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Soldering in Prosthodontics—An Overview, Part I

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Abstract

The fit of fixed multiunit dental prostheses (FDP), traditionally termed fixed partial dentures (FPDs), is an ongoing problem. Poorly fitting restorations may hasten mechanical failure, due to abutment caries or screw failure. Soldering and welding play an important role in trying to overcome misfit of fixed multiunit prostheses. The term FPD will be used to denote multiunit fixed dental prostheses in this review. This is the first of a series of articles that review the state of the art and science of soldering and welding in relation to the fit of cemented or screw-retained multiunit prostheses. A comprehensive archive of background information and scientific findings is presented. Texts in dental materials and prosthodontics were reviewed. Scientific data were drawn from the numerous laboratory studies up to and including 2009. The background, theory, terminology, and working principles, along with the applied research, are presented. This first article focuses on soldering principles and dimensional accuracy in soldering. There is some discussion and suggestions for future research and development. Soldering may improve dimensional accuracy or reduce the distortion of multiunit fixed prostheses. Many variables can affect the outcome in soldering technique. Research science has developed some helpful guidelines. Research projects are disconnected and limited in scope.

In 1958 Ryge[1] wrote, "Dental soldering procedures have been developed in a rather empirical manner on the basis of soldering and brazing practices in the jewelers' trade.... quite diverging techniques prevail in the dental schools, in dental laboratories and among dental clinicians." The precise fit of fixed multiunit dental prostheses (FDP) is considered very important in clinical prosthodontics. Poor internal or marginal fit of cast multiunit restorations may hasten the onset of failure due to abutment caries, or screw fracture/loosening in the case of implant abutments. Soldering and welding continue to play important roles in trying to overcome misfit of fixed multiunit prostheses.

There are two ways of joining metals in dentistry–soldering/brazing and welding. In soldering, an intermediate alloy or solder flows between and around, and unites the parts to be joined. When joining by welding, the parent metals to be joined are fused in the joint area. Numerous processes, which are conventionally called soldering in dentistry, actually use brazing or welding alloys.[2]

Soldering as a technique dates back at least 2000 years to Roman times, with the use of lead-tin solders for joining lead water pipes.[2] Today, joining domestic copper water pipes with lead–tin solders is standard in plumbing. Automated low-temperature soldering is an essential part of the electronics industry. High-temperature brazing and welding are common joining methods in industrial metal constructions. Dental soldering is an adaptation from the jewelry trade, with the important difference that, in dentistry, accuracy, strength, and corrosion resistance are very critical, while color is less so. Alloys selected for intraoral use must be nontoxic and resist tarnish and corrosion, and thus, must be predominantly noble. Alternatively, they must be fabricated metals or alloys that undergo passivation.

Soldering continues to have an important role in dentistry, evidenced by the large selection of solders and fluxes still currently available from alloy suppliers (Tables 1–3). If one excludes silver solders used to join wires in orthodontics and spot welding of orthodontic bands, most soldering/welding applications and research apply to restorative dentistry/prosthodontics. All dentists and technicians are somewhat familiar with the skill involved in joining the components of a fixed multiunit prosthesis or fixed partial denture (FPD). Currently, in general dental practice, most would consider it an emergency, rather than an elective procedure; however, for the master technician and specialist restorative dentist, soldering is a fine art and an indispensable tool.

Soldering presents the dentist and technician with the formidable challenge of producing highly accurate and structurally durable joints of small and irregular cross-sections. Success involves artistic skill, practice, and a precise scientific

Table 1 Crown and bridge solder specifications

Presolder	Color	Flow temp °F	Flow temp °C
Balanced line	Gold	1545	840
.650 Fine	Gold	1470	800
.615 Fine	Gold	1470	800
.585 Fine	Gold	1435	780
.490 Fine	Gold	1410	765
Degulor 2	Gold	1382	750
Regular White	White	1364	740
Degunorm 728	Gold	1290	700
.728 Fine	Gold	1290	700
Paliney Medium Fusing	White	1600	870

(Courtesy: Dentsply Ceramco, Dentsply Int. Inc., 570 West College Ave, York PA)

Table 3 Porcelain postsolder specifications

Postsolder	Color	Flow temp °F	Flow temp °C
Paliney #4	White	1815	990
Paliney Med. Fusing	White	1600	870
Balanced Line	Gold	1545	840
.650 Fine	Gold	1470	800
.615 Fine	Gold	1470	800
.585 Fine	Gold	1435	780
.490 Fine	Gold	1410	765
Degulor2	Gold	1380	750
Regular White	White	1364	740
.728 Fine	Gold	1290	700
Degunorm 728	Gold	1290	700

(Courtesy: Dentsply Ceramco, Dentsply Int. Inc., 570 West College Ave, York PA)

basis. The demand for complex dental restorations has caused the profession and alloy manufacturers to invest significant effort into improving alloys and quantifying and qualifying technique variables. Two significant training manuals[3,4] and many dental textbooks have dealt with the topic at various levels. We lack well-defined technique guidelines for various products. The standard references for solder composition and mechanical properties derive from a study by Coleman in 1928[5] (Tables 4 and 5). Prosthodontics textbooks[6–8] review theory and outline basic principles of soldering and working techniques, while dental materials textbooks[9–12] deal with theory and metallurgical principles.

Of necessity, due to the difficulties with standardization, the success of the soldering process continues to rest with the skill and experience of the operator. The ultimate success of any such procedure depends on its practicality of application, that is, it needs to be a simple, repeatable, controlled procedure giving consistently reliable results.

