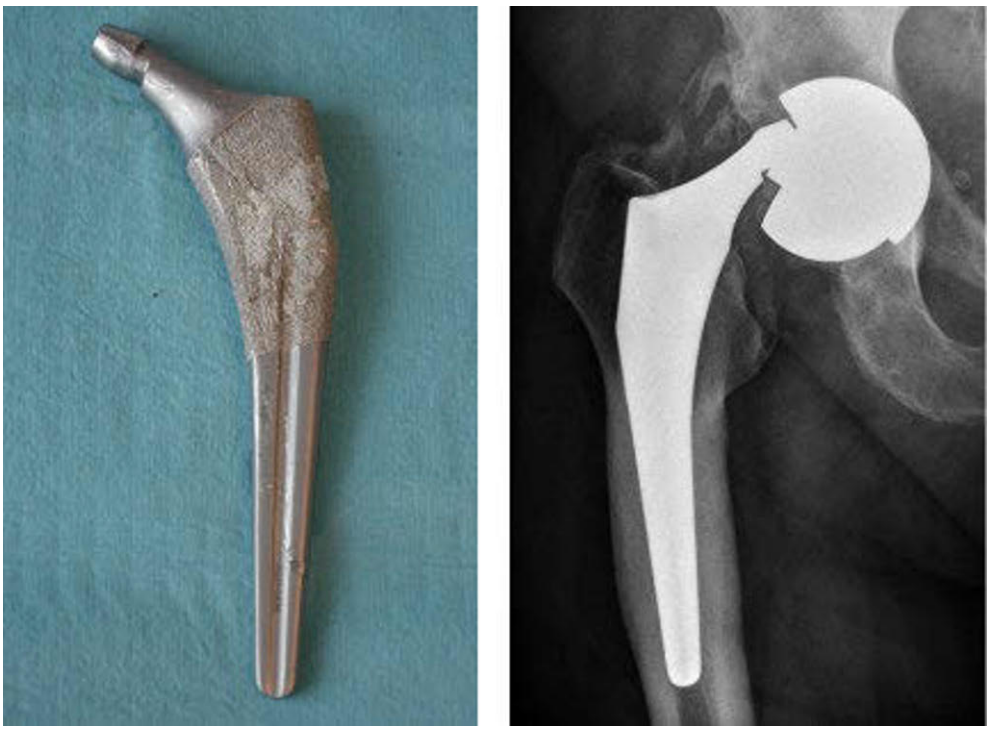

Figure 19. Severely damaged trunnion and "bird beak" appearance of an Accolade stem (left). Anteroposterior radiograph showing the femoral head dissociated from the trunnion after THA (right).

MACC is a multifactorial and poorly understood phenomenon. Affecting factors can be divided into patient-related, component-related, and surgery-related (Goldberg and Gilbert 2003, Gilbert et al. 2009, Jacobs et al. 2014). Patient-related factors include male sex and high body mass index (BMI). Component-related factors include stem design, high-offset implants, head-neck angle, femoral head diameter, and the metal alloy. Surgery-related factors include damage to the head-neck surfaces and inappropriate surgical technique. It has been estimated that 3% of all hip revision procedures worldwide are currently performed due to trunnion corrosion (Porter et al. 2014, Drummond et al. 2015, Mistry et al. 2016). Femoral head dissociation and implant failure still remain a rare complication (Banerjee et al. 2015, Ko et al. 2016).

2.7 Arthroplasty registers

Complications can often become apparent years after successful performance of THA. Even Charnley required detailed follow-up of his patients for monitoring the survival of THA. The purpose of a registry is to collect institutional, regional or national data to analyze and draw statistically significant conclusions regarding patient, surgical technique, and implant associated risk factors that lead to good or poor outcomes (Malchau et al. 2018). Long-term registration has improved the quality of hip arthroplasty, providing information about patient risks, implant safety, and greater efficacy of surgical and cementing techniques (Herberts and Malchau 2000).

The Swedish Hip Arthroplasty Register (SHAR) was the first nationwide register in the world and was established in 1979. The Finnish Arthroplasty Register (FAR) was founded soon afterwards in 1980 by the Finnish Society of Orthopaedic surgeons and is regarded as the second oldest national register. At present, the most important registers are FAR, SHAR, the Swedish Knee Arthroplasty Register, the Norwegian Arthroplasty Register, the Danish Hip and Knee Arthroplasty Registries, the National Joint Registry for England, Wales, Northern Ireland and the Isle of Man, and the Australian Orthopaedic Association National Joint Replacement Registry.

2.7.1 Finnish Arthroplasty Register

The Finnish Arthroplasty Register (FAR) was founded in 1980 and is the second oldest arthroplasty register in the world. In 1987, the authorities responsible for regulating and checking health care services took over the management of the register. The main purpose of the register was to secure the safety and quality of THAs. The national agency for Medicines was responsible for the register until 2009, when the Finnish National Institute for Health and Welfare took over the administration of the FAR (Puolakka et al. 2001b).

Since 1997, orthopedic units have been obligated to provide information essential for maintenance of the register, and data completeness exceeds 95% for primary THA and 81% for revision THA. Dates of death are obtained from the Population Information System maintained by the Population Register Center. The data for the register is collected prospectively by all arthroplasty units and submitted to the register online or after a short delay. Implant register notifications were first done on paper forms and sent to the register. The data content of the FAR was scrutinized and revised in May 2014; since then, all implants have been identified by electronic reading of the reference codes perioperatively in operating theaters nationwide. The updated data now includes detailed information on items such as ASA class, BMI, intraoperative bleeding, duration of procedure, surgical approach,

and reason for revision. The FAR website offers open access to basic reports with implant survival estimates. Figure 20 shows the number of primary THA procedures and gender distribution in Finland from 1980 to 2020.

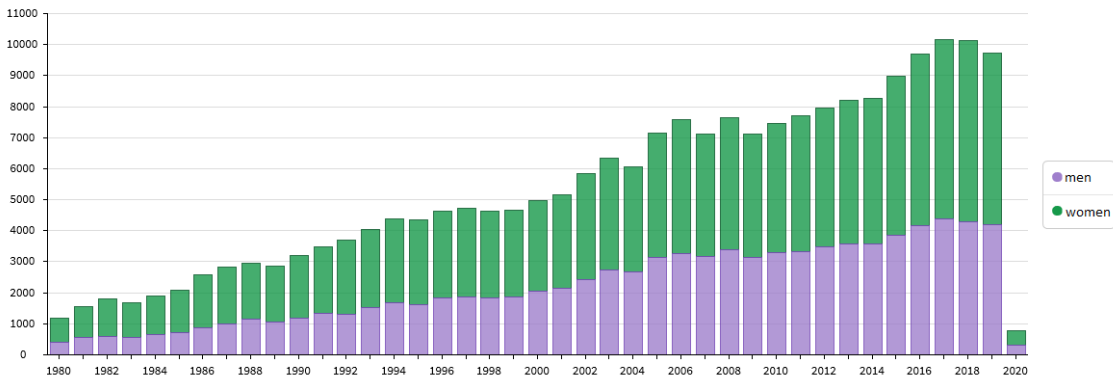

Figure 20. Primary THA procedures in Finland in 1980–2020 with gender distribution.

2.7.2 Strengths and weaknesses of arthroplasty registers

A register's data quality is the most important factor for its ability to conduct continuous qualitative improvement work and clinical research (Malchau et al. 2018). Revision operations have long been the only outcome with which to measure implant survival in the FAR; it is possible that some patients experienced complications without having a revision, for example if they had poor general health contraindicating such risky surgery. However, since 2019, orthopedic units in Finland have been encouraged to gather patient-related outcome measures (PROM) from closer follow-up.

Register maintenance requires teamwork, and synchronization of variables and statistical methods are also crucial for collaboration studies and outcome comparison between different registers in different countries.

3 Aims

The aim of this dissertation is to gain information about specific implant survival and complication rates following primary THA.

1. To compare the revision rate of Continuum cups used in primary THA with the most commonly used uncemented cups made of titanium alloy.
2. To evaluate the overall risk of revision of primary THAs with the Tritanium cup compared to THAs performed with conventional titanium alloy cups.
3. To assess implant survival of vitamin E-infused HXLPE liners compared to moderately crosslinked polyethylene (ModXLPE) liners in THA.
4. To describe a case report on Accolade uncemented stem trunnion corrosion, femoral head dissociation and failure, and introduce treatment options.

4 Materials and Methods

4.1 Patients

4.1.1 Studies I, II and III

Studies I, II and III are based on data from the Finnish Arthroplasty Register (FAR). FAR has been recording patients and implants since 1980, and orthopedic units are obligated to provide information essential for maintenance of the register. The completeness of primary THA data exceeds 95% and of revision THA 81%. Dates of death are obtained from the Population Information System maintained by the Population Register Center. The data content of the FAR was scrutinized and revised in May 2014, and the updated data now includes detailed information on items such as ASA class, BMI, intraoperative bleeding, duration of procedure, surgical approach, and more detailed reasons for revision.

In study I, primary THAs reported to FAR between the 1st of January 2009 and the 31st of December 2017 were selected (n=133,488). The Continuum group consists of 11,390 primary cups and the reference group included 30,372 primary cups made of titanium alloy. The flow chart is presented in Figure 21 and acetabular cups included in the study in Table 1. In all, 4,407 patients had a bilateral hip prosthesis, and in 658 patients both hips were operated simultaneously; 498 patients had the Continuum cup in one hip and a control-group cup component in the contralateral hip. Mortality in the Continuum group was 4% and in the control group 5% during the study period.

