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# Review Article

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## Problem of Stress Shielding and Improvement to the Hip Implant Designs: A Review

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This study reviewed on stress shielding, which had been reported as one of the main problems that lead to bone loss and revision surgery after implanted in hip joint. It started with a brief discussion on hip joint replacement and detailed discussion on stress shielding phenomenon. It also reviewed currently used of several implant materials and its design in order to reduce the problem. The main intended of this study to set a baseline for conditions of improvement and eradications to the mentioned problem. As the review ended, a lot of studies are required in order to have an implant that may behave like a real joint. Hence, design aspects like stem-bone bonding, the stability of the implant inside the femur and bone reaction along interface, should also give the greatest consideration.

**Key words:** Stress shielding, implant design, hip joint replacement, bone loss

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## INTRODUCTION

**Hip joint replacement:** The hip joint can fracture and damage due to various reasons such as involving in road accident, falling down stairs, osteoporosis, or disease that affects joint tissue like rheumatoid arthritis. The hip fracture is a serious injury that can occur to anybody. Buford and Gosawami (2004) mentioned that, in a year 2000 alone, almost 11% from 500,000 operations were performed in The United States of America for patients aged within 40 years. Hip fracture can lead to permanent disability, pneumonia, pulmonary embolism and death. Worldwide, Keyak and Falkinstein (2003) stated that, the numbers of hip fractures are expected to increase to over 6.26 million in the year 2050.

Most of the patients with fracture hip experience difficulty in doing their routine activities. Consequently, they require hip replacement or arthroplasty to overcome this difficulty (Lieberman *et al*., 2003). A hip replacement is a procedure of replacing the diseased hip joint with a new artificial part called prosthesis. It is used to transfer load from the acetabulum to the femur through a metal stem that is inserted into the femur (Terrier, 1999). The procedure is aimed to relieve the pain and improve mobility.

**Revision surgery:** Although patients will be able to return and enjoy their activity even not as active as before the operation, the possibility for revision surgery still exists. The term revision surgery is used when replacing a previously replaced hip joint. Almost 10% from overall operations would undergo for revision surgery (Kuiper, 1993). However this situation depends on patients' conditions and types of prosthesis that were used. For heavier patient and age 30 years old during the operation, nearly 33% of them will need to do the revision operation after 10 years.

Based on the research conducted by Malchau *et al.* (2000), there were almost 20% of 10,000 operations made in Sweden would go for revisions which 7% from it used cemented femur and the other 13% used cementless design. The risk of revision operation is extremely high especially to elderly patients and its complications include cardiac problem, pulmonary problem and mortality (Pagnano *et al*., 2003). Hence, the possibility for it to occur should be minimized.

Havelin *et al.* (1993) also did the same survey in Norway from September 1987 to end of 1990 where the most common reasons for revisions were loosening of the stem, which contributed almost 64%. In other survey performed by Malchau *et al.* (1993) in Sweden from 1987 to 1990, 79% of all revisions were due to implant loosening. Implant loosening is a mode of failure resulting from implant movement or migration in the bone or cement. The most common cause of implant loosening is the loss of bone mass due to stress shielding (Huiskes *et al*., 1992; Tang *et al*., 2002).

**Stress shielding:** Stress shielding in femur occurs when some of the loads are taken by prosthesis and shielded from going to the bone (Kuiper, 1993; Paul, 1999). Normally, femur carries its external load by itself where the load is transmitted from the femoral head through the femoral neck to the cortical bone of the proximal femur as shown in Fig.1a. When stiffer stem is introduced into the canal, it shares the load and the carrying capacity with bone. Originally, the load is carried by bone, but it is now carried by implant and bone. As a result, the bone is subjected to reduced stresses and hence stress shielded (Huiskes *et al*., 1992). The upper part of the femur receives fewer loads. The stress shielded area is whiter as shown in Fig. 1b. The femur around the distal end of the femoral component is overloaded (darker area as shown in Fig. 2b).

