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ORIGINAL PAPER

Coupling of multilayer CAD-CAM prosthetic components: Computing the user interaction influence on the adhesion interface geometry

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Abstract

The fracture resistance of multilayer zirconia crowns has recently been proven to be improved by using lithium millable disilicate glass–ceramic blocks (D'Addazio in Materials, 2020). Accordingly, the framework and the ceramic coating are designed and milled using a CAD-CAM technology and the two separated prosthetic components are then manually assembled by the dental technician and glued with the fusion of a glass–ceramic material. It is essential, during the CAD phase, to design a gap between the framework and the decorative veneer that will later be filled by the fused ceramic.Since the act of gluing the two parts is manually performed by the dental technician, we aim at investigating the operator influence on the final gap with respect to the designed gap. For this purpose, an original geometrical investigation method was developed to enable the 3D digital analysis of the whole fusion interface. During the CAD design stage, two technicians input a different setting for the gap between the two components. The framework and veneering structure were designed, the milled components were produced, and the zirconia framework was sintered, then the two CAD-on prosthetic components were scanned before and after their fusion/crystallization to analyze the physical internal gap. The results show that manual assembly cancels out any effect of the precision settings adopted during CAD-CAM design of the components, as well as any benefit expected from machining on a CNC milling machine, thus requiring, as a last step, manually retouching the prosthesis to correctly fit in the mouth.

Keywords CAD modeling · Interactive design · Bioengineering · Reverse engineering · Dentistry

1 Introduction and background

Duret, in 1971, introduced the concept of computer-aided design and computer-aided manufacturing (CAD-CAM) to the world of dentistry. Since then, CAD-CAM applications have increased significantly [2, 3] providing the dental industry with the opportunity to use wider range of metallic, ceramic, and plastic materials designed specifically for use with this technology. As expected, [4] the digital workflow involved in various stages of the dental technician's work has continued to grow over the past decade [5]. Whereas at the beginning of the digitalization, scanning of plaster-cast models or conventional elastomeric impressions was done in the laboratory, today it is quite common to use hand-held dental scanners [6]; on the 3D model of the dental anatomy, the dental technician designs the prosthesis by means of appropriate CAD modelling software. Such design file, is then processed and produced by sophisticated CNC machines using subtractive or additive techniques [7–9].

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Given the growing attention to dental aesthetics, metal-free materials are increasingly being adopted in the dental field [10–19]. Ceramics suitable for milling can be used to create monolithic prostheses [20] (i.e. the entire dental anatomy is made up of a single piece of ceramic material), or they can be used in the traditional approach, in which a milled framework is prepared and then coated with another material that has better aesthetic properties using various techniques (usually glass–ceramics)[21].

Monolithic ceramic prosthesis can only be colored on the surface, for this reason, the final result is never aesthetically equivalent to the more natural appearance achieved with multilayered glass–ceramic materials. It is worth noting that the translucency characteristics of lithium disilicate allow for monolithic prostheses with a fairly natural appearance, but its mechanical properties are only sufficient for bridges of 3–4 elements and only up to the premolar level [22]. Chipping or flaking of ceramic coatings on zirconia-ceramic prostheses have been identified as a complication that can occur over time with this type of material [23]. The causes related, among others, to the ceramic firing cycles, the design of the framework supporting the aesthetic ceramic coating, and so on [24–28].

To improve the fracture resistance of multilayer zirconia crowns, it has recently been suggested that the feldspathic ceramic traditionally used in the manual veneering stage can be conveniently replaced with a lithium disilicate glass–ceramic material produced in blocks suitable for milling. The framework and ceramic coating are both industrially milled, using a CAD-CAM technology, to obtain semi-processed products (with fewer structural defects in comparison with manually layered ceramic coatings). The prosthesis obtained by means of this fully digital production process have been named CAD-on by the only manufacturer currently working for the dental sector [29–31].

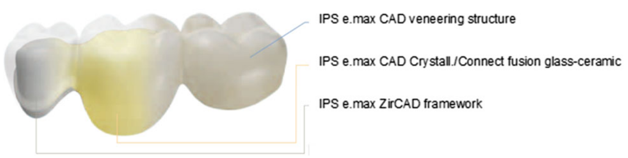


Fig. 1 Schematic view of CAD-on bridge components

IPS e.max is a lithium disilicate glass ceramic that has optimized translucency, durability and strength for full anatomical restorations (see Table 1), available as a pressed ceramic (IPS e.max Layered) and as a CAD/CAM milled restoration (IPS e.max Monolithic).

CAD-on is thus an innovative metal-free bridge and crown manufacturing technique based on the CAD-CAM processing of a framework made of zirconia (IPS e.max ZirCAD) and a veneering structure milled from small blocks of glass–ceramic containing lithium disilicate (IPS e.max CAD). The CAD-on method is appropriate for making single crowns and bridges up to 3–4 elements long on natural teeth or implants (see Fig. 1).

The steps in the physical preparation of a CAD-on prosthesis are reported in Fig. 2.

After the zirconia framework has been prepared, it undergoes sintering in a furnace. The milling process always leaves the framework approximately 20–25% larger than it will eventually need. The controlled production of the blocks is combined with an optimized high-temperature sintering process in a furnace (1500 °C) that enables the contraction of the structures previously milled to larger dimensions to be governed so as to obtain a marginal adaptation and an optimized coupling with the lithium disilicate. The definitive characteristics of the material are achieved during the sintering process, ensuring a high flexural strength (approximately 900 MPa) capable of meeting the clinical demands of the masticatory load, especially in the lateroposterior sectors.