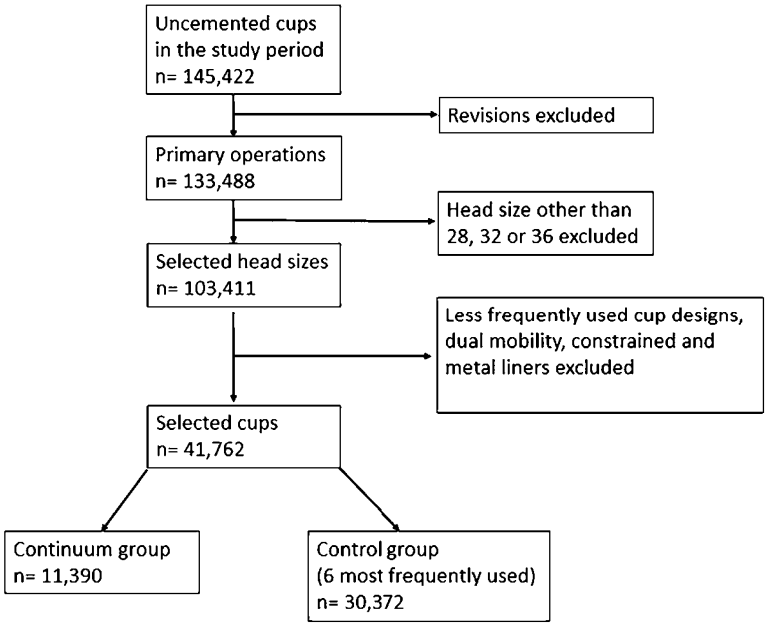

Figure 21. Flow chart of study I (Continuum study).

Table 1. Acetabular cups included in the study I

Cup design	N	%
Continuum [1]	11,390	27
Reference group	30,372	73
Exceed [1]	1,550	4
G7 [1]	1,121	3
Pinnacle [2]	14,844	36
R3 [3]	7,289	18
Trident (shell) [4]	4,279	10
Vision Ringloc [1]	1,280	3

[1] ZimmerBiomet, Warsaw, IN, USA; [2] DePuy, Warsaw, IN, USA; [3]Smith & Nephew, Andover, MA, USA; [4] Stryker, Mahwah, NJ, USA

In study II, 133,488 primary THAs were registered in the FAR between the 1st of January 2009 and the 31st of December 2017. A Tritanium cup was used in 6,080 of these cases. The reference group (N=25,670) consisted of the five most commonly used uncemented cups made of titanium alloy. THAs with a head size other than 28mm, 32mm or 36mm were excluded, as well as dual mobility cups and constrained liners. The flow chart is presented in Figure 22. The mortality in the Tritanium group was 7.0% and in the control group 4.6% during the study period. The number of patients with bilateral hip arthroplasties was 3,126, and in 512 patients both THA

procedures had been performed simultaneously. The total number of patients included in the study was 28,624.

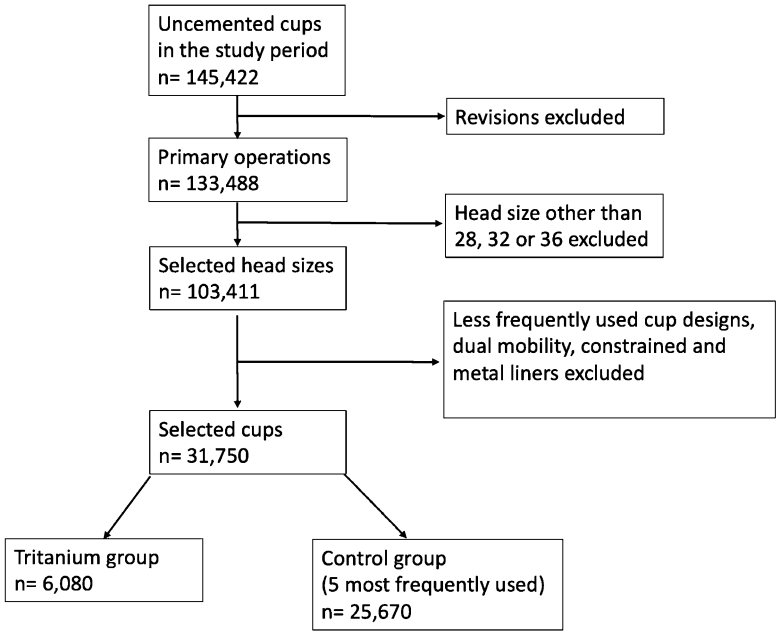

Figure 22. Flowchart of study II (Tritanium study).

In study III, 133,488 primary THAs were reported to the FAR between the 1st of January 2000 and the 31st of December 2017. We included in the study group any THAs in which the vitamin E-infused HXLPE (E1™, E-poly™) liner option was used with one of five uncemented acetabular components from the same manufacturer (ZimmerBiomet, Warsaw, Ind): Biomex, Exceed, G7, Regenerex, and Vision Ringloc). The reference group consisted of THAs operated with ModXLPE liners from the same manufacturer (mostly ArCom™) with the same cup designs. Exclusion criteria were head size other than 28 mm, 32 mm, or 36 mm; metal or ceramic liner; dual mobility acetabular device; or constrained liner. Only THAs with uncemented stems were included in the study. In 5,430 THAs the study inclusion criteria were fulfilled, and femoral head material information was reported to the register (2,723 E-poly or E1 liner THAs). The patient selection flowchart is presented in Figure 23. The mean follow-up time was 5.0 years in the study group (range 0–9.7 years) and patients were operated on between the 1st of January 2008 and the 31st of December 2017. The reference group patients were operated on between the 1st of January 2000 and the 31st of December 2017, with 11.0 years (range 0–18.5 years) mean follow-up time. The number of patients with bilateral

THA was 410, of whom 85 patients had bilateral hip prostheses operated simultaneously. Mortality in the VEPE group was 10% versus 27% in the control group during the study period. Differences in mortality between the groups are explained by the difference in follow-up time.

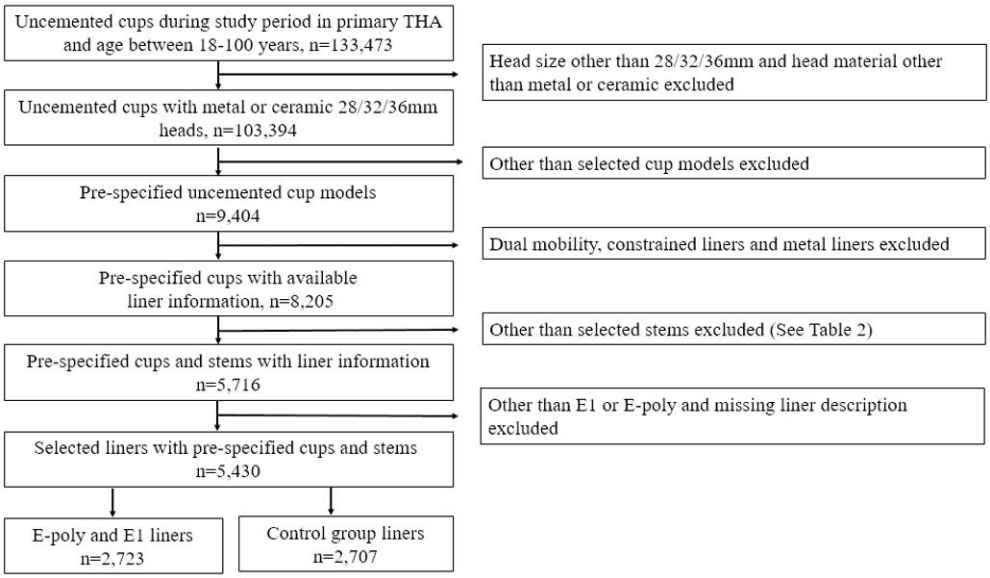

Figure 23. Flowchart of the study III.

4.1.2 Study IV

We describe a case report from our hospital on Accolade uncemented stem trunnion corrosion, femoral head dissociation and failure. The patient was informed that data concerning the case would be submitted for publication and provided consent.

The 75-year-old male with asymptomatic lung asbestosis had somewhat limited physical capacity due to right hip osteoarthritis but was otherwise fit. The patient's BMI was 29 and the goal for post-operative activity was to gain normal physical activity and pain relief. He was operated on in 2008 using a Stryker (Mahwah, NJ, USA) Accolade TMZF size 4 standard offset 127 CCD angle stem with a Stryker Mitch 50mm + 8mm head and a Stryker Mitch uncemented 54mm cup with MoM bearing surfaces. The post-operative X-ray showed a thin 0.5mm radiolucent line at the base of the cup, but otherwise no signs of complications. The cup anteversion was 20 degrees and inclination 37 degrees. Three days after the primary operation the patient fell, and the cup was tilted. An early cup revision operation was performed 7 days after the primary operation using a Mitch 50mm + 8mm head and a Mitch uncemented 56mm cup with MoM bearing surfaces. Bacterial culture from the

revision showed growth of Staphylococcus capitis. A repeat joint aspiration culture gave a negative result, indicating that the first sample was likely contaminated. The patient recovered well and after 1 year was asymptomatic and could walk several kilometers without any problem. The range of motion of the hip was good, the lower limbs were of equal length, and the Trendelenburg test was negative.

The patient's right hip was asymptomatic for 9 years, until he stood up from a chair and felt a sudden pain in the hip. He was unable to bear weight on the hip. Radiographs showed dissociation of the femoral head from the trunnion and probable trunnion damage (Figure 24a). The re-revision was performed 2 days later, revealing the stem. Some metallosis was found in the joint, but no pseudotumor was evident. The trunnion was corroded and severely damaged; thus, the stem needed to be replaced. The stem was well fixed, and an extended trochanteric osteotomy of the femur was performed. The stem was replaced with a modular Arcos revision stem. A 12x150mm STS distal bearing stem and a cone B 60 High-Offset proximal part was used. The cup was exposed, and as the position of the cup was acceptable and the cup well fixed, it was retained to avoid possible damage from component removal. A 56 mm dual mobility system was used to prevent damage and dislocation (Figure 24b).

