

# CASTING METALS IN DENTISTRY: PAST – PRESENT – FUTURE

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## ABSTRACT

**T**his article deals mainly with the development of dental casting techniques and formulation of the different groups of alloys used in the fabrication of ceramo-metal restorations.

It is recognized that in order for the quality of dental cast restorations to be improved, having alloys with the proper composition is not enough. Biocompatibility, good mechanical and physical properties, longevity of the restoration, compatibility with porcelain, and a simple manipulative technique are as important. Researchers have contributed to different aspects of dental castings and have made cast restorations what they are today. Unfortunately, much of the original basic research has been overlooked by present investigators, who have duplicated studies conducted in the past without realizing that the study had already been performed and the research had been published. The main reason for this is that abstracts of articles published prior to 1975 are not available through a library computer-search system. To obtain copies of articles published prior to 1975, one has to search the literature to know where they were published. This article provides references for much of the past work in this area. Also, dental libraries do not carry copies of U.S. patents. This places the majority of researchers located at dental schools at a disadvantage. They are not familiar with what the patents claim, what is taught, and why certain elements are added or eliminated from alloys and investment materials. This article also provides the numbers of many U.S. patents. By having the patent number, one can obtain the text of the patent from the U.S. Patent Office in Washington, DC.

Since esthetics plays an important role in today's society, emphasis will be given only to alloys designed for fabrication of ceramo-metal restorations. Many ceramo-metal alloys are available today, and they are classified differently by different individuals. In this article, classification will be based on the major components of these alloys, as well as on a chronological introduction of one group leading to the development of the next group. Based on this, one can classify these alloys into six major groups. Chemical composition, properties, and the developers of these alloys, along with their U.S. patents, are given.

Recently, two types of all-ceramic restorations have been introduced. The main advantage of the all-ceramic restoration is its superior esthetic quality compared with that of ceramo-metal restorations. Their main disadvantages are low strength and ductility. Their strength, however, is sufficient for single-unit restorations, but not for bridgework. The use of titanium for dental restorations has also been studied, and it has been found to be suitable.

**Future Studies** – Future work should be devoted to the following: (1) the development of stronger and more ductile ceramic materials; (2) further study of the promising palladium alloys from the noble metal group and titanium alloys from the base metal group; (3) the development of easier and less-time-consuming techniques for the fabrication of dental appliances; (4) the development of a powder technique rather than a cast technique for future fabrication methods; and (5) the development of new laboratory equipment, *e.g.*, a single sintering oven capable of sintering both ceramic and metallic particles, which would be accepted if the powder technique is developed.

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## INTRODUCTION

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Casting metals by the lost-wax process has been recognized in industry and the arts for many years. No record exists to indicate exactly when and where

this type of casting procedure was first developed. All that is known is that somewhere along the line – it may have been in ancient Egypt or in ancient China – someone conceived of the idea of making a wax replica of an item to be cast, surrounding this replica with an investment material, letting the investment harden, then melting and burning out the wax, thus producing a mold having a highly intricate

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and accurate cavity. The next steps were melting the metal and pouring it into the cavity.

It has long been the dentist's desire, however, to be able to produce a restoration in the laboratory and place it in the patient's mouth in a relatively short time. This desire probably arose as a result of the early method of placing gold foil fillings. It was a generally accepted practice to work continuously on the patient until all cavities were prepared. This operation often required two or three days. The cavities were then filled temporarily, and the foil was placed at the next appointment.

In the literature, credit is given to Dr. Swasey (1890), who introduced a technique where a solid gold inlay could be prepared. In his technique, the gold foil was first adapted to the shape and contour of the tooth, then removed, invested, and filled with 20-karat gold. Wax was used for making gold inlays for the first time by Martin (1891). According to Martin's technique, there was no need to use a foil liner. He filled the cavity with wax, removed it after hardening, invested it, burned it out, and then poured the molten gold into the mold formed in the investment.

