Review

Dental Materials Journal 15(2): 77–90, 1996

Titanium in Dentistry: Development and Research in the U.S.A.

Hiroshi NAKAJIMA and Toru OKABE

Department of Biomaterials Science, Baylor College of Dentistry-Texas A&M University System
3302 Gaston Avenue, Dallas, TX 75246 U.S.A.

Received July 30, 1996/Accepted October 26, 1996

Titanium has received a great deal of attention from dental researchers and clinicians. In the United States, the history of the application of titanium as a biomaterial started as early as 1940 when experiments with titanium implants were done using laboratory animals. It appears that in 1959, two American researchers were the first to suggest casting titanium to fabricate implant posts. The use of cast titanium for dental prostheses in the U.S. was first reported in 1977. The present survey revealed that during the last decade, the number of research projects on the applications of titanium to dentistry that were presented at annual IADR/AADR meetings has steadily increased. The majority of these presentations have been made by American researchers, and 59% of these were related to dental implantology. The numbers of reports on casting and prosthodontic applications have steadily increased, but they are still more limited. The purpose of this review was to provide information on the development and the current status of research on titanium in dentistry in the U.S.

Key words: Titanium, Casting, Implant

INTRODUCTION

During the recent decade, titanium has drawn a great deal of attention from researchers in dental biomaterials and clinicians because of its excellent biocompatibility and acceptable chemical, physical and mechanical properties as well as the remarkable improvements that have been made in all phases of casting technology. The purpose of this review is to summarize the development and the current status of research on titanium in dentistry in the United States. This report was originally presented at the Third International Symposium on Titanium in Dentistry held in Leura, Australia, August, 1995, and has been updated and revised since the original presentation.

The history of the use of titanium in the U.S. as a biomedical material began about 50 years ago[1]. In 1940, Bothe *et al.*[2] implanted titanium in laboratory animals along with other metallic materials which were used for surgical applications. They reported that titanium was well tolerated, apparently due to its excellent corrosion resistance; this was later confirmed in biological fluids by Clarke and Hickman[3]. Beder and Ploger[4] described the use of titanium for intraoral implants using dogs. They suggested making titanium disc implants by casting. For a long time, it was commonplace for custom-made bone implants to be made of cast cobalt-chromium, whereas it was preferred that prefabricated devices be made of titanium. In the U.S., Linkow[5] is the pioneer in developing milled titanium blade-vent implants, which were introduced in the early 1970's. Titanium and its alloys have gradually been accepted in the U.S. for various dental and orthopedic uses.

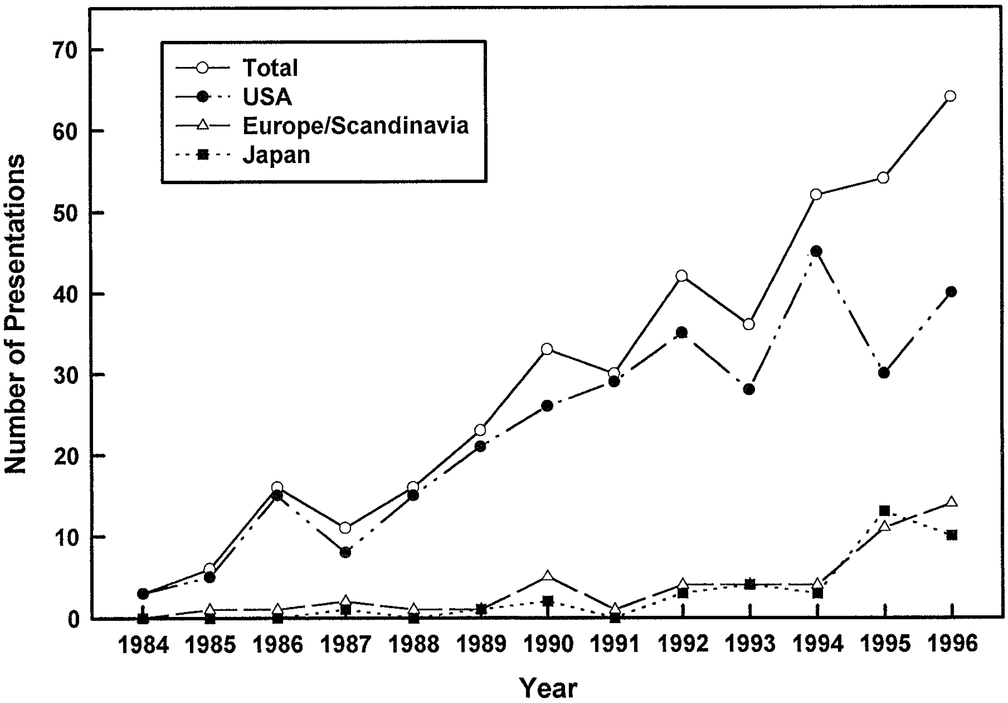

Fig. 1 Changes in the numbers of presentations on titanium from selected countries at AADR and AADR/IADR meetings (1984-1996).

Recent trends in research on the application of titanium to dentistry in the United States are apparent from the numbers of presentations related to titanium that have been given at the annual meetings of the American Association for Dental Research (AADR) and the International Association for Dental Research (IADR) from 1984 to 1996 (Fig. 1). Fig. 2 compares the percentages of the total number of presentations made by American

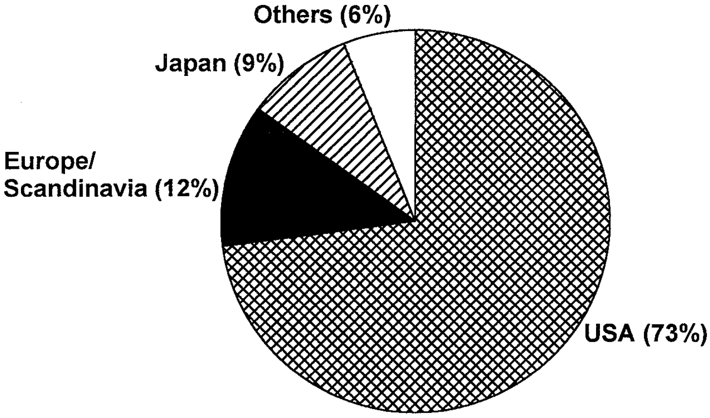

Fig. 2 Breakdown (percentages) of presentations on titanium at AADR and AADR/IADR meetings (1984-1996) by country.