Table 2 Porcelain presolder specifications

Presolder	Color	Flow temp °F	Flow temp °C
SMG-YW	White	2120	1160
SMG-3	Gold	2085	1140
Ceramco White	White	2084	1140
WPG	White	2048	1120
Silver Free Pre	White	2048	1120
SMG-2	Gold	2030	1110
YPG	Gold	1950	1065
Option Pre	White	1940	1060
Bio-Pre	Gold	1905	1040
Degudent G1	Gold	1886	1030
Degunorm 880	Gold	1616	880
Multi-Pre 880	Gold	1615	880

(Courtesy: Dentsply Ceramco, Dentsply Int. Inc., 570 West College Ave, York PA)

The advent of implants in dentistry leads to questions about the precision passive fit of complex castings, which are often screwed/torque-driven into place. Biocompatibility concerns of using dissimilar alloys and implants, together with technological developments, have seen the adaptation of laser welding, and CAD/CAM processing of titanium and ceramic dental prostheses.

Rationale for soldering in prosthodontics

1. *To overcome distortion in multiunit cast fixed prostheses.*[6,8,9] As the length of an FPD increases beyond three units, casting distortion increases significantly. This distortion can be overcome in part by casting the prosthesis in several pieces and then joining these by soldering. Individual units can be custom made in the laboratory, tried in the mouth to verify fit and occlusion, and then joined by soldering. This approach may produce a

Table 4 Typical compositions and fusion temperatures of dental gold solders

Solder	Fineness	Composition (% of Weight) Au	Ag	Cu	Sn	Zn	Fusion temp (°C)
1	0.809	80.9	8.1	6.8	2.0	2.1	868
2	0.800	80.0	3–8	8–12	2–3	2–4	746–871
3	0.729	72.9	12.1	10.0	2.0	2.3	835
4	0.650	65.0	16.3	13.1	1.7	3.9	799
5	0.600	60.0	12–32	12–22	2–3	2–4	724–835
6	0.450	45.0	30–35	15–20	2–3	2–4	691–816

Adapted from Coleman RL: Res Paper No 32, J Res Nat Bur Stand 1928;1:894.
Adapted from Lyman T: Metals handbook, Vol 1, Properties and Selection of Metals (ed 8). Metals Park, OH, Am Soc Metals, 1961
Adapted from Powers JM, Sakaguchi RL: Craig's Restorative Dental Materials (ed 12). St. Louis, Mosby
Elsevier, 2006, pp. 374–380.

Table 5 Typical properties of dental gold solders

Solder	Fineness	Tensile strength Soft/hard MPa	Prop limit Soft/hard MPa	Elongation Soft/hard %	BHN Soft/hard Kg/mm^2
1	0.809	259	142	18	78
2	0.729	248/483	166/424	7/^1	103/180
3	0.650	303/634	207/532	9/^1	111/199
4	0.730	221/483	166/405	3/1	112/154
5	0.650	219/436	176/376	3/1	143/192

Adapted from Coleman RL: Res Paper No 32, J Res Nat Bur Stand 1928;1:894.
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Elsevier, 2006, pp. 374–380.

prosthesis of greater refinement and precision than one cast as one piece.

2. *To join components of dissimilar metals.*[8] Restorations such as inlays and partial-coverage and full-coverage crowns cast in a yellow gold alloy are often joined to metal–ceramic units by soldering. Similarly, precision attachments, bars, or wire clasps of one alloy can be soldered to crowns or removable partial dentures of another alloy.
3. *To overcome firing distortion in metal–ceramic FPDs.* Distortion of metal–ceramic FPD frameworks is likely to occur during porcelain firing procedures.[13-15] This problem can be partially overcome by casting the framework in smaller pieces and soldering them together later, after porcelain application (postsoldering). The distortion that would have been caused by the porcelain firing process is thus eliminated.
4. *To add a proximal contact to a gold crown.*

Objectives of soldering

1. To maintain accurate spatial relation between parts being joined (i.e., dimensional accuracy, or lack of distortion).
2. To produce a strong, nonporous, noncorroding joint between components of a multiunit fixed prosthesis.

Clarification of soldering terms

Soldering

Soldering is the process of joining two or more metallic parts by melting a filler metal (solder alloy) between them. The filler metal should have a substantially lower melting temperature than the parts being joined. Upon melting, the solder alloy flows by capillary action between and around the adjacent heated but unmelted parts to be joined.[9] The solder depends on "wetting" for bond formation, and neither diffusion, nor melting of the parts being joined is required to achieve primary metallic bonding. Some slight surface alloying may occur when there is not a large melting temperature difference between the solder and the parts being joined.[11] New alloys formed by diffusion can have properties different from both parent and solder alloy. It is not known how significant the diffusion phenomenon is, but it does occur quite commonly in high-fusing solder joints, and is an integral part of welding.

Some authors feel the term "brazing" rather than "soldering," is more applicable to the joining of metals in dentistry. The only difference between soldering and brazing is the specified temperature. When the temperature of the joining process is below 450°C (850°F) it is termed soldering, when above 450°C it is termed brazing.[9-11] In dentistry, joining occurs above 450°C and hence the operation should be correctly termed brazing. Since the term soldering is more familiar to the profession, and predominates in the literature, it will be used in this review.