A few years later, Dr. Philbrook (1896) introduced a pressure-casting method of producing gold inlays. His technique was essentially the same as that used today. In his technique, the wax pattern was formed directly in the mouth, mounted on a sprue pin, and invested in a metal ring, with plaster of Paris and silex used as an investment medium. The metal ring was placed in an oven for wax elimination. Finally, the alloy was melted in a crucible formed in the investment, and cast by means of air pressure. At the time, the profession failed to realize the significance of Philbrook's contribution. It is Philbrook whose name should be associated with the method of casting dental castings under pressure. About 10 years later, Dr. Taggart (1907) presented a paper before the New York Odontological Group, in which he discussed his casting technique and machine. Taggart's success was mostly due to his improved casting machine, since his casting technique was not original; the idea of using wax to form the pattern was that of Martin (1891), and using pressure to cast the alloy was that of Philbrook (1896). Whether Taggart or Philbrook or Martin should be called the father of today's dental casting procedure is debatable.

Castings made using Taggart's casting machine and his investment were generally too small and did not fit the cavities properly. Van Horn (1910) suggested and promoted the idea of thermally expanding wax patterns prior to investing. During the decade of the 1920's, the commercial possibilities of Van Horn's technique were suddenly appreciated, and a large number of new casting procedures were introduced, resulting in the marketing of much new equipment without much improvement in the fit of castings. The development of cristobalite investment by Coleman and Weinstein in 1929, who obtained a U.S. patent a few years later (1933), as well as the introduction of

the hygroscopic technique (Scheu, 1932), were responsible for the greatest improvement in the fit of dental castings.

In general, just having a good dental alloy is not sufficient to improve dental castings. Besides a properly formulated and carefully manufactured dental alloy, one needs a good investment, the proper equipment, and well-defined, easily usable technique. The high level of accuracy of the fit that dental castings of today have reached is the result of improvements made in all of these areas — namely, alloy, investment, equipment, and casting technique.

As cristobalite-containing investments became available on the market, many researchers — such as Volland and Paffenbarger (1932), Coy (1933), Phillips (1933), and Sweeney (1933) — published articles showing the results of their closely fitted castings. In the meantime, the desirability of attempting to obtain a significant amount of compensation by means of wax expansion was successfully challenged by Maves (1932) and later by Lasater (1940), when they showed that all wax patterns distorted when heated. As a result of these studies, a casting technique employing investments containing cristobalite (which compensates for a major portion of the shrinkage of alloy and wax pattern by thermal expansion) became popular. In later years, many more investigators published the results of their studies using investments containing cristobalite. Today, such investments are called "thermal-expanding investments" and are more popular than their counterparts, which are low-heat or hygroscopic investments.

From the time that Dr. Scheu introduced his hygroscopic technique, various aspects of hygroscopic investments were studied by many individuals, and some theories were postulated. Researchers such as Degni (1946), Skinner and Degni (1957), Docking *et al.* (1948 a-c, 1949), and Peyton and his colleagues [Landgren (1950); Delgado (1953); Asgar (1954, 1958); Jorgensen (1956); Fusayama (1957); Dickson *et al.* (1955); and Ryge and Fairhurst (1956)] studied various aspects of the hygroscopic expansion of investments, and many theories were set forth. Finally, Mahler and Ady (1960), in their classic paper, showed that the hygroscopic expansion of dental investments is a continuation of setting expansion and proposed the theory which is accepted today. Since the hygroscopic technique is a more complicated technique, compared with the thermal expansion technique, many researchers have modified and developed new casting techniques based on the hygroscopic expansion of the investment. To name a few, these include Scheu (1933), Crawford (1940), Hollenback (1943, 1948), Smyd (1948), Asgar *et al.* (1955), and Sturdevant (1959).

As mentioned earlier, the quality of dental castings would not be where it is today if a better understanding of the basic nature of dental castings and improvement in investments and alloys had not been accomplished. Much work in the various aspects of dental casting techniques — such as the effect of mold

and metal temperature on the fit of castings, castability of the various alloys, choice of sprue as well as its size and location, and the effects of various types of dental wax on the resultant casting — has been reported. It is almost impossible to cite those articles in such a short review; therefore, it will not be attempted.

