Total Hip Arthroplasty: A Surgical Revolution

George A. Shultz, BS; Dana C. Mears, MD, PhD; C. Lowry Barnes, MD; Simon C. Mears, MD, PhD; Benjamin M. Stronach, MD; and Jefferey B. Stambough, MD

Total hip arthroplasty (THA) is one of the most successful orthopaedic procedures, offering significant improvements in pain relief, mobility, and overall quality of life for patients with hip pathology. Since its inception, continuous advancements in implant materials, fixation techniques, and surgical approaches have contributed to enhanced implant longevity and functional outcomes. THA has evolved from early designs to incorporate modern biomaterials, robotic-assisted surgery with improved precision, and three-dimensional printing for patient-specific solutions. Despite its success, challenges such as implant wear, prosthetic joint infection, and the need for revision surgeries remain critical concerns for orthopaedic surgeons. The increasing demand for THA, driven by an aging population and expanded indications, underscores its growing societal impact, including economic benefits through improved productivity and reduced healthcare costs. As research and innovation continue to shape the field, THA remains a cornerstone of orthopaedic surgery, with ongoing efforts to optimize outcomes and address the complexities associated with revision procedures. (Journal of Surgical Orthopaedic Advances 34(3):119-123, 2025)

Key words: total hip arthroplasty, polyethylene, Charnley, bearings, osteolysis

Total hip arthroplasty (THA) is a life-enhancing procedure that is routinely performed following trauma or degeneration of the hip. An estimated 350,000 surgeries are performed in the United States each year with a slightly higher prevalence in female patients when compared to males.[1,2] The goals for THA are to restore the function, relieve pain, and to allow individuals to regain control over aspects of their lives that were previously limited by the diseased joint. Furthermore, successful operations result in substantial quality adjusted life year for patients as they return to work and activities, often with increased productivity.[3] Considering the aging population, expanded indications, and life-altering impact that surgery can provide, THA provides enormous benefit to society on a large scale. This review seeks to provide a brief history of THA and summarize the current situation surrounding THA, with an emphasis on innovation in the field.

Implant Development

The foundation upon which modern THA technique is established began in the 1960's, with Sir John Charnley's introduction of low-friction arthroplasty.[4] At his time, the prevailing theory held that the lubricant of a mobile bearing was the principal determinant of the frictional forces imposed upon the joint (hydrodynamic theory). Charnley hypothesized that the frictional properties of the opposing surfaces were the critical factor. His arthroplasty design consisted of a non-modular, polished stainless-steel femoral component with a fixed size of a femoral head possessing a diameter of 22 mm combined with a polyethylene acetabular component. Deemed an "all-purpose arthroplasty," Charnley aimed to eliminate the intellectualization required to discern between the different surgical options that were employed in his time to address disease of the hip (Fig. 1).[5] This revolutionary combination of stainless steel and polyethylene significantly reduced the intra-articular friction that plagued previous combinations, while maintaining a functional degree of stability, resulting in improved implant survivorship.[6]

Materials

Charnley's use of a stainless-steel femoral component resulted in an arthroplasty that was less prone to fracture under the significant forces that are transmitted though the hip. The contiguous femoral head articulating against a polyethylene cup minimized friction and wear of the articulating surfaces.[5] Despite these advances, the arthroplasty components were vulnerable to excessive wear and loosening secondary to a coefficient of friction that was much higher than that which incurs in a native hip joint. This and other shortcomings were addressed by numerous research investigations.