The homogeneous glass–ceramic fusion between the two separately milled prosthetic components is achieved with a fusion glass–ceramic material (IPS e.max CAD Crystall/Connect). This fusion process takes place simultaneously with the crystallization of the lithium disilicate in a ceramic furnace at a temperature of 840–850 °C

Table 1 Material properties and schematic view of the CAD-on bridge components

Materials	Properties in compliance with ISO 6872 Dental ceramic and ISO 9693 Metal-ceramic dental restorative systems
Lithium disilicate glass ceramic [IPS e.max CAD]	Optimized translucency, durability and strength. Flexural strength (biaxial) 360 ± 60 Chemical solubility 40 ± 10 $\mu g/cm^2$ Coefficient of thermal expansion 10.15 ± 0.4 10^{-6} K^{-1}
Zirconium oxide [IPS e.max ZirCAD]	High mechanical stability, thin restoration walls and natural-looking esthetics. Flexural strength (biaxial) > 900 Mpa Chemical solubility < 100 $\mu g/cm^2$ Coefficient of thermal expansion $9.9 \leq CTE^* \leq 10.9$ 10^{-6} K^{-1}

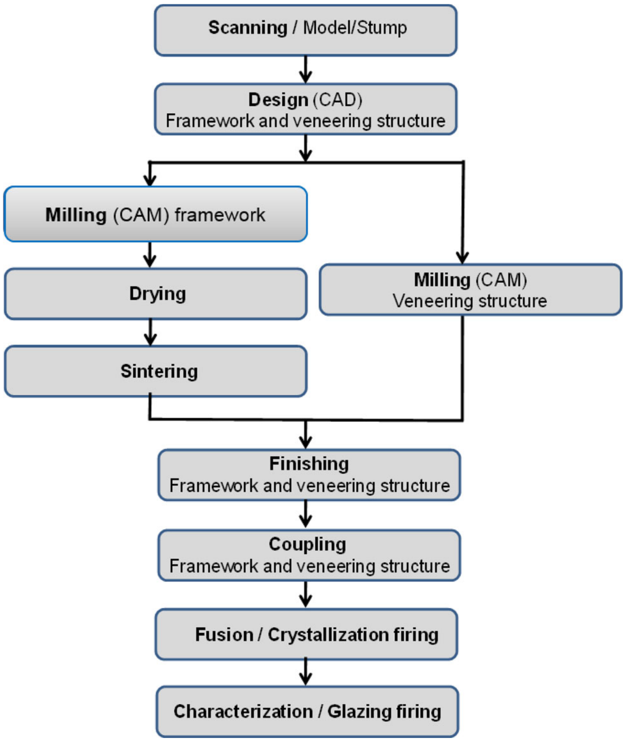


Fig. 2 Steps in the physical preparation of a CAD-on prosthesis

(fusion/crystallization). During this firing process, there is approximately a 0.2% of linear contraction of the lithium disilicate.

The ability to finish the fabrication process, possibly enabling for one-visit fabrication of restorations, is one benefit of employing a CAD-on approach for a ceramic restoration.

One critical parameter that requires defining during the design process is the interface gap between the IPS e.max ZirCAD framework and the aesthetic IPS e.max CAD outer coating that will subsequently be filled by the fusion ceramic (*MERGEFORMAT Fig. 3). Long-term clinical effectiveness of a dental repair highly depends on its marginal adaptability. An inadequate marginal adaptation raises the risk of microleakage, plaque retention, gingival inflammation, and secondary caries. Moreover, an inhomogeneous or excessive internal gap will compromise the fracture resistance of restorations. This gap is defined during the CAD phase, after designing the prosthesis to fit the considered anatomical shape. Before the milling stage, the software automatically processes the restoration into a framework and an aesthetic veneering structure, also considering the volumetric changes that take place during the firing/sintering stages, which is different for the two materials making up the prosthesis. Several parameters can be adjusted during the CAD design stage, such as the thicknesses of the connectors, margins, framework and veneering structure, the setting for the gap between the two components that the milling unit must allow for, and also the coupling taper (with a telescopic angle 0°–15°), depending on the clinical case, to facilitate the assembly of the two CAD-on prosthetic components. Agreement on the perfect virtual space value for CAD-CAM prosthesis with the best marginal adaptation is lacking. The range of gap settings in the CAD design software programs is wide (0–200 mm), and manufacturer recommendations regarding the best gap setting is not specific. As mentioned earlier, the whole process for the production of the two elements forming the CAD-on prosthesis is completed using a CAD-CAM technology, while the two parts are assembled manually by the dental technician. The clinical empirical observation is that, despite the two parts are designed to keep a certain internal gap, such gap is not preserved at the end of the process. The aim of this work is to assess whether the manual assembly phase of the two components (human variable) may influence the internal offset distance.

A consensus on the best MG evaluation method is lacking, with direct microscopy, cross sectioning, and replica methods being the most commonly used [32, 33].

