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Effect of electric arc, gas oxygen torch and induction melting techniques on the marginal accuracy of cast base-metal and noble metal-ceramic crowns

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ABSTRACT

Objectives: The aim of this study was to identify the most appropriate alloy composition and melting technique by evaluating the marginal accuracy of cast metal-ceramic crowns.

Methods: Seventy standardised stainless-steel abutments were prepared to receive metal-ceramic crowns and were randomly divided into four alloy groups: Group 1: palladium-gold (Pd-Au), Group 2: nickel-chromium-titanium (Ni-Cr-Ti), Group 3: nickel-chromium (Ni-Cr) and Group 4: titanium (Ti). Groups 1, 2 and 3 were in turn subdivided to be melted and cast using: (a) gas oxygen torch and centrifugal casting machine (TC) or (b) induction and centrifugal casting machine (IC). Group 4 was melted and cast using electric arc and vacuum/pressure machine (EV). All of the metal-ceramic crowns were luted with glass-ionomer cement. The marginal fit was measured under an optical microscope before and after cementation using image analysis software. All data was subjected to two-way analysis of variance (ANOVA). Duncan's multiple range test was run for *post-hoc* comparisons. The Student's *t*-test was used to investigate the influence of cementation ($\alpha = 0.05$).

Results: Uncemented Pd-Au/TC samples achieved the best marginal adaptation, while the worst fit corresponded to the luted Ti/EV crowns. Pd-Au/TC, Ni-Cr and Ti restorations demonstrated significantly increased misfit after cementation.

Conclusions: The Ni-Cr-Ti alloy was the most predictable in terms of differences in misfit when either torch or induction was applied before or after cementation. Cemented titanium crowns exceeded the clinically acceptable limit of 120 μm.

Clinical significance: The combination of alloy composition, melting technique, casting method and luting process influences the vertical seal of cast metal-ceramic crowns. An accurate use of the gas oxygen torch may overcome the results attained with the induction system concerning the marginal adaptation of fixed dental prostheses.

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1. Introduction

Even though all areas of dental practice are evolving at a considerable pace,[1] metal-ceramic restorations continue to be the most widely used because of their proper biomechanical behaviour, reasonable aesthetic appearance, lower cost and high predictability compared with all-ceramic restorations.[2,3] However, concerns still remain regarding the identification of key factors for the long-term success of these prostheses, such as the best alloy composition and melting and casting method to be applied for obtaining the prosthetic cores.[4,5]

Noble alloys have noteworthy advantages over base-metal alloys in terms of biocompatibility, marginal adaptation, workability after casting and metal-ceramic bonds.[4,6] However, base-metal alloys (*e.g.*, Co-Cr or Ni-Cr based alloys) are often preferred, due to their mechanical properties (increased hardness and Young's modulus) and cost.[7] Regrettably, the casting of base-metal alloys is more technique-sensitive than that of the noble alloys because of their superior melting point and potential for oxidation, which may lead to inaccurate frameworks.[7–9]

Unalloyed titanium has excellent biocompatibility, corrosion resistance and strength-to-density ratio, which allow the construction of lightweight dental structures.[10] Nonetheless, casting the titanium requires a complex process including specific investment materials, a pre-heated oven, a high melting point and inert atmosphere for melting the titanium with an electric arc in copper casting crucibles. This may result in misfitted copings.[4] In this regard, Ni-Cr-Ti alloys have been marketed as an alternative providing adequate biocompatibility, physical and mechanical properties and marginal precision.[11–13]

Besides the alloy composition, the melting technique and the impulsion of the molten alloy onto the casting cylinder are essential steps in the fabrication of dental prosthetic frameworks by the lost wax casting technique.

