Finite Element Analysis of Stress Distribution around Patterned Implants

Lee-Ra Cho¹, Yoon-Hyuk Huh¹², Dae-Gon Kim¹, Chan-Jin Park¹

Abstract

Purpose: The purpose of this study was to investigate the effect of patterning on the stress distribution in the bone tissue using the finite element analysis (FEA) model.

Materials and Methods: For optimal comparison, it was assumed that the implant was axisymmetric and infinitely long. The implant was assumed to be completely embedded in the infinitely long cortical bone and to have 100% bone apposition. The implant-bone interface had completely fixed boundary conditions and received an infinitely big axial load. von Mises stress and maximal principal stress were analyzed. Conventional thread and 2 or 3 patterns on the upper and lower flank of the thread were compared.

Result: The surface areas of patterned implants were increased up to 106~115%. The thread with patterns distributed stress better than conventional thread. Patterning in threads may produce more stress in the implant itself, but reduce stress in the surrounding bone. Stress patterns of von Mises stress were favorable with patterns, while the maximal principal stress was increased with patterns. Patterns in the lower flank showed favorable stress distribution.

Conclusion: The patterns in implant thread reduce the stress generated in surrounding bone, but the number and position of patterns were crucial factors in stress distribution.

Keywords: Finite element analysis, Implant, Patterning, Stress distribution, Thread


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Introduction

Patterning is a technique of surface texturing at a micrometer scale on substratum surfaces. Using the patterning, precisely controlled surfaces can be made without modifying other surface properties. Several studies dealing with patterning up to 10 \( \mu \text{m} \) found that this size of patterning could influence cell and bone tissue response\(^1,2\). To optimize bone ingrowth, however, pattern sizes of several tens up to several hundred micrometers should be considered\(^3\). By the experiment on the bone response of 10 \( \mu \text{m} \) pitch-like pattern on screw implants, Hallgren et al.\(^4\) concluded that photolithography is not suited for large-scale production of patterns on screw implants. In addition, this technique left high carbon concentrations. Laser ablation technique was introduced to overcome these problems. Although the bone response of laser ablated screw implants were superior to the control implants, the procedure caused highly varied patterns and metal cracks on the surfaces\(^5\).

An alternate approach to create patterning is by machining. The machining is a slight modification from other techniques. It requires very few new machines or tools, and produces a less varied pattern, making it easily applied to clinical implants. Machining can only produce patterns in several tens to hundreds of micrometers, which are appropriate size for bone ingrowth.

The appropriate size level for bone ingrowth has been disputed. Itälä et al.\(^3\) demonstrated that new bone could grow into the laser-perforated pores ranging from 50 to 125 \( \mu \text{m} \) on titanium implants. With machined 150–200 \( \mu \text{m} \) grooves, Anselme et al.\(^6\) presented that cell response could be affected by their organization. Hansson and colleagues\(^7,8\) suggested that a minute thread with a depth of 100 \( \mu \text{m} \) could achieve good biomechanical interlocking with bone and have an improved capacity to carry loads when compared with the standard thread profiles.

Larger size patterns produced by machining are one modification of thread shape to improve stress distribution. To reduce stress, square thread shapes (Biohorizons, Biohorizons Implant Systems, Birmingham, AL, USA)\(^9,10\) or progressive thread shapes (Ankylos, Friadent GmbH, Mannheim, Germany)\(^11\) were used for commercial implant systems.

Recently, machined patterning has been applied to the thread of commercial implants such as Groovy\(^\text{TM}\) (Nobel Biocare, Gothenburg, Sweden) and M (Shinhung, Seoul, Korea) etc\(^12,13\). However, articles dealing with optimal size or design of implant threads for bone ingrowth were relatively scarce.

The aim of the present study was to investigate the effect of patterning on the stress distribution in bone tissue using the finite element analysis (FEA) model.