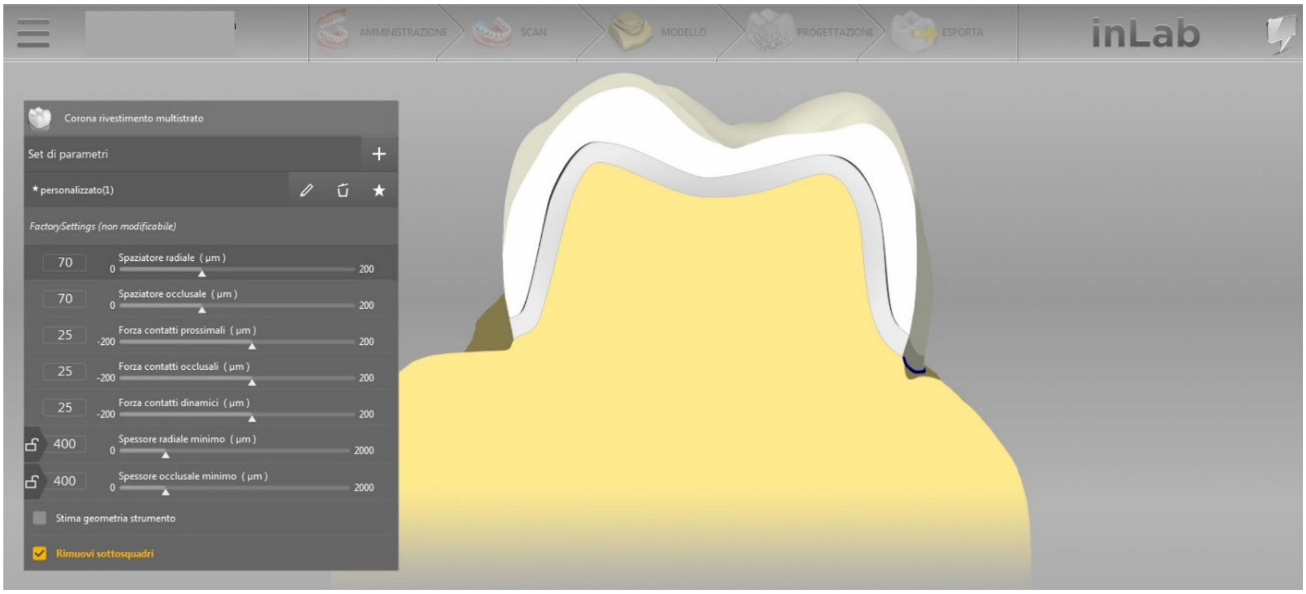
Our main research contribution is the design of a novel nondestructive gap verification methodology that involved the analysis of the geometrical coupling between the veneering structure and the framework of the CAD-on prosthesis. Starting from the plaster cast models obtained for three clinical cases, two independent dental technicians completed their own projects, selecting different settings for the gap between the two components of the multilayer prostheses during the CAM stage. The null hypothesis was that the effective internal gap on CAD-on prosthesis, manually assembled by different technicians, would not differ despite they were designed with different ideal values.

2 Materials and methods

Three real clinical cases were selected for the present study; case 1 is a bridge in the maxilla area that involved the teeth 24, 25, 26, 27; case 2 is a lower bridge that included teeth 45, 46, 47; case 3 is an upper bridge that involved teeth 24, 25, 26.

The CAD-on method was chosen in the selected cases for esthetic reasons, mainly in response to patients' requests to replace old bridges.

Metal-free prosthesis were chosen to both guarantee an optimal chromatic rendering and optimal mechanical characteristics. After obtaining traditional impressions with vinylpolysiloxane (Express™ 2 Penta Putty Soft + Express™ 2 Light Body Flow–3 M Espe), six plaster models were prepared (Fuji Rock-GC) (two for each clinical case) and mounted on articulators. The models were sent to two different dental technicians (TechA and TechB), so that each



Corona rivestimento multistrato

Set di parametri +

* personalizzato(1)

FactorySettings (non modificabile)

Spaziatore radiale (µm): 70 (0–200)
Spaziatore occlusale (µm): 70 (0–200)
Forza contatti prossimali (µm): 25 (-200–200)
Forza contatti occlusali (µm): 25 (-200–200)
Forza contatti dinamici (µm): 25 (-200–200)
Spessore radiale minimo (µm): 400 (0–2000)
Spessore occlusale minimo (µm): 400 (0–2000)

☐ Stima geometria strumento
☑ Rimuovi sottosquadri

Fig. 3 Example of the CAM settings window in the Inlab 15.0 program for manufacturing a CAD-on prosthesis (gap setting at 70 µm)

technician received three models, one for each clinical case. The technicians were asked to produce a CAD project from each model, to obtain the milled CAD-on bridges.

The technicians were asked to perform the task twice to test the robustness of their maneuvers (i.e. intraoperator repeatability), thus obtaining a total of six bridges for technician A, and other six for technician B. The technicians were asked to use different settings for the gap between the frameworks and the veneering structures: TechA chose a 70 µm gap setting, (Fig. 3) and TechB a 200 µm gap setting.

Once the design of the framework and veneering structure was completed, and the corresponding milled components was produced, the zirconia framework underwent sintering; then each pair of CAD-on prosthetic components was scanned, as separate components and then after their assembly. The scanning procedure was performed with an AURUM 3D scanner (Open Technologies Srl Rezzato, BS, Italy), with a maximum appreciable detail and single-acquisition measurement precision of 10 to 20 µm. Subsequently, the CAD-on prosthetic components were returned to the dental technicians for fusion/crystallization. Then the finished CAD-on bridges were scanned, using the same professional scanner as in the previous scanning step. Following digitization of the objects, the STL files were used for alignment, registration, and subsequent fit assessment. In the first step, the framework STL and the finished assembled bridge STL (i.e. template) were registered by manual alignment followed by a best-fit registration. In a successive step, the same protocol was applied to match the veneering structure and the template STL.

The final step was to delete the template and maintain the aligned framework STL and veneering STL for subsequent fit assessment. The 3D inspection software (Suite Geomagic 2013), to geometrically register the scans each another by aligning the framework first, the veneering then, with the assembled template; accordingly, a local 3D analysis was conducted on the internal gap between the two parts; the general procedure is depicted in Fig. 4.

This is a non-invasive method and it allows observation of numerous cross-sections, with no limitation on direction or numbers. This method also improves quality control because it can verify the internal fit of prostheses prior to intraoral installation.

