Development of Biomaterials for Total Hip Joint Replacement

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Abstract. Overall development of hip joints and associated biomaterials is a great challenge for the research engineers and orthopedic surgeons now-a-days. Various biomaterials are developed for manufacturing the hip prostheses. Some successful biomaterials are polymers like PTFE and UHMWPE, metals like 316L steel, Ti alloy and Co-Cr alloy, ceramics like Zirconia, alumina, Titanium coated ceramic alloys, high pressed Al2O3, composite and glass. In recent times, Hydroxyapatite is frequently used throughout the world for hip prosthesis components. The two types of hip joint replacement techniques are hemi-hip arthroplasty and total hip arthroplasty (THA). The first batch hip joint replacement techniques have already been represented by Charnley and other scientists in 1950s. Only few techniques were used with predictable results before 1960s. The lower friction Metal on polythene technique is of great challenge for total hip replacement method and it is also known as the modern Charnley hip prosthesis. This paper presents the chronological development of all technologies relating to the total hip replacement procedure and the associated biomaterials. The history and recent technologies for development of suitable biomaterials and different designs are covered in detail. To this end the new trend and direction in materials development in the research area have also been emphasized.

1. Introduction

1.1 Human Hip Joint

It is a grater load bearing joint of the human body next to the knee joint. This is a kind of socket and ball joint at the junction of pelvis and leg. The ball shaped head is fitted into a cup shaped socket in the pelvis called acetabulum of human structure. The geometry of a normal hip joint indicating various parts is shown in fig.1. It can support half weight of the body along with other orces acting upon the body. It can also sustain the higher repeating forces during many physical activities like running and jumping. Socket and ball structure of the joint enables the femoral bone to move through 360 degrees around its axis through 90 degrees. The radiographic image of a hip joint prosthesis fitted inside the body during total hip replacement surgery is shown in fig.2

![Fig.1 Human Hip Joint](image1)

![Fig.2 Radiographic Image](image2)

![Fig. 3 Bell Shape of Mold Arthroplasty](image3)

1.2. Failure of the Hip Joints

Failures aroused from femoral bone to acetabulum yields some common diseases in hip joint of the body. Human beings suffer from the various hip joint problems such as osteoarthritis, rheumatoid arthritis, osteolysis, avascular necrosis, other inflammatory arthritis, femoral neck fracture, tumour, developmental dysplasia, road accidents etc. Similarly as an after effect individuals are constrained with look for surgical
treatment. Furthermore directing, including bone restoration in place to dispose of their suffice also stay with their joints portable. Now and again that issue about torment is extreme and the condition of the hip. Exactly of the pioneering endeavours in this heading are exhibited here over ordered request.

2. Chronological Development

Sir John Charnley in 1958 used lower friction UHMWPE-on-metal design for total hip arthroplasty. This design faced the problems of higher wear rate and lower life line of joints. Mac Intosh in 1958 introduced the idea of hemi-arthroplasty where the acrylic tibial prosthesis was inserted into the knee joint affected side to correct the deformity and relieve pain. During 1960s, those THA system offered brilliant outcomes. This procedure may have been that genuine innovation of the downright hip substitution cost. Metal-on-metal (MOM) and Ceramic-on-Ceramic (COC) joints are formed with increased wear rates. However, the COC joints bring accepted consideration because of their possibility over decreasing those wear rate for arthroplasties for adolescent animated patients today. Also COC human bearing innovations for hip substitution cost has been done partly on sustainable manufacturing requirements, helping considerably higher cost plans incorporating UHMWPE. Also COC outlines will show implantation technique. Furthermore this plan would be observed less over UHMWPE bearings for an orthopedic specialist who might perform just a couple THA methods for each year. Furthermore COC has been set because of extra exceptional dangers found with long haul toxic quality insert crack. These are not encountered for hip replacements having UHMWPE cup.

2.1. Technique of Hip Arthroplasty

In this case only acetabular parts of the femoral head are replaced. In THA, the acetabular part has been fixed and femoral head moves. Shape of this prosthesis is just like a hollow hemisphere. Orthopaedic surgeon Carnochan in 1840 replaced the hip joint artificially. Another surgeon of Massachusetts, Dr. Marius Smith-Petersen, introduced the mold arthroplasty in 1925. He used [2] the reactive synovial membrane that he found around a piece of glass in a worker’s backyard. The generic design is a kind of ball shaped hemisphere made of glass as shown in Fig.7, which fits over the ball of the hip joint. The aim was to kindle cartilage revival on two sides of the molded glass joint. Smith-Peterson tried to eliminate the glass after the cartilage was restored. Glass provides a new smooth surface for movement. While offering biocompatibility, the glass may not bear the walking stresses and failed immediately. This leads to use other materials like Viscaloid (a derivative of celluloid) in 1925, Pyrex in 1933, Bakelite in 1939, and thereafter, an alloy of a Cobalt-Chromium is called Vitallium in 1936. Vitallium was found out to be inert and durable material for this kind of surgery. It is very strong and corrosion resistant, and thereafter employed in different prostheses. However, the surface feature of this alloy was lower than adequate, therefore, quick relief from pain is not as expected as usual and hip movement was limited for a number of patients.