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**Figure 1. Configurations of models. Left side means the implant, while right side shows surrounding bone.**

**Figure 2. Exact dimension of patterning.**
Materials and Methods

1. Modeling

The investigation was performed using the finite element analysis program from Abaqus Unified FEA product suite (Simulia, Providence, RI, USA). A two-dimensional finite element model of an implant screw shape was developed (Fig. 1). The two-dimensional model was used because it is much more efficient than the three-dimensional model when only a qualitative study is required. The model consisted of identical axisymmetric members where each member mimicked one pitch height of the implant. The thread was assumed to have a V-shape. The detailed profile of the thread was 0.62 mm in thread depth, 0.6 mm in the pitch height with a 60° flank angle (Fig. 2). The shapes of thread were divided into 5 reference models (Figs. 3~7). Reference model 1 had conventional thread. Model 2 had 2 patterns on the upper flank of the thread while Model 3 had 2 patterns on the lower flank of the thread. Model 4 had 2 patterns on the upper and lower flanks of the thread. Model 5 had 3 patterns on the upper and lower flanks of the thread.

Figure 3. Stress contour in surrounding bone of the conventional thread (left: von Mises stress, right: maximal principal stress).

Figure 4. Stress contour in surrounding bone of 2 patterns at the upper flank of the thread (left: von Mises stress, right: maximal principal stress).

Figure 5. Stress contour in surrounding bone contour of 2 patterns at the lower flank of the thread (left: von Mises stress, right: maximal principal stress).
2. Mesh Generation
The models of the implant thread were meshed with four-noded quadrilateral elements with HyperMesh (DECS, East Lansing, MI, USA). The element mesh was built up parametrically and contained 1129 quadrilateral elements (not including the elements outside the straight part at the bottom of the thread). Each element contained four nodes with 2° of freedom for each node. Similar numbers of nodes and elements were applied to all the models and details of the finite element meshes used for each of the threads are given in Table 1.

3. Materials and Loading
The mechanical properties given to the bone and implants were taken from existing literature\(^1\) and are summarized in Table 2. For simplicity, all materials were considered to be isotropic, homogenous and linear elastic. These assumptions were made to control the variables throughout the FEA, and to focus on a comparison of the alternative designs of thread rather than investigating the effect of other variables, e.g., the isotropy of the supporting bone. The length of the implant and embedding condition in the bone were assumed, as in Hansson and Werke’s study\(^7\). It was assumed that the implant was axisymmetric and infinitely long. The implant was assumed to be completely embedded in the infinitely long cortical bone and to have 100% bone apposition. The implant received an infinitely big axial load; however, the bone-implant interface was assumed to

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**Table 1. Number of nodes and elements**

<table>
<thead>
<tr>
<th>Models</th>
<th>No. of nodes</th>
<th>No. of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional thread</td>
<td>21,969</td>
<td>7,125</td>
</tr>
<tr>
<td>2 patterns at the upper flank of the thread</td>
<td>22,632</td>
<td>7,352</td>
</tr>
<tr>
<td>2 patterns at the lower flank of the thread</td>
<td>22,632</td>
<td>7,352</td>
</tr>
<tr>
<td>2 patterns at the upper and lower flanks of the thread</td>
<td>23,701</td>
<td>7,699</td>
</tr>
<tr>
<td>3 patterns at the upper and lower flanks of the thread</td>
<td>25,510</td>
<td>8,290</td>
</tr>
</tbody>
</table>

**Table 2. Mechanical properties of materials\(^{14}\)**

<table>
<thead>
<tr>
<th></th>
<th>Young’s modulus [MPa]</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>13,400</td>
<td>0.30</td>
</tr>
<tr>
<td>Implant</td>
<td>117,000</td>
<td>0.30</td>
</tr>
</tbody>
</table>
The Effect of Patterning on Stress Distribution

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have fixed boundary condition. Therefore, compressive, tensile and shear stresses were transferred between implant and bone.

4. Solution

For each of the thread shapes, von Mises stresses were calculated using Abaqus Unified FEA product suite (Simulia). The maximum principal stress (MPa) was considered as a suitable stress unit for analysis of brittle material, while von Mises stress was a suitable stress unit for ductile material. The surrounding bone was assumed to cortical bone only. The compressive stress in the surrounding bone was essential for analyzing the effect of the shape of thread. Therefore, maximal principal stress was selected for comparing the stress distribution on the bone around the implant’s thread. Studies of von Mises stress in the implant material were also performed. The contour plots of stresses were provided to suggest an overall examination of the stress state in the bone structure, which made identification of the regions of stress concentration easier.