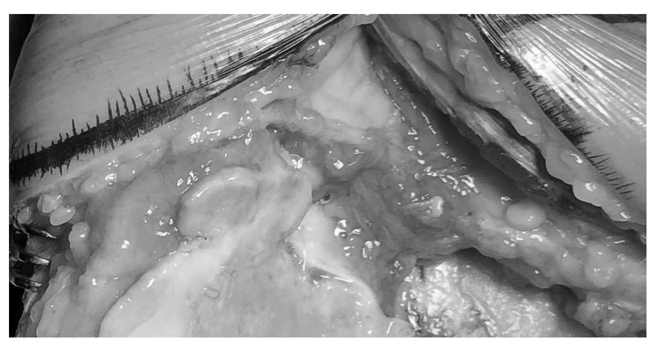

FIGURE 1. Sir John Charnley's illustrations of the four surgical options used to address degenerative arthritis of the hip in 1960. (1) Arthrodesis: sacrifice of mobility to preserve stability. (2) Arthroplasty: an attempt to preserve mobility and maintain stability. (3) Osteotomy for realignment of the diseased hip. (4) Pseudoarthrosis: sacrifice of stability to maintain mobility.

Department of Orthopaedics, University of Arkansas for Medical Sciences, Little Rock, Arkansas. Address correspondence to Jeffrey B. Stambough, MD, 4301 W Markham St, Little Rock, AR 72205; email: JStambough@uams.edu.

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Ceramic Femoral Head Components and Ceramic-on-ceramic Bearings

The 1970's saw the first iteration of ceramic femoral head implants, which provided a lower coefficient of friction than the previous designs. This modification culminated in decreased wear on the acetabular component, as well as a reduction in osteolysis secondary to particulate debris when compared to the metal-on-polyethylene designs. Unanticipated complications arose including catastrophic fracture of the components.[7] Advancements in manufacturing yielded high-purity alumina ceramics with improved strength and a reduced porosity. Sequential improvements of the material culminated in a zirconia-toughened alumina, which maintained the desirable coefficient of friction while further improving its strength.[8] This manufacturing technique reduced the frequency of implant fractures, the most common complication of the earlier ceramic models. Currently, implant manufacturing using the hot isostatic press technique has improved the hardness and strength of the implants. Following this measure, the FDA provided approval for use of the ceramic in THA. A frequent complication of ceramic-on-ceramic bearings has been complaints of audible squeaking from the joint. This liability has been addressed by using an inert ceramic femoral head in combination with a polyethylene cup or acetabular liner.

Metal on Metal Bearings and Innovations for Metal on Polyethylene

Metal-on-metal bearings have also been extensively trialed in THA. In early practice, cobalt-chromium bearings provided superior durability with decreased rates of component wear.[9] However, the fretting corrosion of the components was poorly understood. This process culminated a release of cobalt ions that could induce local adverse inflammatory tissue reactions, including metallosis with granuloma formations.[10] Metal-on-metal bearings subsequently fell out of favor until the late 90's when modern hip resurfacing techniques provided improved preservation of bone and increased longevity of the bearing surfaces. This innovation failed to stifle concerns about local and systemic cobalt toxicity including the formation of pseudotumors. This liability of cobalt-chromium alloys encouraged its replacement with titanium alloys to further improve inertness and to lessen the intrinsic stiffness of the material, but the poor wear resistance of the titanium bearings quickly became an issue. In 2008, reports on metal-on-metal bearings with cobalt-chromium alloy surfaced whereby the bearing surfaces underwent catastrophic failure secondary to excessive wear with systemic toxicity to cobalt.[11] In modern practice, metal-on-metal bearings are implemented selectively, with the principal indication for a hip resurfacing procedure in a young adult with a high level of activity. Ironically, with respect to wear of the bearing surfaces, this indication remains subjective.