In the 1950's, researchers were looking for further improvements in crown and bridge prosthodontics. Their main concern was to improve esthetics. Credit is usually given to Dr. Abraham Weinstein, who was the first to produce a commercially successful dental gold alloy and porcelain composite and who obtained two U.S. patents (Weinstein *et al.*, 1962 a,b). The J.F. Jelenko Company and the J. Aderer Company were the first dental companies to introduce a gold-based alloy on which porcelain could be baked. In the meantime, the Whip-Mix Corporation developed a phosphate-bonded investment in which the high-fusing alloys of Jelenko and Aderer could be cast successfully with the use of existing casting techniques and equipment. With the introduction of these new materials, it was possible for porcelain to be baked successfully over gold-based alloys, and, along with the development of high-speed hand-pieces, the direction of dental practice changed.

Today, relatively few full-metal-cast restorations are made. The public is demanding not only well-functioning restorations, but also those which cosmetically match the natural dentition. Alloys used today in the fabrication of porcelain-to-metal restorations have been classified differently by different individuals. One method of classification is based on major components of the restorations as well as on a chronological introduction of one group leading to the development of the next group. Based on these points, one could classify the restorations into six groups, as shown in the Table.

As mentioned earlier, the first group of alloys was developed in the late 1950's. Compared with the other groups, alloys of this group contain the highest percentage of noble metal — the largest portion of which

is gold (84-88%). The other elements in these alloys are platinum (4-10%) and palladium (5-7%), with 2-3% base metals. In general, these alloys are weak, and their sag resistance is lower than that of the other alloys in other groups. They cast and solder easily and have a yellow color, which is of great help when restorations with light shades are being made. Because of the high gold content, the cost of this group of alloys is relatively high.

Joseph Tuccillo (1976 a,b), while working with the Jelenko Company, obtained a U.S. patent for a second group of alloys. When the composition of these alloys was compared with those of the first group, it showed that platinum, which is the most expensive element in group I alloys, was completely eliminated. The percentage of gold was reduced from 84-87% to 51-54%, and the palladium concentration had been increased from 5-7% to 26-31%, so that the alloys of this group contained 80% noble metal, while the total noble metal content of group I was 97-98%. This group of alloys contained a considerable amount of silver (14-16%). The mechanical properties of this group of alloys were much improved compared with those of the first group. They have higher strength, bridges made of these alloys sag less, they cast well and solder easily. Also, they are much more economical. Two main disadvantages of alloys in this group are: occasional greening of the porcelain due to the presence of silver, and the fact that the color of the alloy is gray, even though the alloys contain about 50% gold. With the gray color of the alloy, it is more difficult to produce a light shade on the porcelain. It is one of the characteristics of palladium to dominate its alloys with a grayish color. For example, an alloy containing 15% palladium and 85% gold will have the color of palladium.

Clyde Ingersoll (1975 a-d) of the Williams Gold Refining Company obtained a U.S. patent for his newly developed alloy. This group of alloys contains 53-60% palladium and 30-37% silver, with the balance being base metals. The mechanical properties of this group of alloys are good, and they cast and solder easily.

TABLE  
COMPOSITION OF PORCELAIN-TO-METAL ALLOYS

| Group 1             | Group 2         | Group 3          | Group 4         | Group 5   | Group 6   |
|---------------------|-----------------|------------------|-----------------|-----------|-----------|
| 96%-98% Noble Metal | 80% Noble Metal | Pd-base Alloys   | 90% Noble Metal | 60-82% Ni | 55-64% Co |
| 84-86% Au           | 51-54% Au       | No Au or Pt      | 45-52% Au       | 20-11% Cr | 25-34% Cr |
| 4-10% Pt            | No Pt           | A) 53-60% Pd     | 38-45% Pd       | 0-9% Mo   | 2- 9% Mo  |
|                     |                 | 30-37% Ag        |                 |           |           |
| 5- 7% Pd            | 26-31% Pd       | 10% Base Metals  | No Ag           | 0- 2% Be  |           |
| 2- 3% Base Metals   | 14-16% Ag       | B) 79-88% Pd     |                 |           |           |
|                     |                 | 4- 5% Co         |                 |           |           |
|                     |                 | Bal. Base Metals |                 |           |           |
|                     |                 | C) 79-81% Pd     |                 |           |           |
|                     |                 | 10% Cu           |                 |           |           |
|                     |                 | 9% Ga            |                 |           |           |

The cost of this group of alloys is lower than that of any other noble metal alloys on the market. The coefficient of thermal expansion of this group of alloys is higher than those of groups I and II. Therefore, for optimum bond strength, they should be used with higher-shrinkage porcelains, and they are not compatible with all porcelains on the market. They contain a much higher percentage of silver compared with alloys in group II, and therefore, the chance of obtaining a green color on the porcelain increases considerably. Today there is a procedure to prevent greening of porcelain in silver-containing porcelain alloys. When this procedure is followed, the greening problem is eliminated.

