

# Historical Overview of Avascular Necrosis of Femoral Head Surgery

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## INTRODUCTION

Avascular necrosis of the femoral head, also known as osteonecrosis or aseptic necrosis, is essentially a poorly understood, and elusive pathological process resulting from interruption of blood supply to bone. Avascular necrosis of the hip is poorly understood but it is the final common pathway of traumatic or non-traumatic factors that compromise the already precarious circulation of the femoral head. Femoral head ischemia then results in the death of marrow and osteocytes and usually results in the collapse of the necrotic segment.

It is a debilitating disease, which usually leads to progressive destruction of the femoral head and the acetabulum in patients who are in their 3<sup>rd</sup>, 4<sup>th</sup> or 5<sup>th</sup> decades of their life. Its prevalence is unknown, but it is estimated that approximately 10,000 to 20,000 patients develop avascular necrosis of the femoral head in a year in the United States. This condition is bilateral in over 60% of cases, and in approximately 15% other bones are also affected, most frequently the humeral head, knee, talus, and small bones of the hand.

These sites have in common a precarious blood supply, which makes them vulnerable to vascular insults from a variety of causes<sup>14,17,19</sup>. In areas such as the femoral head, humeral head, talus, and small bones of the hand, the tenuous vascular supply has been well described and explains, in part, the increased incidence of osteonecrosis<sup>24,34,35</sup>.

Avascular necrosis of the femoral head can be either primary (idiopathic) or secondary. In the past, 15%-20% of cases have been labeled as idiopathic, but with increasing knowledge of etiological factors, this number is gradually decreasing. Secondary avascular necrosis of femoral head could be due to (1)traumatic or (2)non-traumatic causes.

In traumatic cases, the pathology is a result of tearing of the vessels supplying the femoral head in fractures, and mechanical compression due to hip dislocations. Non-traumatic osteonecrosis of femoral head could occur by the following mechanisms: (1)intra-osseous venous hypertension with secondary compartment syndrome, (2)extrinsic vessels pressure from fat cells (Gaucher's disease and cortico-steroids – dosage levels of prednisolone above 30mg per day for at least 30 days have been shown to be of etiological significance<sup>49</sup>), and (3)internal vessel thrombo-embolic injury i.e. sickle cell disease, Caisson disease, hyperlipidemia with fat embolism. Other conditions associated with avascular necrosis would include alcoholism, renal osteodystrophy, coagulopathy<sup>31</sup> (protein C deficiency, thrombophilia-hypofibrinolysis disorders), Perthes disease<sup>12</sup>, inflammatory bowel disease<sup>37</sup>.

There has been intensive research on avascular necrosis of femoral head over the past 30 years, which includes clinical and radiological data, etiologies, pathophysiology, and treatment.

The surgical treatment of avascular necrosis of femoral head continues to be a significant problem in orthopedic practice. Although there has been numerous studies done pertaining to treatment modalities and their effectiveness, there is still no universal consensus. In order to appreciate this debatable issue, it is essential for us to understand and gather knowledge from the historical perspectives of surgical treatment for avascular necrosis of femoral head offered by our predecessors. Only then would we be able to learn, and apply such invaluable information in our continuous pursuit, and exploration of new boundaries in orthopedic surgery.

## History of avascular necrosis of femoral head

Bone death is a concept which Hippocrates put forward in antiquity, and was first described in 1738 by Munro. But it was not until 1794 that James Russell of Edinburgh wrote the first modern-day descriptions. In these cases, infection was then the predominant etiology of avascular necrosis.

In approximately 1835, Cuwiltier depicted femoral head morphologic changes secondary to the interruption of blood flow.

In 1888, König described necrosis of the adult femoral head without infection "copora mobilis of the hip"<sup>33</sup>. Also, osteonecrosis attributed to the circulatory disturbances of the particular vascular supply of the femoral head was then described in 1948 by Chandler as "coronary disease of the hip"<sup>13</sup>.