Result

The surface areas of the 2 patterns at one side are 106% compared to conventional thread. Introducing 2 patterns on both flanks of the thread increased the surface area to 113%. The 3 patterns on both flanks boosted surface area to 115% of the unpatterned surface area. With increased surface area, the hypothesis that stress would be distributed in patterned models was proposed.

The highest maximum principal stress was observed in the conventional stress (Table 3, Figs. 3–7). Introducing a pattern into the conventional thread, the maximum principal stresses were gradually decreased. On the other hand, maximum von Mises stress was reduced from the conventional thread to the 2 patterns at the upper and lower flank of the thread; however, maximum von Mises stress was noted in the 3 pattern group.

In the conventional thread, maximum von Mises stresses were concentrated subjacent to the bottom of the flank. However, the maximum principal stresses were concentrated on the upper part of thread top. The site of patterning didn’t affect the maximum von Mises stress. However, the patterning at both flanks of thread reduced the stress values. Comparing the von Mises stresses of patterns in upper and lower flanks, favorable von Mises stress distribution was observed in the lower pattern model. The maximum principal stress was concentrated mainly on the protruded point of contraflexure. In reference model 5, the maximum principal stress was lowest compared to the other groups. However, the maximum von Mises stress was higher than the other groups. Maximum von Mises stresses in the implant structure increased from no patterns to 3 patterns.

Discussion

The aim of the present study was to determine the effect of variations in the thread pattern upon stress within the bone. For this purpose, several assumptions were made for an optimal analysis. If the bone-implant interface was assumed to be fixed (like in this study), the compressive, tensile and shear stresses were transferred to the surrounding bone\(^{15}\). If the bone-implant interface was assumed to be in a contact state, only compressive stresses were transferred from the implant to the bone. Moreover, this condition permitted frictionless sliding of the contact surface. Many studies on stress transfer from the thread used the contact interface. In some studies, a partially fixed interface condition was assumed because perfect osseointegration could not be achieved\(^{16,17}\). However, instead of a discontinuous fixed interface condition, a partially fixed interface condition was

<table>
<thead>
<tr>
<th>Models</th>
<th>Maximum von Mises stress in bone</th>
<th>Maximum principal stress in bone</th>
<th>Maximum von Mises stress in implant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional thread</td>
<td>4.93636</td>
<td>2.31642</td>
<td>83.04</td>
</tr>
<tr>
<td>2 patterns at the upper flank of the thread</td>
<td>4.70289</td>
<td>2.21385</td>
<td>83.6862</td>
</tr>
<tr>
<td>2 patterns at the lower flank of the thread</td>
<td>4.7864</td>
<td>2.29327</td>
<td>83.9171</td>
</tr>
<tr>
<td>2 patterns at the upper and lower flanks of the thread</td>
<td>4.59862</td>
<td>2.18889</td>
<td>84.0033</td>
</tr>
<tr>
<td>3 patterns at the upper and lower flanks of the thread</td>
<td>4.95127</td>
<td>2.15822</td>
<td>84.1717</td>
</tr>
</tbody>
</table>
assumed in these studies. In this condition, the location of the fixed interface affects the results. Therefore, due to the different interface conditions in various studies, it was impossible to make a simple comparison. Siegele and Soltesz\(^{18}\) emphasized that a fixed interface condition should be used in the study of surface-modified implants, while a contact interface condition should be used in the study of machined implants. Nowadays, most commercial implants have modified surfaces. Therefore, we used a fixed interface condition in this study.

Bone consists of cortical bone and trabecular bone. It is well known that the dense cortical bone has a higher load-bearing capacity compared with that of the more porous trabecular bone. The difference in the elastic modulus of cortical bone and titanium induces stress-shielding in the surrounding bone structure\(^{19}\). If the surrounding bone is assumed to be a trabecular bone, the stress-shielding would be enhanced and it would mask the generation of the stress pattern. Moreover, trabecular bone has a non-homogeneous composition, whereas compact bone has a relatively homogeneous composition. Therefore, the stress generated depends on the type of surrounding bone. To maximize the stress, the bone surrounding the implant was assumed to be cortical bone only.