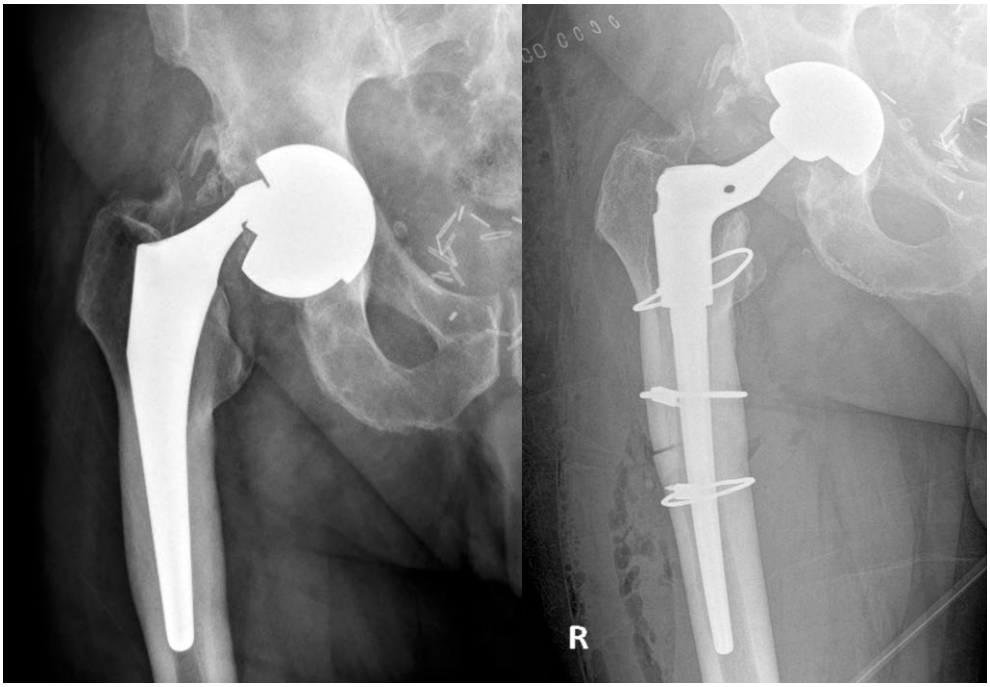

Figure 24. 24a (left) Anteroposterior radiograph showing the femoral head dissociated from the trunnion after THA. 24b (right): Anteroposterior radiograph showing the outcome after revision surgery with an Arcos 12x150mm STS distal bearing stem and a cone B 60 High-Offset proximal body.

4.2 Methods

4.2.1 Study I

The primary outcome was revision for any reason, and secondary outcomes were revision for periprosthetic infection, revision for dislocation, and cup revision for any reason. Patients were followed until the end of the study period and censored for any other event than the outcome. Since the register update in May 2014, it has been possible to assess separately which component has been changed or removed in connection with the revision. Therefore, a subgroup analysis for cup-only revisions was performed only for FAR data after May 2014. In addition, a subgroup analysis was performed for Continuum cups by liner type (neutral or elevated liner) with dislocation revision as the endpoint.

4.2.2 Study II

The primary outcome was the first revision for any reason and the secondary outcome was the first revision for aseptic loosening of the cup. Revision was defined as a change or removal of at least one component. Patients were followed until the end of the study period and censored for any other event than the outcome.

4.2.3 Study III

The primary outcome was revision for any reason and the secondary outcome was revision for loosening of the cup, osteolysis, liner wear or liner breakage. Prior to the register update in 2014, revisions performed for osteolysis and wear were coded as performed for ‘other reason’; therefore, revisions performed for ‘other reason’ prior to May 2014 are included in the analyses for secondary outcome. Patients were excluded for any other event than the outcome.

4.2.4 Study IV

We assessed the risk factors for trunnion corrosion based on the current literature and the patient in our own case report.

4.3 Statistical analyses

Kaplan-Meier (KM) survival estimates were calculated for the study groups and the log rank test was used to compare the survival curves. Revision was described as a change or removal of at least one component. Survival data are presented as

percentages with the 95% confidence interval (CI). Cox regression analysis is presented with the hazard ratio (HR) and the CI. SAS software (Version 9.3/9.4) was used for performance of the analyses.

4.3.1 Study I

KM survival estimates were assessed for both study groups. We adjusted the estimated revision risks in the Cox multiple regression model by gender, age group, diagnosis, femoral head size, operated side, operation year, and fixation of the femoral stem. An additional cup revision analysis was performed, and the type of approach, ASA, BMI, and elevation status of the liner were added to the Cox model as possible confounders for cup revision for any reason as the endpoint. The analysis was done with the date of the primary operation after the register update in May 2014. In the Continuum elevation subgroup analysis, gender, age group, diagnosis, side, stem fixation, and operation year were added to the Cox model (head size was stratified), and other than polyethylene liners were excluded. If the proportional hazards assumption for a variable was not fulfilled in the Cox model, the model was stratified by it instead. Stratification in Cox models means that the hazard functions can be estimated for all level combinations of the stratified variables, and the hazard ratios for the other variables (those that meet the proportional hazard assumption) are then optimized for all these hazard functions. Without stratification we would assume that the hazards were the same for all levels of such variables.

4.3.2 Study II

KM survival estimates with 95% CI were calculated for both study groups at 1, 3, 5, and 7 years for any reason for revision, and for loosening of the cup. To reduce the risk of selection bias, we adjusted the estimated revision risk in the Cox multiple regression model with different factors by age group (18–55, 56–65, 66–75, and 76–100 years), gender, diagnosis (primary osteoarthritis, rheumatoid arthritis, other), femoral head size (28, 32, and 36mm), operated side, operation year (2009–2013, 2014–2017) and fixation of the femoral stem. The type of surgical approach (Hardinge, posterior, anterior), ASA (classes I, II, III and IV), and BMI were added to the Cox model as possible confounders concerning the time period from the 15th of May 2014 onwards (besides age group, gender, diagnosis, femoral head size, operated side, operation year, and fixation of the femoral stem). Results based on the Cox regression model are presented as hazard ratios and 95% CIs. Revision risk for any reason was assessed separately for the whole time period from the 1st of January 2009 to the 31st of December 2017, and for the time period from the 15th of May

2014 onwards. Revision risk for aseptic loosening of the cup was assessed for the whole time period.

If the proportional hazards assumption for an adjusting variable was not fulfilled in the Cox model, the model was stratified by it instead. Stratification in Cox models means that the hazard functions can be estimated for all level combinations of the stratified variables, and the hazard ratios for the other variables (those that meet the proportional hazard assumption) are then optimized for all these hazard functions. Without stratification we would assume that the hazards were the same for all levels of such variables. The proportional hazards assumption was not fulfilled for the variable of interest concerning analyses for the whole period. Therefore, the follow-up time was divided into three time periods: 0–2 years, 2–4 years, and over 4 years. Statistical analyses were also performed using the competing risk method, but the results remained qualitatively the same.

4.3.3 Study III

KM survival estimates with 95% CI were calculated for both groups at 1, 3, 5, and 7 years for any reason for revision and for loosening of the cup, osteolysis, liner wear or liner breakage. We adjusted the estimated revision risks in the Cox multiple regression model by gender, operated side and femoral head material (ceramic, metal). Femoral head size (28, 32, 36 mm), age group (18–55, 56–65, 66–75, >75 years) and preoperative diagnosis (primary osteoarthritis, rheumatoid arthritis, other) were stratified. None of these variables were considered to be along the causal pathway from exposure to outcome but were considered as confounders. The second analysis was performed for loosening of the cup, osteolysis, liner wear or liner breakage as the endpoint. Side, fixation of the femoral stem, femoral head material, gender, and diagnosis were adjusted for in the Cox model, and age group was stratified. Head size was excluded from this model because of large differences in head sizes between the groups.

The Cox model was stratified by a variable if the proportional hazards assumption was not fulfilled. Stratification in Cox models means that the hazard functions can be estimated for all level combinations of the stratified variables, and the hazard ratios for the other variables (those that meet the proportional hazard assumption) are then optimized for all these hazard functions. Without stratification we would assume that the hazards were the same for all levels of such variables. The results of the Cox regression analysis are presented with the hazard ratio and CI.

5 Results

5.1 Survival of Continuum cups in primary THA

In study I, the studied acetabular design Continuum cup was the second most used uncemented cup in Finland during our study period of 2009-2017. The most common reason for THA was primary osteoarthritis (OA) and the second commonest reason was rheumatoid arthritis in both groups. Other reasons included collum fracture, avascular necrosis, osteoarthritis due to hip dysplasia, tumors, congenital hip dislocation, inflammatory arthritis, Legg–Perthes–Calve disease, femoral head epiphyseolysis and status post purulent arthritis, which all presented in similar rates between the groups. The average follow-up time was 3 years (0–9) in the TM group and 4 years (0–10) in the reference group. A 36mm femoral head was used in 79% of cases in the Continuum group and in 80% of cases in the reference group. A ceramic liner was more often used in the reference group (27%) than in the Continuum group (14%). The rest of the liners in both groups were HXLPE. The amount of uncemented femoral components in the Continuum group was 71% versus 83% in the reference group (Table 2).