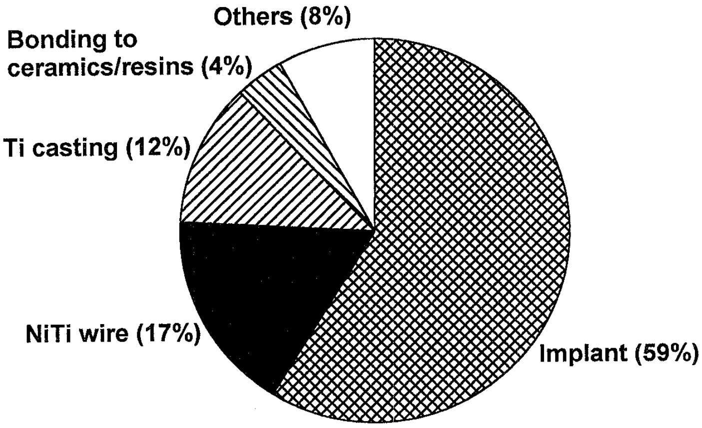

Fig. 3 Breakdown (percentages) of research areas for titanium presentations by American researchers (1984-1996).

researchers and those from other countries for this period. These numbers were obtained from the presentations listed in the meeting abstracts for groups such as Dental Materials, Prosthodontics and Implantology. Since the AADR or AADR/IADR meeting is a major conference each year in these research areas, the trend seen in Fig. 1 can be considered a good indicator of the increase in research on titanium in the U.S.

Applications of titanium for dentistry have been slower to develop. However, during the last decade, the number of presentations related to titanium has steadily increased year by year at the AADR and AADR/IADR meetings (Fig. 1). Since the AADR is the largest division of the IADR and an AADR conference is held every year, it is not surprising that approximately three quarters of the total number of presentations related to titanium were made by American researchers (Fig. 2). Research presentations from Japan, whose research related to titanium casting has been very active, shared approximately 10% of the total number of presentations given since 1984. In Fig. 3, the trend showing the research areas of the investigations on titanium is given. Of the presentations made by American researchers, the majority (59%) have been related to implantology, followed by presentations on NiTi orthodontic wire (17%) and on titanium casting and properties of cast titanium (12%).

This review will provide information on the development of titanium in dentistry in the U.S., beginning with the first research done on oral titanium implants. The review will continue with a discussion of the progress made in titanium casting research on dental prostheses, orthodontic arch wires, soldering/welding and other related applications.

TITANIUM DENTAL IMPLANTS

Since the late 1980's, surface characterization studies of CP titanium and titanium alloys have been performed using state-of-the-art electron spectroscopic equipment because the surface condition of a titanium implant is a significant factor affecting the tissue reactions surrounding these implants. Two American research groups, Keller's group at the University of Iowa and Lucas' group at the University of Alabama at Birmingham have actively investigated the surfaces of titanium implants. Keller and coworkers characterized the CP titanium surface after applying various surface treatments including sterilization, a cleaning process and acid passivation[6,7]. The sterilization procedures examined did not reveal a noticeable variation in the surface morphologies and chemical composition of the surface film. The acid-passivated surface was covered with an approximately 3 nm-thick titanium oxide film on CP titanium[8] and an approximately 8 nm-thick film on the Ti-6Al-4V[9]. Plasma cleaning (radio-frequency glow discharge) produced a slightly thicker oxide film (5nm) than other sterilization methods[10]. A drastic decrease in the contact angle of deionized water (53 *vs.* 18°) was found on surfaces treated with this method. After several surface treatments, the surfaces of Ti-6Al-4V alloy were reported to follow trends similar to those for CP titanium[11].

Lucas and co-workers[12] found that the anodization process increased the thickness of the oxide films formed as much as 4 times and improved the corrosion resistance; however, this surface film was found to be easily removed by the film bonding test. XPS experiments indicated the presence of adsorbed OH species and phosphorous in the surface film on the anodized specimen[13]. The surfaces of CP titanium were examined after immersion in a physiologic solution (α-Minimal Essential Medium)[14]. This study revealed that amorphous oxides and calcium phosphate compounds had formed on the titanium surface regardless of the amount of roughness present.

Cellular and tissue responses to titanium and titanium alloy implant materials have been extensively investigated by both *in vitro* and *in vivo* experiments. Cell attachment to surfaces has been investigated using fibroblasts, epithelial cells and osteoblast-like cells. The group at the University of Iowa has conducted a series of studies on cellular and tissue responses on the titanium surface along with their surface characterization. Cell type, sterilization and cleaning procedures, and surface topography were reported to affect cell attachment to the titanium surface and cell activity[15,16]. Autoclaving the titanium implants decreased the number of fibroblast or osteoblast-like cells attached[17-19]. A sandblasted or rough surface revealed higher levels of cell attachment by osteoblast-like cells and gingival fibroblasts compared to a smooth surface[20-23]. On the other hand, epithelial cells behaved differently[22-24]. Recently an implant made from Ti-13Nb-13Zr was found to have a higher affinity for periodontal tissue cell attachment than a CP titanium or Ti-6Al-4V alloy implant[25].

The behavior of bacteria attached to the titanium surface was investigated by several different research groups under both *in vivo* and *in vitro* conditions. The *in vivo* investigations showed that specific *Streptococci* selectively adhered to the surface[26-28]. The biofilm formed on the titanium surface from contact with saliva or serum decreased bacterial attachment to the titanium surface[29-31]. Inconsistent results were obtained from *in vivo* studies which examined the effect of surface roughness on bacterial attachment; Patel *et al.*[32] reported that the effect of surface topography on the bacterial attachment to the titanium surface was insignificant. On the other hand, Wu-Yuan *et al.*[33] found more bacterial adhesion on sandblasted surfaces compared to smooth surfaces. Further, Yliheikkila *et al.*[30] indicated that the level of bacterial attachment to a rough surface was dependent upon the presence or absence of a saliva-coated layer.

Several factors affecting *in vitro* mineralization have been investigated ; the autoclaving process[34], calcium ion implantation[35] and an excess number of titanium ions in an ambient environment[36] all had a deleterious effect on the mineralization *in vitro*. The surface topography is known to affect osteoblast-like cell activities ; however, it is interesting that *in vitro* mineralization responses were found to be independent of the surface roughness[37]. The research group at the University of Kentucky developed the electrodischarge compaction technique for fabrication of solid-core porous-surfaced implants using a Ti-6Al-4V alloy[38]. This implant demonstrated rapid bone ingrowth and favorable osseointegration behavior[39,40]. Later they fabricated a totally porous titanium alloy implant using this method. This totally porous implant revealed a significant increase in bone ingrowth with time[41].

Coating hydroxyapatite or calcium phosphates on titanium or titanium alloy has become popular for implant materials[42]. Lucas and Lacefield and researchers at the University of Alabama at Birmingham have investigated the hydroxyapatite coating on titanium implant surfaces[43,44]. The shear strengths of the plasma-sprayed hydroxyapatite coating on titanium alloy were determined to be 15-17 MPa. The bond strengh decreased with increased immersion time because of degradation in the coating layers with time[44,45]. A research group at Ohio State University found a limited interdiffusion zone of titanium and calcium at the interface of the plasma-sprayed coating[46]. Other coating techniques, the ion-beam sputter deposition coating of calcium phosphates[47,48] and hydroxyapatite coating by electrodeposition[49] have been studied.