For metal on polyethylene arthroplasties, Charnley's preference for stainless steel on polytetrafluoroethylene was followed by the use of a cobalt-chromium stem to improve the inertness of the metallic component.[9] As the liability of Co-Cr alloys to undergo corrosion with the liberation of Co ion was documented, its replacement with titanium alloys with superior inertness and decreased intrinsic stiffness has progressively increased. The poor wear resistance of titanium precludes its application for bearing surfaces. In current practice, THA implants are mostly comprised of a titanium stem and acetabular shell, with a modular highly cross-linked polyethylene surface, and a large ceramic head to maximize the stability of the hip. Titanium alloy remains the preferred material for acetabular and femoral components in view of its comparatively lower modulus of elasticity, increased strength, inertness, and biocompatibility. The 4th generation of ceramic-on-ceramic implants also remains a viable alternative for THA, with recent studies demonstrating a 96.9% implant survivorship at 6 years in patients under 30 years old.[12]

The evolution of femoral head size

The femoral head component of the implant has also undergone significant development throughout the last century. Charnley utilized a 22 mm head diameter, citing that smaller head diameters would lead to less wear secondary to a decreased frictional torque on the acetabular component. The small size of the femoral head was complicated by a high rate of dislocation. Subsequent designs featured progressively larger heads to increase the "jump distance" for a dislocation. In view of the successful outcome of this modification, the sizes of femoral heads continue to increase with some metal-on-metal implants utilizing a head diameter measuring up to 44 mm. The large size optimizes the range of hip motion by inhibiting impingement of the neck on the socket. However, the larger femoral head is associated with an increased predilection for impingement of bone and soft tissue, most notably beyond a size of 38 mm.[13] The optimal alignment of the acetabular component becomes progressively more critical as the diameter of the head increases to minimize the risk for soft tissue impingement. Another liability of the larger head is an increased rate of volumetric wear.[14] The optimal size for the femoral head component remains a delicate balance between rates of dislocation and volumetric wear. Current literature favors a diameter of the femoral head between 36 mm and 40 mm to minimize the incidence of dislocation and to provide an acceptable frictional torque and stress at the interface between the component and the adjacent bone.[15]

Component Fixation

Bone Cement

The success of Charnley's THA was largely attributable to his introduction of polymethylmethacrylate (PMMA) bone cement for anchorage of the components.[16] While PMMA provided immediate stabilization of the implants, it was attributable to late complications such as cement fatigue and osteolysis secondary to particulate debris. Osteolysis was more frequently observed in young, active patients and in the elderly with a capacious proximal femur in the 1970's, cementation was greatly improved with the introduction of vacuum mixing and pressurized injection.[17] These measures reduced the porosity of the cement to allow for increased interdigitation into bony interstices. Supplementary observations documented the semi-liquid behavior of bone cement at body temperature so that it undergoes a "cold flow" into bony interstices.[18] These techniques and novel theories drastically increased the fatigue life and durability of the cement. However, problems with fracture and loosening were still observed in an active patient population, highlighting the need for further innovation in fixation techniques.

Cementless Fixation

Cementless fixation in THA has emerged as a promising alternative to the use of cement, notably in younger and active adults. This technique relies upon biological fixation, wherein bone grows into the implant (ingrowth) or onto the implant surface (ongrowth) to achieve long-term stability. While initial beaded and fiber metal designs struggled to achieve bone interdigitation and stability, the more recent development of trabecular metal has allowed for superior ingrowth of bone. As an alternative, bioactive coatings such as calcium phosphate and hydroxyapatite have further addressed the previous shortcomings in osseointegration.[19] The novel techniques afford enhanced implant longevity provided that the implants achieve a stable "press-fit" during the surgical procedure. Otherwise, micromotion of the implant can impede bone ingrowth and reduce stability. Cementless fixation is not without challenges. In a patient with poor bone quality or osteoporosis, cementless fixation is vulnerable to failure with premature loosening of the components or an iatrogenic fracture. In elderly, osteopenic individuals, bone cement is the preferred method of fixation secondary to the immediate stabilization that is provided, especially for the femoral component. In many clinical situations, a hybrid fixation is preferred using a cementless acetabular component and a cemented femoral stem.