Table 2. Demographic data of the Continuum group and the Reference group in study I. Time period after data content revision in the FAR starting 15th of May 2014. Number (%) unless stated otherwise

Data	Continuum group	Reference group
Mean age, years (SD)	67 (11)	66 (11)
Body mass index, BMI	28 (5)	28 (5)
Male	3,609 (42)	7,547 (46)
Diagnosis		
Primary OA	7,324 (85)	13,852 (85)
Rheumatoid arthritis	137 (2)	195 (1)
Other	1,113 (13)	2,278 (14)
Femoral head size		
28	29 (0.3)	107 (1)
32	1,832 (21)	3,369 (21)
36	6,713 (78)	12,849 (79)
Status at end of follow up		
Not revised	8,202 (96)	15,792 (97)
Liner material		
Ceramic	619 (7)	2,249 (14)
HXLPE	7,955 (93)	14,041 (86)
Elevated liner		
Yes	3,570 (45)	5,393 (38)
Approach		
Posterior	6,654 (78)	12,884 (81)
Anterolateral	1,667 (20)	2,864 (18)
Other	158 (2)	148 (1)
ASA		
1	1,281 (15)	2,163 (14)
2	4,132 (49)	8,260 (52)
3	2,992 (35)	5,308 (33)
4	105 (1)	195 (1)
Femoral stem fixation		
Uncemented	5,502 (65)	13,209 (81)
Cemented	3,030 (36)	3,057 (19)

Endpoints used in the analyses were 1) revision for any reason, 2) cup revision for any reason, 3) revision due to infection, and 4) revision due to dislocation. A subgroup analysis was done in the Continuum group to determine the risk of revision because of dislocation with or without liner elevation.

THA with a Continuum cup was associated with an increased revision risk compared to other uncemented cups (Table 3). The increased risk was largely explained by revisions for dislocations, and an elevated liner diminished the risk of revision for dislocation.

Table 3. Risk of revision for any reason when using the Continuum cup in primary THA in study I. Adjusted hazard ratios (HR) according to Cox regression model (adjusted for age group, gender, diagnosis, femoral head size, operated side, operation year group, and fixation of the femoral stem).

	Reference group (Ref.)	Continuum group HR (95% CI)
Revision for any reason	1.0	1.3 (1.2–1.5)
Revision for infection	1.0	0.99 (0.8–1.3)
Revision for dislocation	1.0	1.9 (1.5–2.3)
Cup revision as the endpoint	1.0	1.3 (0.8–2.0)

5.1.1 Revision for any reason

The up-to-7-year survivorship for the Continuum group was 94.6% (CI 94.0–95.2) and for the reference group 95.6% (CI 95.3–95.8) for revision for any reason as the endpoint (Figure 25). The risk of revision according to the Cox regression model analysis was slightly higher in the Continuum group than in the reference group for revision for any reason (HR 1.3 (CI 1.2–1.5, p<0.001) (Table 3).

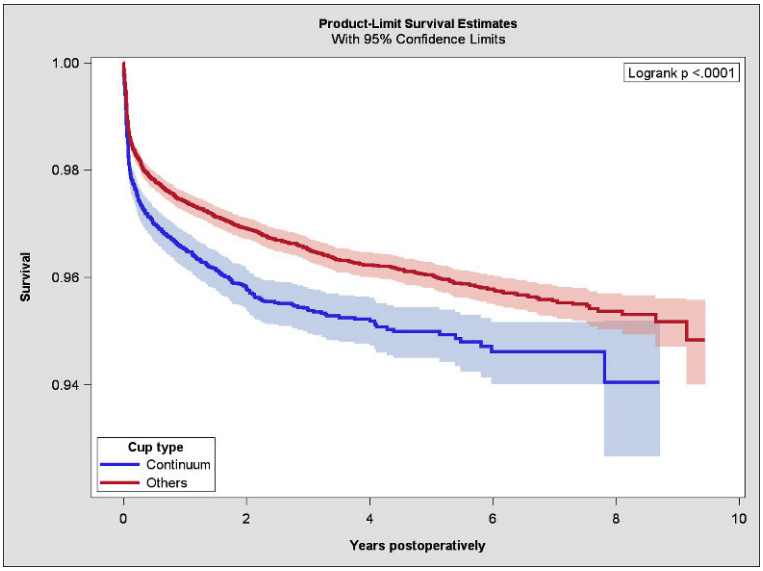

Figure 25. Kaplan-Meier survival for the Continuum group and reference group with revision for any reason as the endpoint. 95% CI levels shown in blue and red.

5.1.2 Cup revision for any reason

This analysis was done with the data on primary operation after register update in May 2014. The 3-year survivorship was the same in the Continuum group as in the reference group: 99.4% vs. 99.6% (CI 99.2–99.6 vs. 99.5–99.7). Risk of cup revision, according to Cox regression analysis, was not statistically different (HR 1.3, Cl 0.8–2.0, p=0.3).

5.1.3 Revision due to infection

When revision due to infection was the endpoint, the 7-year survivorship for the Continuum group was 98.9% (CI 98.6–99.1) and for the reference group 99.1% (CI 99.0–99.2). The adjusted hazard ratio (HR) for revision due to infection did not differ between the groups (HR 1.0, CI 0.8–1.3, p= 0.9).

5.1.4 Revision due to dislocation

The increased revision risk of Continuum cups due to dislocation was the most significant finding in this study (HR 1.9, CI 1.5–2.3, p<0.001). The 7-year survivorship is shown in Figure 26. The Continuum group had a survival of 98.3% (CI 98.0–98.6) and the reference group 99.0% (CI 98.8–99.1), when revision due to dislocation was the endpoint.

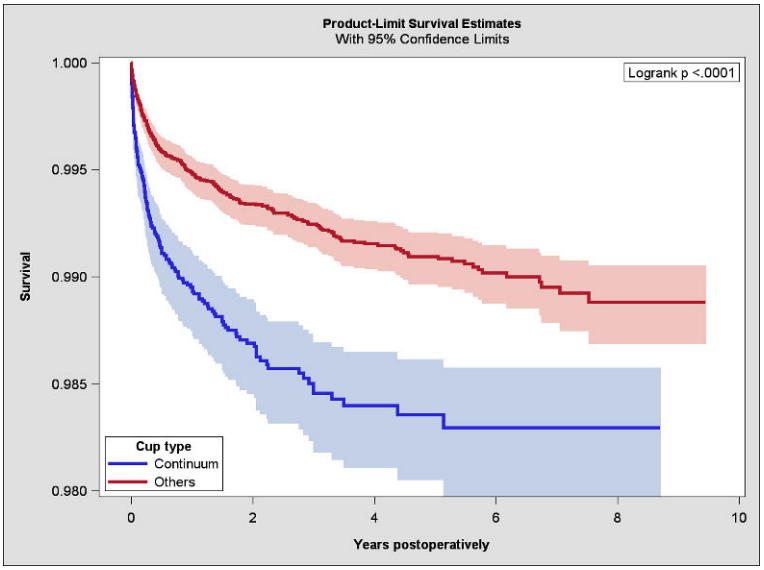

Figure 26. Kaplan-Meier survival for the Continuum group and reference group with revision for dislocation as the endpoint. 95% CI levels shown in blue and red.

5.1.5 Subgroup analyses: Continuum group with or without liner elevation

Statistical analysis revealed that the use of a neutral liner in Continuum THA was associated with an increased risk of revision due to dislocation compared to an elevated rim liner in the Continuum group (HR 1.7, CI 1.2–2.5, p=0.005). KM curves are presented in Figure 27. The 5-year survival for elevated liners was 98.9% (CI 98.4–99.2) and for neutral liners 97.8% (CI 97.3–98.2), when revision because of dislocation was the endpoint (Figure 28).

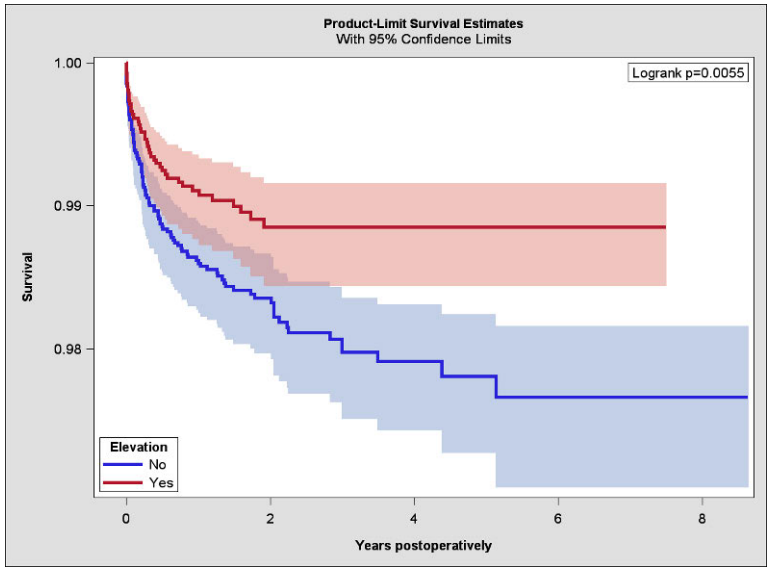

Figure 27. Kaplan-Meier survival by subgroup analysis of Continuum THA with or without elevated liner. Endpoint: revision for dislocations. 95% CI levels shown in blue and red.

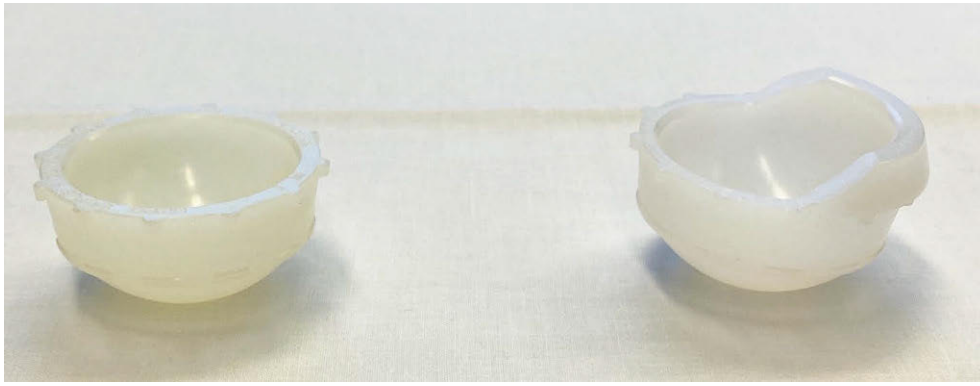

Figure 28. Elevated and neutral liners used with the Continuum cup. An elevated liner was associated with a reduced risk of revision due to dislocation.