At the 1996 AADR/IADR meeting, there was a presentation on a method of evaluating the fatigue resistance of CP titanium[50]. This study was performed because concern has increased about the fatigue failure of implants. The application of marker blocks during fatigue testing was reported to provide useful information about implant fatigue crack initiation.

DENTAL TITANIUM CASTING

Another area of dental titanium study attracting interest in the U.S. is research related to casting technology. In 1959, Beder and Ploger[4] suggested using a centrifugal casting machine with induction heating housed in a vacuum chamber to cast titanium implants. However, they never pursued their research by actually constructing the equipment. It was not until around 1977 that experimental castings of titanium for crowns and partial denture frames were finally made by induction melting in vacuum as Beder and Ploger had earlier suggested[51]. Waterstrat and his associates[51,52] at the National Bureau of Standards consulted Schuyler and others at the Garrett Corporation in Arizona about casting dental prostheses with a titanium alloy containing 13 wt% Cu and 4.5 wt% Ni. Schuyler *et al.*[53] had already performed extensive studies on the casting of industrial titanium alloys. This alloy was chosen since its fusion temperature is much lower than that of CP titanium (1329 *vs.* 1670°C) ;

it was hoped that oxidation during melting and casting and the reaction of the molten metal to the investment material would be minimal. Waterstrat continued his pioneering research efforts on several projects, but his experiments gradually tapered off, mainly because of lack of support from funding agencies. Notable among his work was the construction of specially designed, split-chamber argon-vacuum arc casting equipment which was patented in the U.S. in 1985[54]. His idea of using this equipment for titanium casting with magnesia investment was presented at the IADR/AADR meeting in 1985[55]. He and his associates[56] also presented a clinical trial of titanium crowns placed in patients for as long as 22 months and reported that, although there were problems in the fit of the crowns and some wear on the opposing tooth, patients did not experience any unusual taste or discomfort from the titanium crowns compared to gold crowns. Later Waterstrat was involved in the examination of the properties of commercially available investment materials for titanium with Mueller *et al.*[57,58] at the American Dental Association in Chicago. They reported complex reactions by the investment material (Biovest, Dentsply) which contained cristobalite, but less reaction from a silica-containing investment (Rema Exact, Dentaurum).

Other attempts to research titanium for dental casting began in 1984 by Greener and colleagues at Northwestern University. Their research was initiated at first to develop titanium alloys with a low fusion temperature and focused on finding an alloy with corrosion resistance and biocompatibility equivalent to CP titanium. Alloys they examined included various binary alloys such as Ti-Cu, Ti-Co, and Ti-Ni[59], Ti-Pd[60] and ternary titanium alloys including Ag and Cu[61]. While they found that the elctrochemical behavior of the alloys was comparable to pure titanium, they reported much increased hardness of most of the alloys examined. In 1985, Greener's group began to examine the capabilities of two commercial titanium casting machines acquired from Japan, the Titaniumer made by Ohara and the Castmatic, by Iwatani. In order to minimize the reactions between the investment materials and titanium, they first utilized the "face-coating" technique prior to investing in a phosphate-bonded silica material using yttrium oxide, zirconia or titanium dioxide with a zirconium acetate binder[62]. Using the Castmatic, they cast alloys which contained V (15%), Cu (20%) or Pd (30%), including Ti-6Al-4V alloy and pure titanium. They noted a considerable increase in the strength of the castings, which consisted of quasi-equilibrium phases created by alloying. In corrosion tests, a strong passive trend was seen. Their group also examined the accuracy of fit of pure titanium on MOD inlay dies using five different investment materials[63]. According to Greener[64], quantitative and statistical treatments found that all castings were undersized by at least 100 μm. Later, they tried incorporating Zr powder into the investment material in order to increase expansion, a method that had also been tried in Japan.

The research team at Northwestern is still continuing their initial efforts to study titanium castings from various aspects. These include comparative studies of strength properties[65], castability[66], and electrochemical behavior[67] of pure titanium and Ti-6Al-4V alloy. They also initiated an examination of bonding experimental porcelains to cast titanium or titanium alloys[68-71]. They claimed that experimental SiO_2/Al_2O_3 ceramics bonded well to the castings. In 1991, Tamaki *et al.*[72] examined the effect of two commercial investment materials on the casting accuracy of pure titanium using different types of crucibles. They reported that the types of investment materials significantly affected the fit of MOD inlays but the types of crucibles used did not. In another more recent study from the same group, Pang *et al.*[73] baked Porcera porcelain on milled titanium and found acceptable bonding, whereas Gilbert *et al.*[74] reported that effective bonding strengths for the porcelain baked could be obtained using a titanium bonding agent.

More recently, a research group at the University of Texas Health Science Center at San Antonio became involved in research on dental titanium. In 1989, Blackman *et al.*[75] presented a 90% success rate for a cast titanium RPD pattern based on the observation of voids, peripheral irregularities, etc. Other studies of pure titanium castings at San Antonio include evaluations of marginal fit[76], casting accuracy[77], the effect of investment materials on strength[78], and castability[79] and sprue design[80,81]. One of the interesting studies being done is the x-ray radiographic examination of internal voids of titanium castings; these studies reported on the appropriate radiographic operating conditions for examining castings of various thicknesses[82]. Baez's examination[83] of various commercial ceramics for cast titanium reported promising results of this technique.

There is notable work being performed at other research sites in the U.S. One of the American dental companies, Jelenko, developed titanium casting equipment in early 1990 called Ticast 3000, which uses a helium arc-melting/centrifugal rotating system[84,85]. Other research and experiments in the U.S. have been carried out by Mueller and Fan[86], who examined the permeability of various investment materials, including two commercial materials for titanium casting by the American Foundrymen Society's standard air permeability. They found that, even with the very low standard permeabilities of dental investments, significant differences in the permeability levels exist among the investment materials. Chai and Stein[87] in Boston reported consistent castings of multiple three-unit crowns in the Cyclarc machine (Morita) with Titavest investment. Earlier, this group examined the marginal fit of pure titanium casting crowns[88]. Liles *et al.*[89] compared the electrode potentials of seven different dental alloys with pure titanium and found that except for a Ni-Cr-Be alloy, all other alloys are cathodic to titanium. Oshida and Hashem[90] found that nitriding titanium was effective for producing stronger bonding to porcelain. More recently, Wang and Welsch[91] reported that in their preliminary study on producing a better oxide layer for the porcelain veneering on titanium, the oxide adherence of titanium coated with Pd or Cr was superior to the uncoated titanium.