The standard soldering techniques are called freehand and investment soldering.[11,12] Freehand soldering involves coating wire or strip metal with solder and holding it in a flame until the solder flows. The technique is quick but not precise enough for restorative procedures except perhaps for adding a contact point to a deficient crown. In orthodontics, a small, intensely hot flame is applied to the wires, and the operation is completed very quickly to prevent overheating of the wires and thereby recrystallization and grain growth. When accurate relations of component parts of a prosthesis are required, as in joining the components of an FPD, investment soldering must be used. Investment soldering involves the parts to be joined being indexed together with a suitable medium, and then placed in a low expansion soldering investment.[6-8] This assembly allows for uniform heating and maintenance of accurate relations between components during soldering. Steinman[16] was the first to demonstrate the value of investment soldering in reducing distortion. Soldering investments[17] differ from casting investments in that they use fused quartz (the lowest thermally expanding form of silica) as a refractory[7,8] to minimize setting and thermal expansion.

The terms presoldering, preceramic soldering, or high-fusing joints are commonly used. They refer to soldering of metal ceramic components prior to porcelain application. Similarly the terms postsoldering or postceramic soldering or low-fusing joints are variously applied to soldering after porcelain application. Solder joints between traditional gold casting alloys may also be referred to as low-fusing solder joints. Solder joints are often referred to using the generic term "connector."

Brazing

During brazing,[9,10] metal parts are joined together by melting a filler metal between them at a temperature above 450°C. Brazing and welding are terms most often associated with industrial applications.

Welding

Welding is a process in which the metal parts being joined are partially melted and flowed together; a filler metal may be used.[11] Heat and/or pressure is/are used to melt the pieces to be joined.

In spot welding or electric resistance welding, two pieces of metal may be joined by applying an electric current to a small area, with electrodes under pressure. The technique works well with poorly conducting metals or alloys. This technique can be used to join stainless steel orthodontic wires. It is a widely used industrial process. In laser welding, a light beam melts the metal in the joint area leading to joining of the approximating parts.[18]

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, is a long-established industrial welding technique for joining metals such as stainless steel and light metals such as aluminum and magnesium, and titanium. It uses electric power, a tungsten electrode, an inert gas (usually argon), and a filler alloy to produce very durable low corrosion welds. It is occasionally used in dentistry. The reader is referred to Anderson's text[11] for more information on welding.

Parent/substrate metal/alloy

The parent or substrate is the metal or alloy being joined.[9] The composition of an alloy determines mechanical properties, melting range, and oxidation potential. Oxide formation influences "wettability" and thus, ease of soldering. Commonly soldered alloys include ADA-classified yellow gold casting alloys, low gold variants of these, and alloys for porcelain bonding. Many terms are used in the literature to describe dental casting alloys. The ADA classification for dental yellow gold casting alloys is based on composition and mechanical properties. It lists minimum combined Au–Pt–Pd contents, ranging from 83% for Type I, to 75% for Type IV casting golds.[2,10] Low gold content alloys or "economy alloys" are also in common use. A large number of alloys are available for the metal ceramic technique; an original formula[7] was of 98% noble metal (Au, Pt, Pd) by weight, hence the terms "high noble," or "precious" alloys (based on intrinsic value of the alloy). Since then, alloy development has seen the appearance of lower Au content alloys, along with Pd-Ag, and high-Pd alloys. These are still predominantly noble and may be regarded as "semiprecious" or occasionally, "precious." Another alloy group falls under the heading, "base metal," "nonnoble," or "nonprecious," and includes Ni-base and Co-base alloys.

A suitable solder is generally recommended by the parent metal/alloy manufacturer, especially in the case of alloys for the metal ceramic technique;[7,9] however, when different parent alloys are soldered, compatibility problems may occur. Several authors[19–21] have cautioned against soldering combinations of dissimilar alloys based upon microscopic examination and atomic analysis of the interfacial areas of solder joints. Walters[21] suggested solder unions only be made between similar parent alloys (i.e., all precious or all nonprecious). However, others[22,23] in relatively extensive soldering of alloy combinations did not find joint strength of alloy combinations to be a practical problem.

Solder

Solder is the filler metal or alloy, which when melted, flows over and wets the parts to be joined, and then solidifies, forming the solder joint. It may be more correctly referred to as a brazing alloy.[2,9,10] The compositions of solder alloys are as diverse as those of the parent alloys.[7,9] They are often eutectic alloys, thus having a lower melting point than the major component metals.[11] Dental gold solders are commonly called conventional gold solders. Other solders may have "pre" or "post" designations relating to the firing of porcelain. Postceramic solders are usually conventional gold solders or close variants used to join parts after porcelain application. Preceramic or high-fusing solders are often derived from and designed for a specific metal–ceramic alloy.

The Dentists' Desk Reference[2] presents a good table of compositions, properties, and applications of solders used in dentistry. A dental materials textbook[10] gives the composition, fusion values, and mechanical properties for a variety of gold solders. The major alloy manufacturers usually provide lists of their casting alloys, gold solders, and preceramic solders (Tables 1–3).

Solders may be divided into two major groups: soft and hard.[11,12] Pb–Sn alloys in various composition ranges are an example of soft solder, sometimes referred to as "plumber's solder." They have a fusion temperature around 260°C (500°F) and are used for joining lead, copper, or brass. They have good working and mechanical properties, but cannot be used in the mouth due to the lead content and poor corrosion resistance. Solders for dental use are hard solders. Hard solders have a much higher fusion temperature and are harder and stronger than soft solders. They include gold solders, pre- and postceramic solders, and silver solders. Silver solders are more subject to tarnish and corrosion in the mouth and are generally not used for prosthodontic applications. They can be used for joining stainless steel or other base-metal alloys. Anderson[11] gives a good account of the silver solders suitable for stainless steel.