Surgical Exposures for Total Hip Arthroplasty

Techniques for surgical exposure of the hip joint during THA have also undergone numerous changes over the past century. Charnley employed a lateral longitudinal incision for his Low Friction Arthroplasty, with an osteotomy of the greater trochanter to optimize visualization of the hip.[20] Utilizing the 22 mm femoral head, the procedure necessitated a precise rotational alignment to minimize the risk for a late dislocation. Most other surgeons preferred to eliminate trochanteric osteotomy to reduce the extent of the procedure and eliminate the risk for symptomatic trochanteric nonunion. This resulted in a variety of new approaches for full THA, including a true anterior approach and an anterolateral approach.[9,21] A posterolateral approach was also popularized, specifically in the setting of hemiarthroplasty for femoral neck fracture.[22] Recently, an anterior approach has been widely adopted use in combination with a Hana Operative Table (Mizuho, Union City, CA).[23] A major advantage to this method is the associated supine position that allows for the use of fluoroscopic imaging guidance via conventional 2D systems or newer 3D systems.

Specialty Areas

Robotic Surgery

During the past three decades, innovations in THA pertained to the application of robotic surgical technology. Robotic surgery offered a potential solution to minimize the progressive increase in cost of traditional methods that used a costly kit of hand tools. Extensive hours of manual cleansing, sterilizing, and maintaining the tools added substantially to the associated expenses. In 1992, Robotic THA was first attempted at Sutter General Hospital in Sacramento, California using the ROBODOC ® system (IBM, Fremont, CA). The method employed three dimensional-computed tomography (3D-CT) of the hip to identify the cutting profile for a cementless femoral stem. The success of the operation sparked rapid innovation in the field. While the ROBODOC® system would not gain full FDA approval until 2008, it catalyzed a shift towards technological-assisted surgery and the development of numerous other robots. Of these designs, the MAKO® system (Stryker, Mahwah, NJ) emerged as the most widely adopted robotic system in the United States and foreign orthopaedic marketplaces.[24] Unlike the robotic counterparts used in general surgery, such as the da Vinci Surgical System® (Intuitive Inc, Sunnyvale, CA), current orthopaedic robots do not permit a surgeon to undertake unique capabilities such as truly minimal exposure. Although excitement remains surrounding robotic assisted THA, current literature has yet to demonstrate clear advantages over manual THA. A recent in-depth systematic review on the topic found that while robotic arm-assisted THA results in greater accuracy of component placement, no meaningful differences were discovered in complication rates or survival outcomes.[25] While the use of conventional manual tools remains the standard of care, the future refinements of robotic instrumentation are anticipated to address their current shortcomings and expand their capacity for patient care.

Three-dimensional Printing

Another application of advanced computer technologies includes the introduction of three dimensional (3D) printed implant coatings and whole implants. Additive manufacturing (AM) first emerged in the 1980's. This fabrication technique involves repetitive layering of a heated material on to a substrate until the final design is formed. The first completely 3D printed implant was employed surgically in 2018. The use of 3D printing as an adjunct to traditional fabrication techniques for surgical implant confirmed its numerous attributes. For example, a 3D printed titanium acetabular component creates a device that possesses a low modulus of elasticity for a reduction in stress shielding combined with a highly porous surface that favors vascularization, bony ingrowth, and osteointegration. AM permits the fabrication of trabecular titanium in a way that is far superior to the use of conventional manufacturing techniques.[26] With the use of computer modeling and 3D printing, a unique implant design can be fabricated that is configured to address the presence of anatomical irregularities combined with osteopenic bone, optimizing precise anatomical alignment and bony fixation. During the past decade, the fabrication of three dimensional printed porous surfaces has culminated in the reduction of the incidence of surgical revision for aseptic loosening.