Currently, heat sources such as the torch, induction or electric arc are the most commonly used for melting the alloy, while both the centrifugal and vacuum/pressure systems are the main options for pouring the material onto the casting cylinder.[9] Despite its widespread use, the main drawbacks of the gas oxygen torch are the impossibility of controlling the temperature accurately and the probability of altering the alloy composition by overheating. On the contrary, the induction system facilitates a perfect control of the melting temperature, producing a homogeneous mass of all alloy components by molecular agitation, so that the quick rise in temperature decreases the risk of oxidation and contamination of the molten alloy.[14] When using voltaic arc, the alloy is melted rapidly with temperatures that exceed 4000 °C. This process has a high risk of overheating the alloy; even the castings can be damaged if the overheating continues for a few seconds.[9]

Given the difficulty in achieving a perfect fit with current technologies, the aim of this study is to identify the most appropriate alloy composition and melting technique by evaluating the marginal accuracy of cast metal-ceramic crowns. Several casting methods have previously been compared in terms of accuracy of prosthetic structures.[4,11,15] However, the uniqueness of this study consists in combining different melting systems with vacuum-casting the alloys to assess their effect on the vertical seal of metal-ceramic crowns.

Therefore, the null hypotheses tested were the following: (1) neither the alloy composition nor the melting technique and casting method influences the marginal fit of metal-ceramic crowns, and (2) the cementation process does not affect the vertical discrepancy of differently fabricated metal-ceramic restorations.

2. Materials and methods

2.1. *Fabrication of the crowns*

Seventy standardised stainless steel master dies (height = 6 mm, occlusal diameter = 5 mm, convergence angle = 6° and finish line = chamfer of 1 mm in depth) (Fig. 1) were prepared to receive four series of metal-ceramic crowns that were melted and cast using three different alloys and four manufacturing techniques. All of the materials were handled according to the manufacturers' instructions.

The master dies (Fig. 1) were randomly assigned to four groups depending on the alloy composition to be utilised for constructing the crowns' copings. Group 1 (Pd-Au) used palladium-gold (Cerapall 6, batch no. 0401085, Metalordental, Neuchâtel, Switzerland); Group 2 (Ni-Cr-Ti) used nickel-chromium-titanium (Tilite Premium, batch no. 081208, Talladium Inc., LLeida, España); Group 3 (Ni-Cr) used nickel-chromium (Wiron 99, batch no. 2878, Bego, Bremen Germany) and Group 4 (Ti) used titanium (Biotán, batch no. 045112, Schütz-Dental Rosbach, Germany). Twenty specimens were included per alloy group except for Group 4, which contained 10 samples.

The dies were varnished with three layers of die spacer. Restorations of Groups 1–3 were manufactured using the traditional lost-wax casting technique according to the manufacturers' instructions.

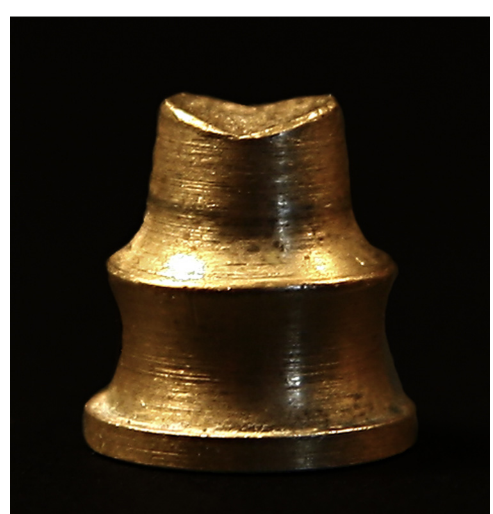

Fig. 1 – Machined abutment utilised in the study.

Before casting the structures of Group 1 (Pd-Au), Group 2 (Ni-Cr-Ti) and Group 3 (Ni-Cr), wax patterns were prepared (Classic modelling wax-blue, Renfert GmbH, Hilzingen, Germany) and invested with a commercial phosphate-bonded investment plaster (Bellavest, Bego, Bremen, Germany) by using cylinders without a metal ring. For Group 1 (Pd-Au), the phosphate-based investing liquid was mixed with deionised water to allow for better control of the noble metal expansion. Patterns of Group 4 (Ti) were invested using a specific spinella investment material (Biotan, Schütz-Dental, Rosbach, Germany).

Half of the specimens of Groups 1–3 was melted and cast using a gas oxygen torch and a centrifugal vacuum-casting machine (TC: G3, Mestra, Bilbao, Spain). The remaining half of samples was melted and cast using induction and a centrifugal vacuum-casting machine (IC: MIE-200C/R, Ordenta, Arganda del Rey, Madrid, Spain) under vacuum pressure (580 mm Hg). The melting temperatures were 1250 °C, 1329 °C and 1450 °C, respectively, for Groups 1, 2 and 3.