A conventional gold solder for joining wrought or cast gold alloys is composed of Au, Ag, and Cu, with small additions of Zn and Sn.[5,10,24,25] The melting range can be narrowed by lowering the Au content and raising the Cu content; Zn and Sn lower the melting point. Au imparts corrosion resistance, and although the exact minimal Au percentage necessary has not been conclusively established, it is probably of the order of 58% to 61% (0.580/0.615F).[6,7] Gold solders have a Au:Cu ratio to permit "order hardening heat treatment," leading to increased strength and hardness and decreased ductility.[10]

Gold solders have been classified by fineness or karat. Karat designation is a traditional term for solders. It means that the solder was formulated for use with a particular karat casting alloy (e.g., 18K casting gold); it does not refer to the Au content of the solder. Fineness refers to parts per thousand of Au in a solder (e.g., 0.650F), and has been recommended as the more desirable designation.[25] Unfortunately, fineness designation ignores other noble elements such as Pt and Pd. In 1949, Taylor and Teamer[25] stated that "in selecting solder, the physical advantages (strength/flow) accruing through the use of lower karat solders in many cases outweigh the possible greater corrosion resistance of high karat alloys." Two authors[26,27] have recently recommended lower fineness solders due to strength and handling characteristics.

Preceramic solders are of proprietary composition, usually being derived from the parent alloys with which they will be used. Pt-group metals and Au impart corrosion resistance, while trace elements must be incorporated for porcelain bonding. Preceramic solders often have a working temperature very close to the melting temperature of the parent alloy, risking meltdown of the parts being joined. A more subtle phenomenon known as "sag" or "creep" of a soldered FPD can occur if the melting temperature of the presolder is close to the firing temperature of the porcelain.[13-15] Thus, the melting temperature of the solder should be comfortably above the firing temperature of the porcelain.

Desirable solder properties

Certain properties of dental solders are considered important.[8,9] The commonly cited list (for conventional gold solders) seems to originate with Taylor and Teamer.[25]

1. *Easy flowing*
   This term refers to fusion or melting temperature. It should be sufficiently lower than the melting temperature of the parent alloy to allow simplicity of manipulation; the greater the difference, the easier the soldering operation.[8,10] This is often difficult to achieve in preceramic soldering.
2. *Free-flowing (good fluidity)*
   The solder should wet and flow freely over the parent alloy at a temperature of approximately 50°C to 100°C (90°F–180°F)[3,8,10] below the latter's solidus temperature. The solder should penetrate small gaps by capillary action. Generally, a solder with a narrow melting range has superior flow characteristics.[9] Also, lower fineness solders are more fluid than higher fineness alloys. O'Brien et al[28] showed that 0.437 fine solder exhibited greater wetting properties than 0.650 fine solder, and that a Pb–Sn solder exhibited perfect wetting.
3. *Strength similar to that of the parent alloy*[8]
   Solders are modified versions of parent alloys and as such are weaker. Fortunately, joint strength is enhanced by heat hardening, and the phenomenon known as triaxiality.
4. *Freedom from pitting*
   Pitting is largely a consequence of poor heating and fluxing technique due to operator error.[25] However, pits may be more prevalent when the solder contains a considerable amount of low-fusing elements such as Zn and Sn. On overheating, these may vaporize and cause pitting.[8]
5. *Resistance to tarnish and corrosion*
   Solder alloys closely resemble the parent alloy to be joined in composition and color. Not only are they formulated to resist corrosion per se (Au, Pt, Pd content), but they must not be susceptible to electrolytic corrosion by anodic action upon the metal to which they are joined. Localized composition differences can give rise to galvanic currents that encourage corrosion.[12] El-Ebrashi et al[29] noted the risk of increased galvanic action and corrosion as a possible consequence of porosity and diffusion. The corrosion resistance/activity of solder, and solder/alloy combinations have not been studied.
6. *Porcelain compatibility*
   Oxide quality and coefficient of thermal expansion should match that of the parent alloy. The melting temperature of presolders should be well above that of porcelain to minimize the problem of "sag"/ "creep." On the other hand, the melting temperature of postsolders should be comfortably below the porcelain glazing temperature to minimize the risk of porcelain damage.
7. *Other properties*
   Properties such as "building qualities,"[9] which relate to modifying deficient castings, and "color match" would appear to be of secondary importance.

Solidus/liquidus[11]

Pure metals have a specific melting point; alloys have a melting range, due to the combination of metals present. The lower end of the melting range is called the solidus, the temperature at which the alloy is completely solid. The upper limit of the melting range is called the liquidus, the temperature at which the alloy is completely molten. At any given temperature between solidus and liquidus the alloy is partly liquid and solid. Dykema et al[8] state that minimum information in solder selection should include the lower limit of the melting range of the parent alloy (solidus), and the upper (liquidus) and lower (solidus) limits of the solder. Common Pb–Sn solders are eutectic alloys that have a convenient melting point rather than a range; this characteristic facilitates speedy handheld soldering operations.