Generally, published cases of non-traumatic avascular necrosis of femoral head were few before 1960. Early in the 1960s, especially in France, reports provided a good description of avascular necrosis of femoral head both clinically and radiologically<sup>15,59,60</sup>. The first French study, however, was first presented in 1951 by Welfling<sup>77</sup>. In 1962, Mankin and Brower<sup>38</sup> revived this entity with the description of 5 cases.

In American literature, after Mankin and Brower, Patterson et al.<sup>52</sup> presented similar observations in 1964.

## Core Decompression

In 1964, Arlet and Ficat<sup>20</sup> recognized the therapeutic effect of core decompression in AVN of femoral head, while they were investigating painful hips in patients, who had normal radiological findings. The procedure involved the removal of 8-10 millimeter diameter cylindrical core of bone from the femoral head and neck with a hollow trephine. Analysis of the specimens showed necrotic bone, and the

patients reported almost immediate pain relieve. Initially, the coring procedure was part of a diagnostic protocol that also included measurements of bone marrow pressure as well as venography (functional evaluation of bone). As elevated pressures and abnormal venographic findings were virtually universal, a rationale was developed for the therapeutic role in which core decompression could play, in the reduction of bone marrow pressure and improvement of intra-osseous blood circulation.

Since the first study in 1964, many other reports of core decompression as a modality of treatment for avascular necrosis of the head of femur have showed great divergence of opinion.

In 1981, Solomon concluded that core decompression had become the mainstay of treatment at his unit<sup>64</sup>.

By 1980, Ficat and Arlet had performed more than 800 cases<sup>1,21</sup>. In 1985, Ficat<sup>22</sup> reported on 133 hips with stages I and II treated with core decompression. He then reported "good to very good" results in 90% of those hips on clinical assessment and 79% through radiological imaging.

Despite these positive results, in 1986, Camp and Colwell concluded that "core decompression should be considered a relatively ineffective procedure with significant morbidity". 60% of pre-collapsed cases treated with core decompression failed either clinically or radiographically<sup>10</sup>. Nonetheless, a further study in 1995 revealed no further surgery was required for 88% of stage-I, 72% of stage-II and 26% of stage-III avascular necrosis of femoral head treated with core decompression<sup>18</sup>.

In Mont et al. 1996, it reviewed 42 reports involving 2205 hips. Core decompression was used to treat 1206 hips and the other 819 hips were treated symptomatically. Satisfactory results were obtained in 64% of the hips in patients, who were treated by core decompression but only 23% showed good results of those hips, which were treated non-operatively. Comparing core decompression to simply symptomatic treatment of pre-collapsed avascular necrosis (stage-I and II) showed a success rate of startling 71% versus 34.5%<sup>47</sup>.

Similarly in Steinberg et al. 2001, core decompression showed better results as compared to symptomatic treatment, with 36.2% requiring total hip replacement after core decompression versus 77% who were treated symptomatically at a mean of 29 and 21 months respectively<sup>39</sup>.

### **Bone Grafting**

Cortical bone grafts have been used in the treatment of avascular necrosis of the femoral head to provide structural support to the subchondral bone, and articular cartilage during the process of healing with core decompression. With a technique popularized by Phemister<sup>54</sup>, Boettcher<sup>4</sup>, and Bonfiglio<sup>5,6</sup>, cortical struts were harvested from the ilium, fibula or tibia and placed into a core canal in the femoral head.

In 1949, Phemister described the first technique for bone grafting of the femoral head, consisting of a cortical strut graft placed into a core tract in the femoral head and neck. Various modifications of this procedure were made when initial reports did not show satisfactory results at long-term follow up<sup>11,12,46,65</sup>.

In 1970, Boettcher initially reported success in 71% of 38 hips in 6 years after the use of cortical tibial strut grafts. However, in 1980, the long term evaluation showed only 29% of 56 hips having acceptable clinical result after a mean of 14 years (range 4 to 27 years)<sup>62</sup>.

