INTRODUCTION

Non-alloyed commercially pure (CP) titanium and titanium alloys have been used for implants and prosthetic appliances as a bioinert metal1-3). Ideally, all restorations should be made without metal, namely, with porcelain and zirconia, for aesthetic and biocompatible reasons4,5). However, the frameworks of removable partial dentures (RPDs) and some implant superstructures will be made, reluctantly, with metal even in the future 6,7). To avoid the presence of various metal combinations in patients’ oral cavities, the use of a single metal for all restorations would be needed to protect against metal corrosion caused by the contact of different metals. For this “one-metal rehabilitation” concept, non-alloyed CP titanium should be used for all restorations, based on the assumption that implant treatment will be carried out if a tooth is lost.

In Tsurumi University Dental Hospital, Yokohama, Japan, CP titanium has been used for not only fixed prosthetic appliances but also prosthetic removable dentures based on the patient-first philosophy —that better safety and excellent biocompatible metal should be used in patients’ mouths— from approximately 25 years ago8,9). Although the benefits of CP titanium dentures have been proved by clinical observations, several laboratory and clinical problems have been found6,9). Of the laboratory problems, casting 10-15), cutting16,17), grinding 18,19), and polishing are not easy 20), and casting apparatus for titanium is more expensive than for the conventional dental alloys. The debonding of the denture base resin from the titanium framework21-23), deformation of the titanium clasp24-30), discoloration of the titanium surface31), severe wear of titanium teeth32-36), and much plaque accumulation37-39) are some of the clinical problems frequently observed in our clinical practice, whereas catastrophic failures have never been found40). Some of these laboratory and clinical problems have been resolved by basic studies and the efforts of laboratory technicians so that cast titanium frameworks for RPDs could be constantly fabricated with clinical success40-43).

The advantages of titanium frameworks as compared to conventional dental alloys include outstanding corrosion resistance44,45), appropriate mechanical properties46,47), their light weight, better fitness accuracy48), and less metal allergy due to its excellent biocompatibility49,50). On the contrary, the occurrence of a chemical reaction layer from the titanium casting is an inevitable disadvantage51,52). As an alternate method for the manufacturing of titanium frameworks, most implant superstructures, including abutments, have been fabricated using computer-aided design/computer-aided manufacturing (CAD/CAM) instead of casting53-55). Using CAD/CAM, titanium frameworks for RPDs have also started being fabricated by milling titanium disks and additive manufacturing from titanium powders.

This review article outlines the laboratory and clinical problems of cast titanium removable dentures and proposes their solutions. In addition, the future trends of fabrication methods for titanium frameworks using CAD/CAM are described based on the “one-metal rehabilitation” concept.

PROBLEMS OF CAST TITANIUM DENTURES

Casting apparatuses for titanium restorations and denture frameworks were developed more than 30 years ago. Since the castability and mechanical properties of titanium castings greatly depend on the
Pattern10,56). Presently, the occurrence of casting defects can be mostly controlled in the titanium castings9). The burnout time of framework patterns before metal casting is longer than for conventional dental alloys16-19). Cutting and grinding times are much longer, and machine tools are easily worn, as compared to gold alloys16,17). Special cutting and grinding tools should be developed to improve the machinability of titanium.

Debonding of denture base resin
Previously, the debonding of denture base resin from a titanium framework was frequently observed for short period after denture delivery31). Recently, bond strengths of metal primers have been remarkably improved; little debonding occurred between the denture base resin and the titanium framework, similarly to Co-Cr and gold alloy frameworks12,23).

Severe wear of titanium teeth
Severe wear was frequently observed on titanium teeth32-36). Kabe32) and Shimura33) tested the wear of titanium teeth using wear-testing apparatus that simulated the chewing function. Severe wear occurred between titanium of the same grade used for maxillary and mandibular teeth (Type 2 vs. Type 2 or Type 3 vs. Type 3). The wear resistance of the α+β alloy, i.e., Ti-6Al-4V and Ti-6Al-7Nb, was better than that of CP titanium. To avoid severe wear of titanium teeth, different grades of titanium (Grade 3 vs. Grade 4) should be used for maxillary and mandibular teeth; otherwise Grade 4 should be used for both jaws.