Among the 1996 AADR/IADR presentations, there are several reports on titanium casting. The accuracy/fit of cast CP titanium crowns was examined by Blackman's group at the University of Texas Health Science Center at San Antonio[92]. When pressure difference casting equipment was used, there was still room for improvement in obtaining acceptable crown margins. A comparison of castability using the mesh pattern method in two different types of equipment (single-chambered and double-chambered pressure difference machines) reported a 99.30% castability rate for the single-chambered *vs.* 48.56% for the double-chambered equipment[93]. In a collaborative study at the University of Texas Health Science Center at San Antonio and the Lackland Air Force Base Medical Center, Sutton *et al.*[94] compared the porosity of CP titanium RPD frameworks made with five different sprue designs using the digital image analysis of radiographs. Their study concluded that although the difference in sprue design did not significantly affect the porosity values, it did affect the castability of the fine peripheral areas. In addition, Baez *et al.*[95] at San Antonio also reported on the effect of the sprue design on the mesh pattern filling using two different pressure difference machines and indicated the importance of the sprue design for the casting equipment they employed.

The evaluation of titanium alloys for dental casting was performed by a group at Case Western Reserve University[96]. Examinations of Ti-Ag and Ti-Ag-Cu alloys with some heat treatment procedures showed that the alloys were strong enough but needed more ductility. At Baylor College of Dentistry, the Texas A&M University System, a research team recently initiated titanium casting research. Watanabe *et al.*[97] reported on initial work using a NIOM-Baylor experimental pressure difference casting unit to find the optimal operating conditions for producing sound CP titanium castings. This study was the continuation of collaborative work on titanium casting with NIOM and Kyoto University.

For the corrosion behavior examination of pure titanium, Gilbert and Mante[98] conducted a comparative electrochemical study on high-purity polycrystalline and single-crystal titanium. The single-crystal titanium prepared by Mante *et al.*[99] showed one order of magnitude better corrosion current in the single-crystal titanium with some crystallographic orientation dependence.

A group at the University of Michigan has been examining PMMA-wrought titanium rod bonding. The most recent study by May *et al.*[100] revealed increased bonding when using surface-treated titanium (treated with alumina air abrasion plus silane and an opacifier). Their study was the extension of earlier work by May *et al.*[101]. This same group also reported in 1993 that titanium could be effectively bonded with All-Bond 2 and Panavia and suggested the potential use of these adhesive cements for bonding Maryland bridges[102].

ORTHODONTIC ARCH WIRES

Since the introduction of shape-memory or superelastic NiTi arch wires to orthodontics in 1971, NiTi arch wires have been investigated in order to characterize their mechanical properties, phase transformation and structures. In the U.S., two types of commercial titanium alloy wires are currently available: beta-titanium alloy (Ti-Mo based alloy) and NiTi alloys. A large number of titanium alloy wires are currently on the U.S. market. Burstone and Goldberg at the University of Connecticut investigated the properties of beta-titanium alloy wires for orthodontic purposes in the late 1970's and 1980's[103-105]. The majority of recent studies have concentrated on the commercially available NiTi wires. The phase transformation behavior of commercial arch wires has been examined by Differential Scanning Calorimetry or x-ray diffractometry[106-112]. Sachdeva and co-workers[113-115] at Baylor College of Dentistry characterized various aspects of the mechanical and corrosion behavior of NiTi alloy wires in collaboration with Indiana University and the University of Tsukuba, Japan. The reported studies suggested that there is a large variation in the properties of the NiTi arch wires on the current market[116-118]. Recently, a potential of Ti-Nb archwire was suggested for use as a finishing wire in orthodontic treatment[119].

SOLDERING/WELDING

Finally, a brief word about soldering, which is often used in prosthodontic dentistry for constructing and joining dental appliances. This procedure is very important for titanium castings. Thus far, some research groups have investigated the properties of soldered[120-122] or welded[123-125] titanium metals. Since 1992, the research team[126] at the University of Washington has observed the clinical performance of laser-welded implant frameworks which were developed in Sweden (Porcera system, Nobelpharma). Their one-year report revealed favorable results, and they continue to follow up the clinical performance of this technology. Welding or soldering is an area of dental titanium technology which has not yet been explored in depth.

SUMMARY

In summary, we believe the future of dental titanium technology looks bright. The potential for wide-spread use of titanium in dentistry is there; however, very little systematic research on dental applications of titanium has been made in the U.S. More extensive research on implantology, casting technology, and other applications must be done in the U. S. and elsewhere in the world before this interesting metal can be fully utilized. Japan is currently the most advanced and active country in the research and application of titanium in dentistry. Other dental materials researchers and clinicians in the world encourage Japanese researchers to present their studies more often at international meetings in order to share with the world their top-notch knowledge in the application of titanium.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of USPHS Research grant DE11787 from the NIH/NIDR, Bethesda, MD, U.S.A. Editorial assistance by Mrs. Jeanne Santa Cruz is also appreciated.

REFERENCES

1) Okabe, T., Herø, H.: The use of titanium in dentisry, *Cells and Materials* 5(2): 211-230, 1995.
2) Bothe, T. R., Beaton, L. E., Davenport, H. A.: Reaction of bone to multiple metallic implants, *Sur Gynecol Obst* **71** (6): 598-602, 1940.
3) Clarke, E. G. C., Hickman, J.: An investigation into the correlation between the electric potential of metals and their behavior in biological fluids, *J Bone Jt Surg* **35B** (3): 467-473, 1953.
4) Beder, O. E., Ploger, W. J.: Intraoral titanium implants, *Oral Surg Oral Med Oral Path* **12** (7): 787-799, 1959.
5) Linkow, L. I.: Implant Dentistry Today: A Multidisciplinary Approach. Vol. 1., *Piccin,* Padua, 1990, pp. 1-80.
6) Keller, J. C., Draughn, R. A., Dougherty, W. J., Wightman, J. P.: Characterization of commercially pure Ti surfaces, *J Dent Res* **67** (SI): 314, Abstract No. 1610, 1988.
7) Draughn, R. A., Keller, J. C., Wightman, J.P., Meletiou, S. D.: Characterization of sterilized cp Ti surfaces, *J Dent Res* **68** (SI): 276, Abstract No. 756, 1989.
8) Keller, J. C., Wightman, J. P., Draughn, R. A., Dougherty, W. J.: Characterization of acid passivated