Analyzing stress at the bone-implant interface is an essential step in the overall analysis of loading, which determines the success or failure of an implant. It has been postulated that both implant and bone should be stressed within a certain range for physiologic homeostasis. Overloading can cause bone resorption around the implant, while underloading of the bone may lead to disuse atrophy and subsequent bone loss. Several studies have reported about the shape of the thread affected stress distribution and Holmgren et al.\(^{20}\) demonstrated that a stepped cylindrical design is most desirable. After analyzing stress concentration patterns using FEA, Mailath et al.\(^{21}\) reported that the cylindrical implant presented better stress distribution than a conical implant. Rieger et al.\(^{22}\) concluded that a tapered implant would be more suitable.

Patra et al.\(^{16}\) reported that the tapered thread design showed higher stress levels in bone than the parallel profile thread of the implant. However, in most clinical implants, the tapered thread design was adopted for reducing stress generated during the implant insertion procedure. Especially, hard compact bone may interfere with the implant insertion procedure and may generate heat. Therefore, only threads having a tapered design were used in this study.

The optimal thread pattern to achieve the best load transfer characteristics is the subject of current investigations. Siegele and Soltesz\(^{18}\) compared the load transfer characteristics of various implant shapes. They concluded that different implant shapes lead to variations in stress distributions in the bone. The authors reported that implant surfaces with small radii of curvature or stepped shapes induce distinctly higher stresses than smoother shapes. This result was opposite to our study’s findings. Thread patterns may produce more stress within the implant itself, while reducing the stress in the surrounding bone. The surface areas of patterned implants were increased from 6% to 15%.

With an increase in the surface area, the stress distribution in the patterned implant models was reduced. In the implant structure, the stress was increased with the introduction of the thread patterns (Table 3).

As mentioned previously, the maximum principal stress was a good indicator of stress in the analysis of brittle materials, while von Mises stress was a good indicator of stress in the analysis of ductile materials. Cortical bone is neither brittle nor ductile. Therefore, a comparison of the results between von Mises stress and maximum principal stress is important. The use of patterned threads resulted in a decrease in the maximum principal stress in the surrounding bone. On the other hand, a decreasing tendency of maximum von Mises stress was identified in 2 patterned threads only. Von Mises stress reached its maximum levels in the 3-thread pattern group. Decreasing amounts of von Mises stress were obvious, meaning that specific thread patterns induced maximum stress distribution. From this study, 2-thread patterns at the upper and lower flanks of the thread would be appropriate when the patient has inferior quality of bone.

Uniform stress state in bone structure makes it easier to identify the regions of stress concentration. Contrary to the maximum von Mises stress, contour plots of maximum von Mises stresses showed favorable stress distribution with the use of patterned threads while the maximum principal stress increased with the introduction of patterned threads. This means that a complicated shape can induce bone resorption in high quality bone.

The site of thread pattern did not affect the maximum von Mises stress. However, the thread pattern at the lower flank showed a more favorable stress contour compared with that at the upper flank. The Groovy\(^{14}\) implant has a thread pattern (known as the groove) at the lower flank only (Fig.
The groove size was 50–125 μm, which coincided with the appropriate size for bone ingrowth. In the conventional thread design, the maximum von Mises stresses were concentrated subjacent to the bottom of the flank. Whereas, the maximum principal stresses in patterned implants were concentrated in the protruding part of the thread. This result was in agreement with the study by Bolind et al. The stress contour plots were similar for all thread types.

In conclusion, thread patterns in implants enhance stress distribution. Especially, thread patterns in the lower flank showed more favorable stress distribution. However, it should be considered that this thread pattern can increase the stress in hard bone.

Conclusion

This study examined the stress patterns and maximum stresses in bone by introducing different patterns of implant threads. The surface areas of patterned implants were increased and threads with patterns showed better stress distribution than conventional threads. Patterned in threads may produce more stress in the implant itself, while reducing the stress in surrounding bone. However, the patterning may result in more stress in extensively hard bone. Patterns in the lower flank induced more favorable stress situations.

References