To superimpose the framework and the veneering file, the template file was set as the reference data. An initial alignment was performed, followed by a best-fit alignment. After the best-fit alignment, the adaptation file was deleted, and the framework and veneering files were used as the reference and measurement data, respectively. Next, the internal gaps were measured. The difference between the reference data and measured data was recorded for each analysed case, as the mean of the sampled distances, together with the related standard deviations values.

Figure 5 shows a cross-sectional view of the aligned parts and an example of how the 3D analytical software sample the two surfaces to evaluate their relative offset. The color codes used to classify the measurements of the above-mentioned gap in preset ranges are depicted in Fig. 6.

All measured data were statistically analyzed using Matlab R2019b. The differences among the two technicians and between the measured regions were evaluated by analyzing the means and the standard deviation of each clinical case.

First, the normal distribution of the data was examined through the Jarque–Bera test, and the data were found to

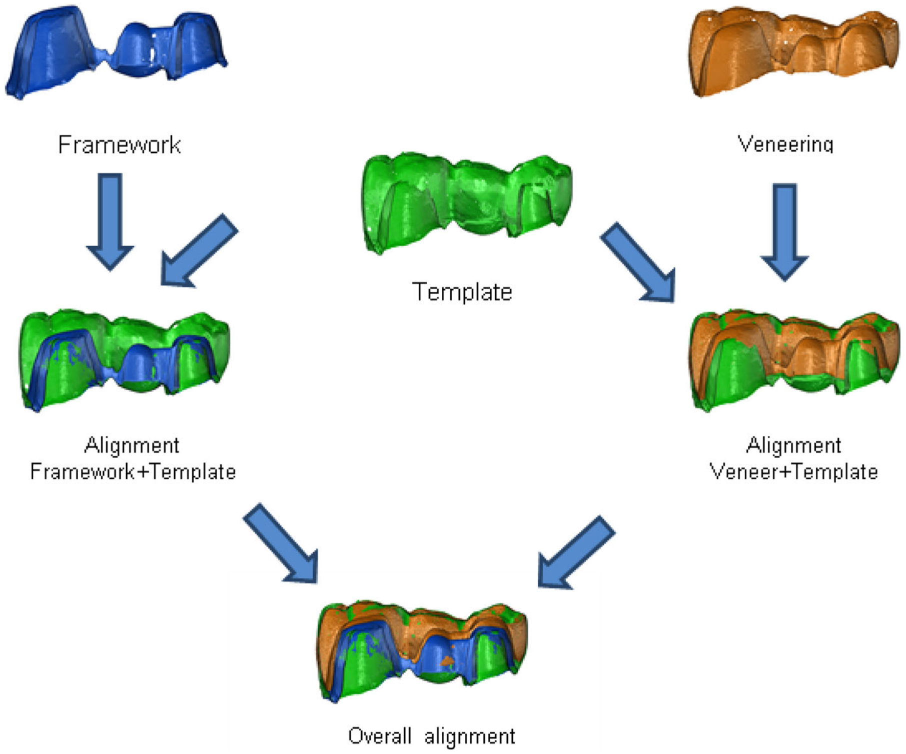


Fig. 4 Pipeline of the procedure for aligning the CAD-on prosthetic components

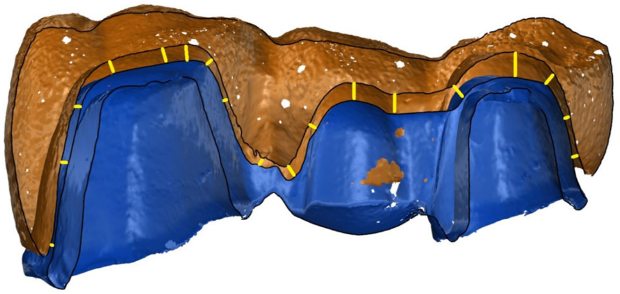


Fig. 5 Cross-sectional view of some sampled gaps between the framework and the veneering structure

be not significantly normally distributed ($p > 0.05$). For this reason, a non-parametric statistical approach (Wilcoxon signed-rank test) was conducted to determine whether the internal gaps were significantly different between each group (i.e. TechA and TechB).

3 Results

Table 2 contains a summary of the results, evaluated by applying the proposed 3D scan-based method to measure the internal gap. The table shows the mean gap between the opposite surfaces of the two bridge components, together with the standard deviation, for each sample. These data can be used to estimate the dimensional range characterizing the gaps between the opposite surfaces over the whole interface (i.e. mean ± SD).

The overall mean gap at the end of the process of all six samples is 0.34 ± 0.034 mm for technician A and 0.33 ± 0.06 mm1 for technician B.

The Wilcoxon signed-rank test revealed a statistical significance in verifying the null hypothesis, i.e. the CAD designed internal gap value is not preserved after the manual assembly phase, ($\alpha = 0.05$) that the resulting gap has the same mean value for both the technicians, despite they set a different virtual gap value during the CAD-on design phase ($p < 0.01$) while only marginally significant were obtained in the intraoperator reliability assessment ($p = 0.0313$).

It is clear from the analysis that there is no significant difference in the mean gap between the frameworks and veneering structures of the six bridges prepared by each of the two technicians.

To physically interpret these numerical values in detail and identify the differences between the two groups TechA and TechB, a local 3D analysis on the coupling between the framework and veneering structure was performed. Such analysis of the six bridges prepared by TechA, revealed very limited areas where the gap between the two components was 70 µm. Gaps up to 200 µm can be found only in very small areas, especially in the palatal areas of the samples, while most of the remaining coupling surfaces presented gaps in the range of 200–350 µm, while only on the occlusal surface the gap increases, sometimes exceeding 500 µm.