In 1977, Dunn and Grow reported only 4 good results in 23 patients treated with Phemister-type bone grafting<sup>16</sup>. In 1990, Buckley et al.<sup>8</sup> described the results after core decompression combined with tibial autogenous grafts (3 hips), fibular autogenous grafts (7 hips), and fibular allografts (10 hips). It reported the best success results to date: 90% of patients (18 of 20 hips) were asymptomatic at an average follow up of 8 years (range 2 to 19 years). In addition, more complex procedures for non-vascularized bone grafting include the addition of graft through a cortical window in the femoral neck, also known as the light-bulb procedure.

In 1983, Ganz and Buchler<sup>23</sup> were the first to report the use of a cancellous bone graft through a window created in the femoral neck. However, they combined this procedure with an osteotomy. Moreover, their paper was just a description of the procedure with no follow up.

This procedure was then modified by Yamamoto et al.<sup>79</sup> in 1983 and subsequently, in 1989, by Itoman and Yamamoto, who used cortical iliac strut autogenous grafts. Itoman and Yamamoto<sup>29</sup> found that 61% (23 of 38) of Ficat stage II or III hips showed an excellent or good clinical outcome at an average follow up of 9 years (range 2 to 15 years).

In 1994, Rosenwasser et al.<sup>56</sup> combined complete evacuation of the femoral head through a window at the head-neck junction of the femur with grafting with cancellous bone from the iliac crest. They reported excellent results in 13 of 15 hips with stage II or III disease at an average of 12 years (range 9 to 15 years).

Another method consists of bone-grafting through a so-called trapdoor that is made through the articular cartilage in the femoral head. Here, grafting through the femoral head cartilage involves exposing the collapsed segment by dislocating the femoral head. Next, the surgeon elevates and hinges the chondral surface on a base, using a combination of scalpels and fine osteotomes. The head is evacuated of all visible necrotic bone via curettage and burrs until a good bleeding area is encountered. The void is then carefully packed with cancellous grafts.

This was initially reported in 1965 by Merle d'Aubigné et al.<sup>21</sup>, 1966 by Judet et al.<sup>41</sup>, and 1983 by Ganz and Bücher<sup>17</sup>. It was then later described in detail by Meyers et al.<sup>43</sup> in 1983.

In 1991, Meyers and Convery<sup>44</sup> reported a good or excellent result in 8 out of 9 Ficat stage III hips at an average of 3 years (range 1 to 9 years).

In 1998, Mont et al.<sup>45</sup> reviewed their results in 24 Ficat stage III and 6 stage IV hips that underwent the trapdoor procedure. They reported good or excellent clinical results in 83% (20 of 24) of stage III hips at a mean follow up of 56 months (range, 30 to 60). The results in stage IV hips were less favorable as it was success in only 2 of 6 stage IV hips.

### **Free vascularized fibular grafting**

Vascularized fibular bone grafting generally involves the

removal of a segment of fibula with attached vascular pedicle. In a separate surgical field, a core is created in the femoral head by removing the necrotic bone. Cancellous bone graft is packed into the cavity followed by transplant of the fibular segment into the remaining cavity. The graft's vascular pedicle is then anastomosed to the lateral femoral circumflex artery and vein.

Implantation of a vascular pedicle into the femoral head was proposed by Horii and Tamai<sup>30</sup> in 1979. They reported new bone formation and revascularization around the graft. In 1981, Judet<sup>32</sup> started introducing a technique of muscle bone pedicle graft using the posterior part of the greater trochanter on fractures of the femoral neck. Meyers<sup>42</sup> and Palazzi<sup>50</sup> also used similar muscle bone pedicle procedure, and obtained satisfactory results in treating femoral neck fractures and Ficat stages I and II osteonecrosis of femoral head. However, these procedures could not provide sufficient mechanical support under the necrotic and unstable subchondral bone.

The results of various classic bone grafting techniques used in treating avascular necrosis of the femoral head were generally unpredictable. Ultimately, the basis of free vascularized grafting techniques was to provide a strut mechanical support, and at the same time, enhance revascularization and introduce osteoprogenitor cells into the avascular region.