5.2 Implant survival of Tritanium cups in primary THA

The average follow-up time was 3.7 (0–9.5) years in the reference group and 3.6 (0–8.8) years in the Tritanium group. The proportion of female patients was 61% in the Tritanium group and 53% in the reference group. The most common head size was 36mm in both groups. Uncemented stems were used markedly more in the reference group (90%) than in the Tritanium group (57%). A posterior approach was the most commonly used technique in both groups. Mean BMI was 27.8 in the study group and 28.3 in the reference group. ASA class 2 was the most common class in both groups. Patient demographic data are given in Table 4.

Table 4. Demographic data of the Tritanium group and reference group in study II. Number (%) unless stated otherwise

Data	Tritanium group	Reference group
Male	2,372 (39)	11,832 (46)
Diagnosis		
Primary osteoarthritis	5,225 (86)	22,059 (86)
Rheumatoid arthritis	107 (2)	432 (2)
Other	748 (12)	3,719(12)
Femoral head size of prosthesis		
28	21 (0,4)	266 (1)
32	726 (12)	5,161 (20)
36	5,333 (88)	20,243 (79)
Status at end of follow-up		
Not revised	5,820 (96)	24,738(96)
Revised	260 (4)	932 (4)
Liner material		
Ceramic	108 (2)	7,557 (29)
HXLPE	5,972 (98)	17,942 (70)
Unknown		171(1)
Operation year		
2009–2013	2,414 (40)	10,017 (39)
2014–2017	3,666 (60)	15,653 (61)
Femoral stem fixation		
Uncemented	3,446 (57)	22,995 (90)
Cemented	2,634 (43)	2,675 (10)

*Missing data: Gender N=10, Operated side N=32

5.2.1 Revision for any reason

The 5-year survival of Tritanium cups was inferior to that of the reference group, when revision for any reason was the endpoint (94.7% (95% CI 94.0–95.4) versus 96.0% (CI 95.7–96.3)) (Figure 29). Cox multivariant analysis revealed that the Tritanium group had an elevated risk for revision for any reason compared to the reference group for the time period 4 years and over (HR 3.12, (95% CI 1.82–5.35, p<0.001)).

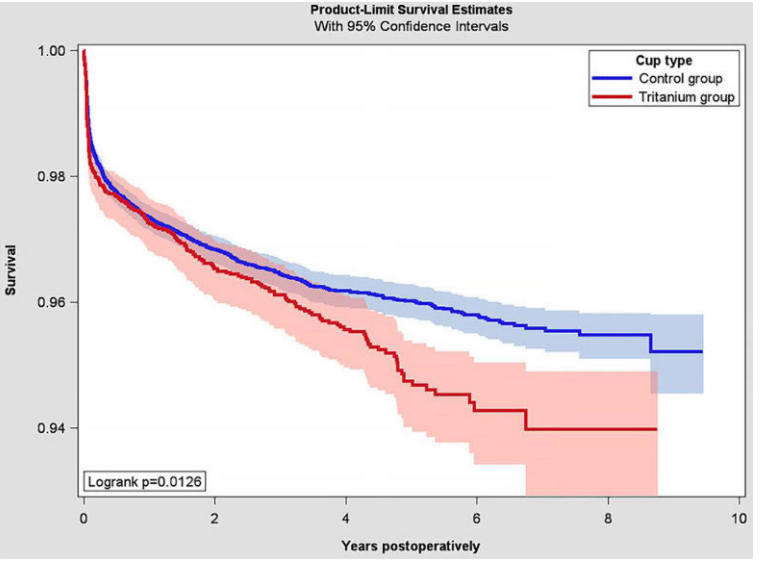

Figure 29. Kaplan-Meier survivorship of the Tritanium group and reference group for any reason of revision with 95% confidence intervals.

5.2.2 Cup revision for aseptic loosening

The 5-year Kaplan-Meier survivorship for the Tritanium group (99.0% (95% CI 98.5–99.3)) was inferior to that of the reference group (99.9% (95% CI 99.9–99.9)) (Figure 30). In the Cox regression analysis, the Tritanium group had an increased risk of revision compared to the reference group both for the time period 0–2 years (HR 3.80; 95% CI 1.76–8.24, p<0.001) and 2–4 years (HR 11.2; 95% CI 3.28–38.0, p<0.001). It was not possible to assess the time period of 4 years and over separately, because there were no revisions for cup loosening in the reference group.

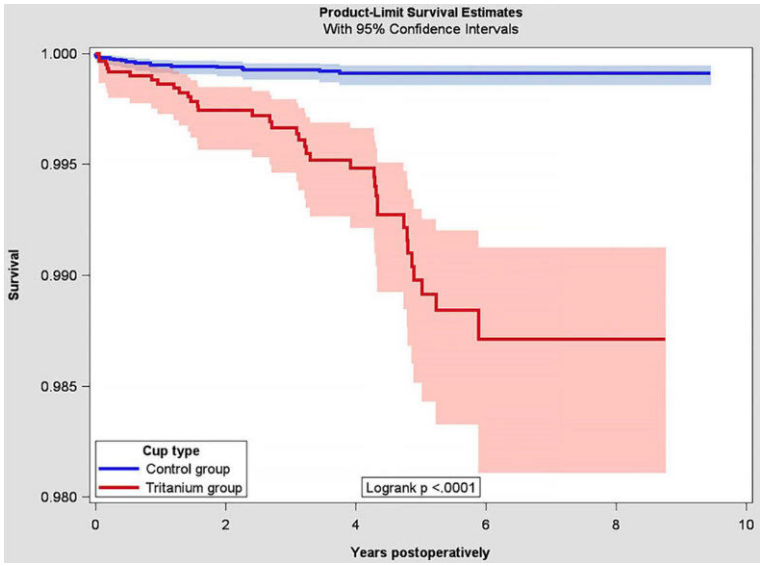

Figure 30. Kaplan-Meier survivorship of the Tritanium group and reference group for aseptic loosening of the cup with 95% confidence intervals.

5.3 Implant survival of vitamin E-infused highly crosslinked polyethylene liners in THA

The most common cup design was the Vision RingLoc (ZimmerBiomet, Warsaw, USA) (36% in the VEPE group, 78% in the control group) in both groups. The Echo stem (ZimmerBiomet, Warsaw, USA) was the most frequently used stem in the VEPE group (50% of all VEPE THAs) and Bi-Metric (ZimmerBiomet, Warsaw, USA) in the control group (91% of all THAs in the control group). A ceramic head was used in 30% of cases in the VEPE group compared to 8% in the reference group. A 36mm femoral head was the most commonly used in 88% of cases in the VEPE group and a 28mm femoral head in the control group (82%). More detailed demographic data is presented in Table 5.

Table 5. Demographic data of the VEPE group and reference group in study III. Number (%), unless stated otherwise.

Data	VEPE group	Reference group
Mean age, years (SD)	67 (10)	64 (9)
BMI (SD)	29 (5)	28 (5)
Male	1,341 (49)	1,357 (50)
Diagnosis		
Primary osteoarthritis	2,328 (86)	2,274 (84)
Rheumatoid arthritis	59 (2)	83 (3)
Other*	336 (12)	350 (13)
Femoral head size		
28	4 (0.2)	2,229 (82)
32	321 (12)	284 (11)
36	2,398 (88)	194 (7)
Femoral head material		
Ceramic	822 (30)	220 (8)
Metal	1,901 (70)	2,487 (92)
Status at end of follow-up**		
Not revised	2,571 (94)	2,348 (87)
Revised	152 (6)	359 (13)
Operation year		
2000–2008	6 (0.2)	2,376 (88)
2009–2017	2,717(99.8)	331 (12)

*Fractures, avascular necrosis, osteoarthritis due to hip dysplasia, tumors, congenital hip dislocation, Mb Legg-Calve-Perthes, femoral head epiphyseolysis
**Excluding death

5.3.1 Revision for any reason

The 7-year survival with revision for any reason as the endpoint was comparable (94.0%; 95% CI 92.9–94.9 and 93.0%; 95% CI 91.9–93.9, respectively). In the Cox regression analysis, the risk of revision between the VEPE group and the reference group was equal (HR 0.7, (CI 0.4–1.1, p=0.09) (Table 6).

Table 6. Risk of revision for any reason when using the VEPE liner, study III. Adjusted hazard ratios (HR) according to the Cox regression model (adjusted variables are mentioned below, stratified by head size, age group and diagnosis).

Group	HR	95% CI		p
Endpoint: All revisions				
VEPE group vs. Reference group	0.69	0.44	1.06	0.088
Adjusting variables				
Left vs. right side	0.98	0.82	1.17	0.836
Female vs. male	0.99	0.83	1.19	0.924
Femoral head material				
Ceramic vs. metal	1.15	0.90	1.46	0.264

5.3.2 Revision for aseptic loosening of the cup, osteolysis, liner wear, or liner breakage

The 7-year survivorship of the two groups was equal (VEPE group 99.1% (95% CI 98.6–99.4); reference group 99.2% (95% CI 98.7–99.5)). The risk of revision was not statistically different between the VEPE and reference groups (HR 1.3 (95% CI 0.7–2.5, p=0.4)).