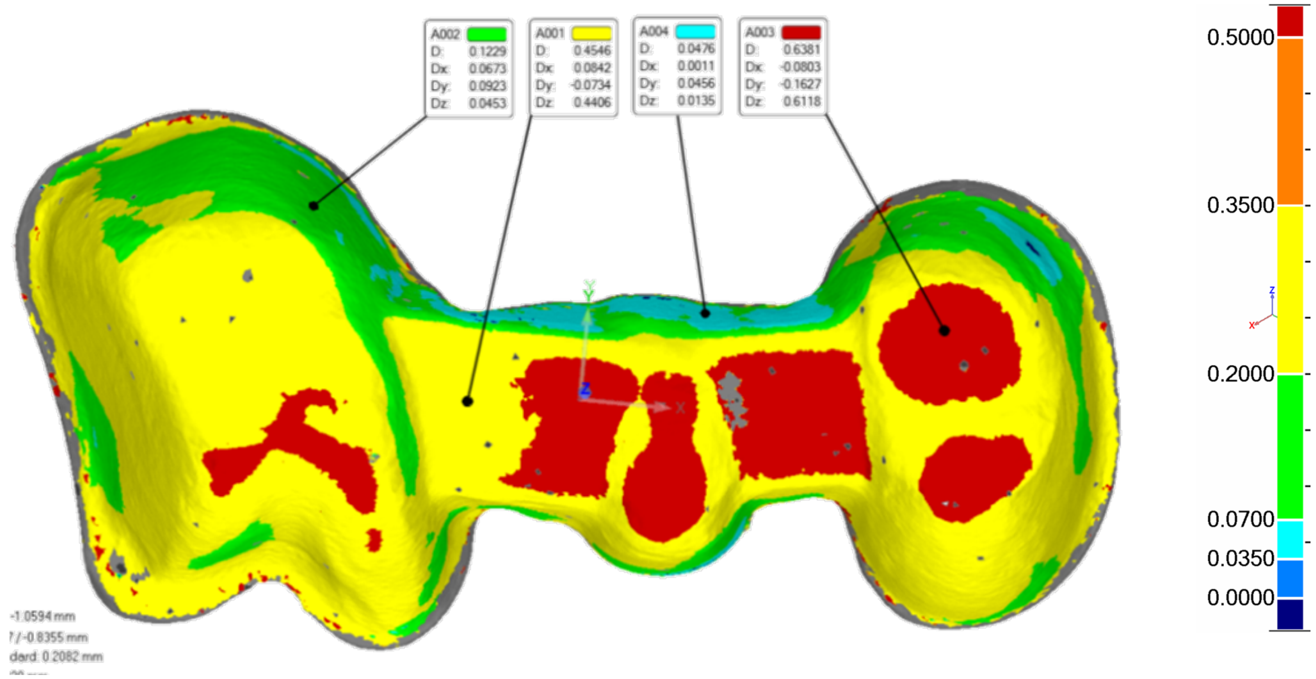


Fig. 6 Example of the 3D analysis of the gap between framework and veneering structure: each color identifies areas in the same range of gap measurements (see legend)

Table 2 Mean gaps between frameworks and veneering structures, and corresponding standard deviations

Dental technician	Sample	Mean [mm]	SD [mm]
TechA Gap setting 70 μm	1a	0.341	0.268
	1b	0.280	0.227
	2a	0.374	0.327
	2b	0.356	0.336
	3a	0.341	0.452
	3b	0.371	0.445
TechB Gap setting 200 μm	1a	0.329	0.208
	1b	0.336	0.242
	2a	0.355	0.334
	2b	0.357	0.356
	3a	0.407	0.363
	3b	0.223	0.390

Small areas of contact/friction between the framework and veneering structure can be identified in small areas where the lithium disilicate margins closed over the zirconia framework (Fig. 7).

However, there is a difference in the distribution of the areas with the narrowest gaps (between 70 and 200 μm) in some cases (Fig. 8 TechA, sample 1b, Fig. 10 TechA sample 3a and b) in which the gaps within this range were more symmetrical, in both the vestibular and the palatal regions. This is noticeable in the cases illustrated in in Fig. 10 of TechA (3a and b), where this type of crack covers a significantly larger area, more than 50% of the entire mating surface.

All the bridges prepared by TechA showed a better adaptation between the surfaces on the palatal than on the vestibular side. In all the samples, there were also some gaps with a negative sign when the meshes for the two components were superimposed. These findings probably relate to small inaccuracies occurring in the scanning and realignment of the points clouds for the CAD-on prosthetic components before their fusion-crystallization.

As for the six bridges made by TechB (Figs. 8, 9 and 10), a setting of 200 μm was chosen during the design stage for the gap between the framework and the veneering structure.

The 3D analysis of the CAD-on prostheses projects prepared by TechB on the same clinical cases using the same CAD-CAM procedures, clearly shows here again that the palatal region of the bridges had a larger area where the gap is in the range of 70–200 μm; gaps is instead wider over the whole occlusal surface and about half of the vestibular surface, where it increases to approximately 350 μm; it can be noted that the gap is greater than 500 μm over hardly half of the occlusal surface. It is only in one case, the longest bridge (Fig. 10 TechB's sample 3b), that there is a better, more even distribution of the gaps between the two prosthetic components, with more than half of the total surface area with a gap of less than 200 μm, and only a small area in the occlusal region exciding 500 μm.