2.2. Technique of Femoral Stem

In this technique the artificial femoral stem is inserted into the cavity of femoral marrow with or without any kind of cementing. Here only head of femur is altered and acetabulum is mobilised on the fixed bell. The shape of the prostheses is given in Fig. 4 and 5.
It is also called Hemiarthroplasty. This is a partial hip substitution method in which only head or ball of the femur is altered with a metallic implant. This is a general surgery for fracture of the femoral neck of older people above age of 80 years. Gluck in 1890 tested the stem with an ivory joint and found that human body cannot tolerate larger outside objects. Delbet has used the rubber head of femur for treating the neck fracture of femur in 1919. Groves positioned an ivory pin to alter the articular head surface of the femur in 1926. This prosthesis possessing a metal stem was located inside the cavity of the femoral marrow, attached in one piece with a metallic ball fitted onto the socket of hip joint.

Moore and Bohlman in 1939 worked together for the production and implantation of a highly customized Vitallium head of hip prosthesis for a patient with a repeated giant cellular tumour. This prosthesis worked better and later on affected on the progress of long stem femoral head prosthesis [3]. Jean Judet and Robert Judet in 1938 have used an acrylic material for replacing arthritic hip surfaces in Paris. This acrylic surface is very smooth, but the implant became loose unfortunately. The first small stemmed prosthesis was developed by Judget brothers [4] in 1946 as shown in Fig.8. It is designed based on Groves nail and material used for manufacturing it was polymethyl methacrylate (PMMA). It has a spherical head attached to a small stem. Small stemmed prosthesis was very compact, but failed due to acrylic wear debris.

Moore and Thompson developed the well-liked long stem prosthesis in 1950s. This prosthesis had a self locking mechanism as shown in Fig.9. This feature later became crucial for biologically fixing the prosthesis. These are used for treating the hip fracture and assured arthritis cases. McKee-Farrar Self-locking prosthesis [5] has been engaged in the cemented fixation as shown in Fig 5, whereas the McKee’s Ring prosthesis [6] developed in the 1960s, engaged screw fixation as shown in Fig 6.

2.3 Technique for Cup Arthroplasty

Initially, the mold arthroplasty has a rim around its edges to provide good stability. But, this rim encouraged unnecessary fibre tissues and less motion. Thus high alteration rate has been inspired the improvement of hemispherical cup designed by Otto Aufranc. This design separated the rim and included appropriate inner and outer contours. This model was called Cup arthroplasty. This design is a milestone in hip joint surgery and its principle motivated later development.

2.4 Technique for Total Hip Arthroplasty Technique

In this technique the acetabular cup and head of femur both can be replaced. The development of the total hip arthroplasty aroused because of femoral arthroplasty related failure, acetabular problems, cup arthroplastic problems and hip socket arthroplastic failure. Many people have needed total hip surgery to mitigate their suffering due to pain and joint immobility. There are some early surgeries to eliminate arthritics incited calcium deposition and irregularities in the cartilage to smoothen the joint surfaces.
McCutcheon described the chemically bound water to be self pressurized for hydrostatic lubrication of the hip joint in 1959[7].

3. Direction of Hip Prosthesis and Biomaterials Development

Many prosthesis materials developed in the past, but few of them are successful and many failed because of various reasons. The recent trends in hip prosthesis material’s research shows porous coated surfaces with good mechanical properties and good biocompatibility.

Fig.8 Schematic Diagram of a Natural Synovial Joint in the Lower Limb

Fig.9 Charnley Flanged Stem

Fig.10 Hydroxyapatite coated acetabular cup

Generation of wear debris is a main problem with modern hip and knee replacements. The polythene particles released from the cup liner influences the immune system of the body and destroys the bone around the implant and loosens the implant. Moreover the adverse cellular reactions with wear particles inside the body are caused by the wear debris induced osteolysis. There are different kinds of material combinations as discussed below.

3.1 Metal-on-Metal: Metallic prosthesis possesses higher strength and toughness. However, it renders problem in the human body due to wear, corrosion, and undesirable reaction with host tissues. The metallic ions create soluble metallic salts that go into the urine and blood of the body. Usually nickel is quickly eliminated from the body through urine, whereas Co-Cr remains for long time in the body, even Chromium stays in body's host tissues [9, 10].