6 Discussion

A successful THA is a combination of adequate surgical technique and appropriate implants performed for carefully selected patients. A definition of modern medicine is conventional healthcare based on the evidence-based practice for diagnosing and treating diseases. In order to optimize treatment in orthopedic conditions, both traditional clinical research and registry research are needed. Whereas randomized clinical studies have the capacity to detect causality and answer a specific study question, registers allow us to analyze the performance of implants and patients in large volume to detect unanticipated complications and outlier implants. Complications can often emerge years after successful performance of THA; thus, it essential to have ongoing follow-up of these patients. A good example is problems with MoM implants, which first became apparent in the arthroplasty registers (Graves et al. 2011). Registers also enabled follow-up to be arranged for those patients with problematic implants. Even though there are complications associated with current devices, it is worth remembering that the implants we use at present are top of the line and are carefully tested and reported before submission to competitive tendering at our hospital. The differences in outcomes between the devices are often small, and it should be kept in mind that success is the sum of many factors.

6.1 Survival of Continuum cups in primary THA

Complications in THA often result from a conglomeration of different factors, of which our first study is a good example. We found that use of the Continuum THA was associated with a slightly higher risk of revision than with other uncemented titanium alloy cups. The Continuum study group and the reference group had a similar risk of revision due to infection, but the risk of revision due to dislocation was higher in the Continuum group, although this could be reduced by using an elevated rim liner. The Continuum cup was designed to allow better range of motion; thus, the rotation center is outside the cup, meaning the cup is shallower. This feature means that the Continuum cup has a shorter jumping distance which can thus predispose to dislocation, as Pakarinen et al. (2020) have reported (Figure 31). The effect of a reduced jumping distance is highlighted with the use of a posterior

approach, and based on our findings, we recommend the use of an elevated rather than neutral rim liner as the primary choice when using a Continuum cup in primary THA to avoid dislocation.

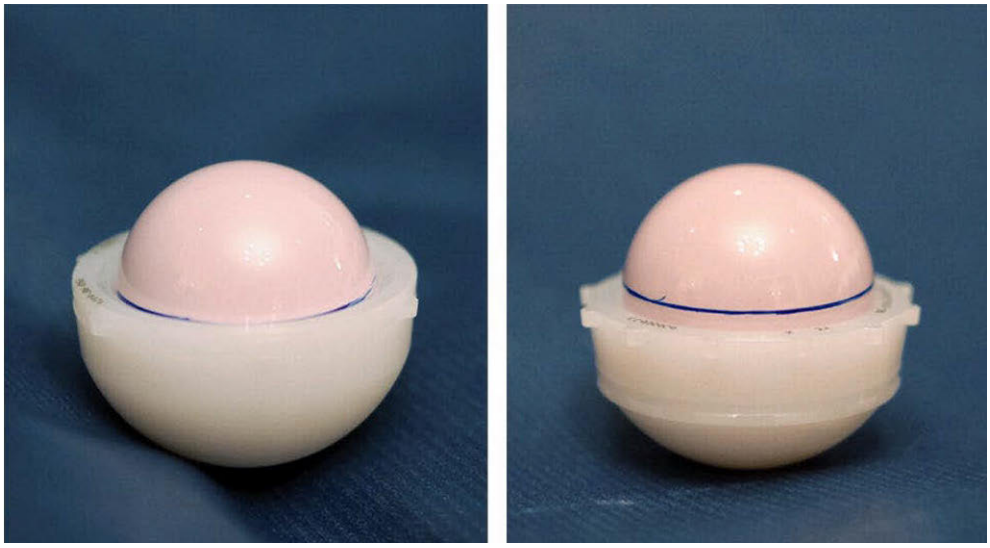

Figure 31. Difference in coverage of the Pinnacle and Continuum neutral liners. The same ceramic head was first placed in the Pinnacle neutral liner (left), and the line at the rim was marked with a pen. The head was moved into a same-sized Continuum neutral liner (right). (Pakarinen et al. 2020, printed by permission).

The outer surface of the Continuum cup is made of TM. The use of TM cups in primary THA is increasing in Sweden and Australia (Laaksonen et al. 2018). Continuum was the second most common cup design in the FAR data of the present study. Due to the good grip and high primary stability of TM, Continuum cups have been preferred in more demanding THAs. To reduce the risk of selection bias towards more difficult cases being treated with Continuum cups, we adjusted the revision risks in the Cox regression models. Our data suggests that use of the Continuum cup in primary THA does not give superior results compared to other uncemented devices. However, TM cups are a reliable option when treating large bone defects in revision or complex primary THA, and the results in these cases have been excellent (Weeden and Schmidt 2007, Macheras et al. 2010). The revisions in the Continuum group in the current study were mainly due to dislocations, and the number of revisions for early lack of osteointegration or aseptic loosening was minimal.

In an earlier large register study based on Australian and Swedish data, the revision risk due to dislocation was not assessed separately, although the overall revision risk of TM cups was increased compared to the other uncemented cups

(Laaksonen et al. 2018). Our findings are in line with those of Laaksonen et al.; in addition, we found that the elevated revision risk is largely explained by the difference in the revision rate due to dislocation. In the subgroup analysis of the Continuum group, we found that cups with a neutral polyethylene liner are associated with a 1.7-fold dislocation revision risk compared to Continuum cups with an elevated liner.

Elevated liners were first introduced by Charnley in the early 1970s to decrease the tendency for posterior dislocation by providing more coverage (Charnley 1979). The improved stability in primary THA when using an elevated rim liner was first reported in 1996, and although these liners are widely used, there is only limited clinical evidence to support their use (Cobb et al. 1996, Sultan et al. 2002, Carter et al. 2011). Also, the benefit of routine use of elevated-rim liners in instances in which the acetabular component otherwise is positioned satisfactorily has been questioned (Harris et al. 1991). In addition, there might be potentially harmful side effects. Theoretically, the elevated liners may predispose the neck of the prosthesis to impinge on the acetabular rim, forcing the head out of the cup anteriorly. However, such a risk has not been confirmed in clinical studies (McCollum and Gray 1990, Sultan et al. 2002). Despite these suspicions, elevated liners have not been associated with increased revision rates during 5 years of follow up (Cobb et al. 1997). Also, the use of lipped liners with modular uncemented acetabular components has been associated with a decreased rate of revision due to instability after primary THA, according to a register study from New Zealand (Insull et al. 2014). Our data supports these findings; we did not observe any trend toward an elevated risk of revision due to increased wear. It is nevertheless prudent to remember that wear-related problems usually appear in the long term and our follow-up time was just 3 years.

PJIs are a growing challenge, as an increasing number of joint arthroplasties are being performed and the life expectancy of patients is increasing (Huotari et al. 2015). Indeed, the cumulative incidence of PJI in the USA and in the Nordic countries is reportedly growing (Dale et al. 2012, Kurtz et al. 2012). One aim of this study was to compare the revision rates for infection, because a recent study presented promising results of TM components possibly having a protective effect against PJI (Tokarski et al. 2015). However, these results were not confirmed in a large collaborative register study by Laaksonen et al. in 2018, similarly to our results: the risk for revision due to PJI was similar in the Continuum and reference groups.

6.2 Survival of Tritanium cups in primary THA

The second study highlighted the need for follow-up of implants. Despite promising early results with the Tritanium cup, some concern has been voiced over higher radiolucency prevalence compared to other porous designs (Carli et al. 2017,

Vutescu et al. 2017). In our material, patients treated with the Tritanium cup had a greater risk of revision for any reason from 4 years onwards compared to the reference group of other commonly used titanium alloy cups based on data from the Finnish Arthroplasty Register. Additionally, the Tritanium group had an increased risk of revision compared to the reference group with revision for aseptic loosening of the cup as the endpoint, even though our follow-up time was relatively short and prevalence of aseptic loosening increases with longer follow-up.

There are only a few peer-reviewed publications concerning implant survival of the ultraporous-coated Tritanium cup, and the results are somewhat contradictory. Naziri et al. assessed 288 hips in 252 patients with a primary THA performed using a Tritanium cup from 2008 to 2010. Mean follow-up was 36 months. At final follow-up, no cup failures had occurred. The mean Harris Hip Score (HHS) improved from 53 points preoperatively to 91 points postoperatively. On radiologic evaluation, no signs existed of progressive radiolucencies or changes in cup position (Naziri et al. 2013). Carli et al. compared the clinical and radiographic results of 109 hips in 95 patients using a Tritanium primary cup with age, BMI, and a gender-matched cohort of 100 patients who received a contemporary cup (Stryker Trident PSL HA). At an average follow up of 4.2 years, implant survivorship of the Tritanium primary cup was 98.2%, with two cups revised for failure of osseointegration. One-year radiographs revealed radiolucent lines in two or more DeLee zones in 30% of cups and three zone involvements in 8%. These proportions increased (40% and 17%, respectively) at minimum 5-year follow-up. Tritanium primary components with radiolucency in two or more zones exhibited significantly lower HHS at 2 years compared to Trident PSL components (Carli et al. 2017). Faizan et al. (2017) compared radiolucencies around Tritanium (3D) and Trident (2D) (Stryker) cups in a cadaveric setting. They found that both cups had an equivalent mean metal-bone contact, but artifactual radiographic lucencies were found in the contact radiograph images of the 3D cup. Yoshioka et al. (2018) compared consecutive cases of primary THA using a Tritanium cup (130 cases in 118 patients) and a matched cohort using a Trident cup (130 cases in 130 patients) between 2011 and 2014. The mean follow-up duration was 41 and 38 months for the Tritanium and Trident groups, respectively. There were significant differences between the groups for radiolucent lines, but no differences in the clinical results. Radiolucent lines increased in the Tritanium group (36% at 3 months and 61% at final follow-up), whereas they decreased in the Trident group (3% at 3 months and 1% at final follow-up). The occurrence of radiolucent lines was significantly higher in the Tritanium group than in the Trident group during each follow-up period. However, only one cup loosening in the Tritanium group was identified at the final follow-up evaluation.