Based on Wolff's law, a bone develops a structure most suited to resists the force acting upon it. Areas of bone experiencing high load or stress will respond by increasing bone mass and areas under lower load or stress will respond by decreasing bone mass (Bugbee *et al*., 1996). Decreasing in bone mass is known as bone resorption, may lead to the loosening of failure of the implant.

Most of the previous work quantified the stress shielding in implanted femur from the stress differences with intact femur. Typically a finite element model of the femur is used to calculate the stresses in the bone. Then the change in stress, caused by the introduction of the implant, is used as a comparison. Joshi *et al.* (2000) measured the stress shielding from the difference in the stress for each element in the bone before and after THA was calculated and divided by the stress occurring in the element pre-THA. This ratio was then volume-averaged over a specific region. Weinans *et al.* (2000) defined the stress shielding as a change in strain energy (SE) in each element of the implanted bone relative to a reference value of SE in the intact bone as in Eq. (1).

$$\text{Stress shielding} = \frac{\text{SE(treated)} - \text{SE(reference)}}{\text{SE(reference)}} \quad (1)$$

Where the strain energy (SE) is calculated as the strain energy density divided by the apparent density. Other definitions related to stress or strain might be applicable as well. Gross and Abel (2001) measured the

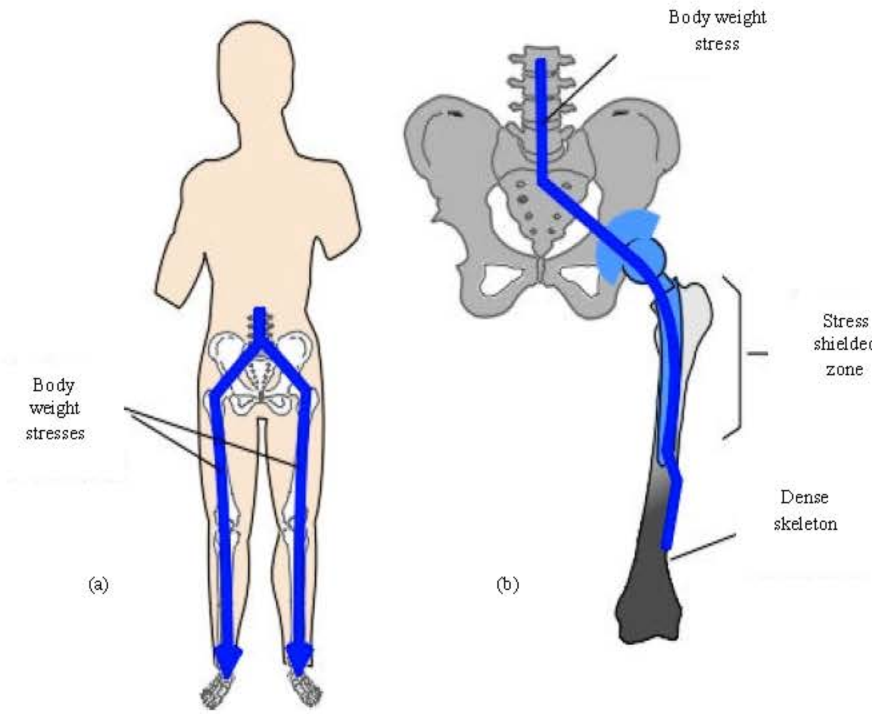



Fig. 1: Simple scheme of stress shielding (Surin, 2005)

stress shielding by taking the ratio of maximum bone stress that occur in implanted femur to the reference implant.

The location where stress shielding occurs can also be determined in finite element model as shown in Fig. 2 (Swanson et *al*., 1977). The analysis compared the stress distribution occurred in intact (without implant) and after implanted at 16 different points along medial and lateral sides. As shown in Fig. 2a and b, the stress in each point (noted as O) was reduced after the implant had been inserted into the femur. This reduction occurred both in medial and lateral side. The most differences in stress occur at the proximal medial part similar as in Terrier (1999).