Since 1979, numerous studies have been performed to establish the effectiveness of free vascularized grafting in avascular necrosis of the femoral head as a technique to treat and prevent progression of pre-collapsed osteonecrosis of the femoral head.

In 1995, James R. Urbaniak<sup>74</sup>, of Duke University, School of Medicine, reported on the results of 103 consecutive hips in 89 patients with avascular necrosis who underwent free vascularized fibular grafting. All patients were followed up for a minimum of 5 years. 31 of 103 (30%) hips required total hip replacement eventually. The average Harris hip scores had improved at the latest follow up evaluation, and had decreased the need for pain medication for 86% of the hips that had not been subsequently treated with an arthroplasty.

Although there are studies showing promising results, comparisons with other surgical therapies are important to isolate the contribution of the vascularization. For example, the surgery for vascularized fibular grafts also includes core decompression, and other grafting techniques such as non-vascularized autologous or allogenic cortical grafts to provide a similar strut as the fibular graft. Therefore, the vascularization is the unique component of the overall procedure.

### Osteotomy

Thomas Porter McMurray in 1935 described his technique for femoral osteotomy, which involved medial displacement of the distal fragment under the acetabulum to unload the hip. He was the first to perform a displacement osteotomy for un-united fractures of the neck of the femur and arthrosis of the hip.

In 1965, Merle D' Aubigne et al.<sup>22</sup> first introduced varus osteotomy with the intention to load the most lateral part of

the femoral head, which was usually not the part involved in necrosis.

In 1972, Sugioka devised a rotational osteotomy by rotating the head and neck anteriorly. Reports had shown 95% success rate for a mean of 5 years in the hips where the intact area of the posterior surface of the head was more than 30%. However, when this area was less than 30%, good results were only present in 56% of the hips operated<sup>69</sup>. In 1976, Pauwells<sup>51</sup> introduced valgus-extension osteotomy, whereby the necrotic area is moved laterally and posteriorly. In order to enlarge the weight-bearing surface area, capital drop osteophyte was also loaded.

In 1984, Bombelli focused on the shape of the femoral head, and the angle of the femoral neck, thereby expanding on Pauwell's theory to include the sagittal planes in osteotomy. Both studies showed good results even at 10 year follow up, with excellent functional pain relief, despite the presence of some limitations in movement.

In 1979, Schneider<sup>58</sup> proposed a flexion inter-trochanteric osteotomy aimed at rotating the intact posterior portion of the femoral head into the weight-bearing portion of the acetabulum, with the intention of shifting the load away from the necrotic region.

In 1984, Simonnet et al.<sup>61</sup> reported good results in 72% of their results on an average of 42 months of follow up. The patients had good results for both pain and mobility. In 1986, Candell et al.<sup>11</sup> reported an improvement in clinical results at a mean follow up of 4.3 years, with a satisfactory outcome in 91% of the patients with stage II disease, 56% with stage III disease, and 32% in stage IV disease.

In 1989, Gottschalk<sup>26</sup> reported good results in 59% of his patients at a mean follow up of 36 months. However, his patients did not have functional improvement. In 1993, Scher and Jakim<sup>57</sup> reported a satisfactory outcome at 10 years follow up in 87% of the patients who underwent osteotomies.

For Sugioka osteotomy, results in European studies have been poor. In a 2005 study, 26 hips in 22 consecutive patients were followed up for 8.7 years (range 6.6 to 10). At review, 17 hips had been converted to total hip arthroplasty. The clinical survival rate was 56% after 7 years (95% C.I. 36%-76%). The radiological survival rate was only 54% after one year (95% C.I. 35%-73%)<sup>55</sup>.

### Arthrodesis

The first arthrodeses were performed to stabilize the flail joints resulting from infantile paralysis.