Discoloration
One significant problem might be the discoloration of the titanium surface shortly after delivery35). This discoloration was caused by the immersion of the titanium denture into an alkaline denture cleanser6). Dentists must instruct patients to avoid using strong alkaline denture cleaners for titanium dentures.

Adherence of denture plaque
Plaque adheres easily to titanium frameworks as compared to conventional dental alloys37,38). Urushibara et al.39) reported higher amounts of biofilms formed by unfiltered, fresh human saliva or Streptococcus mutans and/or Candida albicans on CP titanium than on other alloys and resin samples. The biocompatibility of titanium would promote the adherence of denture plaque.

Others
A few patients wearing titanium dentures commented about a “slightly strange taste”57). The reason for this phenomenon is unknown; future study is necessary regarding patients’ sense of taste when using titanium dentures.

ADVANTAGES OF CAST TITANIUM DENTURES
Although laboratory and clinical drawbacks remain, CP titanium has many advantages for clinical use, including biocompatibility, fitness accuracy, their light weight, laser welding, and one-metal rehabilitation.

Biocompatibility
The biocompatibility of titanium can be emphasized as its most beneficial point2-5. Clinical reports have indicated that changing to porcelain or hybrid resin restorations and titanium dentures is the best way to
treat patients with metal allergies. Recently, allergic reactions to titanium implants have been reported and may gradually increase in the future. Although implants, superstructures, and crown-bridges can be fabricated with zirconia as metal-free restorations, it would be difficult to use zirconia for RPD frameworks because zirconia bars and clasp arms are easily breakable.

**Fitness accuracy**

More than 800 titanium dentures have been delivered through our hospital over the past 25 years; appropriate fitness accuracy could be clinically confirmed similarly to conventional dental alloys. Muraishi examined the fitness accuracy of titanium and Co-Cr clasps; there were no significant differences between them.

**Lightweight**

Because titanium has low density, titanium dentures can be fabricated that weigh less than those made of gold and Co-Cr alloys. Thus, titanium would be suitable for use in large RPD frameworks. Especially, some patients prefer light maxillary dentures because they believe that lightweight dentures will be more comfortable. These patients prefer titanium dentures for the maxillary jaw. Facial prostheses must be lightweight because of their poor retention; using titanium for lightweight facial prostheses is clinically significant.

**Laser welding**

Titanium has a lower thermal conductivity value and an excellent rate of laser beam absorption; therefore, laser welding can be performed easily to fabricate frameworks and repair dentures. Since there are four grades of CP titanium from 1 to 4 with mechanical properties ranging from flexible to rigid, RPD components can be made separately from the appropriate grade of CP titanium. After casting, each component can be joined using laser welding. Alternatively, rather than constructing new dentures, existing titanium dentures can be rebuilt to add or enlarge denture components using laser welding. Even broken clasps can be rejoined using laser welding, and the retentive force does not decrease after clasp repair. In addition, the wear resistance of titanium teeth can be improved by laser irradiation.

**Surface modification**

To improve the fatigue strength of titanium, surface modification has been performed in the industrial world. The clasp is the most easily broken RPD component, due to its slender shape and the concentration of stress during insertion/removal. Hayashi et al. and Tokue et al. examined the effect of shot peening on the fatigue resistance of titanium clasps. Micro-spheroidal particles are strongly impacted to the titanium surface, and the surface became smoother while the mechanical properties increased.

**One-metal rehabilitation**

Generally, there are many different dental alloys in most patients’ oral cavities. Using CP titanium, all metal restorations, prosthetic frameworks, and implants can be unified to single metal.