Implant survival of the most common hip implants are presented, besides peer-reviewed publications, in the annual yearbooks of some national arthroplasty

registers. In the Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR 2018), the 5-year KM estimate (cumulative percent revision) of 756 uncemented THAs using an Accolade I (Stryker, Mahwah, NJ, USA) stem and Tritanium cup was 3.6 (95% CI 2.4–5.2). The 1-year KM estimate of 878 uncemented Accolade II/Tritanium THAs was 3.0 (95% CI 1.9–4.6). For 3,884 hybrid THAs with a cemented Exeter (Stryker, Mahwah, NJ, USA) stem and a Tritanium cup, the 5-year KM estimate was 3.2 (95% CI 2.6–4.0). Implant survival of the Tritanium THA in the current study is slightly inferior to that of Accolade I/Tritanium THA and Exeter/Tritanium THA in Australia. The stem models used in Finland are essentially the same (Accolade I and II, Exeter). The cumulative revision rate of Accolade II/Tritanium in Australia is relatively high, and similar to our results. However, the signal detection method of the AOANJRR has not considered the Tritanium cup as an outlier product in Australia.

In the NJR annual report (National Joint Registry for England, Wales, Northern Ireland and the Isle of Man 2019), the 5-year KM estimate of 3,681 hybrid Exeter/Tritanium THAs was 2.3 (95% CI 1.7–3.0). The New Zealand Orthopaedic Association Joint Registry (NZOA 2018) describes the risk for revision using the rate/100 component years. The revision rate of 735 Accolade II/Tritanium THAs was 0.57 (0.3–1.1) and that of 2,702 hybrid Exeter/Tritanium THAs 0.7 (0.6–1.0). These unadjusted survivorship data from national registers do not seem alarming. Adjusted analyses with special interest in aseptic loosening of the cup would be required to properly compare survivorship between registers.

6.3 Survival of vitamin E-infused highly crosslinked polyethylene liners in THA

As mentioned earlier, polyethylene wear and osteolysis is one of the main limiting factors for long-term survival of THA (Harris 1995). In the third study, we assessed whether vitamin E-infused liners (VEPE) enhance survival compared to conventional moderately crosslinked (ModXLPE) liners from the same manufacturers but without vitamin E. We found that VEPE liners perform comparably to ModXLPE liners at mid-term follow-up. The risk of revision in the VEPE group was lower when revision for any reason was the end point but the result was not statistically significant (HR 0.7, (CI 0.4-1.1, p=0.09)). This is one of the largest studies of VEPE liners with a mean follow-up of 5 years. Our findings support the assumption that VEPE liners are durable and safe; however, further studies with longer follow-up are needed to assess the long-term survival and possible benefits of this material (Sillesen et al. 2016, Nebergall et al. 2017, Galea et al. 2019).

Highly crosslinked polyethylene (HXLPE) was introduced in the late 1990s to decrease polyethylene wear and periprosthetic osteolysis and to increase the long-

term survivorship of THA (Bragdon et al. 2013). Crosslinking is accomplished by irradiating PE at a dose higher than required for sterilization (Muratoglu et al. 1999). This process induces the formation of covalent bonds between the polymer chains of PE (crosslinks), resulting in increased resistance to wear (McKellop et al. 1999). HXLPE has shown lower wear rates in vitro (McKellop et al. 2000) and in vivo (Bragdon et al. 2013) compared to conventional (non-crosslinked) UHMWPE. The amount of free radicals formed in the crosslinking procedure can be reduced by heating the material above its melt temperature, or annealing below its melt temperature after crosslinking (Baker et al. 2003). However, the processes do not eliminate all free radicals (Currier et al. 2007, Kurtz 2009). One potential solution is to add vitamin E (α-tocopherol), which acts as a free radical scavenger. It stabilizes the material and increases the resistance of polyethylene against oxidation (Oral et al. 2006b, 2006a).

Liner wear is often assessed by measuring the penetration of the femoral head into the liner with radiostereometric analysis (RSA). However, the real penetration rate comprises not only the true loss of PE but also creep deformation of the liner. Several randomized controlled studies have been performed comparing femoral head penetration rates of VEPE and ModXLPE liners using RSA. Some authors have reported lower penetration rates in VEPE patients at short- to medium-term follow-up, although wear rates have been very low in both groups (Salemyr et al. 2015, Scemama et al. 2017, Shareghi et al. 2017, Galea et al. 2018, Rochcongar et al. 2018). Almost as many authors have reported equal penetration rates at medium-term follow-up (Nebergall et al. 2017, Galea et al. 2019, Busch et al. 2020). Lindalen et al. compared 32mm versus 36mm ceramic femoral heads with VEPE liners and did not find any differences in wear rates in RSA measurements at 6-year follow-up (Lindalen et al. 2019). The wear rates have been low in both groups and well below the reported osteolytic threshold of 0.1 mm/year (Dumbleton et al. 2002); therefore, the measured statistically lower penetration rates might not be clinically relevant, and longer follow-up is needed.

The AOANJRR has reported a similar revision risk for THAs with antioxidant inserts compared to ModXLPE inserts (AOANJRR 2019). The 8-year KM estimates (cumulative percent revision) of 6,046 conventional THAs using the Ringloc cup with XLPE or VEPE liners were 2.5 for both groups (2.5 (95% CI 2.0–3.2) and 2.5 (95%CI 1.9–3.1), respectively). The 4-year KM estimate for 2,729 THAs using the G7 cup with VEPE liner was inferior to that for the XLPE liner (1.8 (95% CI 1.3–2.5) and 2.9 (95% CI 1.3–6.3), respectively), although the number of XLPE liners was limited. Recently published work based on the National Joint Registry (NJR) found that VEPE liners, HXLPE liners (radiation ≥5 mrad), and liners heated above the melting point were associated with best survival in a cohort of 292,920 primary THAs. For VEPE liners, the 8-year cumulative incidence function of revision due to

aseptic loosening was 0.3 and due to reasons other than aseptic loosening 1.7 (values estimated from the figure). However, the follow-up time of 11,926 VEPE liners was relatively short (3.3 years) (Davis et al. 2020). A multinational collaboration study of 977 patients reported equal performance between the VEPE liner and ModXLPE liner at 3-year follow-up, and no early in-vivo adverse effects were observed (Sillesen et al. 2016). Our findings support these earlier findings. Our study design was to compare the same cup brands from the same manufacturer with either a VEPE or ModXLPE liner. We think this is an optimal study setting to compare differences between these liner materials as cup designs do not bias the results. The reference group consist of ModXLPE liners whereas VEPE- liners are made of HXLPE. The amount of crosslinking and thus wear resistance increases with increasing radiation dose (McKellop et al. 1999), but higher doses are also associated with a decrease in tensile and fracture toughness (Gomoll et al. 2002). All in all, a recent large register study of 292,920 primary THAs did not find any difference in the survival of moderately and highly irradiated liners at maximum follow-up of 14 years (Davis et al., 2020).

Prior to the Finnish register revision of 2014, liner wear was not recorded separately but as “other reason”, which may cause minor bias. The proportion of revisions performed for loosening and wear in our study is in line with other registers (AOANJRR 2019). There were two revisions performed due to liner breakage in the VEPE group versus three revisions in the reference group after 2014 accounting for 5% of revisions in the VEPE group and 3% in the reference group. Reports of VEPE liner breakage in the literature are rare (Bates and Mauerhan 2015, Brazier and Mesko 2018), and current data support the previous findings. Concerns over safety issues have not been raised in previous studies, and our results are in agreement with this (Gigante et al. 2015). It has also been reported that VEPE liner insertion into the G7 cup component is more difficult due to the harder liner material, but it is not clearly understood whether this inconvenience is caused by the vitamin E.

6.4 Accolade TMZF trunnion corrosion and mechanical failure

In the field of scientific research, the importance of a single case report is limited, and further conclusions cannot be drawn, but several reported cases can create interest and lead to more detailed studies. This case report was also my personal introduction to writing and publishing a scientific article, and the whole process is a good example of the theory that if you try long enough, you can’t always fail. This case report also serves as a good introduction to trunnion corrosion, and it has been estimated that 3% of all hip revision procedures worldwide are currently performed

due to trunnion corrosion (Porter et al. 2014, Drummond et al. 2015, Mistry et al. 2016).

Mechanically assisted crevice corrosion of trunnion and femoral head dissociation is a catastrophic event after THA. MACC is a multifactorial phenomenon affected by patient-related, component-related, and surgery-related factors. Severe trunnion corrosion due to MACC is a rare complication. It is important to recognize these patients and organize further examinations.

There are different severity levels of MACC and trunnion corrosion and variable presentations. Wear and corrosion at the head-neck interface can induce ALTR through molecular mediators (Weiser and Lavernia 2017). The combination of ALTR symptoms includes pain in the groin, thigh, or buttock and limb (Cooper et al. 2012). The symptoms occur typically 3.7–4.3 years after the primary surgery (Cooper et al. 2012, Plummer et al. 2016). Pain is not universally present, and some patients might have the first symptoms when the femoral head dissociates, which was the situation with the patient in our case. If suspicion of trunnion corrosion and ALTR is raised, serum cobalt and chromium ion levels need to be measured. It has been reported that patients with clinically important trunnion corrosion often have elevated Co and Cr at a ratio of 5:1 (Cooper et al. 2012). It should also be kept in mind that symptoms of periprosthetic joint infection and those of ALTR resemble each other and PJI needs to be ruled out properly.