Arthrodesis of the hip was by means of using an extra-articular iliofemoral graft, to avoid interfering with the diseased area. However, this was unable to correct the deformity, and the graft failed to fuse at the lower end as the femur was pulled away by the predominating power of the adductors and abductors. Next, intra-articular methods were developed. These consisted of removing the articular cartilage and bone from both surfaces of the joint, followed by prolonged immobilization in a double plaster of Paris spica. It was a formidable procedure and as recently as 1929, Robert Jones, in the standard textbook of the day, relegated the operation to being a small type, and described it as "a fairly severe test of endurance of the patient".

Different intra-articular and extra-articular arthrodeses

have since been described. For example, those of Albee, of Ghormley, and of Hibbs, made use of iliofemoral grafts but often failed because of the propensity of the hip to adduct. In 1942, Brittan overcame this difficulty by adapting Trumble's ischio-femoral arthrodesis in such a way that adduction compressed the graft and thus, assisted fusion<sup>7</sup>.

The next step followed naturally on the development of the technique to internally fixate transcervical fractures of the neck of the femur by Smith-Petersen and Sven Johannsen in the late 1920s and early 1930s. Basically, it was to drive a triffin nail across the joint into the ilium to resist the adducting forces, which would be acting on the joint. The first occasion when Dr Philip Wiles attempted this, after excising the joint, was in 1933, and had continued to use this method, or its modifications ever since. The operation was also developed independently by Burns (1936)<sup>9</sup>, and Watson-Jones (1938)<sup>76</sup>, who had extra long and strong triffin nails made especially for this purpose.

### Hip Arthroplasty

The earliest arthroplasties were performed with the intention of mobilizing ankylosed joints. The joint surfaces were refashioned and neighbouring soft tissue was interposed to prevent their fusion again. The idea was pioneered by Ollier, who interposed the periarticular soft tissues, usually in animals, ranging from pig's bladder to rubber sheeting, zinc foil and collodion in the late 19<sup>th</sup> century.

In 1902, Robert Jones successfully reconstructed a hip using gold foil, and in the same year, Murphy obtained satisfactory results by interposing a flap of fat and fascia. Some time later, Whitman described a reconstructive procedure in which the head and neck of femur were excised and the greater trochanter being transplanted to a lower level. Until the Second World War, few surgeons have been bold enough to advise hip arthroplasty using either the Whitman procedure, or the Murphy technique as developed by Vittorio Putti, Willis Campbell and the others.

Cup arthroplasty – It was a unique type of interposition arthroplasty, which played a paramount role in the treatment of patients with disorders of the hip, and more importantly, laid the foundation for the development of modern total hip replacement used in the treatment of post-collapsed femoral heads in avascular necrosis.

It began with a surgeon, M N Smith-Petersen, from Boston, Massachusetts, who deserves the credit for putting hip arthroplasty firmly on the surgical map. He described the anterior approach to the hip, which goes by his name in 1917, whilst he was still a resident. Subsequently in 1923, he performed his first arthroplasties. In his pursuit of relieving patients from pain and agony, he created a prosthetic made of glass to fit securely over the femoral head of the hip joint. His idea of creating a smoother surface with less friction for joint movement was logical, but the glass proved to be unsuitable for the amount of stress which the hip retains. Undeterred, he experimented with plastic and stainless steel, hoping they would be more resistant to the stress. These two materials, although still not great, were far superior to glass, and eventually led the transition into mould arthroplasty seen in the 1940s.

In 1937, Venable et al<sup>75</sup> described Vitallium as a

biologically inert material, which might serve a myriad of in vivo applications. Shortly after, Smith-Petersen began using Vitallium cups.

The operation soon reached its final form in 1938, and by 1947, Smith-Petersen had operated upon more than 500 hips in 420 patients<sup>63</sup>. A surgeon of great mastery, an enthusiast, and a man of endearing personality, he nursed back the function of the hip, and retained the confidence of his patients, so that even when revision was required, he was still able to encourage them and provide spiritual support. His work was then continued by Aufranc, and in 1957, he reported on 1000 cup arthroplasties performed at the Massachusetts General Hospital with 85% having good results<sup>2</sup>.