Other example of the stress shielding phenomena is shown in Fig. 3. This figure showed a comparison between the bone stresses that occur in a noncemented femoral stem and cemented stem at the same external loads. The stress shielding is clearly reduces from proximal to distal. Below the tip of the stem the stresses are again normal. The amount of stress shielding is more severe for noncemented stem as compared to cemented due to the difference in flexibility of the two methods of fixation. The size of noncemented stem is larger than cemented stem, hence stiffer and takes away more load from the bone, thus create more stress shielding.

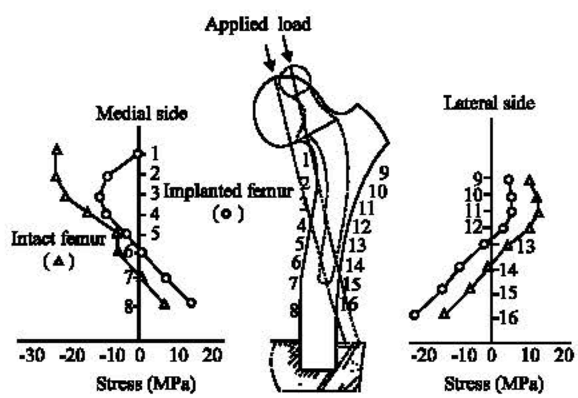



Fig. 2: Stress distribution along medial and lateral sides when 4000 N applied load was given onto proximal head (Swanson *et al*., 1977)

**Bone loss:** Stress reduction observed in implanted bone will lead to bone loss. Niinimäki *et al*. (2001) defined bone loss as the difference between the operated and the non-operated sides. If is seen through x-ray film, there will be small gaps along bone/implant interface. Dual Energy X-ray of Absorptiometry (DEXA) is a widely used method for quantifying bone mass and bone mineral density (BMD) at the lumbar spine, proximal femur, distal radius and other skeletal sites. Lozynsky *et al*. (1996) quantified

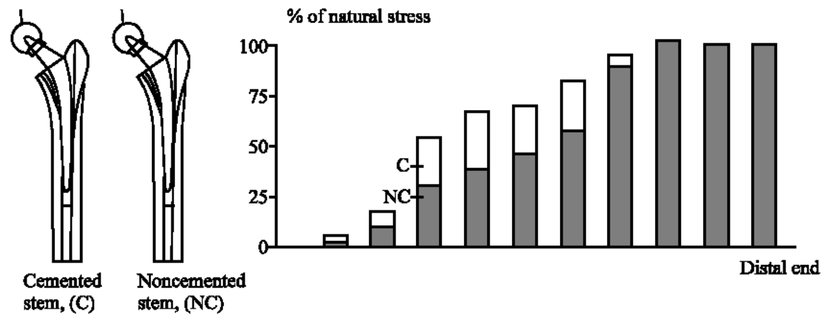



Fig. 3: An illustration of stress shielding around a cemented (C) and a noncemented (NC) femoral stem. The cortical bone stresses are shown, in each case, as a percentage of the natural case for the same hip joint load if the stem were not present. The difference between natural and actual is the extent of stress shielding (Huiskes, 1993)

the Bone Mineral Content (BMC) and Bone Mineral Density (BMD) of proximal femur in autopsy retrieved from cemented femoral stems. DEXA radiographic analysis was used to quantify bone content and density in 13 femurs containing cemented implants with duration of 12-191 months. The proximal region had the greatest bone loss, on average 40%. McAuley (2002) also reported that out of 426 patients that used cementless stem; on average 24% of them show loss of BMC.

All of these data proved that, there would be a reduction in volume of femur after hip replacement operation. The changes in bone's volume and mass will take a few years, as its reaction to outside environment is too slow (Bagge, 2000). However, after certain period of time, the implant will no longer stabilise in femur. Stress shielding reduces the support of the implant and therefore increases the risk of implant loosening. The effects from implant loosening and micromotion of prosthesis relative to femur can cause difficulties to patients whenever they do daily activities. If this situation continues, revision surgery will be most beneficial and likely to be carried out.