A few years later, Paul Cascone (1978) of the Jenkeno Company obtained a U.S. patent for his alloy, which did not contain any platinum or silver. Alloys of this group may contain 45-52% gold and 38-45% palladium, such that 90% of the alloy is noble metal and the balance is base metals. Mechanical properties, castability, solderability, and dimensional accuracy of this group are better than those of other noble metal alloys. The coefficient of thermal expansion of this type of alloy is slightly lower than that of the other groups of alloys. Like the palladium-silver group of alloys, this group is not compatible with all of the porcelains on the market. Optimum porcelain-alloy bonding is obtained with porcelains that also have a lower coefficient of thermal contraction. The main advantage of this group of alloys over those in group II is that these alloys do not contain any silver, and the chance of obtaining a green line on the porcelain does not exist. Later, Cascone (1985 a,b) obtained another U.S. patent for gold-palladium alloys containing no silver. The main advantages of the second group of alloys are that they have a higher coefficient of expansion (making them more compatible with various porcelains) and that they contain a lower percentage of gold (making them more economical).

Boyajian (1981), while working on his Ph.D. at the University of Virginia, developed the first palladium-based alloy containing no gold, platinum, or silver. With the addition of 5% cobalt and the proper percentages of tin and indium, he managed to raise the strength as well as the coefficient of thermal expansion of the alloy to be compatible with those of existing porcelains. Later, he obtained two U.S. patents for his formula, in which he limited the cobalt content of the alloy to 7.5%. Palladium alloys containing more than 7.5% cobalt become electromagnetic. Studies have not been able to detect whether magnetic or non-magnetic alloys are more beneficial in practical cases. However, the magnetic alloys do set off the security check mechanisms located in airports.

Cascone (1985) later introduced a palladium-based alloy containing only 4% cobalt, which makes it non-magnetic. The main advantage of this alloy was that by properly balancing its ingredients and by special manufacturing procedures, it was possible for a single-phase, stable Pd-Co alloy to be formed.

Schaffer (1983) of the J.M. Ney Company obtained a U.S. patent for the introduction of a palladium-based alloy for porcelain-to-metal restorations containing 10% copper. Prior to Schaffer's palladium-copper alloy, those in the field believed that the presence of copper in the alloy would cause discoloration of the porcelain. This belief was based on some unpublished work performed in the early 1950's, but that work had been performed on gold-based alloys and not on palladium-based ones.

An attempt was initiated prior to the 1950's to bake porcelain on nickel-based alloys. Due to the lack of a suitable porcelain, a good investment, and the proper casting technique, this was not successful. After development of the proper materials, the fabrication of the porcelain-to-metal restoration became popular in dentistry; usage of nickel-based alloys for crown and bridge prostheses increased at a very fast rate. In the late 1970's, the price of gold increased considerably, and the use of nickel-based alloys for porcelain-to-metal restorations became very popular. These alloys contain a very large percentage of nickel (60-82%), chromium (11-20%), molybdenum (0-9%), and beryllium (0-2%) by weight. Even though the beryllium content is usually about 2% by weight, on an atomic basis it becomes 12%. Beryllium also has a very high vapor pressure compared with that of other elements present in nickel-based alloys. At a casting temperature of 1370°C (2500°F), an alloy containing only 2% by weight beryllium will have a vapor pressure 20 times higher than that of the nickel or chromium in the alloy. The vapor pressure of molybdenum, however, is very low; its vapor pressure at this casting temperature is less than  $10^{-7}$  times that of beryllium. Beryllium-containing alloys cast better, and they form a stronger porcelain-to-metal bond than do those not containing beryllium. Other elements found in these alloys are aluminum, silicon, titanium, tungsten, iron, tin, gallium, and phosphorus. The mechanical properties of nickel-based alloys available on the market for porcelain-to-metal restorations vary considerably from one alloy to another. The 0.2% yield strength varies from 870 MPa (120,000 psi) to 28 MPa (40,000 psi), and the elongation from 3 to 20% (Asgar, 1982). The mechanical properties of the noble metal alloys belonging to the same group do not vary to this extent. Thus, it is incorrect to generalize that base metal alloys are stronger and tougher than noble metal alloys because some are stronger and some are weaker. Properties that all nickel-based alloys share are high hardness, higher modulus of elasticity, and a somewhat higher melting temperature when compared with that of noble metal alloys.