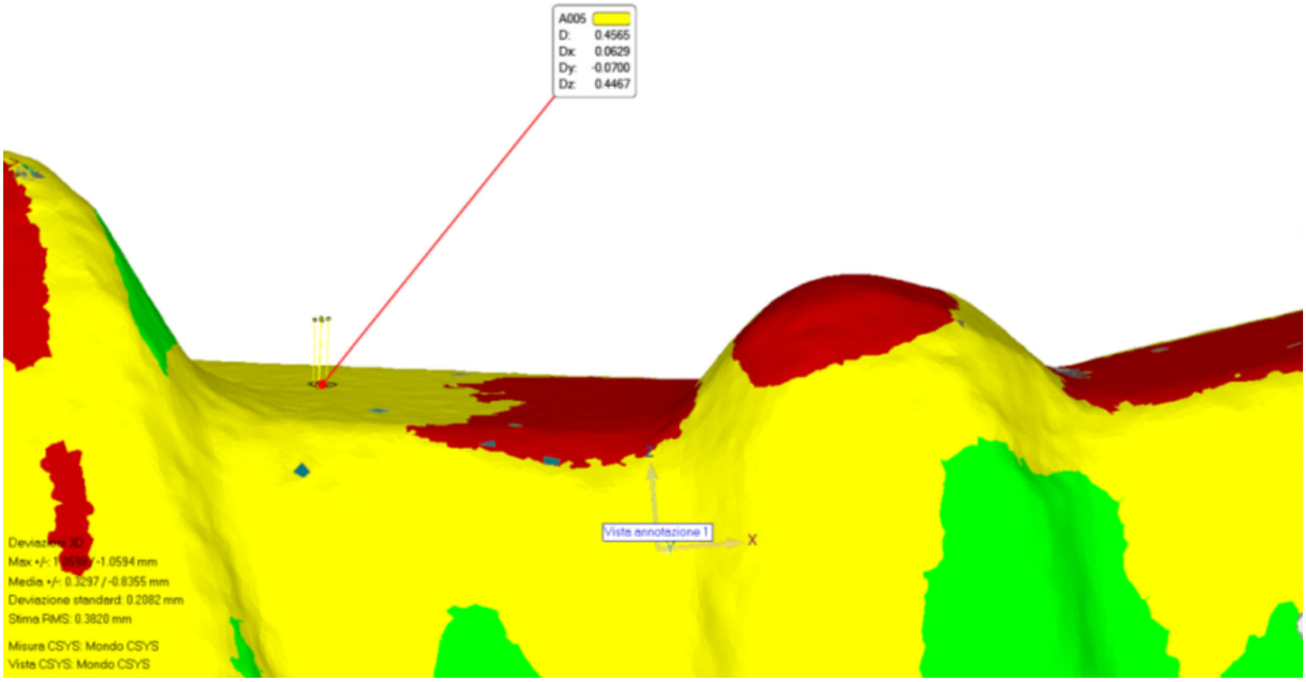


Fig. 7 Detail of the 3D analysis: the software can graphically represent differences even in very small areas

Fig. 8 3D analysis: comparison between technicians **A** and **B**, clinical case 1