However, the bone around the removed femoral component has less bone stock. Therefore, the new implant needs to be longer and thicker so that it will be stabilised steadily in the bone. But, the same problem like stress shielding may occur. The new implant possibly works for another years until it will loose again and needs to be replaced. Normally, this process does not continuously occur. There must be some limit such as how many years as one can expect to keep a series of prostheses depends on patient's bone stock. After that, patient needs to consider bone grafting. Thus, after considering this entire problem, the phenomena like stress shielding must be eliminated.

## MATERIALS AND METHODS

There are two primary issues in material science about bone replacement material. They are mechanical properties and biocompatibility (Katti, 2004). The term biocompatibility can be briefly described as the way of the body tissues interact with the biomaterial. Biomaterial is defined as a material of natural or manmade origin that is used to direct, supplement or replaces the function of living tissues (Katti, 2004). As with all foreign objects in the body, a hip implant may stimulate an auto-immune response, which could be ruinous for the success of the implant. The materials selected should minimize the risk of rejection.

Hip implant has been made using variety of materials such as metals, ceramics, polymers and composites. In early 1960s, the stainless steel femoral total hip replacement (THR) component was mated with a polytetrafluoroethylene (PTFE) acetabular cup. However due to poor wearabality, the stainless steel was replaced by the Cobalt-chromium-molybdenum (Co-Cr-Mo) alloy, whereas the PTFE was replaced by ultra high molecular weight polyethylene (UHMWPE). Both materials have shown a good wear resistance. Wear might occur on surfaces which are always in contact especially when the ball is articulating within the acetabular cup in every patient's movement. As well as metals, ceramics like alumina and zirconia are also widely used as a femoral head. In fact, it has been reported that wear rates for alumina on UHMWPE are 20 times less than metal on UHMWPE (Katti, 2004).

The Co-Cr-Mo is about 10 times stiffer than femur, whereas the alumina is about 19 times stiffer than femur as shown in Table 1. These differences can be a significant problem associated with stress shielding, which is directly

Table 1: Mechanical properties of alloys, polymers and ceramics used in total hip replacement

| Materials | Tensile strength (MPa) | Elastic modulus (GPa) |
|---|---|---|
| **Alloy** | | |
| Co-Cr alloys | 655-1896 | 210-253 |
| Co-Cr-Mo | 600-1795 | 200-230 |
| Ti-6Al-4V | 960-970 | 110 |
| Stainless steel 316 L | 465-950 | 200 |
| **Polymers** | | |
| UHMWPE | 21 | 1 |
| PTFE | 28 | 0.4 |
| **Ceramics** | | |
| Zirconia | 820 | 220 |
| Alumina | 300 | 380 |

related to the difference in stiffness of the femur and the implant material. Titanium (Ti) alloy has low modulus of elasticity as compared to Co-Cr-Mo alloy and alumina. It is also shown improvement in wear properties, even it is much lower when compared to Co-Cr-Mo alloy and ceramic but it has the highest fatigue strength among all alloys reported. Hence, it can be a suitable candidate for THR components.

## RESULT AND DISCUSSION

**Implant design to reduce stress shielding:** Almost all of the previous works that have been carried out to reduce stress shielding problem focused on stem design. Aspects like stem stiffness, geometry and shape had been getting serious attentions by most of the authors.

**Implant stiffness:** Decreasing stem stiffness would be expected an increase in load transfer from the stem to the proximal femur, hence decreasing the stress shielding (Diegel *et al*., 1989). Stem stiffness was influenced by implant material and its cross sections.

The modulus of implant materials is a core factor in adequate transfer of stress to the surrounding bone. The elastic modulus of the stem (e.g., Cobalt Chromium is 200 GPa) is typically much higher than the cortical bone it replaces i.e., 20.3 GPa (Bitsakos *et al*. 2005). The more rigid the stem, the less load it transfers proximally so the greater the stress shielding of the proximal femur. By decreasing the implant modulus of elasticity enhances implant-to-bone stress loading and can minimize bone atrophy due to stress shielding.