Because of the potential health hazard of nickel and beryllium present in nickel-based alloys, some cobalt-based alloys have been introduced to the market. In general, their castability, solderability, and bond strength are not as good as those of the nickel-based alloys containing beryllium. They are harder and more technique-sensitive than are nickel-based alloys.

Meanwhile, Sozio (1986) at the Coors Porcelain Company developed a new type of ceramic material which undergoes substantially no shrinkage when fired and obtained a U.S. patent for his discovery. In a cooperative effort, researchers at Coors and Johnson & Johnson managed to develop a technique whereby a ceramic coping could be injected onto a unique epoxy die, forming a coping as if it were a cast metal coping. Once porcelain is applied over the ceramic coping, an all-ceramic restoration is formed.

At Corning Glass Works, Beall (1972) patented his method for developing a crystalline micro glass-ceramic material. His material exhibited good machinability, mechanical strength, and impact resistance. A year later, Grossman (1973), also of Corning, developed and patented a new formula for a castable glass-ceramic material. Articles cast from such a material exhibited even better machinability and mechanical strength, moderate thermal expansion, and good acid durability. Such a glass-ceramic is essentially tetrasilicic fluormica crystals uniformly dispersed throughout a glassy matrix. A few years later, Peter Adair (1984), a dental technician, patented the idea of forming dental appliances by casting ceramic materials. The idea was then proposed to the Corning Glass Works. Then, Corning Glass, with the cooperation of Dentsply International, modified Grossman's glass-ceramic formula and introduced a full-cast ceramic material to dentistry.

The main advantage of Coors' and Corning's ceramic materials is the esthetic quality of the restorations, which is superior when compared with that of ceramo-metal restorations. Their two main disadvantages are (1) low strength and (2) absence of ductility. Their strength is not sufficient to withstand stresses that are developed in dental bridges. Also, the cavity preparations have to be perfect—deformations due to minor undercuts in preparations would fracture the restoration during its fabrication in the dental laboratory. With ceramo-metal restorations, however, such minor deformations are no real problem. Therefore, not every dentist can successfully use full-ceramic restorations time after time.

In the area of metallic restorations, suitability of titanium alloys for dental use is being studied. Some information has been reported by Waterstrat and Giuseppetti (1985) and Rupp (1985, 1986), from the National Bureau of Standards, as well as by Greener and his colleagues (Moser *et al.*, 1984; Taira, 1985) at Northwestern University. It seems that titanium alloys are well-suited for fabrication of dental appliances.

## FUTURE STUDIES

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Esthetics is important in today's society. Dentists and researchers share this concern, and they have even more demands: They insist on good mechanical and physical properties of materials as well as on

reasonable longevity of the restoration. They also require that the technique of preparing such a restoration be relatively easy and that the cost not exceed that of existing materials designed for the same purpose. Full-ceramic restorations need more research to develop materials to fulfill these requirements. At the present time, neither Johnson & Johnson's nor Dentsply's materials on the market have sufficient strength to withstand stresses induced by 3- or 4-unit bridges. Even if today's materials *did* have sufficient strength, the cavity preparation technique would limit its usage. Only dentists capable of preparing ideal cavity preparations could use them successfully. A single crown made of these ceramics fractures during fabrication in the laboratory if the preparation has even a very minor undercut. Making a bridge increases difficulty of preparation considerably, not only because of possible undercuts on the abutments, but also because of the nonparallel lines of draw, and because of deflection caused by the normal forces of mastication.