cp Ti implant surfaces, *J Dent Res* **68** (SI): 872, Abstract No. 44, 1989.
9) Keller, J. C., Stanford, C. M., Wightman, J. P., Draughn, R. A., Zaharias, R.: Characterizations of titanium implant surfaces, III, *J Biomed Mater Res* **28**(8): 939-946, 1994.
10) Swart, K. M., Keller, J. C., Wightman, J. P., Draughn, R. A., Stanford, C. M., Michaels, C. M.: Short-term plasma-cleaning treatments enhance *in vitro* osteoblast attachment to titanium, *J Oral Implantol* **18** (2): 130-137, 1992.
11) Keller, J. C., Wightman, J. P., Draughn, R. A.: Surface characterization of Ti-6Al-4V alloy surfaces, *J Dent Res* **70** (SI): 301, Abstract No. 285, 1991.
12) Lucas, L. C., Reddrick, T., Long, J. L., Lemons, J. E.: Properties of titanium oxide films, *J Dent Res* **71** (SI): 183, Abstract No. 619, 1992.
13) Ong, J. L., Lucas, L. C.: Surface characterization of titanium oxides, *J Dent Res* **72** (SI): 228, Abstract No. 1001, 1993.
14) Ong, J. L., Raikar, G. N., Lucas, L.C.: Characterization of titanium surfaces in a physiologic solution, *J Dent Res* **73** (SI): 401, Abstract No. 2396, 1994.
15) Keller, J. C., Draughn, R. A., Wightman, J. P., Dougherty, W. J., Meletiou, S. D.: Characterization of sterilized CP titanium implant surfaces, *Int J Oral Maxillofac Implants* **5** (4): 360-367, 1990.
16) Stanford, C. M., Keller, J. C., Solursh, M.: Bone cell expression on titanium surfaces is altered by sterilization treatments, *J Dent Res* **73**(5): 1061-1071, 1994.
17) Keller, J. C., Grotendorst, G. R., Dougherty, W. J.: Cell attachment to sterilized cp Ti surfaces, *J Dent Res* **68** (SI): 276, Abstract No. 757, 1989.
18) Michaels, C. M., Keller, J. C., Stanford, C. M., Rittman, G. A.: In vitro PDL fibroblast attachment to plasma cleaned Ti surfaces, *J Dent Res* **69** (SI): 369, Abstract No. 2087, 1990.
19) Michaels, C. M., Keller, J. C., Zaharias, R.: Osteoblast responses to sterilized titanium of different roughnesses, *J Dent Res* **70** (SI): 366, Abstract No. 809, 1990.
20) Michaels, C. M., Keller, J. C., Stanford, C. M., Solursh, M., Mackenzie, I. C.: In vitro connective tissue cell attachment to cp Ti, *J Dent Res* **68** (SI): 276, Abstract No. 759, 1989.
21) Bowers, K. T., Keller, J. C., Wick, D. G., Randolph, B. A.: Optimization of surface morphology or osteoblast attachment, *J Dent Res* **69** (SI): 370, Abstract No. 2091, 1990.
22) Zaharias, R., Keller, J. C.: In vitro responses of soft tissue cells to surface morphology, *J Dent Res* **71** (SI): 184, Abstract No. 626, 1992.
23) Grube, J. M., Keller, J. C., Zaharias, R.: Surface roughness affects gingival fibroblast responses, *J Dent Res* **71**(SI): 184, Abstract No. 625, 1992.
24) Rubey, T., Zaharias, R., Keller, J. C.: The nature of epithelial cell adhesion to implant surfaces, *J Dent Res* **74** (SI): 190, Abstract No. 1425, 1995.
25) Haney, L., Davidson, J. A., Dabbous, M. K. H.: Periodontal ligament fibroblast and osteoblast adhesion to various implant surfaces, *J Dent Res* **75** (SI): 78, Abstract No. 486, 1996.
26) Imoberdorf, M. J., Fine, D. H., Mendieta, C., Furgang, D.: Attachment of pioneer bacteria to titanium vs. enamel surfaces, *J Dent Res* **68** (SI): 377, Abstract No. 1567, 1989.
27) Rams, T. E., Roberts, T. W., Feik, D., Molzan, A. K., Slots, J.: Early microflora of hydroxyapatite-coated and pure titanium human dental implants, *J Dent Res* **70** (SI): 488, Abstract No. 1777, 1991.
28) Maxson, B. B., Syed, S. A.: *In vivo* adherence of oral bacteria to two dental implants, *J Dent Res* **70** (SI): 488, Abstract No. 1779, 1991.
29) Eganhause, K., Keller, J. C., Drake, K., Grigsby, W., Wu-Yuan, C. D.: Attachment of Porphyromonas gingivalis to titanium surfaces, *J Dent Res* **72** (SI): 140, Abstract No. 294, 1993.
30) Yliheikkila, P. K., Kononen, M., Meurman, J. H.: Effect of surface processing of titanium on the attachment of Streptococci, *J Dent Res* **72** (SI): 141, Abstract No. 297, 1993.
31) Edgerton, M., Lo, S. E., Scannapieco, F. A.: Titanium salivary pellicle inhibits adhesion of Streptcocci species, *J Dent Res* **73** (SI): 373, Abstract No. 2168, 1994.
32) Patel, M., Drake, D., Keller, J.: Bacterial adhesion to titanium implant surfaces: Development of an in vitro model, *J Dent Res* **69** (SI): 369, Abstract No. 2085, 1990.
33) Wu-Yuan, C. D., Keller, J. C., Eganhause, K.: Oral bacterial accumulation on titanium surfaces with different textures, *J Dent Res* **71** (SI): 145, Abstract No. 314, 1992.