For casting the structures of Group 4 (Ti), a pressure differential casting machine (Rematitan, Dentaurum, Ispringen, Germany) was utilised, consisting of a two-chamber pressure/vacuum system that smelts the titanium at the temperature of 1668 °C with a voltaic arc under an inert argon atmosphere.

After casting, all of the metal frameworks were retrieved and carefully cleaned using airborne-particle abrasion with aluminium-oxide powders (50 μm) for 10 s at a working distance of 5 mm and a pressure of 50 ± 3.5 N/cm^2 to remove the investment residues.[13]

Oxidation of the crown frameworks was completed in a vacuum ceramic oven (Programat P500/G2, Ivoclar-Vivadent AG, Schaän, Liechtenstein) following the manufacturers' instructions. Two layers of opaque porcelain that underwent two separate firing cycles of 30 min/cycle were built up. The first opaque layer was heated at 950 °C[16,17] for samples of Groups 1–3 and at 790 °C for samples of Group 4.

Subsequently, the structures were coated with compatible feldespathic ceramics trough the stratification technique, using dentine and enamel ceramics in the abovementioned oven at 770 °C for every cycle. VM 13 ceramic (Vita Zahnfabrik, Bad Säckingen, Germany) was used for veneering the copings of Groups 1–3, while TitanKeramic (Vita Zahnfabrik, Bad Säckingen, Germany) was selected for veneering the frameworks of Group 4. Finally, the glaze firing was made at 880 °C for VM 13 ceramic and at 770 °C for TitanKeramic.

2.2. *Luting procedure*

Crowns were randomly luted to the metallic abutments with glass-ionomer cement (Ketac Cem, 3M Espe, Seefeld, Germany) in standard fashion. A special clamp was designed to maintain the constant seating load of 10 N for 10 min.[15] Two master dies fitted onto their respective supports were incorporated onto the clamp basis in each cycle of cementation.[5,13]

The axial surfaces of the abutments placed in the clamp were varnished with a thin layer of cement before inserting each pair of crowns. The clamp press was unscrewed until its base made contact with the specimens' occlusal surfaces.[4] The upper screw that controlled the press was fitted with a dynamometric key[12,13] (USAG 820/70, SWK Utensilerie SRL, Milan, Italy).

2.3. *Vertical misfit evaluation*

As in related experiments,[11,15,18–20] the vertical misfit (or the distance parallel to the abutment axis between the lower edge of each crown and the upper margin of the preparation cavo-surface angle of each master die) was assessed using an image analysis software (Optimas 6.1, Media Cybernetics, Inc., Rockville, USA) in combination with an optical microscope (Olympus SZ 4045TR-CTV, Tokyo Japan) connected to a digital camera (Hitachi CCTV-HV 720E, Tokyo, Japan) at 40× magnifications.[11,15]

Due to the rounded shape of the crowns, samples were fitted into customised aluminium platforms and inclined at an angle of 25° from the horizontal so that the vertical gap at the crown/abutment interface was always situated perpendicularly to the optic axis of the microscope. To standardise the misfit analysis, specific landmarks were traced with an indelible pen in the middle of the axial surfaces of each master die. This procedure allowed the best projection angle and ensured repeatable positions.[19,20]

The gap width was quantified at the marked points by focusing on the middle of the next axial planes to take the images: 0° = buccal surface; 90° = mesial surface; 180° = lingual surface and 270° = distal surface.[18–21] The image-analysis software (Optimas 6.1, Media Cybernetics) traced 30 equidistant vertical lines on each micrograph, dividing it into 31 identical parts. According to criteria described in previous experiments,[4,19,21] the vertical misfit was then calculated at 30 locations established by the software on each image to reduce operator bias. When a cavo-surface margin appeared rounded, a point was chosen by the microscope software on that margin along the line bisecting the angle between the outer and inner contours of the structure.[22]

Following the described protocol, measurements were taken before and after cementing the crowns,[15,18] which yielded a total of 120 discrepancy values per marginal contour in each case. The misfit analysis was blindly performed by a specialised operator[21] at the National Centre for Metallurgical Research (CENIM, Madrid, Spain). A total of 8400 vertical misfit measurements were obtained.