Ceramics of the future can be improved in many areas. They should have greater ductility, greater yield strength, and not be as technique-sensitive. Their *in vivo* wear properties and the durability of stain materials placed on them to achieve the desired shading should be studied; these are as yet undetermined, even for today's ceramic materials. It seems that this is a large order and that these problems will probably not be solved during the next 10 to 20 years. Are we, within the next 20 to 30 years, going to be able to replace metallic structures completely with ceramics? The answer is NO, and we will probably never be able to replace metallic restorations completely. When and if the properties of ceramics are improved considerably, they will probably replace the ceramic-metal restorations to a great extent, but will never completely replace them. Damages caused by accidents and disease will probably demand either full metallic structures or ceramic-metal combinations. In the area of partial dentures and metallic denture bases for complete denture patients, where the transfer of heat and cold for healthier tissue is important, metals will be around dental laboratories and dental offices for a long time.

In the area of research for ceramo-metal or for full-cast metal appliances, it seems that the metals of the future are palladium from the noble metal group and titanium from the base metal group. Both palladium- and titanium-based alloys, with some modifications, could be used as partial denture alloys, as well as in metal palates in complete denture cases.

Palladium, being one of the noble metals, has a very good *in vivo* corrosion resistance. In many respects, it resembles platinum, and on today's market it costs about 75 to 78% less than platinum. Palladium has a face-centered cubic structure with a melting point of 1555°C. Even though it is believed that palladium has the highest vapor pressure of the platinum group metals, reliable data are not available. Compared with

other metals, however, its vapor pressure is low. The thermal expansion of palladium is about  $11.6 \times 10^{-6}/^{\circ}\text{C}$ , which is too low compared with that of the porcelains on the market ( $14.0 \times 10^{-6}/^{\circ}\text{C}$ ). In order to raise the coefficient of thermal expansion of palladium and increase its strength, various metals such as gallium, tin, indium, copper, cobalt, and others are added. The solubility of these elements in one another is low, causing most silverless palladium alloys to have two phases. Phase diagrams of these elements clarify these points. The existence of two phases for porcelain-to-metal restorations is not an advantage, since one of the phases may have a lower melting temperature, which would soften during the baking of porcelain, causing distortion of the restorations. In general, having silver in the palladium-based alloys increases the solubility of additive elements in the alloy and yields a single phase structure, but the presence of silver discolors the porcelain unless some precautions are observed. More work needs to be done in this area in order to have a single phase alloy, one with good castability and mechanical properties, to which porcelain could adhere without discoloration and produce sufficient bond strength. Also, more work in the porcelain area needs to be done in order to have a porcelain with good esthetics, easy application by dental technicians, stable coefficient of thermal expansion, and high bond strength with palladium alloys.

In the base metal area, the most promising metal is titanium. In 1977, Dr. Waterstrat (1977) started emphasizing that titanium alloys needed to be studied. Unfortunately, he did not receive the necessary financial support from granting agencies or moral support from his colleagues. Fortunately, he did not give up and continued to pursue his research interests. Today, suitability of titanium alloys has been established. It seems that research in the area of titanium alloys for dental usage should be encouraged in order to gain the ground lost during the past seven to eight years.

Probably the area that has been most ignored in the past by researchers is technique. The dental laboratories of today are facing great financial problems in obtaining the equipment necessary to fabricate appliances from newly developed materials. Consider the two ceramic materials that are on the market today. Each requires an oven and casting machine different from the ones used for casting metal appliances. This equipment is quite expensive. As a result, the small laboratories do not try to fabricate these materials, and the larger laboratories are hesitant as to whether they will be able to recover the cost before another material requiring yet a different set of equipment will be introduced. For this reason, dental laboratories are not easily persuaded to invest in new equipment and make dental appliances from newly developed ceramic materials. However, they are willing to try to use a newly developed alloy if they are

convinced that it has better properties and if they do not have to invest in any new equipment.

It seems that future techniques should be powder techniques and not cast techniques. Theoretically, it can be visualized that dental laboratories would invest in a uniform burnout and sintering oven, which is capable of sintering any alloy or ceramic particle. A new die material needs to be developed on which the powder of an alloy or ceramic material can be pressed under isostatic pressure, and sintered at the proper temperature for that material. After necessary finishing, the restoration would be delivered to dental offices and finally to the patient. It seems that unless uniform equipment and techniques are available, it will be difficult for the benefit of newly developed materials to be passed on to the patients, which is the main goal of NIDR as well as of every researcher.