The effects from flexibility of implant material towards stress shielding have been studied by Bobyn *et al*. (1990). Two porous-coated femoral implants of substantially different stiffness were compared, i.e., cobalt-chromium (Co-Cr) alloy and titanium alloy. Femur with the flexible stems consistently showed much less bone resorption than those with the stiff stems. This finding was also verified by Sumner and Galante (1992) who did the experiments to the canine using a low stiffness cementless porous-coated stem. The result showed that the bone loss in its proximal part was reduced. Although the flexible stem can reduce stress shielding problem and bone resorption when compared to rigid stem, however it has also increased the stress along proximal implant/bone interface and may possibly leads to implant failure (Huiskes *et al*., 1992).

Foam metals, which are basically metal-air composites, are also one possible solution to reduce elastic modulus of implant. As porosity increases, Young's modulus will decrease. Rahman and Mahamid (2002) have tried to use cellular metallic alloy implant which was more compliant and acts nearly as a normal femur. The cellular implant has a topology like a spongy bone and it has increased the load transfer to the bone when compared to the solid implant. Hence, may slow down the potential for stress shielding to occur. However, one of the undesirable effects is that the strength of the foamed metal also decreases significantly as the porosity increases.

Modifying the stem cross-section can reduce its flexural stiffness. Thicker stem will take more loads from the bone when compare to thinner stem. From radiographics findings by Jergesen and Karlen (2002) to the patients with larger stems showed higher grades of stress shielding compared with femur implanted with medium stems and small stems. Most of the current designs are to develop a stem geometry that restores, as much as possible, the natural load-transfer mechanism through the proximal femur.

Munting and Verhelpen (1995) have designed an implant without stem that was different from the conventional concept. The implant was fits into the femoral neck and strongly supported by several trans-tochanteric screws. Form their *in vitro* experiments showed minimal micromotion and from the short-term clinical studies have shown low initial failure rates. However Munting has claimed that the stemless implant was effective for short term fixation and besides there were no significant data or results proving that the problem can be reduced in real situation.

Joshi *et al.* (2000) work was an extension to Munting and Verhelpen (1995). He and his colleagues designed the prosthesis with a new geometry. According to him, the shortened stem can reduce stress shielding problem and shear stress along the interfaces. He used a rectangular plate to uniformly distribute the stress throughout the femur and the implant. A few cables as shown in Fig. 4 have been used to support the implant. Then the design was compared with Munting's work and conventional design by various regions on femur using FEM and it showed less of stress shielding everywhere except at underneath of the greater trochanter.

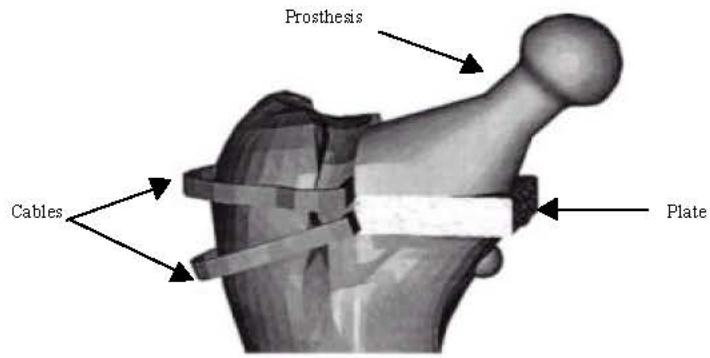
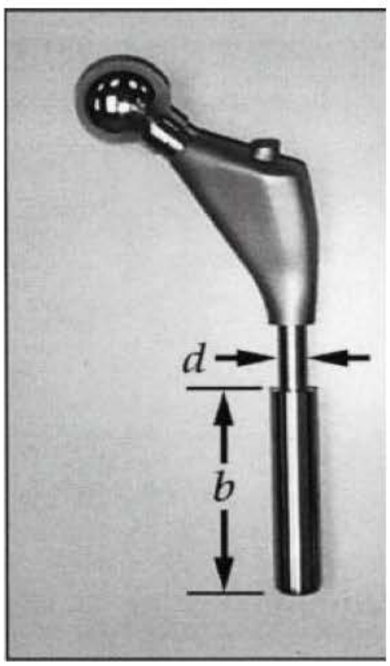



Fig. 4: Schematic design for shortened implant as been suggested by Joshi *et al.* (2000)




b-The distance from distal end
d-Reduced stem diameter

Fig. 5: Implant designed proposed by Chang *et al.* (2001)

Niinimäki *et al.* (2001) used DEXA to measure the BMD in 24 patients with total hip replacement using a short anatomic femoral stem. The results show that the proximally porous-coated short anatomic stem seemed to be better for bone mass preservation than cemented and longer stiff prostheses.