Surface replacement arthroplasty – During the 1950s, various modifications of cup arthroplasty were taking place. In 1951, Haboush<sup>27</sup> at the Hospital for Joint Disease in New York introduced the use of fast setting dental acrylic cement for fixation of his Vitallium total hip prosthesis. Results were poor, primarily because he had used the acrylic cement for fitting the prosthesis in place, and not for the purpose of transmission of load with the equalization of forces. In 1952, Townley began performing a hemi-arthroplasty using a metal cup mounted on a short curved intra-medullary stem<sup>73</sup>. The femoral head was not removed, but was reamed to fit within the thin walled metal cup. Thus, this device combined certain features of a cup arthroplasty and that of a femoral endoprosthesis.

In 1960, Townley combined this femoral component with a polyurethane acetabular cup, but the plastic degraded with time. In 1977, he started using polyethylene acetabular components, which were attached with cement, and was referred to as a total articular replacement arthroplasty or TARA<sup>63</sup>.

In 1960s and 1970s, various surface arthroplasties were developed. But perhaps the most popular surface replacement in the United States was the THARIES (Total Hip Articular Replacement using Internal Eccentric Shells), designed by Amstutz et al<sup>1</sup>. It was a good alternative to total hip replacement, especially in the young adults, but the failures were evident within the first 5 years of follow up<sup>66</sup>. Endoprostheses – Delbet<sup>67</sup> used reinforced rubber as a replacement for the femoral head in 1919. In 1927, HeyGroves in England used ivory for this purpose as well<sup>53</sup>. Then, as early as 1938, Dr. Jean Judet and his brother, Dr. Robert Judet, of Paris, attempted to use an acrylic material to replace arthritic hip surfaces. This acrylic provided a smooth surface, but unfortunately it had a tendency to come loose, and pain relief was only transient.

In 1940, Moore and Bohlman replaced the upper end of the femur in a patient with malignant giant cell tumor with a 12 inch long stainless steel prosthesis<sup>48</sup>. It functioned well till the patient's death, and was credited for being the first of the modern endoprostheses.

In 1950, Thomson developed a short-stemmed metal device, which came to be known as the light bulb prosthesis<sup>72</sup>. However, they were soon replaced to longer-stemmed intra-medullary prostheses, which were comparatively more superior<sup>71</sup>.

In the early 1950s, McKeever and Collison developed the bipolar endoprostheses, which used Teflon-lined metal

cups placed over the metallic femoral prosthesis, in an attempt to improve on the results with the conventional unipolar endoprostheses.

According to Murray<sup>36</sup>, in the beginning of 1973, Giliberty and Bateman developed the prototypes of the current bipolar prostheses, which were lined with high density polyethylene, independently.

The prostheses developed by Frederick R. Thompson of New York, and Austin T. Moore of South Carolina, functioned so well that minimal modifications had been made up to this day.

Total hip replacement – It is often the treatment of choice for most severe cases of avascular necrosis, as its goal is to relieve hip pain and improve functionality of the joint<sup>3</sup>.

In 1890, Gluck<sup>25</sup> in Germany is said to have performed the very first total hip replacement. His experimental prosthesis consisted of a carved ivory ball and socket, which he fixed in place with a bone glue composed of colophony or rosin, pumice powder, and plaster of Paris.

It was not until 1938 that Wiles<sup>78</sup>, in London, first introduced the idea of a total hip prosthesis consisting of a femoral component and an acetabular component. Wiles inserted the device, which was made of stainless steel, in six patients with Still's disease. The femoral component was secured to the neck of the femur by a bolt, and the acetabular component was anchored to a buttress plate by screws. When Wiles first reported the results of his procedure in 1950, he stated that they were not satisfactory. Generally, there were two major problems, loosening and breakage of both the bolt and the screws that held the components in place.