Hardening heat treatment

Two types of hardening occur in dental casting and soldering alloys. Alloys containing Au and Cu undergo order hardening during cooling. Order hardening involves rearrangement of atomic structure, thereby setting up strain, leading to reduced ductility, but increased hardness and strength. This is more predictably achieved by quenching (plunging into water) to room temperature from above the temperature at which ordering commences. This disordered alloy can then be ordered at a predetermined temperature and time. Precipitation hardening of complex alloys relates to the solubility of metals in each other in liquid/solid states. As an alloy cools, complete separation of metals/alloys from each other will create strain fields that resist movement of dislocations, causing the same effect as order hardening. Steinman[6] showed that quenching a soldering assembly in water immediately after soldering resulted in distortion, and the practice has since been discouraged. Ryge[1] recommended bench cooling for 5 minutes prior to quenching. This allows some order hardening but also allows the solder to maintain some of its ductility. A strong but ductile solder joint is presumably more likely to stand up to fatigue stresses in function. Dental textbooks[6-8] and the soldering literature refer to this latter technique as a standard procedure for conventional gold soldering. Bergman and Bjornham[30] and others[9,31] have warned against heat treatment of soldered FPDs, due to potential composition changes in the solder/parent alloys.

Heat source

The heat required to melt the solder may be applied in a number of ways. These include gas flames, electric resistance furnaces, infrared energy ovens,[10,12,32] and electrosoldering devices.[15,32] Others[33,34] have used hydrogen/oxygen or acetylene/oxygen torches with limited success.

The most commonly used heat sources in dentistry are torches using a mixture of natural gas with air or oxygen, and electric porcelain furnaces. It is standard practice to heat the

Table 6 Thermal properties of flame types

Flame type	Flame temp °C	Heat content Btu/ft
Natural gas + air (Bunsen)	1250	-
Natural gas + air (Blowpipe)	1800	-
Natural gas + Oxygen	2200	1000
Butane + air/Oxygen	-	-
Propane + Oxygen	-	2385
Hydrogen gas + Oxygen	2420	275
Acetylene	3500	1448

Adapted from Anderson JN: Applied Dental Materials (ed 5). London, Blackwell, 1976, pp. 128–141.

components to be joined (parent metal/soldering assembly), rather than the solder. The properly heated parent metal will permit proper flow and wetting by surface tension and capillary action of the molten solder; solder being added when soldering temperature has been reached.[1,9] Overheating or prolonged heating of the parent metal and solder has detrimental effects, such as excessive oxide production, pitting and porosity, and diffusion at the solder/parent alloy interface, leading to deleterious effects on strength and dimensional accuracy.[1,9,10] Operator skill in manipulating a gas flame greatly determines control over the flow of the solder and speed of soldering. Therefore, the use of alternative heat sources (furnace/oven) eliminates a prominent source of technique sensitivity in soldering. The many details and guidelines for heating technique may be found in prosthodontics and dental materials textbooks[6–12] and alloy manufacturers' instructions.

The efficacy of heating depends on several factors, such as the efficiency of the heat source (flame/furnace), the size of the soldering assembly, and the thermal diffusivity of the metal(s) being soldered. Anderson[11] states that a material of high specific heat and high density (e.g., Au and Pt) requires more heat energy to bring about a rise in temperature, and therefore has a low thermal diffusivity. Examples of commonly used flames are listed in Table 6. Heat content and flame temperature values are available for some of these flames.[9,11] The efficiency of a flame is determined by flame temperature and heat content (cal/m^3 or Btu). The maximum melting temperature that can be achieved is just over half the listed flame temperature. Longer heating times are required with lower heat content fuels (e.g., H_2 and O_2, Natural gas and O_2), and therefore incur a higher risk of oxidation of the work being soldered. Anusavice[9] recommends propane as a good choice in terms of flame temperature, heat content, and purity. Acetylene is a powerful heat source, but torch positioning is critical, and risk of contamination with carbon and hydrogen is high. Natural gas is generally non-uniform in composition and is frequently contaminated with water vapor.[9]

Flux

A flux is a powerful reducing agent. Its purpose is to facilitate "wetting" of the parent metal by the molten solder by preventing oxidation and by dissolving and removing surface oxides that form during the soldering operation.[11] Fluxes are powerful reducing agents at elevated temperatures. Flux should be applied to the clean metal prior to heating. Overheating can produce tenacious metallic borates.[11] Fluxes are custom designed for various techniques and parent alloys. Due to the temperature ranges for optimum activity, fluxes designed for presoldering may not work well for postsoldering.[9] Anderson[11] states that a flux suitable for use with hard solders to join precious metals, brass, and copper would be a mixture of dehydrated borax ($Na_2B_4O_7$), boric acid (H_3BO_3), and silica (SiO_2). A flux for hard soldering stainless steel, Ni–Cr, or Co–Cr alloys must contain fluoride, for example mixtures of borax or boric acid with KF or KHF_2. Fluorides dissolve Cr, Ni, and Co oxides.[11] Anusavice and Shafagh[35] reported that alkali bi-fluorides combined with borax or boric acid were more effective at reducing oxides of Cr and Be. Borax fluxes are liquid at 1400°F and dissolve oxides of Fe, Si, Ag, and Ni, but not Al, Cr, and Be.