34) Zaharias, R. S., Collins, J. M., Keller, J. C.: Effect of sterilization on mineralization by osteoblast-like cells, *J Dent Res* **73** (SI): 400, Abstract No. 2387, 1994.
35) Keller, J. C., Marshall, G. W., Brown, I.: Effects of Ca ion implantation on bone cell responeses, *J Dent Res* **73** (SI): 400, Abstract No. 2388, 1994.
36) Monteith, M. R., Zaharias, R., Stanford, C. M., Keller, J. C.: *In vitro* mineralization of bone-like cells is affected by Ti^{+4}, *J Dent Res* **74** (SI): 189, Abstract No. 1423, 1995.
37) Engelhardt, G., Zaharias, R., Keller, J. C.: Effect of cp Ti surface roughness on osteoblast mineralization, *J Dent Res* **74** (SI): 189, Abstract No. 1424, 1995.
38) Okazaki, K., Lee, W. H., Kim, D. K., Kopczyk, R. A.: Physical characteristics of Ti-6Al-4V implants fabricated by electrodischarge compaction, *J Biomed Mater Res* **25** (12): 1417-1429, 1991.
39) Kopczyk, R., Sammon, P., Geisler, R., Okazaki, K., Kim, D., Domenici, J.: Comparison of porous titanium and Ti-6Al-4V implants, *J Dent Res* **70**(SI): 367, Abstract No. 811, 1991.
40) Anderson, S., Drummond, J., Geissler, R., Okazaki, K., Kopczyk, R., Mitchel, R., Dominici, J., Sammon, P.: Osseointegration into porous titanium and titanium alloy implants, *J Dent Res* **71** (SI): 638, Abstract No. 980, 1992.
41) Renshaw, W., Drummond, J., Dominici, J., Okazaki, K., Mitchell, R: Histomorphometric assesment of totally porous titanium alloy implants, *J Dent Res* **72** (SI): 389, Abstract No. 2285, 1993.
42) Kay, J. F.: Calcium phosphate coatings for dental implants. Current status and future potential, *Dental Clinics of North America* **36**(1): 1-18, 1992.
43) Whitehead, R. Y., Lucas, L. C., Lacefield, W. R.: The effect of dissolution on plasma sprayed hydroxylapatite coatings on titanium, *Clinical Materials* **12** (1): 31-39, 1993.
44) Whitehead, R. Y., Lacefield, W. R., Lucas, L. C.: Structure and integrity of a plasma sprayed hydroxylapatite coating on titanium, *J Biomed Mater Res* **27** (12): 1501-1507, 1993.
45) Kay, J. F., Marcho, M., Logan, G., Embry, J.: Physical and chemical characteristics of hydroxlapatite coatings on metal, *J Dent Res* **65** (SI): 222, Abstract No. 472, 1986.
46) Tufekci, E., Brantley, W. A., Mitchell, J. C., Foreman. D. W., McGlumphy, E. A.: Microstructures of plasma-sprayed calcium phosphate-coated titanium dental implants, *J Dent Res* **73** (SI): 138, Abstract No. 289, 1994.
47) Ong, J. L., Lucas, L. C., Lacefield, W. R., Rigney, E. D.: Structure, solubility and bond strength of thin calcium phosphate coatings produced by ion beam sputter deposition, *Biomaterials* **13** (4): 249-254, 1992.
48) Ong, J. L., Prince, C. W., Lucas, L. C.: Cellular response to well-characterized calcium phosphate coatings and titanium surfaces *in vitro, J Biomed Mater Res* **29** (2): 165-172, 1995.
49) Vijayaraghavan, T. V., Bensalem, A.: Hydroxyapatite (HA) coating by electrodeposition on alpha and alpha-beta Ti alloys, *J Dent Res* **74** (SI): 474, Abstract No. 589, 1995.
50) Holloway, J. A., Denry, I. L., Mayers, T. A., McGlumphy, E. A., Litsky, A. S.: Identification of fatigue crack initiation in commercially pure titanium, *J Dent Res* **75** (SI): 76, Abstract No. 469, 1996.
51) Waterstrat, R. M.: Alternatives to gold alloys, DHEW Publication No. (NIH) 77-1227, *U. S. Department of Health, Education, and Welfare,* Bethesda, 1977, pp. 224-233.
52) Waterstrat, R. M., Rupp, N. M., Franklin, O.: Production of a cast titanium-base partial denture, *J Dent Res* **57** (SI): 254, Abstract No. 717, 1978.
53) Schuyler, D. R., Petrusha, J. A., Gall, G. S., Seagle, S. R.: Development of titanium alloy casting technology. *U.S. Department of Commerce, National Technical Information Service,* Washington, D. C., 1976.
54) Waterstrat, R. M.: Arc-furnace for the production of small investment castings of reactive or refractory metals such as titanium, U. S. Patent No. 4,627,482, 1985.
55) Waterstrat, R. M., Giuseppetti, A. A.: Casting apparatus and investment mold material for metals which melt at very high temperatures, *J Dent Res* **64** (SI): 317, Abstract No. 1278, 1985.
56) Rupp, N. W., Waterstrat, R. M., Giuseppetti, A. A., Conner, M. L.: Cast titanium rstorations: Clinical observations, *J Dent Res* **66** (SI): 247, Abstract No, 1121, 1987.
57) Mueller, H. J., Reyes, W. D., Moser, J. B., Giuseppetti, A. A., Waterstrat, R. M.: Particle-, pore-size distributions and thermal behavior of investments for titanium, *J Dent Res* **67** (SI): 345, Abstract No.

1861, 1988.
58) Mueller, H. J., Giuseppetti, A. A., Waterstrat, R. M.: Phosphate-bonded investment materials for titanium casting, *J Dent Res* **69** (SI): 367, Abstract No. 2072, 1990.
59) Moser, J. B., Lin, J. H., Taira, M., Greener, E. H.: Corrosion and microhardness of Cu-Ti, Co-Ti and Ni-Ti systems, *J Dent Res* **63** (SI): 258, Abstract No. 790, 1984.
60) Moser, J. B., Lin, J. H. C., Taira, M., Greener, E. H.: Development of dental Pd-Ti alloys, *Dent Mater* **1** (2): 37-40, 1985.
61) Al-Jabab, A. S., Greener, E. H., Lautenschlager, E. P.: Low melting titanium dental casting alloys, *J Dent Res* **69** (SI): 131, Abstract No. 184, 1990.
62) Taira, M., Moser, J. B., Greener, E. H.: Studies of Ti alloys for dental castings, *Dent Mater* **5** (1): 45-50, 1989.
63) Takahashi, J., Kumura, H., Lautenschlager, E. P., Chern Lin, J. H., Moser, J. B., Greener, E. H.: Casting pure titanium into commercial phosphate-bonded SiO_2 investment molds, *J Dent Res* **69** (12): 1800-1805, 1990.
64) Greener, E. H.: Titanium casting in the U. S. A, Proceedings of the Second International Symposium on Titanium in Dentistry, The Society for Titanium Alloys in Dentistry, ed., January 1992, Kyoto, pp. 34-35.
65) Greener, E. H., Moser, J. B., Opp, J., Szurgot, K., Marker, B. C.: Dental castability of Ti and Ti-6Al-4V, *J Dent Res* **65** (SI): 301, Abstract No. 1190, 1986.
66) Greener, E. H., Moser, J. B., Opp, J., Szurgot, K., Marker, B. C.: Properties of centrifugally cast commercial Ti and Ti-6Al-4V, *J Dent Res* **65**(SI): 317, Abstract No. 1329, 1986.
67) Waldmeier, M. D., Menis, D. L., Cohen, J., Greener, E. H.: Polarization resistance of selected dental alloys, *J Dent Res* **65** (SI): 317, Abstract No. 1330, 1986.
68) Riesgo, O., Greener, E. H., Moser, J. B.: Titanium alloys with dental porcelain, *J Dent Res* **63** (SI): 319, Abstract No. 1336, 1984.
69) Menis, D. L., Moser, J. B., Marshall, S. J., Greener, E. H.: Characterization of three experimental porcelains for bonding to cast titanium, *J Dent Res* **65** (SI): 764, Abstract No. 342, 1986.
70) Menis, D. L., Moser, J. B., Greener, E. H.: Experimental porcelain compositions for application to cast titanium, *J Dent Res* **65** (SI): 343, Abstract No. 1565, 1986.
71) Menis, D. L., Moser, J. B., Marshall, S. J.: Characterization of commercially available enamels for use on cast titanium, *J Dent Res* **66** (SI): 294, Abstract No. 1496, 1987.
72) Tamaki, Y., Miyazaki, T., Lautenschlager, E. P., Greener, E. H.: Titanium castings with newly developed phosphate bonded investments, *J Dent Res* **70** (SI): 485, Abstract No. 1755, 1991.
73) Pang, I., Gilbert, J., Lautenschlager, E., Chai, J.: Bonding characteristics of low-fusing porcelain to titanium, *J Dent Res* **73** (SI): 320, Abstract No. 1743, 1994.
74) Gilbert, J. L., Covey, D. A., Lautenschlager, E.: Bond characteristics of porcelain fused to titanium, *J Dent Res* **73** (SI): 370, Abstract No. 2147, 1994.
75) Blackman, R., Tran, H., Barghi, N.: Casting accuracy of pure titanium used for RPD frames, *J Dent Res* **68** (SI): 396, Abstract No. 1715, 1989.
76) Baez, R., Blackman, R., Barghi, N., Tseng, E.: Margin fit of pure titanium cast crown copings, *J Dent Res* **68** (SI): 269, Abstract No. 700, 1989.
77) Blackman, R., Baez, R., Barghi, N.: Marginal accuracy and geometry of cast titanium copings, *J Prosthet Dent* **67** (4): 435-440, 1990.
78) Blackman, R., Nonaka, T., Baez, R.: Strength comparisons of cast titanium using three phosphate type investments, *J Dent Res* **70** (SI): 485, Abstract No. 1756, 1991.
79) Baez, R. J., Nonaka, T., Blackman, R.: Ti castability and surface characteristics with three phosphate bonded investments, *J Dent Res* **70** (SI): 486, Abstract No. 1757, 1991.
80) Almquist, P., Chan, D. C. N., Blackman, R., Kaiser, D. A.: The effects of sprue number and position on titanium crown margins, *J Dent Res* **70** (SI): 486, Abstract No. 1758, 1991.
81) Guillory, V. L., Chan, D. C. N.: Effects of number of sprues on roughness and porosities of titanium crowns, *J Dent Res* **71** (SI): 541, Abstract No. 204, 1992.
82) Blackman, R., Baez, R., Cuadra, R.: Accurate radiographic assessment of internal voids in titanium