2.4. *Statistical analysis*

An average misfit value was assigned to each sample before calculating the mean and standard deviations (SD) for the vertical misfit parameter. Normal data distribution was confirmed by the Kolmogorov–Smirnov test, and homogeneity of variances was verified according to Levene's test.[4,19–22]

Two-way analysis of variance (ANOVA) was used to assess the contributions of each alloy type and melting and casting method to vertical discrepancy. The Duncan's multiple range test was run for *post-hoc* comparisons.[11,15,18,23] The Student's *t*-test for independent samples allowed for investigating the effect of the luting process on the marginal fit independently from the metallic composition and fabrication procedure of the crown copings.[11,24]

Table 1 – Mean (SD) misfit values (μm) recorded in the experimental groups.

Alloy	Melting and casting method	Before luting	After luting
Pd-Au	Torch + centrifugal (TC)	17.63 (9.70) ^{1a}	32.76 (14.86) ^{1b}
	Induction + centrifugal (IC)	36.04 (14.94) ^{2b}	43.82 (9.90) ^{2b}
Ni-Cr-Ti	Torch + centrifugal (TC)	42.45 (13.76) ^{23b}	48.87 (13.56) ^{2bc}
	Induction + centrifugal (IC)	48.01 (9.06) ^{23bc}	54.72 (12.27) ^{2c}
Ni-Cr	Torch + centrifugal (TC)	60.39 (19.73) ^{4c}	74.98 (21.36) ^{3d}
	Induction + centrifugal (IC)	72.90 (31.70) ^{5d}	85.38 (30.39) ^{3e}
Ti	Electric arc + vacuum-pressure (EV)	55.09 (16.08) ^{34c}	127.7 (31.64) ^{4f}

Different superscript letters in rows and numbers in columns indicate significant differences ($p < 0.05$).

The statistical significance level was set in advance at $\alpha = 0.05$.[5,13,22,23] All of the statistical analyses were made using statistical package software (SAS 9.1, SAS Institute Inc., Cary, NC).

3. Results

The means and standard deviations (SD) for vertical discrepancy values are displayed in Table 1. The vertical seal was affected by the alloy composition ($p < 0.0001$), the melting technique and casting method ($p = 0.0246$), and the cementation process ($p < 0.0001$). Interactions between the three factors were significant ($p < 0.0001$) although no interaction was found between the alloy type and the melting and casting procedure ($p = 0.88$).

Before luting, the best overall adaptation corresponded to Pd-Au crowns fabricated using the TC method ($p < 0.0001$). Ni-Cr-Ti samples showed significant intermediate misfit values between Pd-Au/TC and Ni-Cr specimens ($p < 0.0001$). Pd-Au/IC and Ni-Cr-Ti samples performed equally in terms of misfit. Ti/EV crowns showed comparable marginal fit to Ni-Cr-Ti and Ni-Cr/TC restorations before luting (Table 1).

After cementation, Pd-Au crowns manufactured with the TC system resulted in the best fitted samples ($p < 0.0001$), followed by Pd-Au/IC and Ni-Cr-Ti restorations, which yielded no significant differences to each other. In turn, Pd-Au/IC and Ni-Cr-Ti luted crowns showed better marginal adaptation than did Ni-Cr crowns, regardless of the melting technique and casting method. Ti luted samples fabricated with EV showed the greatest significant discrepancies ($p < 0.0001$) (Table 1).

Misfit values significantly increased after cementation within each melting and casting subgroup ($p < 0.01$), except for Pd-Au/IC and Ni-Cr-Ti crowns, which did not show significant changes. No significant differences were found between the TC and IC melting systems within the Ni-Cr-Ti group, while Pd-Au and Ni-Cr samples exhibited better fit when the TC method was selected ($p < 0.0001$). Regardless of the alloy composition, EV demonstrated worse fit than did TC and IC in the post-cementation analysis ($p < 0.0001$) (Table 1).

4. Discussion

This research attempts to compare the accuracy of four alloys and three melting and casting methods for constructing porcelain-fused-to-metal crowns, and also to investigate possible differences in misfit after cementation. Microstructural variations of natural teeth preparations and other subsequent variables related to impression, pouring techniques and prescriptions[19,20,25,26] were avoided by using standardised metallic models[15,18,27] (Fig. 1).