Low nobility and or nonnoble alloys will tend to oxidize more easily during soldering, thus requiring more powerful fluxes in greater quantity. Contrarily, high noble or precious alloys may require no fluxing at all.[4] Staffanou et al[22] indicated that minimal fluxing was needed to solder precious metals, light fluxing was needed to solder semiprecious metals, and heavy fluxing was needed to solder base metals. Anusavice et al[36] stated that fluxes exhibit decreasing ability to dissolve oxides of Ni, Cr, and Be. Some researchers[33,37,38] have experimented with argon atmospheres in an attempt to minimize oxidation. O'Brien et al[28] briefly examined the role of flux in the wetting process between solder and parent metal, and the relative interfacial energies of the three elements (solder, parent metal, flux). Anusavice[9] emphasizes the relative difficulty of wetting oxidized and nonoxidized metal surfaces. The role of fluxes in soldering requires considerable research and standardization in terms of types of fluxes, their activity, compatibility, and techniques for their use.

Antiflux

An antiflux acts to limit the flow of solder on clean metal surfaces. A layer of graphite (C), whitening (ZnO_2), or rouge (Fe_2O_3) can be applied over the parent metal/alloy, where appropriate, for this purpose.[5,11]

Pioneering research

Prior to 1970, some of the luminaries in the art and science of soldering were Coleman,[5] Taylor and Teamer,[25] Steinman,[16] Ryge,[1] Smyd,[39] Hollenback and Shell,[40,41] and Johnston et al.[42] Coleman[5] classified dental gold casting alloys and solders on the basis of their composition and melting characteristics. Taylor and Teamer[25] studied the desirable properties of dental gold solders (melting temperatures and flow characteristics) in relation to their basic Au–Cu–Ag content, and suggested a fineness range of 0.435 to 0.800. They designed tests (specifications) to determine practical working characteristics of gold solders. Steinman[16] studied the reasons for warpage/distortion in soldering, and although he used wires (Au–Pt–Pd wire), his findings still relate closely to current soldering practices. He showed that factors such as parallel approximating surfaces in close contact, investment soldering, and the use of a minimum of solder all reduced distortion. He also showed that the practice of immediate quenching and heat treatment increased distortion.

Ryge[1] studied the influence of soldering gap distance on distortion in the investment soldering technique for dental bridges. He outlined basic technique principles such as cleanliness, use of fluxes and antifluxes, use of investment, and heat application. His recommendations include: (1) a minimum gap distance of 0.005 inches, (2) preheating in a furnace, (3) applying the solder at the soldering temperature, and (4) bench cooling for 5 minutes followed by quenching to minimize grain growth and joint brittleness. He demonstrated that overheating or prolonged heating caused undesirable diffusion of solder at the solder/parent alloy interface, and "contrary to common belief a strong solder junction can be obtained without noticeable diffusion between the solder and the parent alloy."

Hollenback and colleagues[40,41] studied soldering distortion as a function of investment, and noted the importance of investment expansion. They reported that the shape of the joint had no appreciable effect on soldering distortion. Smyd[39] discussed the various expansion and contraction factors involved in soldering, with emphasis on soldering investment. Johnston et al[42] reported postsoldering as many as ten metal ceramic units at one time in a porcelain furnace "without any clinical evidence of warpage." These authors set the stage for more recent work in the field.

Dimensional accuracy of soldering

Soldering distortion may result in an inaccurate, ill-fitting dental prosthesis. Distortion involves the 3D change in relative position of components being joined. Dimensional change is caused by the interplay of technique and material variables such as indexing material, investment setting and thermal expansion, investment block size/shape, joint gap width and configuration, expansion/contraction of parent alloy, solidification shrinkage of solder alloys, thickness and configuration of retainers, and heat application/removal.[43]

From the clinical viewpoint, using the example of a three-unit FPD, dimensional accuracy relates indirectly to the ability of the retainers to fit the tooth preparations as they did when tried individually on the abutment teeth, prior to indexing and soldering. A reference number of 50 μm for marginal fit of individual dental castings is a generally accepted standard, with a goal of 25 μm or less; the latter being the cement thickness of an ADA Type I luting agent.[44-46] There is always some degree of distortion and thus misfit after soldering. The degree of misfit of retainers may be partially overcome clinically by the natural mobility of abutments.[47] With the advent of successful dental implants, which are relatively immobile, casting/soldering accuracy becomes more critical.

Several investigators[48-54] have recommended one-piece casting or soldering of FPDs of varying lengths on the basis of misfit due to distortion. However, distortion also occurs when an FPD is cast in one piece. Huling and Clark[48] found that laser-welded and cast 3-unit FPDs fit more accurately than soldered specimens (202.7 μm). Fusayama et al,[49] comparing the fit of 4-unit FPDs concluded that cast FPDs were more accurate (200 μm) than soldered FPDs. The relative inaccuracy of soldering was attributed to linear shortening caused by solder shrinkage not compensated for by investment expansion. Bruce[50] claimed that cast FPDs up to 15.5 mm in length could be cast with reasonable accuracy. His observations were based on fit and linear change in specimens. Ziebert et al,[51] comparing cast and soldered 3-, 4-, and 5-unit FPDs, noted that the fit of all the 3-unit FPDs was similar (presoldered 32 μm, postsoldered 33 μm, cast 42 μm), the marginal misfit increased as span lengths increased, and simulated porcelain firing cycles produced no significant distortion. Others[14,15] did not agree. They suggested that FPDs exceeding 4 units be soldered. Another similar study[52] showed satisfactory fit of cast 3-unit FPDs (34 μm) but significantly better fit with soldered specimens (19.1 μm); others[54] found converse results.