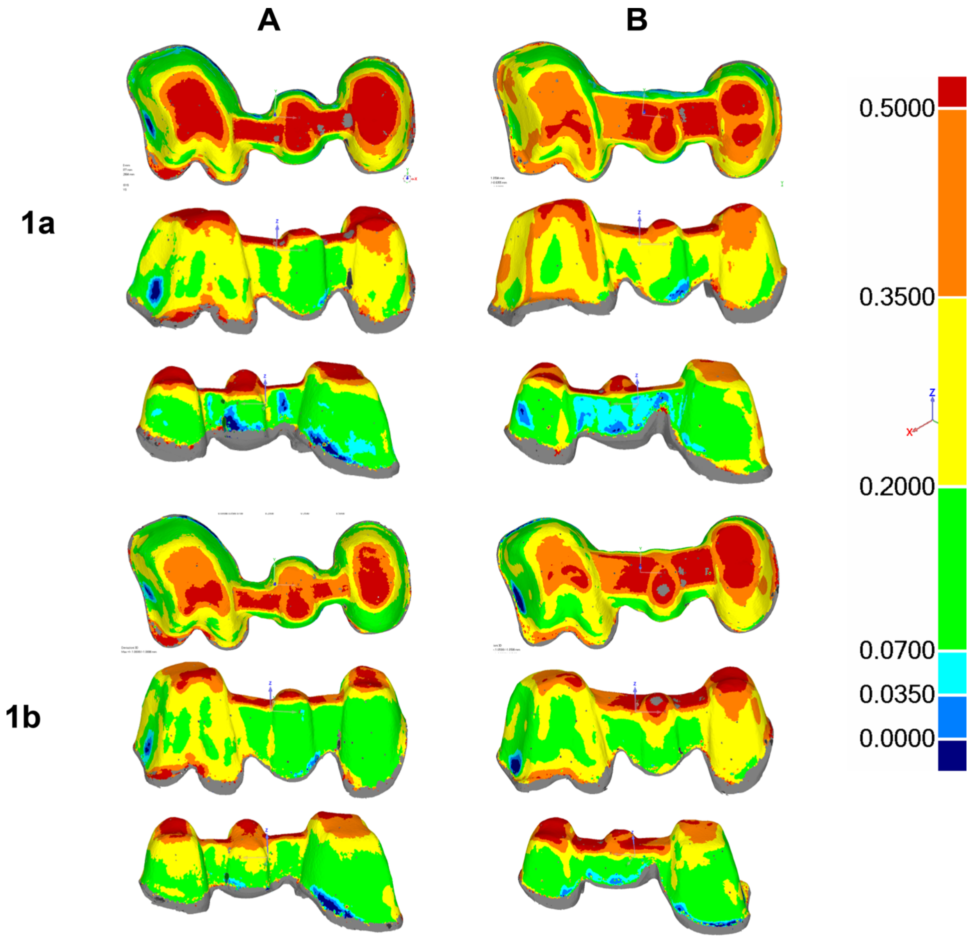
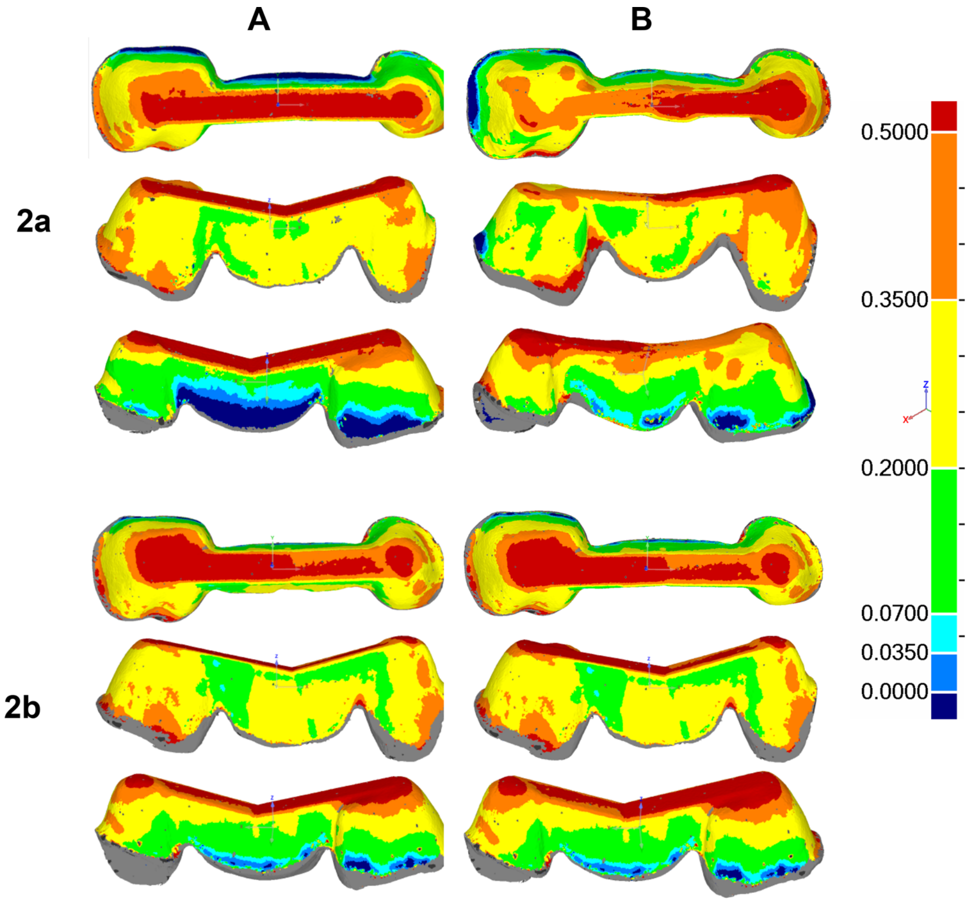


Fig. 9 3D analysis: comparison between technicians **A** and **B** clinical case 2



The bridges made by TechB also revealed a few small areas of contact with a negative gap, due to small errors in the overlap of the scans of the frameworks and veneering structures.

4 Discussion and conclusions

Chipping or flaking of ceramic coatings have been identified as a complication that can occur over time on multilayer zirconia-ceramic prostheses. The IPS e.max CAD-on technique enables the production of restorations for coupling with teeth or implants in the lateroposterior sectors using two different materials: zirconia for its excellent mechanical strength, and lithium disilicate that offers good aesthetic results combined with superior mechanical characteristics in comparison with the glass–ceramic solutions commonly used for manually applied veneers on zirconia frameworks. Both components of the CAD-on prosthesis are prepared using CAD-CAM technology, and thus exploiting the superior mechanical characteristics of the materials (which are industrially produced in small blocks), and the optimal aesthetic qualities of a coating material that is also produced for computer-controlled processing. The result is a completed prosthetic device of superior strength obtained with a more efficient production process, and a predictable quality of the finished product.

The gap between the framework and the aesthetic outer coating calculated during the design phase that will be filled by the fused ceramic, results crucial to both guarantee the expected mechanical properties and to diminish the number of retouches after the prosthesis installation. Since the act of gluing the two parts is manually performed by the dental technician, we aim at investigating the operator influence on the final gap with respect to the designed gap.

We thus proposed the design of a novel gap verification methodology that involved the analysis of the geometrical coupling between the veneering structure and the framework of the CAD-on prosthesis to assess the human interaction influence in the final bridge geometry. Two dental technicians designed their own CAD projects on the same clinical cases. They chose different settings for the gap between the two components of the multilayer prosthesis during the CAM stage, while they adopted the same configuration for the other settings between the framework and the veneering structure. Their products were compared to see how the different gap setting on the milling unit (machine variable) and the manual assembly of the two prosthetic components (human variable)