The study's results require rejection of the first null hypothesis, as differences in vertical fit were found depending on the alloy composition and melting technique (Table 1).

Consistent with the literature,[4,6,9] the noble alloy submitted to the TC system provided the lowest discrepancies in the study (Table 1).

Moreover, Ni-Cr-Ti restorations exhibited similar misfit values than those of the Pd-Au samples melted with induction (Table 1), which confirms the predictability of the Ni-Cr-Ti alloy for making the copings. The values obtained for Ni-Cr-Ti and Ni-Cr crowns are in agreement with those published for Ni-Cr-based alloys, ranging between 25 μm and 95 μm[28–32] (Table 1).

Titanium pieces attained the worst fit after luting (Table 1). This might be somehow explained by titanium's inherently difficulty to cast because of its high melting temperature; strong affinity with oxygen, hydrogen and nitrogen; and high reactivity with most investment, crucible and ceramic coating materials.[5,33] The discrepancies published for cemented titanium-based prostheses range from 22 μm to 124 μm,[10,15,34–36] which concurs with the mean of 127 μm attained in this experiment (Table 1).

A small number of articles are available on the effect of the manufacturing technique on the quality of castings for FDPs.[11,37–39] In this investigation, the torch provided better fit than did the induction for fabricating noble crowns, while the misfit of Ni-Cr-Ti samples was not affected by the melting technique (Table 1). Nevertheless, it should be taken into account that the success of the torch mainly depends on the operator experience while the induction technique allows objective control of the temperature. Finally, EV showed the worst fit in the post-cementation analysis (Table 1). According to related research,[15] this may be attributed to inherent pressure differences between fusion and mold chambers, investment permeability, gas diffusion into the mold chamber, or differences between casting and mold temperatures that could accelerate the metal solidification.[38]

To systematise the crowns' fabrication, the same skilled technician waxed, invested, melted, cast and veneered all of the restorations in a standard manner. Although the study entailed manual work, the random distribution of the abutments, the operators' abilities and the number of measurements taken, may help substantiate the findings.[22]

Holmes et al.[40] defined the "vertical marginal discrepancy" as the vertical distance parallel to the path of insertion of the structure between the prosthesis and the respective abutment. In this research, a trained blind operator consistently examined the discrepancy in equidistant points on each micrograph to avoid bias.[4,22] As a sole examiner performed all of the measurements, systematic error was moderately controlled.

Furthermore, the second null hypothesis was rejected, since a significant increase in misfit was noticed after cementation except for Pd-Au/IC and Ni-Cr-Ti restorations (which showed the same trend despite the lack of statistical significance) (Table 1). According to previous investigations,[15,18–20] all tested crowns were luted using the same material. Glass-ionomer cement was chosen because of its low viscosity, high plastic deformation in compression and widespread use.[41] Even though samples were cemented under constant seating load, slight changes in the cement layer's thickness may have altered the misfit values. However, the manual mixing simulate clinical conditions.[4,21]

Consistent with the literature,[18,42,43] the cementation process determined a misfit increase of $26.04 \pm 14.34\ \mu m$ regardless of the alloy composition and fabrication method tested (Table 1). Although the American Dental Association states that a dental restoration should fit its abutment within a 50 μm range,[44] most authors empirically accept 120 μm as the maximum tolerable misfit.[15,18–20] Excluding the cemented Ti crowns, exhibiting the greatest discrepancies, the remaining groups did not exceed such limit (Table 1). The relevance of *in vitro* investigations consists of achieving excellence by predicting undesirable results.[45] However, the findings should be reasonably extrapolated to the clinical environment, as dental restorations are subjected to far more complex thermal–biomechanical interactions than those incorporated in *in vitro* tests.[13,46]

5. Conclusions

Within the limitations of this study, the following conclusions may be drawn:

1. The Ni-Cr-Ti alloy was the most predictable in terms of differences in misfit when either torch or induction was applied before or after cementation.
2. Cemented titanium-based metal-ceramic crowns exceeded the clinically acceptable limit of 120 μm.
3. An accurate use of the gas oxygen torch may overcome the results obtained with the induction system concerning the fit of metal-ceramic crowns.
4. The cementation process generally increases the marginal discrepancy.

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