Evaluation of soldering accuracy

When studying the accuracy of the soldering process, the many soldering variables involved are difficult to control, and skilled technicians should be used to minimize errors. Soldering distortion has been studied using two methods of measurement.

A clinical model[51,52] compares the misfit of retainers and linear changes in cast and soldered FPDs on standardized dies. This approach gives valuable information to the clinician in tangible clinical terms (i.e., comparative marginal adaptation of castings). Given the number of casting and soldering variables involved and the difficulties in measuring marginal gaps, it is only possible to draw narrow conclusions based on the actual conditions of each experiment. Some researchers[40,41] have evaluated soldering distortion indirectly without measuring marginal misfit. They measured linear changes between sprue extensions on FPD castings or between die bases.

A laboratory model measures relative distortion without reference to clinical casting adaptation. This method allows precise 3D measurement comparisons, and may be a valuable way of screening technique variables and materials, but gives relative values that are difficult to extrapolate to a clinical situation. The reader is referred to Nicholls'[55,56] excellent treatise in two parts on distortion measurement for a better understanding of the subject.

The influence of the following major factors contributing to soldering distortion has been studied:

1. Indexing/connecting
2. Investment
3. Joint configuration
4. Gap width
5. Assembly heating/cooling.

Indexing/connecting

Several authors[41-43,49] have recommended plaster or stone indices for investment soldering. Others[1,16] have used sticky wax, and Patterson[57] described the method for using autopolymerizing acrylic resin. One manual[4] recommends either of two autopolymerizing acrylic resins, Duralay resin (Reliance Mfg, Worth, IL) or Caulk's "Orthodontic" resin (Caulk/Dentsply, Milford, DE).

Harper and Nicholls[58] compared the 3D distortion caused by various indexing media. They concluded that ZOE bite registration paste was the most accurate indexing method, plaster and Duralay resin were less accurate, and sticky wax least accurate. Moon et al[59] found the least distortion with a plaster nonremoval technique, followed by Duralay resin. They also determined that assembled units should be invested as quickly as possible, and that thick resin indices (6 mm) were less accurate than thin (3 mm) ones. Others[60-63] have quantified the shrinkage of indexing resins, and have shown that the accuracy of resin indices decreases dramatically with time.

Investment

The composition of a soldering investment is much like that of conventional investments for gold casting, with quartz preferred to cristobalite as a refractory to minimize thermal change.[7,8,39] As the contraction of gold during casting is compensated for by investment expansion, so the shrinkage of solder must be compensated for by the setting and thermal expansion of the investment.

Steinman[16] produced objective evidence for the use of investment to minimize soldering distortion. Meyer[53] also stated that the use of investment would eliminate distortion in bridgework. Ryge[1] and Anderson et al[64] studied linear change of 3-unit FPDs caused by indexing, investing, investment expansion, and soldering. Indexing (sticky wax) and investing led to no linear change or distortion. Preheating to 1100°F led to gap closure of up to 0.004 inches between the metal parts but increased the length of the FPD assembly, indicating thermal expansion of both metal parts and the investment. Ryge[1] recommended a minimum solder gap of 0.005 inches (0.123 mm), since a smaller gap would lead to metal contact due to thermal expansion, and hence, significant soldering distortion. Hollenback and coworkers[40,41] concluded that most of the distortion in FPDs was a result of investment expansion changes, and emphasized the selection of investments with appropriate expansion. Ryge,[1] Fusayama et al,[49] and Ziebert et al[51] all found that soldered FPDs decreased in length, whereas Stackhouse[43] found the opposite. Willis and Nicholls[65] found that indexing and investing led to a net increase in gap distance due the setting expansion of both media. They found significant linear change (net decrease in length), but insignificant rotational change due to the actual soldering procedure.

Pazzini et al[66] studied the effect of different investment formulations on dimensional changes in 3-unit FPDs. They concluded that investment thermal expansion on the order of 0.7% was optimum for minimizing FPD distortion. Gegauff and Rosenstiel[67] found that a higher thermal expansion investment (1%) produced a clinically acceptable fit, whereas a lower expansion investment (0.6%) produced a clinically acceptable fit. On the basis of existing knowledge, the composition and characterization of soldering investments, and their influence on soldering accuracy, require closer study.

Joint configuration

Steinman[16] noted the adverse effect of wedge-shaped joints and solder shrinkage on wire joints. Shillingburg et al[6] continued to recommend the use of flat opposing joint surfaces, rather than wedge-shaped approximating axial surfaces, to minimize distortion. Other authors dismissed joint shape as a significant factor in distortion.[1,40,41]

Willis and Nicholls,[65] studying distortion in a two crown system with a symmetrical curved joint configuration, found minimal rotational distortion between soldered crowns. However, their test model does not relate well to the clinical situation, and joint shape was not a variable. Byrne et al[52] used standardized parallel joint configuration in their study and showed no significant difference in fit between single crowns and soldered 3-unit FPDs; they did not include other joint shapes in the study. Other authors[48-51] using curved joint configuration have noted FPD retainer misfit without being able to attribute the distortion to joint shape, or other specific variables.