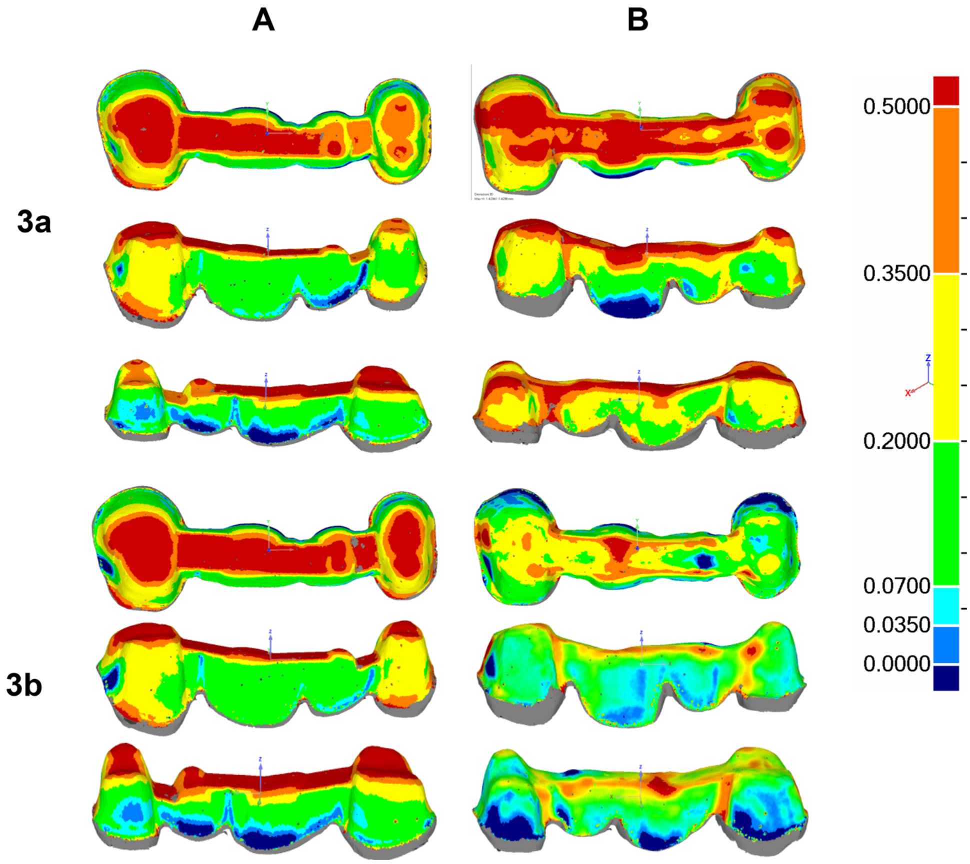


Fig. 10 3D analysis: comparison between technicians **A** and **B** clinical case 3

influenced the geometrical coupling between the framework and the veneering structure.

The results of the study confirm the first null hypothesis that there would be no difference in the internal gap of the framework and veneering parts of a cemented CAD-on prosthesis with a virtual gap setting of 70 µm or 200 µm.

The 3D analysis of our results demonstrated that the adaptation of the two CAD-on prosthetic components solely relying on a visual inspection of the effective coupling of the two parts (without the aid of a coupling template, for instance) makes this stage in the process susceptible to not preserve the virtual internal gap.

By leveraging the flexibility of the proposed 3D approach, we also analysed the local geometry of the gap between the framework and the veneering structure to provide recommendation on the choice of the best virtual gap settings according to the bridge geometry.

In the bridges prepared by TechB, using a 200 µm gap setting, there was a greater and more symmetrical distribution of the gaps between the two prosthetic components. This is probably due to the choice of a wider gap setting that facilitated the assembly stage and enabled a better coupling between the two components of the multilayer CAD-on bridge. The result was nonetheless far from the homogeneous gap that might be expected between the two components based on the machine settings adopted during the CAM stage. There was only one case (one of the longest bridges, sample 3b Fig. 10) in which there was a better, more even distribution of the gaps measured between the framework and the veneering structure, with more than half of the total surface area revealing a gap of less than 200 µm, and only a small area on the occlusal surface where the gap exceeded 500 µm.

As the CAM stages may influence the entity of the gap identified by our 3D measurements, nonetheless, there were discrepancies between what was designed as the residual gap between the two CAD-on prosthetic components and the picture identified by the 3D analysis. These discrepancies can be due, for instance, to the geometry of the coupling between the two components, and/or to the workflow involved in the production of the prosthesis, including issues that may involve the milling unit. It is also worth considering design software errors, machine calibration errors affecting the settings for the thicknesses of the prosthetic components and/or the gaps between them, wear and tear on the machine tools, and so on. Furthermore, dental technicians must manually fit the framework and veneer together, relying on a visual assessment of the connection, and this technique brings all of the flaws and risk of inherent errors in any manually completed action, no matter how thoroughly and scrupulously it is done. The samples prepared by both the technicians showed signs of small areas of contact—where the gap measured was less than 0 µm: these findings were attributable to small errors in the overlapping of the meshes representing the framework and veneering structure of each prosthesis, and therefore to the analytical method used, but they can be disregarded for the purposes of the present study.

The analysis of the clinical cases show that the dental technicians are not able to manually keep the designed gap when they manually assemble the two parts. In fact, after this phase, there were no substantial differences, in terms of accuracy of the coupling between the two CAD-on prosthetic components, between the bridges prepared by TechA and TechB, despite the different settings for the gap between the framework and the veneering structure during the CAM stage of the production process.

Even with the limitations related to the nature of the experimental method used to obtain our geometric measurements, it is reasonable to state that, although CAD-on prostheses are produced with CAD-CAM technologies, and therefore under the best possible conditions of machining precision and reproducibility, the final stage in which the framework and the coating are entirely manually assembled, cancels out any effect of the precision settings adopted during CAD-CAM design of the components, as well as any benefit expected from machining on a CNC milling machine, thus requiring, as a last step, the manual retouching of the prosthesis several times.

Based on the findings of this in study, the authors obtained the following research results:

1. The 3D scan-based method is suitable for measuring the internal 3D adaptation of bridge dental prosthesis
2. The CAD designed internal gap value is not preserved after the manual assembly phase
3. The local 3D analysis suggest choosing larger gaps to diminishing the resulting internal gap errors and to provide a more uniform offset distribution.

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