However in other work done by Rietbergen and Huiskes (2001) to investigate the effects of reducing stem length to load transfer in ABG (Anatomique Benoist Girard) hip prosthesis, it was found that by reducing the length can hardly increased interface failure probability. The short design might also have other disadvantages such as the possible of loss of initial stability and are not positioned correctly during an operation.

**Optimising implant:** Mattheck *et al.* (1990) analysed a hollow stem prosthesis using FEM and found that the hollow geometry helps to decrease the stress peak beneath the tip of the prosthesis, while at the same time increases the stress in the proximal cortical bone about 20%. The increase in the loading of the bone causes a reduction in stress shielding in this region. Schmidt and Hackenbroch (1994) studied 40 patients that implanted with the hollow stem. From their clinical results, they found that after one year, the implantations were very satisfactory and no thigh pain has been reported, which is probably due to the effectiveness of the increased elasticity and the better fit of the stem.

Gross and Abel (2001) optimised a hollow stem to reduce stress shielding and simultaneously reduced the maximum stress occurred in cement. The implant inner diameter was chosen as a design variable and cement stress was selected as the design constraint. The stress distribution in hollow optimised stem was compared with reference solid stem. However, the study only used a cylindrical shape with a simple point load and boundary conditions.

Chang *et al.* (2001) designed a thin mid-stem diameter to maintain satisfactory stability. Two variables were selected in order to improve load transfer by reducing cross-sectional area of the stem and to increase stability of the implant within the bone. The two variables were shown in Fig. 5.

The author tried to look at the potential and application of topology optimisation method in order to reduce stress shielding problem (Ridzwan *et al.* 2006). The

Table 2: List of several implant designs to reduce stress shielding

| Objectives | Focus | Design Aspect | Authors |
|---|---|---|---|
| Reducing implant stiffness | | | |
| | Implant material | Flexible stem | Bobyn *et al.* (1990), Sumner and Galante (1992) and Huiskes *et al.* (1992) |
| | | Cellular stem | Rahman and Mahamid (2002) |
| | Implant geometry | Stemless stem | Munting and Verhelpen (1995) |
| | | Shortened stem | Joshi *et al.* (2000), Niinimäki *et al.* (2001) and Rietbergen and Huiskes (2001) |
| Optimisation | Shape optimisation | Hollow stem | Mattheck *et al.* (1990), Schmidt and Hackenbroch (1994) and Gross and Abel (2001) |
| | | Robust implant | Chang *et al.* (2001) |
| | Topology optimisation | Implant inside topology | Ridzwan *et al.* (2006) |

idea of topology optimisation is to get the best distribution of material within a fixed domain as we applied the boundary conditions. Load transfer has increased in femur with the optimized implants compared to before optimize in medial and lateral side. Hence, it showed that the new optimized implants were better than the conventional implant in order to reduce stress shielding problem. Table 2 summarised the objectives done by other people in the literature in order to reduce the stress shielding problem.

## CONCLUSIONS

Hips are very important in helping us to accomplish our daily activities such as walking to the workplace, playing games, cycling, getting up from the seat, climbing upstairs etc. Unfortunately, there is no guarantee that our hips will always be in a good condition. Thigh bone or femur can be broken in an accident or damaged by osteoporosis and disease like rheumatoid arthritis. Damaged femur needs to be replaced with an implant through the operation like total hip arthroplasty or hemiarthroplasty. The phenomena of stress shielding occurred after the implant was inserted into the femur. The problem came when the metal implant took more loads which originally transferred only to the femur. For the past few years, many methods to reduce the problem have been applied by several of researchers.

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