castings, *J Dent Res* **73** (SI): 124, Abstract No. 183, 1994.
83) Baez, R. J.: Dental ceramics for use with pure titanium, *J Dent Res* **73**(SI): 319, Abstract No. 1742, 1994.
84) Brodersen, C., Prasad, A.: System and method for casting and reworking metallic materials, U. S. Patent No. 5,161,600, 1992.
85) Prasad, A., Broderson, C., Day, G. P., Garcia, F., Weissbecker, H., Kobakov. Y.: Dental titanium castings: The promise fulfilled, *Trends Tech Contemp Dent Lab* **10** (1): 94-97, 1994.
86) Mueller, H. J., Fan, P. L.: Standard air permeabilities of investment materials, *J Dent Res* **69** (SI): 368, Abstract No. 2074, 1990.
87) Chai, T-I., Stein, R. S.: Porosity and accuracy of multiple-unit titanium castings, *J Prosthet Dent* **73** (6): 534-541, 1995.
88) Arango, J., Stein, R. S., Millstein, P. L.: Castability and marginal fit of pure titanium castings, *J Dent Res* **70** (SI): 539, Abstract No. 2187, 1991.
89) Liles, A. C., Salkend, S., Sarka,R N. K.: Galvanic corrosion between Ti and selected crown and bridge alloys, *J Dent Res* **72** (SI): 195, Abstract No. 734, 1993.
90) Oshida, Y., Hashem, A.: Oxidation kinetics of nitrided pure titanium during porcelain firing process, *J Dent Res* **73** (SI): 408, Abstract No. 2449, 1994.
91) Wang, R. R., Welsch, G. E.: Characterization of protective coatings for titanium-ceramic restorations, *J Dent Res* **75** (SI): 32, Abstract No. 119, 1996.
92) Blackman, R. B., Baez, R. J., Lopez, M., Naffah, D. M.: Titanium crown margin accuracy comparisons between different casting systems, *J Dent Res* **75** (SI): 166, Abstract No. 1187, 1996.
93) Burkett-Guitierrez, L. R., Burgess, J. O.: Castability and internal porosity of cast titanium patterns, *J Dent Res* **75** (SI): 163, Abstract No. 1168, 1996.
94) Sutton, A. J., Norling, B. K., Cronin, R. J., Dove, S. B. Verret, R. G., Phoenix, R. D.: Sprue design effects on castability and porosity of titanium RPDs, *J Dent Res* **75** (SI): 163, Abstract No. 1168, 1996.
95) Baez, R. J., Blackman, R. B., Lopez, M., Naffah, D. M.: Influence of casting machine and sprue configuration on titanium castability, *J Dent Res* **75** (SI): 166, Abstract No. 1188, 1996.
96) Welsch, G. E., Wang, R. R., Cvetichan, R., Hull, D., Garlick, R., Castro-Cedano, M.: Ti-Ag-Co alloys for dental castings, *J Dent Res* **75** (SI): 366, Abstract No. 2785, 1996.
97) Watanabe, I., Watkins, J. H., Nakajima, H., Okabe, T.: Optimizing cast titanium quality through pressure difference, *J Dent Res* **75** (SI): 62, Abstract No. 359, 1996.
98) Gilbert, J. L., Mante, F.: A combined polarization-impedance analysis of high purity titanium single crystals, *J Dent Res* **75** (SI): 76, Abstract No. 468, 1996.
99) Mante, F. K., Zhang, S., Romanow, W. J.: Growth of titanium single crystals using the floating zone technique, *J Dent Res* **75** (SI): 76, Abstract No. 468, 1996.
100) May, K. B., Billy, E. J., Fox, J., Lang, B. R.: The silane and opaquer effect on PMMA-titanium bond strength, *J Dent Res* **75** (SI): 164, Abstract No. 1175, 1996.
101) May K. B., Russell, M. M., Razzoog, M. E., Lang, B. R.: The shear strength of polymethyl methacrylate bonded to titanium partial denture framework material, *J Prosthet Dent* **70** (5): 410-413, 1993.
102) Lorey, R. E., Edge, M. J., Lang, B. R., Lorey, H. S.: The potential for bonding titanium restorations, *J Prosthod* **2** (3): 151-155, 1991.
103) Goldberg, A. J., Burstone, C. J.: An evaluation of beta titanium alloys for use in orthodontic appliances, *J Dent Res* **58** (2): 593-600, 1979.
104) Burstone, C. J., Goldberg, A. J.: Beta titanium: A new orthodontic alloy, *Am J Ortho* **77** (2): 121-132, 1980.
105) Wilson, D. F., Goldberg, A. J.: Alternative beta-titanium alloys for orthodontic wires, *Dent Mater* **3** (6): 337-341, 1987.
106) Khier, S., Brantley, W., Fournelle, R.: Structural characterization of superelastic NiTi orthodontic wire alloys, *J Dent Res* **67** (SI): 361, Abstract No. 1988, 1988.
107) Khier, S., Brantley, W., Fournelle, R., Ehlert, T.: XRD and DSC studies of NiTi orthodontic wire alloys, *J Dent Res* **68** (SI): 386, Abstract No. 1638, 1989.
108) Fletcher, M. L., Miyake, S., Brantley, W. A., Culbertson, B. M.: DSC and bending studies of a new

shape-memory orthodontic wire, *J Dent Res* **71** (SI): 169, Abstract No. 505, 1992.