Revision THA Including the Use of DUAL Mobility Devices

Revision total hip arthroplasty presents a significant challenge for orthopaedic surgeons due to its complexity, longer operative times, costly implants, and higher complication rates compared to primary THA. Revisions present challenges such as altered anatomy, compromised bone stock, and the presence of scar tissue, all of which can complicate explant and implant of revision components. During and after revision THA, the risks for a complication including infection, dislocation, neurovascular injury, and periprosthetic fractures are much greater than for primary arthroplasty. Following revision THA in a young patient, the incidence of a further surgical revision at ten years is currently 11%. For elderly patients, the comparable rate of revision approaches 4%.[27] In view of the increasing frequency of THA in the general population, revision THA merits further efforts by orthopedic surgeons to undertake additional research with further refinements of the operation.

Dual Mobility Devices

Recurrent dislocation of the arthroplastic hip is a major source for surgical revision. In the 1970's, dual mobility devices were introduced as a way to optimize the stability of a THA, often in a patient with a neuromuscular disorder or an anatomical deformity that predisposed the patient to a postoperative dislocation.[28] The device possesses a femoral head component that is captured in a polyethylene shell. In turn, the shell is housed in a larger metallic femoral head. The last device articulates in a larger, conventional HDPE-lined acetabular component. When this approach is employed in patients over aged 70 years, it has demonstrated a marked reduction in dislocation rates. The method is vulnerable to uncommon forms of mechanical failure, including a fracture of the polyethylene liner with onset of pain and acute shortening of the limb.[29,30]

Prosthetic Joint Infection

One of the major complications of THA is the development of a prosthetic joint infection (PJI). PJI can be managed through one of several pathways. These include a primary debridement with an accompanying surgical revision of infected or loose components, or a multiple staged revision that includes an initial explant of the hardware, subsequent washouts, and a belated replant of new implants. The preferred procedure depends upon multiple factors including the duration and severity of the infection, the presence of various medical comorbidities, and the preference of the surgeon. Typically, the patient is managed with the use of intravenous antibiotics for multiple weeks, which requires placement of a peripherally inserted central catheter (PICC) line and regular outpatient evaluations. PJI necessitates an extraordinary investment of time by the surgical team and a potential exposure of the patient to multiple operations. During a primary THA, multiple strategies are employed to minimize the risk for a PJI including preoperative medical evaluation for septic foci, low albumin levels, and other medical factors that greatly increase the risk for infection. Preoperative sterilization of the surgical field is accompanied by use of prophylactic antibiotic therapy. In the operating room, diverse sterilization procedures, including air handling, is undertaken to minimize iatrogenic introduction of bacteria into the joint.[31] Despite all of these efforts, PJI after primary THA occurs in about 1.3% of patients.[32]

Current and Future Expectations of THA

THA remains one of the most successful orthopaedic interventions. Current data suggests a 37.7% increase in THA operations from 2018 to 2060.[33] This increase in numbers and frequency of the THA operations will broaden the societal impact of the procedure. In turn, a higher percentage of the population will experience the improved quality of adjusted live years that follow a successful THA. Since the innovation by Charnley, the extraordinary advancements in implant design, surgical technique, and biomaterials have culminated in marked improvements for the patients with respect to their day-to-day quality of life. Associated advancements in healthcare technology and medicine have allowed for developments such as day-of-surgery-discharge for outpatient procedures, reducing the financial burden for patients and hospitals.[34] New theories on the effect of spinal deformities on acetabular alignment promise novel ways to address hip disease. Developments, such as articular chondrocyte replication in a suitable simulated cartilaginous matrix, may culminate in the provision of therapeutic alternatives to THA.

The Lancet has named THA as one of the most successful surgical interventions performed in the last 50 years. This accolade is a notable attribute for a surgical procedure with such a high volume.[6] Despite this extraordinary attribute, high rates of revisional operations and an aging population necessitate further innovations in both the biomaterials and the surgical technique. While the documented history of THA highlights its remarkable progress, further improvements are required to address the persistent problems of infection, premature mechanical failure, and the exorbitant cost of revision arthroplasties. Orthopaedic surgeons have a unique opportunity to enhance the quality of patients' lives. This factor should induce surgeons to continue the pursuit of excellence in arthroplasty research and development.

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