Gap width

Gap width is considered an important soldering parameter from both accuracy and strength perspectives. Many gap widths have been used in research, including 0.005 inches,[1] 0.3 mm,[22] 0.5 mm,[23] 0.15 mm,[26] 0.4 mm,[35] 0.15 mm,[52] and 0.012 inches[68] (calling card). Dental textbook[8,9,11] suggestions also vary: 0.2 mm (business card), 0.13 mm,[10] 0.15 to 0.2 mm, 0.25 mm. Once a gap has been created, several factors influence its size during the soldering operation. These include the setting and thermal expansion of the soldering investment, and the thermal expansion of the metal components.[4,43] Ryge,[1] studying various gap widths (0.005 inches, 0.025 inches, 0.039 inches), recommended a minimum gap width of 0.005 inches (0.123 mm). He showed that if the gap were too small, the metal units would expand and contract during heating, leading to porosity and distortion. Other authors[43,65] have also shown increased distortion when there was no soldering gap. Willis and Nicholls[65] studied the influence of gap distance (0.0 mm, 0.15 mm, 0.3 mm, 0.45 mm) on distortion. They concluded that a minimum gap distance between metal parts, without contact, was desirable.

Heating/cooling

Steinman[16] cautioned against quenching or heat treatment lest they contribute to distortion. Ryge[1] later recommended a compromise of bench cooling followed by quenching as a means of optimizing joint strength without causing distortion.

Ryge[1] was also an early proponent of preheating (1100°F), followed by a "brush" blowpipe flame angled obliquely to the assembly, which was positioned over a Bunsen burner. It was emphasized that efficient heating and rapid soldering minimized porosity and distortion, whereas repeated heating led to greater distortion. Similarly, preheating regimes have been recommended by others to promote even heating of the invested assembly, allowing more rapid and efficient flame soldering, presumably to minimize porosity and distortion; Johnston et al[42] recommended 900 to 1000°F, Jelenko[4] recommended 1200°F, and Meyer[53] recommended preheating to1500°F and then using a vertical flame angle. The Jelenko manual[4] claimed that preheating in a furnace at 750°F to 900°F effectively eliminated distortion of the investment block caused by preheating with a Bunsen burner. Stackhouse[43] found that the symmetry of the investment block, with the work in the center, was an important factor in preventing distortion. It was also suggested that a flame application angle of 45° caused less distortion than other positions. Variation was attributed to uneven heating of the soldering block and metal. An investment block thickness of 0.5 inch was recommended by Johnston et al.[42]

It is important to note that the flame application variable is eliminated when electric or infrared heating ovens are used for soldering. Oven postsoldering has become popular for postsoldering operations[42] to reduce the risk of porcelain contamination.

In 1967 Honigsberg et al[69] first introduced an infrared heat source as an alternative to torch soldering, and stated that its use resulted in four changes in positional relationships, reduced working time, and produced a satisfactory union of the parts. Others[38,52,70,71] have used the technique successfully. Carlberg and Wictorin[38] reported on an infrared heat source in a closed vacuum or reducing atmosphere (argon). Byrne et al[52] found the fit of infrared soldered FPDs to be comparable to the fit of individual abutment crowns.

Discussion

It would seem that while some scientific progress has been made, the practical difficulties of soldering have not been solved, and soldering remains more or less an art form. This may somewhat explain its gradual decline and replacement by alternatives. In his textbook Anusavice[9] states, "Skill is an important element of successful brazing. It is a composite of ability, technique, and practice . . . Skill cannot be maintained, particularly with torch brazing, without practice."

For soldering to be a useful everyday procedure, it must be predictable for the average operator and produce consistent results. Researchers must build on existing knowledge and desist from haphazard, isolated experimentation. In particular, fluxes, investments, and solder-parent alloy compatibility must be studied and guidelines clarified. The potential researcher would be well advised to refer to the work of Bergman,[19] Hollenback and colleagues,[40,41] Nicholls and co-workers,[55,56,58,65] and Anusavice and colleagues.[35,36]

Oven soldering has helped to standardize technique as compared with flame soldering, but it is not applicable in all cases, and the standard problem of distortion still remains. Precise marginal fit of FPD castings on natural tooth abutments has always been a central theme of restorative dentistry with the objectives of precise internal fit, and minimal marginal gap for cement loss and potential caries. Precise casting and soldering can solve part of the distortion equation[72] between impression making and seating of restorations in the mouth.

The advent of predictably successful dental implants has focused attention on the accuracy of metal superstructures and the difficulty of producing precise "passive fit" of fixed multiunit dental prostheses by cast or cast/soldered methods. This is desirable in order to minimize stress indirectly on the bone surrounding the implant fixtures, and on retaining screws. Implant fixtures allow no "abutment" movement to accommodate a slightly distorted prosthesis. Torque-driven screw fixation has been an accepted method for fixed implant restoration retention. The inherent inaccuracy of traditional dental castings often requires sectioning and soldering of a multiunit prosthesis to eliminate gross inaccuracies. However, this may not be an acceptably accurate solution when dealing with implants. Laser welding may provide the answer to most of the basic problems of soldering provided it becomes economical enough to be widely available. This method of joining seems particularly appropriate for low specific gravity/low conducting metals like titanium. Another alternative is computerized milling (CAD/CAM) of metal or ceramic superstructures. This latter technology has the potential to eliminate all the step inaccuracies found in traditional FDPs.

Conclusions

Soldering is a useful and technique-sensitive procedure. It may improve the dimensional accuracy of multiunit fixed prostheses. Many variables in soldering technique affect the outcome. Research science has developed some helpful guidelines. Research projects are disconnected and limited in scope. New technologies such as CAD/CAM and laser welding may replace soldering in dentistry, although such technologies are likely to remain beyond the resources of many populations for some time.

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