During the 1940s, collaboration between McKee and Watson-Farrar<sup>40</sup> of Norwich, England, produced a successful metal-on-metal prosthesis fixed with methymethacrylate. Finally, came John Charnley, who is often recognized as the pioneer of hip arthroplasty. This Englishman and his innovative ideas were often denounced by other doctors and physicians. Nonetheless, in 1958, he addressed the eroded arthritic socket by replacing it with a Teflon implant, hoping that this would allow for a smooth joint surface to articulate with the metal ball component. When the Teflon did not achieve this goal, he went on to try polyethylene, which worked wonderfully well. In order to obtain fixation of this polyethylene socket as well as the femoral implant to the bone, Charnley borrowed polymethacrylate from the dentists. This substance, known as bone cement, was mixed during the operation, and used as a strong grouting agent to firmly secure the artificial joint to the bone. Truly, this was the birth of "total hip replacement."<sup>28</sup>

By 1961, Charnley was performing the surgery regularly with good results. He further improvised on the techniques and component designs. Thousands of people were successfully relieved of their hip pain, and the long term results became very predictable. The Queen of England knighted him for his immense contributions, and he is now known as Sir John Charnley.

Since that time, many skilled surgeons have improved upon the concepts which started in central England. Methods of fixation and actual cementing techniques are significantly better nowadays. Refinements and modifications in the design of the prostheses have evolved. Today, over 100,000 hip replacements are performed annually in the United States

using the principles of a low friction arthroplasty with a polyethylene socket and metal femoral prosthesis.

An important long term problem encountered in total hip replacement would be aseptic loosening. Early follow up studies have reported loosening rates of cemented femoral stems, at a maximum ten year follow up of between 4.2% and 40%<sup>70</sup>.

### Stepping into the 21<sup>st</sup> century

As we progress into the 21<sup>st</sup> century, the continuous search for new advancements in surgical and non-surgical treatment of avascular necrosis of the femoral head does not cease.

We foresee a need for intensive research into the patho-etiological process and natural history of this elusive disease, so that we can retard or even reverse the progression of the condition. We feel that the absolute cause of avascular necrosis has not been sufficiently understood. But once there is a greater understanding of the etiology, we can hopefully prevent such a devastating condition from occurring in the first place. Thus, future medical treatment should be aimed at the causes of avascular necrosis so that pre-operative measures can be initiated early.

Additional refinements of magnetic resonance imaging may allow more accurate methods of staging the disease. More studies are also needed to optimize the use of pharmacological agents, which include vasodilators, fibrinolytic and lipid lowering drugs.

With advancements made in stem cell research, the possibility has been raised that bone marrow containing osteogenic precursors implanted into the necrotic lesion could be of benefit in this condition. Indeed, bone marrow contains adult stem cells, such as haematopoietic stem cells, mesenchymal stem cells and pluripotent stem cells, which might possess osteogenic properties. The efficacy of bone marrow implantation into the osteonecrotic zone has been studied in two prospective trials<sup>68</sup>.

Further refinement of electrical stimulation could increase its efficacy as a non-invasive method of treatment, or even improve operative treatment by using it as an adjunct, together with cytokines to promote early recovery.

As our knowledge of materials science, engineering and biology expands, we might find better materials for the prostheses. Current technologies have their limitations, and there would certainly be issues and future challenges in tissue engineering. It may seem simple to produce a tissue-engineered product in the laboratory, but it is another thing all together to produce hundreds of products of consistent quality for clinical use. New technologies need to be discovered and invented. Indeed, tissue engineering is likely to create an impact on the evolution of orthopedic implants.

As one can see, in addition to the current treatment methods which were previously mentioned – core decompression with or without bone graft, free vascularized fibular grafting, osteotomy, arthrodesis, and arthroplasty – it is a never ending journey in our quest for a more effective therapeutic method in the treatment of avascular necrosis.

A myriad of ideas had been put forth by our predecessors over the past centuries, laying the very foundation of femoral avascular necrosis surgery for us to continue to improvise on. The history of femoral avascular necrosis had been

fascinating, and filled with surprises. Certainly, there is going to be many more chapters to go, and many more great ideas to come in the near future.

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