## APPENDIX

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Even though the emphasis in this paper is on the development of various alloys, porcelains, and investment materials from various manufacturers, this information could not have been gained without the research activities carried out at various institutes and support by the N.I.D.R. It would be impossible to cite all the papers published in this area by different individuals; however, they should not be completely ignored. Therefore, it was decided in the text of this paper to limit alphabetical citations of the directors of research at various centers, but to list some of their publications in the bibliography:

Anusavice and his co-workers at the University of Florida (Anusavice, 1985, 1986; Anusavice *et al.*, 1982, 1983, 1985, 1986; Kaminski *et al.*, 1985; Dehoff and Anusavice, 1985, 1986); Civjan, Huget, and Vermilyea and their colleagues at the Walter Reed Army Medical Center (Civjan *et al.*, 1972, 1974, 1975, 1977; Huget *et al.*, 1976, 1978 a,b; Vermilyea and Vilca, 1982; Townsend *et al.*, 1983; Vermilyea *et al.*, 1983); Fairhurst and his group at the Medical College of Georgia (Fairhurst, 1979, 1980, 1981; Ringle *et al.*, 1977, 1978, 1981, 1982, 1983, 1986; Anusavice, 1980; Anusavice *et al.*, 1977 a-c, 1979; Smith *et al.*, 1980; Mackert *et al.*, 1983, 1986; and Parry *et al.*, 1986); Fusayama of Japan (1958 a,b, 1959, 1964; Fusayama and Yamane, 1973); Goodkind and his colleagues at the University of Minnesota (Lubovich and Goodkind, 1977; Rasmussen *et al.*, 1979; De Long *et al.*, 1982; Marker *et al.*, 1986); Greener and his group at Northwestern University (Greener *et al.*, 1986 a,b; Nakayama *et al.*, 1984; Menis, 1986; Taira, 1986); U.S. Patents and publications of Clyde Ingersoll of the Williams Gold Company (1973, 1975 a-d, 1976, 1981, 1982; Ingersoll and Agarwal, 1978, 1983); McLean from England (1980, 1983; McLean and Sced, 1973 a,b); Meyer and Nally at the University of Geneva, Switzerland (Nally and

Meyer, 1969; Nally *et al.*, 1968, 1972, 1979); Moffa at the U.S. Army Institute of Dental Research in San Francisco (1982; Moffa and Dent, 1982; Moffa and Watanabe, 1985; Moffa *et al.*, 1973, 1984, 1986); Nielsen, Tuccillo, and Cascone at the Jelenko Company (Nielsen, 1978; Shell and Nielsen, 1962; Schulman and Nielsen, 1983; Tuccillo and Nielsen, 1964, 1967, 1968, 1971, 1972; Tuccillo, 1967, 1969, 1973; Tuccillo and Cascone, 1983; Cascone, 1979, 1983; Cascone and Nabatian, 1982; Cascone and Tuccillo, 1977; Cascone *et al.*, 1978); O'Brien, Asgar, and co-workers at the University of Michigan (O'Brien, 1977; O'Brien and Ryge, 1964, 1965; Woolsey, 1984; Walton and O'Brien, 1985; Asgar and Arfaei, 1976; Asgar and Giday, 1978; Asgar *et al.*, 1975, 1986; Cecconi and Asgar, 1975; Dootz and Asgar, 1986; Fuys *et al.*, 1973, 1976 a,b; Lang *et al.*, 1982; Nitkin and Asgar, 1976; Ogura *et al.*, 1981; Rowe and Asgar, 1976; Rowe *et al.*, 1974); Pask at the University of California at Berkeley (1980; Pask and Boron, 1966; Pask and Fulrath, 1962; Pask and Tomsia, 1985; Pask *et al.*, 1985); Tesk at the National Bureau of Standards (1978; De Rijk and Tesk, 1986; Dudek and Tesk, 1977; Hinman and Tesk, 1985; Meiser *et al.*, 1985; Natarajan *et al.*, 1986; Tesk *et al.*, 1981, 1983, 1985, 1986); and many others at different research centers, whose articles appear in the bibliography, and who have greatly contributed to the literature on dental castings.

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