**CAD/CAM TITANIUM DENTURES**

**Milled titanium framework for RPDs**

First, a CP titanium framework has been milled for implant superstructure after the framework pattern was fabricated and scanned by a laboratory scanner. A one-piece full-arch fixed prosthesis framework can be also milled from a CP titanium disk, so that a higher fitness accuracy could be confirmed. Regarding the RPD framework, a sacrificial pattern is produced by CAD/CAM (milling or rapid prototyping technology), and investment-casting and finishing techniques are generally carried out in accordance with conventional techniques. Although milling manufacturing for RPD frameworks from titanium disks has been tried, it would be a wasteful process, since the bilateral RPD framework is significantly thinner with a slender-shaped clasp and connector. The disadvantages of milled titanium frameworks include; 1) it is not easy to cut the complicated shapes and/or undercut areas, 2) large quantities of cutting chips are discharged, 3) milling accuracy deteriorates when cutting tools are worn, and 4) long processing times are required.

Today, yttria tetragonal zirconia polycrystals (Y-TZP) and ceria-stabilized zirconia/alumina nanocomposites (Ce-TZP/A) have been popularly used for crowns, bridges, implant superstructure, and palatal plates instead of CP titanium for metal-free restorations and greater esthetics. However, zirconia would not be suitable for RPD frameworks even now because of the following reasons: 1) difficulty in cutting and grinding for corrections, 2) difficulty in adjusting retentive force, 3) the breakability of zirconia clasps, 4) the impossibility of soldering and laser welding, 5) bad aesthetics of zirconia clasps because the color is too white, and 6) no clinical evidence for a long-term prognosis. Presently, RPD frameworks milled from titanium disks might be better than zirconia frameworks.

**Additive manufacturing of titanium framework for RPDs**

The fabrication of frameworks for dental applications by laser sintering and metal additive manufacturing has been tried recently. As compared to the milling process, additive manufacturing has many advantages: 1) no cutting chips are produced; 2) shapes with free curves, undercuts, and hollow structures can be fabricated; 3) accuracy is not diminished by worn cutting tools; 4) many frameworks can be prepared simultaneously; and 5) the cost is relatively low. However, one big problem of conventional additive manufacturing is that it creates surface that are too rough because the particle size used is lager (more than 50 µm) (Fig. 9).
Since bilateral RPD framework is significantly thinner with a slender-shaped clasp and connector, milling manufacturing of RPD frameworks would be waste process from the titanium disks.

One big problem of conventional additive manufacturing of RPD frameworks is that it creates surface that are too rough.

Hybrid processing of repeated laser sintering and high-speed milling as one simultaneous process is now being tried for fabricating RPD frameworks. Using a hybrid processing machine (LUMEX Avance, Matsuura, Fukui, Japan), accurate molding and smooth surfaces can be produced. Nakata et al.\textsuperscript{79} examined the fitness accuracy and retentive force of Akers clasps fabricated by conventional casting and
hybrid processing and suggested that the surface of the sintered and milled clasp was smoother than those of cast clasps. The retentive forces of hybrid processing clasps were also significantly higher than those of cast clasps. Although the retentive forces of cast clasps were remarkably decreased, hybrid processing clasps demonstrated a constant or slight decrease from 1,000 to 10,000 insertion/removal cycles (Fig. 5). These results suggest that hybrid processing CAD/CAM clasps can be recommended instead of cast clasps.

Although CP titanium crown copings and RPD frameworks could be cast with clinically acceptable accuracy, high-level laboratory skills are necessary to ensure titanium casting success\textsuperscript{6}. Milled titanium is already used with great success for most implant superstructures and fixed prosthesis appliances, whereas milling or additive manufacturing of titanium RPD frameworks is unlikely to be widespread in the near future\textsuperscript{79}. The hybrid processing of repeated laser sintering and high-speed milling is expected to make up for the drawbacks of only milling or additive titanium for the manufacturing of RPD frameworks\textsuperscript{79}. Future basic research and clinical observations regarding hybrid processing on titanium RPD frameworks are necessary for appropriate clinical use.

CONCLUSIONS

Although laboratory and clinical problems remain, CP titanium can be used for all restorations and prosthetic appliances using the casting process. Using CP titanium as a bioinert metal, one-metal rehabilitation would be performed in patients’ mouths. With CAD/CAM, milling manufacturing is suitable for implant superstructures and crown-bridges, and the hybrid process of laser sintering and high speed milling would be good way for RPD frameworks to improve both drawbacks.
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