**Introduction**  
Titanium and its alloys have excellent mechanical properties and biocompatibility. In the field of dentistry, smooth surfaced titanium implants inserted into the facial bones perform very well. After implantation, well-fixed dental implants, which are not subjected to weight loading during some period after implantation, exhibit direct contact with bone without intervening fibrous tissue under light microscopic level. This is termed osteointegration. However, in skeletal bones, smooth titanium implants usually tend to be encapsulated by a fibrous tissue and show only weak bonding to bone in animal experiment even under unloaded conditions. Thus, recently, fixation of titanium implants to bone usually depends on biological fixation of its porous surfaces. A simple new method of enhancing the bone-bonding abilities of titanium and titanium alloy orthopaedic implants, involving immersion into NaOH solution and subsequent heating, has been developed. We describe the evaluation of the bone-bonding strengths of titanium and titanium alloy implants with and without alkali and heat treatments using the conventional canine femur push-out model. If smooth titanium metals have an ability to bond to bone strongly without forming intervening fibrous tissue, cementless THA implants may be able to achieve long-term stability even without porous coatings.

**Purpose**  
The purposes of this study were to compare the bone-bonding strengths of four alkali- and heat-treated titanium metals using conventional push-out test and to determine which of these metals would be the most suitable bioactive material after alkali and heat treatments.

**Materials and Methods**  
Four kinds of smooth cylindrical implants, made of pure titanium (Ti) or three titanium alloys (Ti6Al4V, Ti6Al2Nb1Ta, and Ti15Mo5Zr3Al), were prepared. The diameter of the implants was 6 mm and the length was 13 mm. The halves of the 4 types of the implants were soaked in NaOH solution at 60 °C for 24 h (alkali treatment), then heated at 600°C for 1 h (heat treatment). The concentrations of NaOH solutions were 5 mol/L for Ti implants and 10 mol/L for the other alloys. The remaining halves were left untreated. The implants were inserted hemitranscortically into bilateral femora of 14 beagle dogs in randomized manner. The bone-bonding shear strengths of the implants were measured at 4 and 12 weeks after implantation using push-out tests. Some of the implants, which were not mechancially tested, were prepared for undecalcified specimen for histological evaluation.

**Results**  
At 4 weeks all types of alkali- and heat-treated implants showed significantly higher mean bonding strength (2.4-4.5 MPa) than their untreated counterparts (0.3-0.6 MPa)(Fig.1). At 12 weeks the mean bonding strengths of the treated implants showed no further increase, while those of the untreated implants had increased to 0.6-1.2 MPa. At 4 weeks among the treated implants Ti15Mo5Zr3Al exhibited significantly greater shear strength than Ti6Al4V or Ti6AI2Nb1Ta. At 12 weeks, among the treated implants, the shear strength of pure titanium was significantly higher than that of Ti6Al4V, and that of Ti15Mo5Zr3Al was significantly higher than those of Ti6Al4V and Ti6AI2Nb1Ta. Histologically, no foreign body or inflammatory reaction were noted with either the untreated or the alkali- and heat-treated implants throughout the study, regardless of the kind of metal used. Furthermore, none of the four metals produced any substantial difference in the histological findings. With the treated implants, new bone formed in the gap created at the implantation site within 4 weeks, and the new bone was in direct contact with the implant. On the other hand, with the untreated implants, only an intervening fibrous layer or a small amount of bone was in direct contact. At 12 weeks, the treated implants had almost the same amount or a little more bone in contact with them than at 4 weeks. In contrast, the untreated samples still showed intervening fibrous tissue or a limited amount of bone in direct contact with the implants. In some untreated samples, the fibrous tissue at the interface between the bone and implant was much thicker than at 4 weeks.

**Discussion**  
Alkali- and heat-treated titanium implants have a thin reactive layer formed as results of the alkali and heat treatments on their surfaces. This layer can form apatite in SBF, like bioactive glasses and glass-ceramics and this is also thought to occur in vivo. Apatite formation on the surface of the material is considered a prerequisite for direct bone-bonding and this phenomenon seems the reason for the strong bonding between alkali- and heat-treated titanium and bone.

In this study, untreated titanium metal produced few areas of direct bone-implant apposition or intervening fibrous tissue at the interface between bone and titanium implants even at 12 weeks. These histological findings regarding untreated titanium metals implants are in accordance with previous studies. In contrast, the alkali- and heat-treated titanium metals used in the present study showed direct bone-implant apposition and osteoconductive characteristics more similar to those displayed by HA-coated implants than by untreated titanium metals. These results indicate that quite simple alkali and heat treatments can induce osteoconductive properties in implants manufactured from titanium and its alloys. These histological findings support the results of the push out tests. Alkali- and heat-treatment improved the bone-bonding abilities of pure titanium and titanium alloy implants as early as four weeks after implantation, compared with their untreated counterparts. Among the four types of metals tested, pure titanium and Ti15Mo5Zr3Al seemed most suitable for the manufacture of alkali- and heat-treated implants, although further studies will be needed to determine the optimal conditions for the alkali- and heat-treatments. This technique has potential to become an accepted method of enhancing the bone-bonding abilities of titanium-based metal orthopaedic implants.

**Conclusion**  
Alkali and heat treatments enhanced the bone-bonding strengths and bone apposition of smooth titanium and titanium alloy implants within 4 weeks and this effect lasted for at least 12 weeks.

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**Fig. 1 Results of Push-out Test (mean value)**

<table>
<thead>
<tr>
<th></th>
<th>untreated</th>
<th>alkali- and heat-treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti15Mo5Zr3Al</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti6Al2Nb1Ta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti6Al4V</td>
<td></td>
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<tr>
<td>Ti</td>
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</tbody>
</table>

**Shear strength (MPa)**

0 1 2 3 4 5

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