109) Thayer, T. A., Bagby, M. D., Moore, R. N., Deangelis, R.: X-ray diffraction of NiTi orthodontic archwires, *J Dent Res* **72** (SI): 139, Abstract No. 288, 1993.

110) Bradley, T. G., Brantley, W. A., Culbertson, B. M.: Differential scanning calorimetric study of nickel-titanium orthodontic wires, *J Dent Res* **73** (SI): 414, Abstract No. 2496, 1994.

111) Quo, S. D., Marshall, I S. J., Marshall, G. W.: Chemical and phase contents analysis of Ni-Ti wires, *J Dent Res* **73** (SI): 413, Abstract No. 2492, 1994.

112) Quo, S. D., Pelton, A. R., Marshall, G. W., Marshall, S. J.: Mechanical and structural characterization of NiTi orthodontic wires, *J Dent Res* **74** (SI): 474, Abstract No. 587, 1995.

113) Sachdeva, R., Oshida, Y., Prewitt, J., Miyazaki, S.: Corrosion behavior of superelastic (SE) NiTi, *J Dent Res* **70** (SI): 482, Abstract No. 1725, 1991.

114) Sachdeva, R., Farzin-Nia, F., Oshida, Y.: The effect of bending on austenitic finish temperature of orthodontic NiTi wires, *J Dent Res* **71** (SI): 140, Abstract No. 276, 1992.

115) Sachdeva, R., Smith, S., Farzin-Nia, F.: Load deformation characteristics of orthodontic arch wires, *J Dent Res* **72** (SI): 140, Abstract No. 290, 1993.

116) Hurst, C. L., Duncanson, M. G., Nanda, R. S., Angolkar, P. V.: An evaluation of the shape-memory phenomenon of nickel-titanium orthodontic wires, *Am J Orthod Dentofac Orthop* **98** (1): 72-76, 1990.

117) Kusy, R. P., Wilson, T. W.: Dynamic mechanical properties of straight titanium alloy arch wires, *Dent Mater* **6** (4): 228-236, 1990.

118) Khier, S. E., Brantley, W. A., Fournelle, R. A.: Bending properties of superelastic and nonsuperelastic nickel-titanium orthodontic wires, *Am J Orthod Dentofac Orthop* **99**(4): 310-318, 1991.

119) Sachdeva, R., Farzin-Nia, F.: Titanium niobium orthodontic archwire, *J Dent Res* **75** (SI): 384, Abstract No. 2936, 1996.

120) Angelini, E., Bonino, P., Bruzzone, G., Pezzoli, M.: Corrosion resistance of solder joints for removable partial dentures, *J Dent Res* **66** (SI): 247, Abstract No. 1126, 1987.

121) Wang, R. R., Welsch, G. E., Boyle, A. M.: Analysis of three joining techniques for titanium or Ti-6Al-4V alloy, *J Dent Res* **73** (SI): 212, Abstract No. 885, 1994.

122) Hsu, C. C., Stein, R. S., Millstein, P. L.: Analyses of titanium infrared soldered connectors, *J Dent Res* **74** (SI): 425, Abstract No. 196, 1995.

123) Berg, E., Wagner, W. C., Davik, G., Dootz, E. R.: Mechanical properties of laser welded, cast and wrought titanium, *J Dent Res* **74** (SI): 237, Abstract No. 1808, 1995.

124) Haney, S., Eichmiller, F., Meiers, J.: *In vitro* study of intraoral welding procedures for pure titanium, *J Dent Res* **73** (SI): 212, Abstract No. 886, 1994.

125) Yamagishi, T., Ito, M., Oshida, Y., Hashem, A.: Tensile strength and elongation of laser-welded titanium, *J Dent Res* **72** (SI): 131, Abstract No. 224, 1993.

126) Rubenstein, J. E.: Stereo laser-welded titanium implant frameworks: Clinical and laboratory procedures with a summary of 1-year clinical trials, *J Prosthet Dent* **74** (3): 284-293, 1995.

本号掲載論文の和文抄録

歯科用チタン：アメリカにおける研究の推移

中島　裕，岡部　徹
Department of Biomaterials Science, Baylor College of Dentistry

近年，チタンは材料学研究者や臨床医に大きく注目を浴びてきている．アメリカでのチタンの生体材料としての歴史は，1940年にチタンインプラントの動物実験が行われた時から始まる．その後，1959年，口腔内インプラントを作製するにあたりチタン鋳造の必要性をアメリカのBedgerとPlogerがはじめて唱えた．1977年には最初のチタン鋳造による歯科補綴物が作製する試みがなされたと報告されている．過去10年間，IADRおよびAADRにおいてチタンに関連する発表数は毎年増加し続けている．大多数の研究発表は，アメリカからの研究であるが，そのうち半数以上は歯科用インプラントに関連したものである．チタン鋳造や補綴物としての応用に関するアメリカからの報告は，近年増加しているものの，今のところ数が限られている．このレポートは，アメリカにおける歯科用チタンの発展と研究の動向を報告する．

磁石と吸引する試作コンポジットレジンの性質

平野　進，安川宏美，野本理恵，森山圭介，平澤　忠
鶴見大学歯学部歯科理工学教室

SUS 444ステンレス鋼フィラーを含み，磁石と吸着する化学重合型コンポジットレジンを作製した．フィラーには種々の濃度のシラン処理を施した．このコンポジットレジンは操作性がよく，保存安定性に優れていた．もっとも良い性質を示したコンポジットレジンは以下のようであった．市販磁性アタッチメント用の磁石に対する吸引力は磁石附属のキーパシステムのそれの1/3-1/4であった．曲げ強さとヌープ硬さは各々76 MPa (7.7 kgf/mm^2)ならびに64 KHNで，市販の化学重合型コア用コンポジットレジンよりも低い値であった．コンポジットレジンからの溶出金属量は1％乳酸溶液7日間浸漬の結果0.7 mg/cm^{2}で，0.9%NaCl溶液7日間浸漬では検出できなかった．

フィラー形状および粒径が試作光重合型コンポジットレジンの機械的性質に及ぼす影響

宮坂　平
日本歯科大学歯学部歯科理工学教室

平均粒径1.7～21.5 μmの無定形フィラー4種類，平均粒径0.46～31.2 μmの球形フィラー5種類および平均0.04 μmのミクロフィラーのうちから，それぞれ2種類づつを組み合わせて混合した二成分系のハイブリッド型フィラーを用い光重合型コンポジットレジンを試作し，圧縮強さおよび間接引張強さを測定した．この結果，無定形フィラーと球形フィラーを混合すると，組み合わせるフィラーの粒径が小さいほど強度は大きくなる傾向