3.2 Ceramic-on-Ceramic: The COC are better than MOM implants because they show lesser wear as compared to MOM implants. The common ceramics Al₂O₃ and ZrO₂ exhibit good biocompatibility and higher mechanical strength. COC components produces considerably lower wear as compared to conventional MOP (metal-on-plastic) prostheses. Therefore, these enhanced wear features lengthen life of the implant. Table-1 shows the comparison of wear of various kinds of implants. However, ceramic implants possess lower fracture toughness as compared with polymers or metals, which is undesirable for any implant.

| Materials for Cup-on-Head       | Wear Volume (mm³ / year) |
|--------------------------------|--------------------------|
| UHMWPE-on-Metal                | 56                       |
| Cross linked UHMWPE-on-Metal   | 2.8                      |
| MOM                            | 0.9                      |
| COC                            | 0.004                    |
3.3 Bioceramic: Recently the materials like hydroxyapatite (HA) has drawn the attention of the researchers in last two decades. The Technique for Femoral Stem has greatly influenced on the development of such bioceramic materials [12].

3.4 Porous Coating on Metal or Metal alloy: Porous coating surface generally provides unusual joints and tissue growth takes place inside the pores of implant coatings. It offers stable and strong bonding to the joint. At the same time, the metallic joint must be well designed considering factors like fractural toughness of the implant. For long term performance of ceramic coated metallic implants, the acetabular shell is very important. Generally the cement less implant is fixed to the bone with or without using bone cement. In addition to this the arc deposition technique and HA coating play important role in the acetabular shell design.

The Chronological development of hip joint replacement techniques and materials development have been discussed in detail in this paper and a summary of implant developments presented shortly below.

4. Year wise Design and Associated Biomaterials

The Chronological development of hip joint replacement techniques and materials development have been discussed in detail in this paper and a summary of implant developments presented shortly below.

In 1840 Carnochan was the first person to replace the human hip joint by wooden blocks. In 1890, T. Gluck first introduced the concept of ivory joint for the hip joint. In 1919, Deblt has used rubber head in place of the femoral ball for the hip joint. In 1925, Smith-Peterson used glass as bioceramic material for the hip joint. Other material used was viscaloid (derivative of celluloid). In 1926, the ivory nail used by Grooves to change the ball articular surface. In 1933, biocompatible material used is Pyrex.

In 1936, Vitallium (Co-Cr alloy) was discovered as an excellent material for hip replacement surgery. In 1939, both Moore and Bohlman introduced a 12 inch long Vitallium ball. During the period 1938 to 1946, the stemmed Prosthesis was developed by Judet brothers and brought revolution in this field. In 1950s, Moore and Thompson had used long stemmed prosthesis for better life. In 1950, Kiarer has introduced the use of acrylic cement for implant fixation. In 1951, this prosthesis was used by McKee Farrar and in 1952 Acetabular Cup prosthesis was used by Gaenslen. In the year 1955, McBride used this prosthesis and in 1957, this prosthesis was used by Artist. In 1958, John Charnley introduced low-friction material for arthroplasty called Teflon (PTFE). In the year 1961, John Charnley also introduced PMMA as a low-friction arthroplastic material. In 1970, the alumina-on-alumina ceramics was first time used by Pierre Boutin as implants for Total Hip Arthroplasty. During the period 1973 to 1976, McKee Farrar has used CoCrMo alloy. In 1977, Willert used a new kind of Hip joint prosthesis and during 1980s, many studies were based on Tribological function. During 1990s, new COC (alumina and Zirconia) designs are developed. In 1992, Sedel carried out many tests on the COC (Alumina ceramic) for Total Hip Arthroplasty and found its suitability. In the year 1994, Fisher minimized wear rate and wear debris and controlled the undesirable biological reactions. In 1995, the Co-Cr alloy pairs were used by Pierre Boutin for Total Hip Arthroplasty. During 2000s, the growing acceptability of Hydroxyapatite materials with porous surface has encouraged bone growth for Hemi & Total Hip Arthroplasty.

5. Conclusion

This study provides the year wise development of hip joint prosthesis with suitable biomaterials. The main reasons of the hip joint failure are prosthesis loosening due to wear debris, unstability, and adverse reaction of the prosthesis with the tissues. Almost all the polymers, metal, ceramics and their material combinations fail to provide a stable, long term success in the joint components, porous coating with high strength and toughened metal/alloys are being used to get a stable joint. Porous metal surfaces are
designed in such a way that they encourage bone healing and growth. Hydroxyapatite can also be used as a suitable biomaterial for bone replacement. All the studies relating to functional biomaterials, tissue engineering and biological activities are widely recognised in this century for the repair and replacement of diseased tissues. Advanced medical grade materials like porous coated metals and ceramic polymer composites are investigated and considered for stability and long term success in the total hip joint replacement procedure.

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