Diagnostic imaging includes anteroposterior pelvic and cross-table lateral hip radiographs. Dissociation of the femoral head is easily diagnosed from radiographs, and osteolysis in the calcar and greater trochanter areas might implicate ALTR (Plummer et al. 2016). Patients with suspected ALTR need further imaging, and metal artifact reduction sequence magnetic resonance imaging (MARS MRI) is currently considered to be the gold standard. MARS MRI enables evaluation of the soft tissue envelope around the hip joint (Kwon 2014). Nevertheless, MARS MRI findings should be interpreted critically, since abnormal imaging findings are often seen even in well-functioning MoP THA (Fehring et al. 2015).

Once corrosion of the trunnion has been diagnosed, revision surgery should be planned carefully. If the components are well fixed and positioned, the revision could be accomplished with liner and femoral head exchange (Cooper et al. 2012, Plummer et al. 2016). Short-term data suggests that doing so did not increase the re-revision rate with 3.3 year follow-up (Engh 2014). In the case of head dissociation or cold welding, the stem needs to be replaced and the revision components must be available when performing these procedures. After removing the head, the trunnion should be cleaned and inspected for damage. If the trunnion is crushed or severely damaged, it needs to be replaced and the surgeon should perform stem revision, which may require an extended trochanteric osteotomy. A component-specific sleeve adapter can be used and combined with a ceramic head if the trunnion is only

minimally damaged. Exchange of the cobalt-chromium (CoCr) femoral head with another CoCr femoral head should be avoided, since it has been reported that this could result in relapse of ALTR (Plummer et al. 2016). A liner change is recommended instead, due to potential embedded metal debris (Cooper et al. 2012, Plummer et al. 2016).

Although gross trunnion corrosion and failure remain a rare complication, there is a slight increase in the number of cases of Accolade trunnion corrosion being reported. Ko et al. reported five cases from their clinic of catastrophic Accolade trunnion failure (Ko et al. 2016). They reported that risk factors associated with failure were head size ≥36mm, a CoCr femoral head, a femoral head that further increased neck length, and a lateralizing offset stem with head-neck angle of 127°. Other authors have also published case reports of trunnion corrosion and neck failure, and the patient characteristics have essentially been the same as those described by Matsen Ko et al. (Spanyer et al. 2016, Raju et al. 2017, Wylde et al. 2020). Elevated serum cobalt levels and MARS MRI-diagnosed ALTR have also been reported with cases of gross trunnion failure with Stryker V40 tapers (Patel et al. 2016, Runner et al. 2016). The severity of trunnionosis varies, and trunnionosis combined with elevated metal ion levels without component failure are reported with Accolade TMFZ stems (Craig et al. 2014).

The trunnion failure problem is not limited to Accolade stems. Banerjee et al. (2015) reported gross trunnion failure after THA from five different manufacturers with MoP or CoP bearings, but no common factor was detected from these patients (Banerjee et al. 2015).

Patient-related factors affect the risk of trunnion corrosion. Greater load on the trunnion-head interface is associated with accelerated corrosion; thus a high BMI is a risk factor (Panagiotidou et al. 2015). Male gender and higher activity levels are also linked with this complication (Ko et al. 2016). The patient in our case report had all of these criteria: male gender, BMI 29 and an active lifestyle.

Component-related factors include stem design and geometry, offset, head-neck angle, femoral head diameter, and metal alloy. The Accolade TMZF stem is composed of beta titanium (Titanium Molybdenum Zirconium Fluoride), a titanium alloy with 25% greater flexibility than the standard Ti-6Al-4V alloy (Casper et al. 2011). Because of this lower modulus of elasticity, it is possible that the normal forces during gait increase bending of the titanium trunnion within the CoCr femoral head (Ko et al. 2016). Taper geometry has been reported to have more influence than stem design on corrosion (Nassif et al. 2014). When the taper is smaller and made up of a more flexible alloy, the likelihood of corrosion is higher (Goldberg et al. 2002). A low head-neck angle (i.e., 127°) is another risk factor. The horizontal offset increases the forces at the head and neck junction, leading to increased corrosion (Langton et al. 2012). An important factor is that all femoral heads in these case

reports were made of CoCr alloy, which, when combined with a titanium trunnion, can lead to galvanic corrosion and weakening of the trunnion interface (Panagiotidou et al. 2015). The phenomenon is stronger with large (over 36mm) heads, and both laboratory and retrieval studies have shown that a large head increases the frictional torque and thus accelerates wear (Goldberg et al. 2002, Howie et al. 2012, Cooper and Della Valle 2014). Trunnionosis occurs similarly in MoM and MoP THA, as both head-neck junctions consist of MoM surfaces.

The V40 taper has an angle of 5°40', is smaller and shorter than other taper designs, and allows better clearance and prevents impingement (Raju et al. 2017). Accolade has a very low surface roughness at the trunnion (Munir et al. 2015), which could be a potential factor leading to dissociation of the head from the taper (Raju et al. 2017).

The combination of patient demographics (heavy, tall, and male), component factors (a large-diameter CoCr femoral head and a stem of flexible titanium alloy), and surgical technique (high offset) may all contribute to this catastrophic event (Ko et al. 2016). According to Ko et al., precautions can be taken such as checking serum cobalt and chromium levels in high-risk patients—i.e., those who are young, are active, have a higher BMI, are male, and have a 36 mm-diameter femoral head. These levels should definitely be checked in symptomatic patients, and patients with elevated metal-ion levels should undergo a MARS MRI scan. The Accolade TMZF stem was available on the market from 2001 to 2011, and reports of failure have been published more than 7 years after implantation; thus, we may face more of these catastrophic complications in the future.

6.5 Strengths and weaknesses

The primary strength of this nationwide register study is the large population-based setup with moderate follow-up times. The register gathers information from most total hip implantations across the country, and data coverage on primary THA exceeds 95% and on revision THA 81% (FAR).

We acknowledge that our study has some limitations. First, in a population-based register study like ours, we were not able to assess radiologic findings. Second, data on patient comorbidities are not included. Patient comorbidities might have differed between the study groups and biased our results. However, we do have ASA classification available since May 2014, and there were no major differences according to ASA class distribution between the study groups. Third, we were only able to use revision as the outcome. Some of the patients might have experienced pain or other implant-related problems without having a revision, for example, due to poor general health contraindicating risky revision surgery. We do not have data on any patient-reported outcome measures either.

In the first study, as we were not able to assess radiographs to evaluate preoperative bone loss, it is possible that Continuum cups have been used in more demanding cases. However, Continuum being the second most used uncemented cup during our study time does suggest that it is used routinely for primary THA. It has also been questioned whether positioning of the Continuum cup is more demanding due to its high porosity, but a recent study failed to show a significant difference in cup positions between trabecular metal cups versus other uncemented cups (Laaksonen et al. 2020). Further, we were only able to analyze factors included in the register dataset. It is possible that patients had comorbidities that we are not aware of that could have influenced their dislocation risk. Patients might have suffered a single dislocation without a need for revision.

In study II, it is theoretically possible that Tritanium cups were used in more demanding cases than the cups in the reference group. However, the overall number of Tritanium cups in the current study was high, and the proportion of patients with primary osteoarthritis was similar to that of the reference group (86%); thus, we believe the bias to be of minor importance. Due to a lack of radiographs, we were not able to assess postoperative radiolucent lines around the cup either, which is the major limitation of our study. Radiolucencies around the cup are not a definitive sign of loosening, and it is possible that some patients had ended up getting a revision operation with a stable cup. I would argue that every orthopedic surgeon performing hip revisions has begun a cup revision operation for suspected aseptic loosening, only to find a well-fixed cup.

The most significant limitation of the third study is the short follow-up time. The possible differences in revision rates due to liner wear can be seen after 10 or 15-years post-implantation. Besides, it is possible that the study contains a type 2 error. There might be a difference between the groups which we were unable to detect, due to the short follow-up time or limited number of implants included in the study. We were aware of this when planning the study, and the aim was to control the survival of novel implants and detect possible outliers. Another limitation of the study is that we were not able to assess radiographs to evaluate wear. Further, the study groups were operated in somewhat different time eras. However, this is also a strength of our study, as we wanted in particular to assess two generations of liner materials from the same manufacturer using the same acetabular components. Femoral head size increased so significantly during the study period that we were not able to use it as a variable in the Cox model with osteolysis and wear as the endpoint (wide confidence intervals). The portion of ceramic heads between the groups was somewhat different (30% VEPE group versus 8% Reference group), but a recent study failed to detect a significant difference in wear rates between metal and ceramic heads (Gaudiani et al. 2018). Despite the weaknesses of the study, we do not feel that our message is undermined, and we consider this to be an optimal study

setting to compare differences between these liner materials, as cup designs do not bias the results.

The most remarkable limitation of the fourth study is the single case included in the report. Further conclusions cannot be drawn based on a single case, but similar failures have been described by other authors. As the combination of an Accolade TMFZ stem and a Mitch cup with MoM bearing has not been used on the US market, our report replenishes the failure pattern.

7 Conclusions

Based on the current thesis, the following conclusions can be drawn:

1. THA with a Continuum cup is associated with an increased risk of revision compared to other uncemented cups, mainly due to revisions because of dislocation. Our results support the use of an elevated liner when Continuum cups are used for primary THA.

2. Use of the ultraporous-coated Tritanium cup for primary THA does not provide an advantage over traditional uncemented cups and, in fact, Tritanium was associated with an increased revision risk of aseptic loosening of the cup.

3. After an observation period of 7 years, E-infused liners show results equal to those obtained with crosslinked polyethylene liners. Longer follow-up is required to assess potential long-term results.

4. Mechanically assisted crevice corrosion of the trunnion is a multifactorial phenomenon. The affecting factors can be divided into patient related, component related, and surgery related. Severe trunnion corrosion due to MACC is a rare complication.

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